

MODERN FOUNDRY PRINCIPLES AND PRACTICE

BY

Aondona-Paul Awua Ihom

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The author of this book welcome constructive criticism that will make the work better than this first edition. All your observations forwarded to me through the publishers or directly mailed to me shall be properly addressed in the Second Edition of the book. The author wish to categorically say that he assume responsibility of any error or misrepresentation of information and shall gladly address such if brought to his notice.

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ABOUT THE AUTHOR

Aondona-Paul Awua Ihom was born during the Nigerian Civil war to Engr. & Mrs. Philip Awua Ihom of Mbagen in Benue State of Nigeria. He did his primary and secondary school in different schools this was because the father was a civil servant and was often on

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His quest to acquire excellent business management skills took him to Imo State University, Owerri where he obtained PGDM and MBA in Management. He is a member of several professional bodies and a registered engineer with the Council for the Regulation of Engineering in Nigeria (COREN). He has attended so many local and international conferences. He has vast experience, and over 120 publications in journals and professional proceedings of conferences, locally and internationally. He is also the author of several other books and a consultant to several organizations. A well trained professional who have attended several training courses at home and abroad. He is an alumnus of JICA. He worked in the research sector for fifteen (15) years before joining the services of University of Uyo in 2012. He was the Head of Foundry and Heat Treatment Shop in NMDC Jos. He is currently a Professor with the University of Uyo, Uyo-Akwa Ibom State–Nigeria. He is happily married with many children.



PREFACE

It has been predicted that the 21st Century will witness unprecedented technological revolution in all fields of engineering. This is no doubt very true; sophisticated production processes are emerging, the creativity of man and his ingenuity is at its peak and very best so to say. It is amazing today to watch 3-D printing process (layer by layer printing) where solid parts are printed in one single piece. Despite the current developments foundry technology is still very relevant in engineering and as a production process; the fact is that

foundry as a production process has also experienced its own developments, and new innovations have been introduced over the years from the design, moulding stage, down to the final casting and cleaning stages, both in terms of raw materials utilization, equipment and furnaces used. Castings, the products of the metal founding industry, are manufactured in a single step from liquid metal without intermediate operations of mechanical working such as rolling or forging, shaped castings are thus distinguished from ingots and other cast forms which are only at an intermediate stage of their metallurgical life. The basic simplicity of this, the most direct of all metallurgical processes has provided the foundation for the growth of a vast industry with a wide diversity of products. We here emphasize that the key to the development of Nigeria's automobile sector is with a well- developed foundry sector, with it we can have made in Nigeria cars and not assembled cars.

My twenty three years of engineering practice has exposed me to both theory and practice. My experience as a practical foundryman on the shop-floor, and as an academician has informed the need for this book, "Modern Foundry principles and practice". This is because there is a big difference between theory and practice. It should also be noted that experience not shared is as good as wasted knowledge. This was the case with early practitioners of foundry in Nigeria, it is on record that several parts of the country today called Nigeria, were skilled practitioners of foundry, unfortunately their knowledge of the art was not documented, and so it disappeared with them, when that generation died. In this work the author have made strenuous effort in explaining foundry technology, the first chapter is foundry technology at a glance, here the author have explained foundry and castings, the relationship with other engineering fields, advantages and disadvantages when compared with other production processes, foundry development in Nigeria, opportunities for foundry engineers, production figures of castings in the world and others are briefly explained. This book is written from a practical background, and so the arrangement of the topics reflect the importance of things in the foundry. The knowledge of how cast metals and alloys solidify is discussed in details to help the student. Furnaces and measurement in the foundry as a topic is discussed, with the need for control in foundry clearly stressed. Moulding materials properties, preparation, and testing procedures, which are rarely discussed in other foundry books are here discussed in details with diagrams and illustrations. Casting design which is very important in realizing specification of castings is treated in details with recent developments in the use of 3D-Printing at the design stage for pattern production. This book captures the whole gamut of the casting process including different casting techniques and finishing processes associated with castings production. The remaining chapters all addressed important aspects of foundry practice from inspection and quality control in the foundry to post-casting treatments and environmental issues. The melting practice for some commonly cast metals have also been examined in this book. It is the belief of the authors that this book is capable of laying a very solid foundation for students who hope to take up a career in foundry engineering. I therefore strongly recommend this book for HND, B.Eng, M.Eng programmes in Foundry engineering, Materials and Metallurgical engineering, Mechanical engineering, researchers in foundry, and other related courses offering foundry technology. Foundry practitioners will find this book very useful, the use of computers for casting simulation is now well entrenched in foundry industry; this book has captured clearly how computers are used for casting design and simulation. Researchers will equally find this book very useful, since it has very strong roots in research presentations peculiar to Nigeria. This is because it is written by a Nigerian and not an expatriate.

ACKNOWLEDGEMENTS

The author want to acknowledge his colleagues back in the days at the National Metallurgical Development Centre in Jos, together we both took on various challenges in the Foundry shop. I equally want to acknowledge all my professional colleagues who kept encouraging me to pen down my experience to assist the Nigerian student and researcher to understand more about the practice of the profession. Materials used in this work that are not original have been acknowledged by way of reference and bibliography. Lastly the author wish to acknowledge his family for been there for him during the long period of absence from home to work on this book. It is a common saying that greatness does not come without sacrifices neither do success come without hard work. Development in any

field of endeavor is a relay race and someone must stand on somebody's shoulders to be able to see far; the author therefore once more thank every source from where information was harvested during the course of this work.

Dr Aondona -Paul Awua IHOM

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STEELS MATERIAL DESIGNATION

In this book the Japanese Standard for designation system for metallic materials in Japanese Industrial Standard is used. The Japanese standard is however based on International Standard (IS). Other standards used include the imperial system, the British standard, the Deutsche system (DIN) and the S.I. system of measurement. There is therefore need to clearly explain the standards and the units used in this book so that the reader of the book will be able to comprehend.

In general, the JIS symbols for metallic materials consists of the following three parts.

1. The first part represents the sort of materials by the initial letter in English, Greek, Japanese or by the chemical symbol of elements.

For Example

S: Steel -----SS400, S10C, SCr435, SC360

S: Ferrum-----FC100, FCD700, FCMB270

F: Ferro -----FSi1, FMnH1, FW1

M: Metallic ----- MSi1, MCr, MMnE

Si: Silicon ----- SiMn3

2. The second part represent the sort of products by the initial letter of shape, application, type of processing etc, in English or Japanese, or by the chemical symbol for alloying elements.

SS -----S= Structure SACM ----- A= Al

SM ----- M = Marine SPC ----- P= Plate, C = Cold rolled

SK ----- K = Kogu (tool) SAPH ----- A = Automobile, P = Plate, H= Hot- rolled

SKH ----- H = High speed steel

SMn ----- Mn = Manganese SUP ----- U= Special use, P = Spring

SCr ----- Cr = Chromium SUJ ----- J = Jiku –Uke (Bearing)

SCM----- C =Cr, M= Mo SUS ----- S= Stainless steel

SNCM ----- N = Ni SC, FC ----- C = Castings

Exception: carbon steel for machine structural use

S10C-----10 = Midrange of % C x 100, C = Carbon steel

S15CK ----- K = Kouzou (structure)

3. The third part represent the grade of materials by the minimum tensile strength in N/mm² or midrange of carbon content, or arbitrary number.

Example

Tensile strength -----SS330, 400, 490, 540

S C360, 410, 450, 480, (Steel castings)

FC100, 150, 200, 250, 300, 350 (Grey iron castings)

FCD350, 400, 500, 600, 700, 800 (Ductile iron castings)

Midrange of % C x 100 ----- SK140, 105, 95, 90, 85, etc

Arbitrary number----- SKH2, 3, 4, 10, 51, 52, 53, 54, 55, 56, etc

SUS201, 304, 410, 430, 631 etc.

Exception: the first digit 2, 4, 6, 8, in low alloyed steels for machine structural use,

SNC236, SCM440, SNCM631, SNCM815 etc

SI Units and their Relation to Other Units

The International System of Units (SI System) is based on Six Primary Units:

Quality	Unit	Symbol
---------	------	--------

Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric Current	ampere	A
Temperature	degree Kelvin	K
Luminous Intensity	candela	cd

Multiples

SI Prefixes are used to indicate multiples and submultiples such as 10^6 or 10^{-3}

	Prefix	Symbol		Prefix	Symbol
10	deca	da	10^{-1}	deci	d
10^2	hecto	h	10^{-2}	centi	c
10^3	kilo	k	10^{-3}	milli	mm
10^6	mega	M	10^{-6}	micro	μ
10^9	giga	G	10^{-9}	nano	n
10^{12}	tera	T	10^{-12}	pico	p

Example one millionth of a metre is expressed as one micrometer, $1\mu\text{m}$.

Derived Units

The most important derived units for the foundryman are:

Quality	Units	Symbol
Force	newton	$\text{N}(\text{kgm/s}^2)$
Pressure, stress	newton per square metre or pascal	N/ m^2 (Pa)
Work, energy	joule	J (Nm)
Power, heat flow rate	watt, joule per second	W (J/s)
Temperature	degree Celcius	$^{\circ}\text{C}$
Heat flow rate	watt per square metre	W/m^2
Thermal conductivity	watt per metre degree	W/Mk
Specific heat capacity	joule per kilogram degree	J/kgK
Specific latent heat	joule per kilogram	J/kg

SI, Metric Non-SI and Non-Metric Conversions

Length

$$1\text{ in} = 25.4\text{ mm}$$

$$1\text{ ft} = 0.3048\text{ m}$$

$$1\text{ m} = 1.0936\text{ yd}$$

$$1\text{ km} = 1093.61\text{ yd} = 0.621371\text{ miles}$$

$$1\text{ mile} = 1.60934\text{ km} = 1760\text{ yd}$$

$$1\text{ yd} = 0.9144\text{ m}$$

Area

$$1\text{ in}^2 = 645.16\text{ mm}^2$$

$$1\text{ ft}^2 = 0.092903\text{ m}^2$$

$$1\text{ m}^2 = 1.19599\text{ yd}^2 = 10.7639\text{ ft}^2$$

$$1\text{ mm}^2 = 0.00155\text{ in}^2$$

$$1\text{ yd}^2 = 0.836127\text{ m}^2$$

$$1\text{ acre} = 4840\text{ yd}^2 = 4046.86\text{ m}^2 = 0.404686\text{ hectare}$$

$$1\text{ hectare} = 2.47105\text{ acres} = 10000\text{ m}^2$$

Volume:

$$1\text{ cm}^3 = 0.061024\text{ in}^3$$

$$1\text{ dm}^3 = 1\text{ L} = 0.035315\text{ ft}^3$$

$$1\text{ ft}^3 = 0.028317\text{ m}^3 = 6.22883\text{ gal (imp)}$$

$$1\text{ gal (imp)} = 4.54609\text{ L}$$

$$1\text{ in}^3 = 16.3871\text{ cm}^3$$

$$1\text{ L (litre)} = 1\text{ dm}^3 = 0.001\text{ m}^3 = 0.21997\text{ gal (imp)}$$

$$1\text{ m}^3 = 1.30795\text{ yd}^3 = 35.3147\text{ ft}^3$$

$$1\text{ pt (pint)} = 0.568261\text{ L}$$

$$1\text{ US gal} = 3.78541\text{ L} = 0.832674\text{ gal (imp)}$$

$$1\text{ ft}^3/\text{min (cfm)} = 1.699\text{ m}^3/\text{h}$$

$$1\text{ ft}^3/\text{sec} = 28.3168\text{ L/s}$$

Mass:

$$1\text{ lb (pound)} = 0.453592\text{ kg}$$

$$1\text{ cwt} = 50.802\text{ kg}$$

$$1\text{ kg} = 2.20462\text{ lb}$$

$$1\text{ oz} = 28.349\text{ g}$$

$$1\text{ ton} = 2240\text{ lb} = 1.01605\text{ t (tonne)} = 1016.05\text{ kg}$$

$$1\text{ ton (US)} = 2000\text{ lb} = 907.185\text{ kg}$$

Force:

$$1\text{kgf } 9.80665\text{N} = 2.20462\text{ lbf} = 1\text{kp (kilopond)}$$

$$1\text{lbf} = 4.44822\text{ N}$$

$$1\text{pdl (poundal)} = 0.138255\text{N}$$

Density:

$$1\text{kg/m}^3 = 0.062428\text{ lb/ft}^3$$

$$1\text{lb/ ft}^3 = 16.0185\text{kg/m}^3$$

$$1\text{g/cm}^3 = 1000\text{kg/ m}^3$$

Pressure, Stress:

$$1\text{kgf/cm}^2 = 98.0665\text{kPa (kN/ m}^2)$$

$$1\text{kgf/ mm}^2 = 9.80665\text{ N/mm}^2 = 1422.33\text{lbf/in}^2 = 0.63497\text{ tonf/in}^2$$

$$1\text{lbf/in}^2 (\text{psi}) = 6.89476\text{kPa (kN/m}^2)$$

$$1\text{Pa (N/m}^2) = 0.000145038\text{ lbf/in}^2$$

$$1\text{ in w.g. (in H}_2\text{O)} = 249.089\text{ Pa}$$

$$1\text{N/mm}^2 = 1\text{MPa} = 145.038\text{lbf/in}^2 = 0.06475\text{ tonf/in}^2 = 0.10197\text{ kgf/cm}^2$$

Power:

$$1\text{kW} = 3412\text{ Btu/ hr}$$

$$1\text{hp} = (\text{horsepower}) = 0.745700\text{kW}$$

Energy , heat, work:

$$1\text{Btu} = 1.05506\text{ kJ}$$

$$1\text{cal} = 4.1868\text{J}$$

$$1\text{kWh} = 3.6\text{MJ} = 3412\text{ Btu}$$

$$1\text{therm} = 100000\text{ Btu} = 105.506\text{ MJ}$$

$$1\text{kJ} = 0.277778\text{ W. h}$$

Specific heat capacity, heat transfer:

$$1\text{ cal/ g } ^\circ\text{C} = 1\text{kcal / kg}^\circ\text{C} = 4.1868\text{J/ kg.K}$$

$$1\text{Btu/lb}^\circ\text{F} = 4.1868\text{J/kg.K}$$

$$1\text{Btu/h} = 0.293071\text{W}$$

$$1\text{cal/ cm.s}^\circ\text{C} = 418.68\text{ W/m.K (thermal conductivity)}$$

$$1\text{Btu.in/ft}^2\text{h}^\circ\text{F} = 0.144228\text{ W/m.K (thermal conductivity)}$$

$$1\text{ Btu/ ft}^2\text{h}^\circ\text{F} = 5.67826\text{ W/ m}^2\text{.K (heat transfer coefficient)}$$

Miscellaneous:

1 standard atmosphere = 101.325 kPa = 760 mm Hg = 1.01325 bar

1 bar = 100 kPa = 14.5038 lbf/in²

1 Cp (centipoise) = 1 mPa.s

1 cSt (centistokes) = 1 mm²/s

1 cycle/s = 1 Hz (Herzt)

1 hp = 745.7 W

Useful approximations:

1 Btu = 1 kJ 1 kg = $2\frac{1}{4}$ lb

1 ft = 30 cm 1 kgf = 10 N

1 gal = $4\frac{1}{2}$ L 1 Standard atmosphere = 1 bar

1 ha = $2\frac{1}{2}$ acres 1 km = $\frac{5}{8}$ mile

1 hp = $\frac{3}{4}$ kW 1 litre = $1\frac{3}{4}$ pint

1 in = 25 mm 1 lbf = $4\frac{1}{2}$ N

1 therm = 100 MJ 1 yd = 0.9 m

1 tonf/in² = 15 N/mm²

1 psi (lbf/in²) = 7 kPa

1 N (newton) = the weight of a small apple!

Temperature:

°F = 1.8 x °C + 32

°C = (°F – 32) / 1.8

0°C (Celsius) = 273.15 K (Kelvin)

Conversion Table of Stress Values

American (lb/ in ²)	Equivalent stresses		SI (N/ mm ²)
	British (ton/ in ²)	metric (kgf/ mm ²)	
250	0.112	0.176	1.724
500	0.223	0.352	3.447
1000	0.446	0.703	6.895
2000	0.893	1.406	13.789
3000	1.339	2.109	20.684

4000	1.788	2.812	27.579
5000	2.232	3.515	34.474
10000	4.464	7.031	68.947
15000	6.696	10.546	103.421
20000	8.929	14.062	137.894
25000	11.161	17.577	172.368
30000	13.393	21.092	206.841
35000	15.652	24.608	241.315
40000	17.875	28.123	275.788
45000	20.089	31.639	310.262
50000	22.321	35.154	344.735
55000	24.554	38.670	379.209
60000	26.786	42.185	413.682
65000	29.018	45.700	448.156
70000	31.250	49.216	482.629
75000	33.482	52.731	517.103
80000	35.714	56.247	551.576
85000	37.946	59.762	586.050
90000	40.179	63.277	620.523
95000	42.411	66.793	654.997
100000	44.643	70.308	689.470
Conversions			
10000	4.464	7.031	68.947
22399	10	15.749	154.438
14223	6.349	10	98.066
14504	6.475	10.197	100

Other books by Engr. Dr. A.P. Ihom include the following:

1. Foundry Raw Materials and Testing Procedures
2. Self Curing Binder System for Core Making
3. Perilous times
4. Surface Finishing Engineering and Technology for Engineers and Scientists (coauthored with Engr. Prof. Aniekan Offiong)
5. Fundamentals of Foundry Technology (Co-authored by A.P. Ihom, Cyril Ocheri and Aniekan Offiong)

6. Not a Lost Battle
7. The Mysterious Duplex by the side of the Ocean
8. Foundry, Metal Joining and Finishing Technology

CHAPTER ONE

FOUNDRY TECHNOLOGY AT A GLANCE

INTRODUCTION

Castings, the products of the metal founding industry, are manufactured in a single step from liquid metal without intermediate operations of mechanical working such as rolling or forging, shaped castings are thus distinguished from ingots and other cast forms which are only at an intermediate stage of their metallurgical life. The basic simplicity of this, the most direct of all metallurgical processes has provided the foundation for the growth of a vast industry with a wide diversity of products (Beeley, 1982).

The foundry industry does not exist in a vacuum. Due to the scope of the foundry industry and the widespread use of castings, engineers often find themselves in a position where a knowledge of foundry processes and casting problems have become a vital part of their work.

Design of castings, specifications, intelligent use of properties of cast metals, purchase of castings, and processing of castings, all require the application of engineering principles unique to casting and foundry process.

The engineer who designs a casting must have accurate information about the properties of the cast metal he would use. Further he may have sufficient knowledge of economics that minimize moulding, coring and other foundry overhead costs. Aside, foundry has a lot to do with material science, industrial engineering and production engineering.

Fig. 1.1 vividly illustrates the interdependence of technologies in a production foundry.

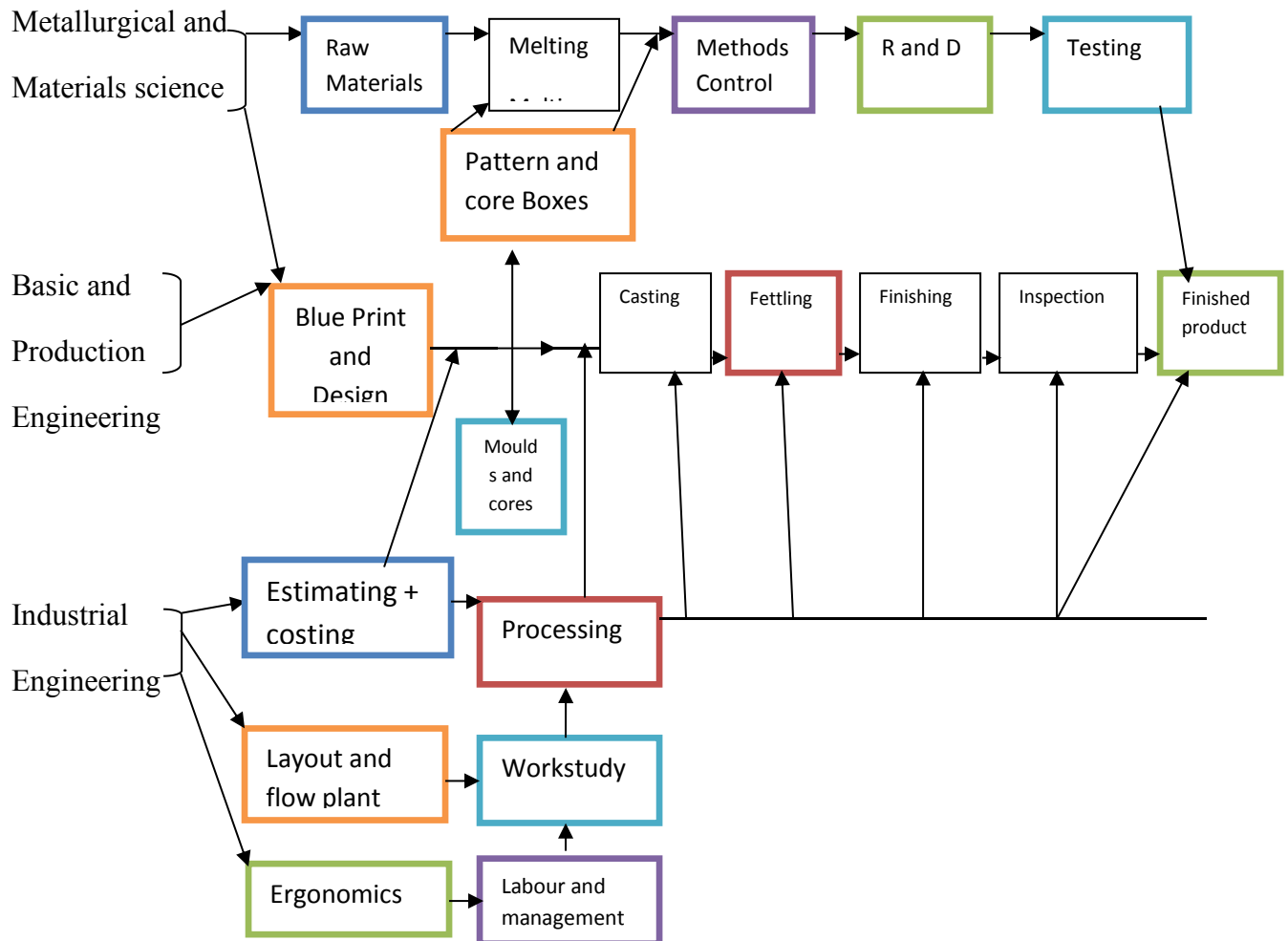


Fig. 1:1 Interdependence of technologies in production foundries Source: Rund (2000)

Availability of Metals

Of the 102 chemical elements (as of 1969) that have been isolated, approximately 70 are metallic, and about 40 of the metals are used commercially. Only 8 elements are used in common engineering alloys: aluminium, copper, iron, lead, magnesium, nickel, tin, and zinc, the 32 are not considered basic engineering metals, either because the supplies are limited or because extraction from their ores is expensive. These metals, however, are important in metallurgy because they are responsible for the important properties of many alloys. Among the most important are antimony, beryllium, calcium, cobalt, chromium, manganese, mercury, molybdenum, titanium, tungsten, vanadium, and zirconium. Some of these metals are not available in Nigeria, and must be imported if needed. Of the basic engineering metals only

aluminium, iron, and magnesium are present in the earth's crust to the extent of or more than 2 percent. They are found in physical or chemical combination with other elements, and must be extracted from their ores and purified for use. Many of our most useful metals, including copper, lead, and zinc, are present in large amounts, although in much less quantities than are aluminium, iron, and magnesium. Such metals as gold, platinum, and silver occur in only relatively very small amounts.

A perusal at the periodic table shows that about $\frac{2}{3}$ of the 110 elements currently shown in the table are metals. Imagine for instance that the following metals do not exist!

Iron and steel	-	probably the most important metal/alloy
Aluminium	-	The light metal
Copper	-	Conductivity metal
Lead	-	Plumber's metal
Tin	-	The metal that tins the can
Nickel	-	The versatile metal
Magnesium/Beryllium	-	Ultralight metal
Titanium	-	The strong middle weight
Chromium	-	Stainless steel
Tungsten	-	The filament metal
Gold, Silver, Platinum	-	The precious trio
Gallium	-	The transistor metal
Tantalum	-	The condenser metal
Cadmium	-	Weather resistor
Osmium	-	The heaviest metal
Lithium	-	The light metal
Calcium, potassium, sodium	-	The reactive metals
Mercury	-	The liquid metal
Niobium, Zirconium, Selenium, Tellurium	-	Some new arrival
Indium, Rhodium	-	Some rare metals
Plutonium, Radium, Thorium, Uranium	-	Radioactive metals

Practically, all metals are initially cast either directly or indirectly into the final shape or into intermediate shapes or ingots which may then be mechanically worked by rolling, forging, drawing, extrusion among others to obtain desired shapes (Ihom and Adeajaiyi, 2014).

Development of Foundry

A foundry is a commercial establishment for producing castings. A casting may be defined as a metal object obtained by allowing molten metal to solidify in a mould, the shape of the object being determined by the shape of the mould cavity.

From the beginning, foundry technique developed in three distinct directions. First, the extraction of the metal from the ore by the use of furnaces. Secondly, especially in the case of iron, the refinement of metal by treating the metal mechanically (by hammering). Finally, casting of liquid metals in moulds to obtain objects of everyday use or work of art.

The foundry industry dated as early as 5,000 BC. The art of metal casting is very old and it remains one of the world's basic industries. As early as 9th century hot wax techniques were practiced. At the end of the middle age, the early renaissance witnessed a general revival and development of metallurgy and iron making; waterwheels produced power for the drop hammer and the rolling mills were introduced. Very important is the work of Georg Agricola or to give his Latin name, Agricola, who came to Saxony and whose *De re Metallica* was published in 1506, this gave reliable information on mining and metallurgical techniques. Biringuccio was the first to describe a furnace which would provide the high temperatures necessary to obtain virgin cast iron: starting with the low Catalan ovens, he raised the height to over six feet and provided a square section of about 20 inches. Then came French Cupola Ovens, the English shaft furnace, the German Stiefkoben, the Swedish and Finnish types – Osmund (lump) furnaces often designed exclusively for the production of cast iron. They were eighteen feet high and by working continuously achieved an enormous saving in fuel. Known as flussifens, these furnaces were regarded as the modern blast furnace. This was the turning point in iron metallurgy.

After about a century, pig iron already employed for casting, would also be used for the mass production of steel. By 1600 open-hearth furnaces for the refinement of cast iron came into use for casting purposes. In 1707 Abraham Darby introduced the first cast iron into England for the manufacturing of pipes and household articles. It was in England that the first attempt to use (roasted fossil coal) coke was made because the blast furnace had completely devoured the forest.

In the field of steel making, rolling mills had also become part of industry, while machine tools for cold working metals were developing rapidly. By the middle of the 19th century the foundation had been laid for the highly gifted inventor Henry Bessemer, to design his converter which assumed the quick, economical and easy production of steel and cast iron. At this point a new chapter in the history of metallurgy was opened, the transition from craftwork to large scale industry (Ihom and Adeajaiyi, 2014).

1.1 The History of the Foundry Industry in Nigeria.

The industry's product, castings, enters into every field in which metals serve man. Castings are used in transportation, communication, construction, agriculture, power generators, in aerospace, and atomic energy applications, and in other activities too numerous to describe. Because of their wide spread use, castings are produced almost everywhere that manufacturing occurs (Heine et al, 1967)

Foundry practice in Nigeria is said to be dated back to the 10th century, which is the era of the Ogiso Dynasty of the Benin kingdom in Nigeria, during which bronze castings were specially made for the Oba. The Oba used these bronze castings to decorate the palace for the purpose of recording events and the worship of his ancestors. Some palaces in Ile-Ife (Osun state), Awka and Igbo-Ukwu (Anambra state), to mention but a few; started metal fabrication by casting in the early ages (Olanrewaju and Oyetunji, 2008). There is abundance archeological evidence that iron was being smelted in the Northern and Central parts of Nigeria by the later part of the first millennium B.C. This development enhanced the capability to clear the forests for agriculture, dig wells for water and produce beautiful and complex works in terracotta designated as belonging to the Nok culture. It was not really clear the technology that was used to produce the artifacts use in production, but excavation in Tagura about 55 kilometers South-East of Abuja led to the discovery of thirteen iron-smelting furnaces and iron artifacts dated to around four century B.C., the oldest so far discovered in West Africa.

Other excavations made in Bussa are, Borgu in 1966 to 1968 and 1975 showed that these also were agricultural communities using iron tools before the end of the first millennium B.C. About 200 objects made of iron were discovered. The thirteen furnaces excavated were all low shaft furnaces consisting of pits dug into the ground and containing slag and charcoal. Some tuyeres were found, though not in position. Iron was smelted probably from limestone and hematite pebbles, magnetic sand and ferrigenous sand stone all of which are abundant in many part of Nigeria.

One interesting aspect of the development of metallurgy in Nigeria is the fact that the Iron Age preceded the Bronze Age, unlike the other parts of the world. The first bronze castings discovered in Nigeria were at Igbo-Ukwu, about 40km South-East of Onitsha, which by radio-carbon dating can be traced to the 9th to 10th centuries A.D. the excavations made at Ile-Ife about the turn of the last century were rather stimulating.

A national survey conducted by National Committee on Industrial Development (NCID) Project team in 1991 revealed that there were about 50 foundries in Nigeria with a total installed capacity of 35,350 tonnes of cast iron, 1350 tonnes of steel and 3,350 tonnes of nonferrous castings (Agboola, 2008). Furthermore, the report of the strategic consultative group on foundries and forges, 1991 put the average capacity utilization of foundries in Nigeria at 15%. Consequently, the annual production of foundry castings in the country was as follows:

Grey Cast iron -	5,302 tonnes
Steel -	202.5 tonnes
Non-ferrous -	450 tonnes

Total for all foundries in Nigeria – 5,954.5 tonnes.

Annual casting output per foundry from the above was :

Grey cast iron -	106 tonnes
Steel -	4.1 tonnes
Non-ferrous -	9.0 tonnes
Total:	119.1 tonnes

According to Nwajagu and Ugwuoke (1996) in Ihom and Onche (2007), Nigeria has a total of 60 foundries, five of which are commercial. (This figure showed that additional 10 foundries came on stage between 1991 to 1996). The authors put the capacity of the Nigerian foundry industry at about 152,700 tonnes per annum. The 60 foundries mentioned above fall under small scale foundry industry. Today, far less than the 60 foundries mentioned as existing in 1996 still exist, this is due to their inability to cope with energy cost, and labour cost as occasioned by the issue of the minimum wage in the country. Most foundries in Nigeria can be described as nonferrous and cast iron foundries. Currently less than 10 foundries in the country have the capacity to melt steel (Ihom and Onche, 2007). To understand how underdeveloped the foundry industry is in Nigeria, we would compare the production figures above with those of other developed and developing countries. According to Foundry International Trade Journal of March, 1991, Japan has about 1,513 foundries in 1989, producing a total of 7.81 million tonnes of castings with a breakdown as follows:

Iron casting	6949 tonnes
Cast iron pipes and fittings	22678 tonnes
Malleable cast iron	7346 tonnes
Steel castings	3993 tonnes
Nonferrous metal casting	1219 tonnes
Die casting	4,005 tonnes
Precision castings	283 tonnes
Total	46473 tonnes

As far back as 1980, statistics in the world foundry directory showed that India has about 7000 foundries producing castings as follows:

Grey cast iron	1,350,000 tonnes
Malleable iron	21300 tonnes
Special grade iron	6900 tonnes
Steel castings	75, 000 tonnes
Nonferrous	60000 tonnes
Total	2,513,200 tonnes

Thus, annual casting output per foundry in India is as follows:

Grey cast iron	3,357 tonnes
Malleable iron	30400 tonnes
Special grade iron	0.99 tonnes
Steel castings	10.71 tonnes
Nonferrous	8.57 tonnes
Total	3, 681.27 tonnes

The current figures for foundries in India has since exceeded 7000

According to federal office of statistics report of 1981 to 1985, the National demand pattern of cast productions have steadily increased from 192,000 tonnes annually in 1981 to 292,000 tonnes in 1985 for which the National Committee on Foundry Development estimated 40% of these requirements as automotive components and spares (Agboola, 2008).

Modern foundry in Nigeria started with the establishment of a captive foundry in the 1930s by the Nigerian railways where brake shoes and other spare parts were produced (Ihom, 2012). Nigerian Foundries Limited (NFL) Lagos was established in 1969 by a private investor having realized the roles the foundry industries will serve to Nigeria's technological development and possibly solve the problem of non-availability of spare parts that are likely to be facing most industries in Nigeria (Oyetunji, 2005). The integrated steel companies of Ajaokuta, and Delta Steel Company Aladja all have a captive foundry with the capacity to meet their internal spare part needs as well as that of other companies. Table 1.1 shows foundry capacities and distribution in Nigeria as at 2002. Most of the companies in the table are no longer in production, while others are producing on skeletal basis. Much needs to be done in reviving the foundry in Nigeria, if Nigeria's drive to become an industrialized country is to be met. One cannot see Nigeria achieving her vision 2020:20 without her reviving the foundry sector: which is a veritable tool for industrial development.

Table 1.1: Foundry Capacities and Distribution in Nigeria as at 2002

S/N	Foundry	Location (State)	Installed Capacities Tons/annum (Public Sector Foundries)		
			Cast	Steel	Non-ferrous
1	Ajaokuta Steel Company Ltd.	Kogi	3550	3,260	190
2	Delta Steel Company Ltd, Aladja (GIHLN)	Delta	400	800	-

3	ARCEDEM, Ibadan	Oyo	2,500	-	-
4	FIRRO, Oshodi	Lagos	200	-	100
5	Nigerian Railways Corporation, Ebute-Metta	Lagos	2,500	-	100
6	University of Lagos	Lagos	50	-	25
7	Nigerian Ports Authority	Lagos	500	-	-
8	Federal Science Equipment Centre, Akure	Ondo	100	-	-
9	Government Technical College, Enugu	Enugu	60	-	-
10	Project Development Institute, Enugu	Enugu	500	-	100
11	Nigerian Railway Corporation, Enugu	Enugu	500	-	200
12	NMDC Jos	Plateau	15	-	100
13	Defence Industries Corporation, Kaduna	Kaduna	1500	-	100
14	Industries Development Centre, Zaria	Kaduna	N/A	-	N/A
15	Council for Appropriate Technology, Ilorin	Kwara	N/A	-	N/A
16	University of Ilorin	Kwara	N/A	-	N/A
17	Federal Ministry of Works and Housing, Ijora	Lagos	N/A	-	N/A
18	Oyo State Ministry of Works Eleyele, Ibadan	Oyo	N/A	-	N/A
19	Kwara Polytechnic	Kwara	N/A	-	N/A
20	Nigeria machine Tools Limited, Oshogbo	Osun	700	1200	N/A
21	Abayomi Foundry Engineering Works, Ibadan	Oyo	500	-	40

22	Adebowale Engrg. Services	Ogun	6,000	-	200
23	Adilis Engineering Ltd. Isolo	Lagos	300	150	180
24	Modern Foundry Products, Apapa	Lagos	-	-	750
25	Nigerian Sugar Company, Bacita	Kwara	70	-	20
26	Selia Industries, Offa	Kwara	1,000	-	N/A
27	Sudic Aluminum Manufacturing Company Limited, Ibadan	Oyo	-	-	180
28	Systemax Foundries & Engineering Works, Oshodi	Lagos	400	-	-
29	Western Nigeria Tech. Co. Ltd, Ibadan	Oyo	100	-	-
30	Muhawak Co. Ltd, Owo	Ondo	60	-	15
31	Union Steel Company, Ajaseipo	Kwara	800	-	-
32	Auto Components Ltd., Otta	Ogun	500	-	N/A
33	Aqua Agro Nig. Ltd. Isolo	Lagos	1,000	-	N/A
34	Continental Foundry Ltd., Akiode	Lagos	800	-	200
35	Nigerian Foundries, Ilupeju	Lagos	2,200	1,200	-
36	Grand Foundry Ltd., Ikeja	Lagos	3,000	1,200	125
37	Emcast Limited	Lagos	500	-	25
38	Standard Foundries, Akure	Ondo	500	1,500	-
39	Jimex Industries, Nnewi	Anambra	500	-	600
40	Olympic Tech. Works Ltd., Abagana	Anambra	1,200	-	N/A
41	Bamford International, Jos	Plateau	6,625	-	-
42	Golden Unique Enterprises Ltd., Kaduna	Kaduna	850	-	-
43	Kaduna Machine Works Ltd.	Kaduna	500	-	-
44	Basic Tech. Industries, Kano	Kano	1,000	-	310
45	Total Steel, Kaduna (2007)	Kaduna			

46	Camplast Lagos	Lagos			
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Source: Report of the Strategic Consultation Group on Foundries & Forges, 2002.

1.2 Shaping Processes

The principal methods of shaping metals may be classified in five groups:

1. **Casting:** The production of shaped articles by pouring molten metal into moulds.
2. **Mechanical working:** The shaping of metals in the solid state by plastic deformation above or below the recrystallization temperature – by hot or cold working. The starting point for this group of processes is the cast ingot or billet and the metal must possess the capacity for plastic deformation. Much output in this category is of standard primary or semi-finished shapes such as bars, plates, sheets and sections, produced by rolling and extrusion and providing the basic material for further shaping operations. Other mechanical working processes, for example forging, produce varied shapes more directly analogous to castings.
3. **Fabrication by Joining:** The production of structural units by the joining of smaller components manufactured in other ways. The most notable method employed is welding, much of which is carried out using components cut from standard wrought materials. Weld-fabrications compete directly with castings over a considerable weight range, but composite structures are also produced in which the two processes can be combined to mutual advantage. Welding is also extensively used for the assembly of very large monolithic structures; applied on this scale as a field joining process, however, welding is in competition not with founding but with reversioning, bolting and other fastening devices.
4. **Machining:** The production of shaped articles by cutting from plain or roughly shaped wholly by cutting from blanks, machining is also frequently needed as a finishing operation to develop accurate final dimensions on components formed by other methods.
5. **Powder metallurgy:** The production of shaped parts by the die pressing and sintering of metal powders.

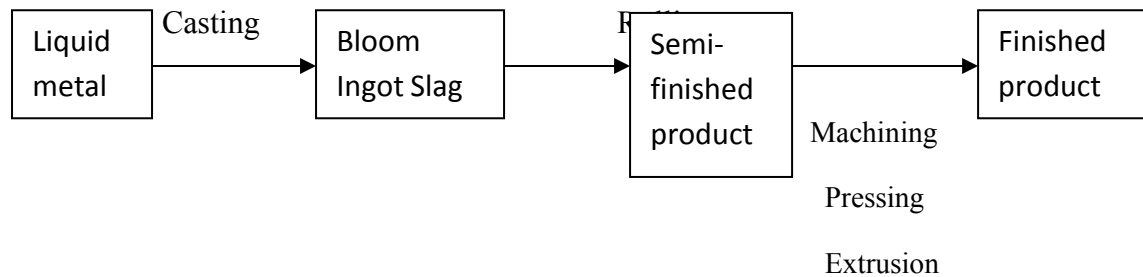
Consideration of this brief outline shows that the main shaping processes are in many respects complementary. Over wide fields, however, their capabilities overlap, allowing alternative decisions and providing a basis for competition with respect to properties and cost, castings must variously compete with forgings, weldments, and sintered compacts, quite apart from plastics, ceramics and other non-metallic materials (Beeley, 1982).

Manufacturing Processes

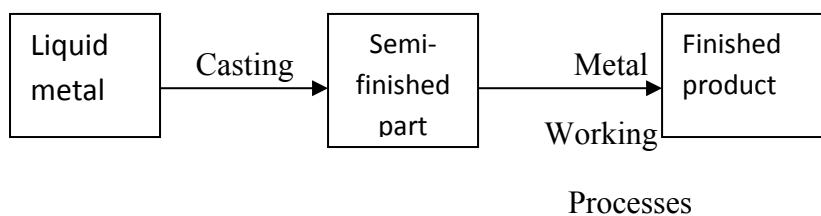
This is transformation of materials from one physical state to another. There are many options in manufacturing processes from the liquid metal to the finished product.

Three prominent routes are represented in figure 1.2:

Route 1



Route 2



Route 3

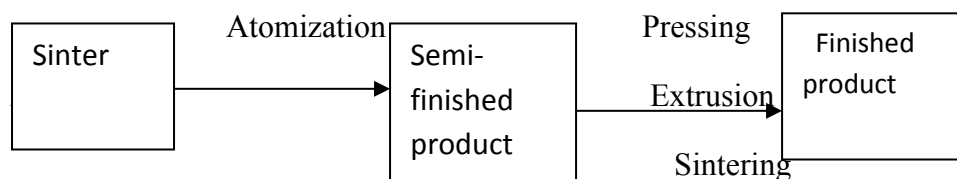


Figure 1.2: Three prominent routes of production

In choosing a method, these factors must be borne in mind:

- i. Cost
- ii. Metal property
- iii. Dimensional tolerances, microstructural and mechanical properties of finished product.
- iv. Complexity or otherwise of the desired finished product.

(1) **Cost:** Going through route 1, a manufacturer is likely to incur more cost than route 3, but cost is not the sole controlling factor for the manufacturing method.

(2) Properties of the engineering materials are taken cognizance of: for example, titanium cannot be rolled. Stellite cannot be rolled, forged or machined.

Zirconium is extremely difficult to machine. Hence method (1) is not an appropriate manufacturing process; the most applicable method is the one of powder metallurgy.

(3) Another factor affecting the choice of manufacturing processes is dimensional tolerance, microstructural and mechanical properties of finished product.

In the manufacturing of a machine tool, say a bolt is required with dimensional accuracy of 10 ± 0.001 and process (1) is chosen (casting has the poorest tolerance), the product has to be machined. Method 3 has greater tolerance. Powder metallurgy has assumed an important manufacturing process in recent times because it has its own advantages over casting, which include the following:

(i) **Climate:** High humidity and high temperature favour corrosion, powder metallurgy is considered advantageous.

(ii) **Technological Backwardness:** Where intricate machine parts are not easily cast by casting, powder metallurgy is an answer.

(4) **Complexity of the finished product:** This determines which of the three options/processes is to be chosen. It is better for example, for an engine block to be cast rather than machine.

We see that none of these factors can be considered alone. Serious consideration are given to these factors one after the other in order to reach a decision as to which method is to be employed to manufacture a particular finished product.

1.3 Advantages of the Metal-Casting Process

Certain advantages are inherent in the metal-casting process. These may form the basis for choosing casting as a process to be preferred over other shaping processes in a particular case. Some of the reasons for the success of the casting process are as follows:-

1. The most intricate of shapes, both external and internal, may be cast. As a result, many other operations, such as machining, forging, and welding, may be minimized or eliminated.

2. Because of their metallurgical nature, some metals can only be cast to shape since they cannot be hot-worked into bars, rods, plates, or other shapes from ingot form as a preliminary to other processing. The highly useful and low cost cast irons, which exceed the total of all other metals in tonnage cast, illustrate this fact.

3. Construction may be simplified. Objects may be cast in a single piece which would otherwise require construction in several pieces and subsequent assembly if made by other methods.
4. Metal casting is a process highly adaptable to the requirements of mass production. Large numbers of a given casting may be produced very rapidly. The use of castings in the automotive industry provides ample illustration of this point.
5. Extremely large, heavy metal objects may be cast when they would be difficult or economically impossible to produce otherwise. Large pump housings and hydroelectric plant parts weighing up to 200 tons can be produced by casting.
6. Machinability and vibration damping capacity in cast iron:
 - a) More uniform properties from a directional standpoint; i.e., properly made castings exhibits the same properties regardless of which direction is selected relative to the original casting for the test piece. This is not generally true for wrought metals.
 - b) Strength and lightness in certain light metal alloys which can be produced only as castings.
 - c) Good bearing qualities are obtained in cast bearing metals. In general, a wide range of alloy composition and properties is produced in cast form.
7. A decided economic advantage may exist as a result of any one or a combination of points 1 to 6. The price and sales factor is a dominant one which continually weighs the advantages and limitations of any process used in a competitive system of enterprise.

The list of advantages accruing to the metal-casting process may be extended beyond that given above. It is also true that conditions may exist where the casting process must give way to other methods of shaping. Such conditions are those in the area of the principal advantages to be gained by the other metal-processing methods. For example machining produces smooth surfaces and dimensional accuracy not obtainable in any other way; forging aids in developing the ultimate of fibred strength and toughness in steel; welding provides a convenient method of joining or fabricating wrought or cast products into more complex structures; and stamping produces lightweight sheet-metal parts. Thus the engineer may select from a number of metal-processing methods that are or combination which is most suited to the needs of his work (Heine et al, 1967).

Disadvantages of Casting

- i. Problems with internal defects such as gas porosity due to gases dissolved in molten metal during melting
- ii. Dimensional variations in cast products due to shrinkage.
- iii. Occurrence of trapped impurities such as solid and gaseous matters.
- iv. Difficulty in producing smooth surfaces especially in sand casting.
- v. Cost components do not possess the toughness characteristic of forged parts.

- vi. Casting cannot be easily used to produce thin parts which are preferably produced by stamping and deep drawing.

Some of the major groups of casting alloys are summarised in Table 1.2, which demonstrates the variety of available compositions. However, whilst almost any individual alloy composition can be cast, best results are obtained from casting specifications which have been specially developed to exploit the optimum combination of foundry and engineering properties.

Table 1.2: Casting Alloys

Alloy Group	Main types of alloy	Principal casting processes	Principal British Standard for Castings	Some alloying elements
Cast irons	Grey cast irons, Malleable Cast irons, spheroidal graphite cast irons. Heat resistant, chemical resistant and wear resistant alloy irons	Sand casting	1452 309; 310; 3333 2789	C, Si, P, Ni, Cr.
Steels	Carbon and low alloy steels; high alloy steels, including stainless, chemical resistant, wear resistant and heat resisting alloy steels.	Sand casting, ceramic mould process, investment casting.	3100	C, Mn, Cr, Ni, Mn
Copper base alloys	Brasses, including high tensile brasses; miscellaneous bronzes and gunmetals, including aluminium and silicon bronzes	Sand casting Die casting	1400	Zn, Sn, P, Pb, Ni, Al, Fe, Mn, Si.
Aluminium base alloys	Alloys for sand and die casting	Sand casting, die casting, investment casting.	1490	Si, Cu; Mg, Mn, Zn, Ni
Magnesium base alloys	Alloys for sand and die casting	Sand casting, die casting.	2970	Al, Zn, Zr, Mn, rare earths
Zinc base alloys	Pressure die casting alloys	Pressure die casting	1004	Al, Mg, Cu

Superalloys	Nickel-base, cobalt-base for heat, corrosion and wear resistance. High temperature alloys.	Investment casting		Cr, Co, C, Ti, Al, Cu, Cr, Mo, Si.
Miscellaneous	Lead and tin base alloys, especially for bearings; permanent magnet alloys; titanium, chromium, molybdenum and other special materials for high temperature and corrosion resistance.			Sn, Pb, Sb, Cu Cr, Ni, Mo, W, Nb Fe, Co, Ni, Al.

Source: Beeley: 1982; Clegg, 1991

1.4 The Technology of Founding

The processes employed in the industry include gravity and pressure die casting, investment casting and centrifugal casting, but the general characteristics of founding can be conveniently introduced in relation to a central theme, the production of sand castings by conventional moulding. The basic steps in the sequence from design to finished product are summarized in the flow diagram in figure 1.3. A similar sequence applies with minor modifications to a wide range of casting processes. The major exception is die casting, in which the principle of a pattern and an expendable mould is replaced by that of a permanent mould containing a negative impression. The individual features of both these systems will be examined in detail in the chapter 8 of the book.

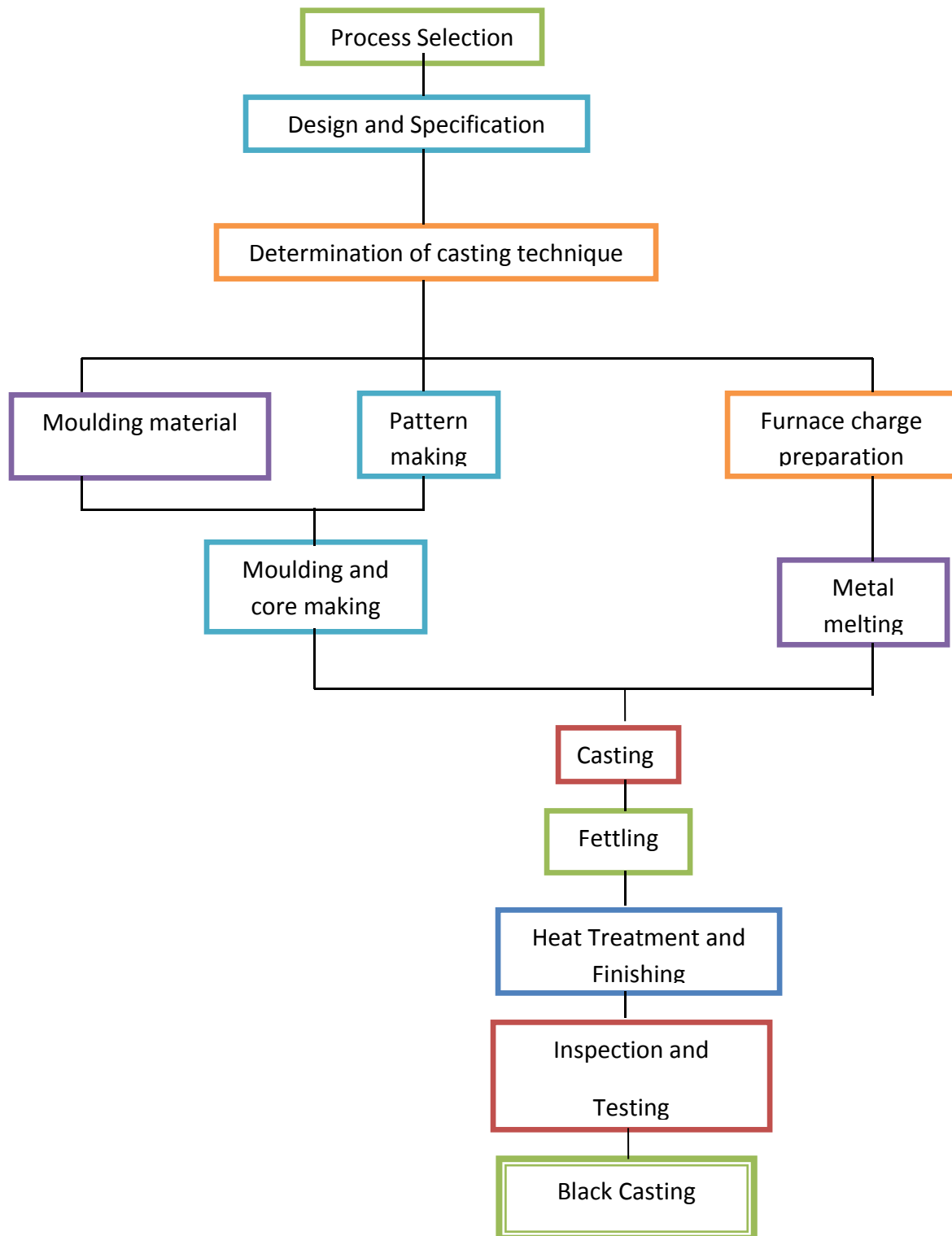


Figure 1.3: Flow diagrams of Casting Production (Ihom, *et al.*, 2014)

The variety of technology problems encountered in metal casting arises largely from differences in the physical properties and constitution of the alloys. This is exemplified in the wide range of process temperatures. Table 3 lists the melting points of parent metals of important groups of casting alloys. Other significant differences include chemical activity and solubility for gases, mode of solidification, and contraction characteristics. These affect the problems of metal flow, mould stability, feeding, stress-free cooling and the structure and properties of the cast material: individual techniques are thus required to meet conditions peculiar to the type of alloy.

Once the essential foundry techniques have been established the quality of casting is influenced by numerous process variables. Some of these can only be adjusted within narrow limits.

Table 1.3: Melting Points of some metals

Metal	Melting Point
Iron	1573
Nickel	1453
Copper	1083
Aluminium	660
Magnesium	650
Zinc	420
Lead	327
Tin	232

Source: (Ihom et al., 2014)

Metal composition, for example, is often restricted by specification, although in the broader sense the needs of the casting process have influenced the ranges adopted in cast alloy specifications: these accounts for the frequent use of alloys close to eutectic composition, which show favourable characteristics with respect to fluid, feeding and freedom from hot tearing. However, inoculation with very small amounts of certain elements can exercise potent effects both on foundry characteristics and casting structure, whilst control can also be exercised through moulding material properties, melting practice, casting temperature and pouring speed. These variables together with the techniques of gating, risering and chilling can be used to control the entire pattern of cooling: this is the main key to the structure and quality of the finished casting.

Control is exercised through many types of observation and measurement. In some cases direct determinations of temperatures, time, composition or properties are useful, whilst other

empirical tests bear specific relationship to aspects of foundry behaviour, for example metal fluidity, mould gas evolution or scabbing tendency. These techniques, whether used in the laboratory or the foundry, form part of the framework for the scientific control of metal founding. This also depends upon systematic evaluation of the cast product by non-destructive testing and metallurgical examination, and its correlation with production variables: statistical process and quality control systems can play an important role in this respect.

The application of sciences to founding is also seen in research into the fundamentals of casting and cast materials. This involves basic studies of the phenomena of liquid metal flow and solidifications high temperature stress-strain relationships in cast alloys and mould materials, and the origins of various forms of defect. Frequent reference will be made to such research since it has a major bearing on the future development of metal founding.

Perhaps the most crucial areas for investigation are the process structure – properties relationships in cast materials. Modern engineering requirements involving high stresses and extreme service conditions must be met by more exacting standards of quality and reliability. Apart from the development of new casting alloys and improved techniques of non-destructive examination, the capacity to control structure can provide more positive correlation between the true properties within castings and the minimal or test bar values. This approach is seen in the concept of ‘premium’ castings with their high and guaranteed levels of internal properties. It seems probable that such an approach will eventually form the normal basis for casting design.

Other major activities lie in the fields of process development and production engineering work on casting processes is directed towards higher standards of precision and material quality and includes extensions in the capabilities of die and investment casting processes as well as completely new techniques of casting. The challenge in production engineering is mainly economic and concerns how to combine the philosophy of mass production with the flexibility of the casting process for moderate quantities of components, thus keeping down unit costs. This is tied in with the previously mentioned trend away from craft and manual skills and towards engineering, with emphasis on the design of pattern equipment and manufacturing techniques before the work reaches the shop floor.

The nature of production problems in casting is closely associated with design features, so that the task of the foundry industry can be greatly simplified by cooperation during the preliminary stages between designer and producer. Apart from possibilities for personal contact, much has been accomplished in recent years to establish principles for use by the engineer in the design of castings. Proper communication can ensure that the most economic and technically sound use is made of foundry processes and that the casting is correctly assessed in relation to the whole range of metal products. The modern casting can emerge from such assessments as a versatile and reliable unit (Beeley, 1982).

1.5 The Engineer and the Foundry Industry

Because of the scope of the industry and the widespread use of castings, engineers often find themselves in a position where knowledge of foundry processes and casting problems becomes a vital part of their work. Design of castings, specifications, intelligent use of the properties of cast metals, purchasing of castings, and processing of castings, all require the application of engineering principles unique to castings and the foundry process. The engineer who designs a casting must have accurate information about the properties of the cast metal he would use. Further, he may achieve considerable economics by selecting a design that facilitates moulding, coring, and other foundry problems and costs rise. Designs which make it difficult to obtain sound castings result in low mechanical properties in the cast metal, so that handbook data are not reliable. Many engineers face these problems in their work even though, they themselves are not directly engaged in foundry work. Engineers are also finding increasing opportunity for professional work in the foundry field itself. To provide a foundation for work in this field, indirectly or directly, course work in the principle of metal casting finds a place in the educational preparation of student engineers. In addition, certain principles of materials science and engineering are best studied in the foundry processes.

The Casting Process

The basic steps involve in casting are described as follows:

- i. Moulding: a mould cavity having the desired final shape, has to be produced with due allowance for shrinkage of the solidifying metal. Any complexity, internal or external desired in the casting to be produced must exist in the cavity. The mould material must therefore satisfy these important properties, viz:
 - It must be sufficiently refractory so that it is not significantly affected by the very high temperature of the molten metal.
 - It must be able to perfectly produce the required details of the casting.
 - It should permit easy removal of the castings produced.

An expendable mould (or single-use mould) or a permanent mould made from a material that permits repeated castings can be used. Permanent moulds are usually made from graphite or gray cast iron and are therefore expensive and are therefore used for large production runs only single-use moulds made from materials such as silica sand are preferred for the production of smaller quantities of castings.

- ii. Melting: the melting process must produce a molten metal with the following characteristics.

-Appropriate Pouring Temperature

-Acceptable quality, free from excessive solution of gases.

-Desired quantity and at a reasonable cost

- iii. pouring: the pouring technique must provide for:

-introduction of molten metal into the mould cavity

-easy escape of air or gases in the mould cavity before pouring and gases generated by the interaction of molten metal and the mould material.

iv. the solidification Process

the solidification process needs to be properly designed and controlled to permit solidification shrinkage without formation internal porosity or voids

v. mould shakeout: after a casting has solidified and cooled down sufficiently (about 400-500°C), mould shakeout and core knockout is done. Shake-out is usually done by means of vibratory knockouts, jolting gride and vibrators. The mould is intensely jolted and broken up. After shakeout, the cores of heavy castings are knocked-out. In hydraulic knockout, the cores are broken up and washed out with a jet of water supplied at a pressure of 25 to 100 atmospheres.

vi. cleaning, finishing and Inspection: cleaning or fettling involves the removal of adhering sand, the gating system and metal excesses (fins) at mould parting line.

Surface cleaning to remove adhering sand can be done in tumbling barrels, sand blasting, pneumatic shot-blasting and airless shot-blasting machines. A number of equipment are available to remove fins, runners and sprues from castings, by mechanical cut-off, torch-cutting, chipping, grinding, etc.

Classification of Foundries

Foundries may be classified as ferrous and non-ferrous. They can be classified according to the nature of their work and their organization framework.

In a jobbing foundry, many different kinds of castings of all sizes and weights are made in limited numbers. The production foundry is usually larger and the work is generally limited to a few patterns from which thousands of castings are made. Usual classification of foundry is shown in Fig. 1. 4.

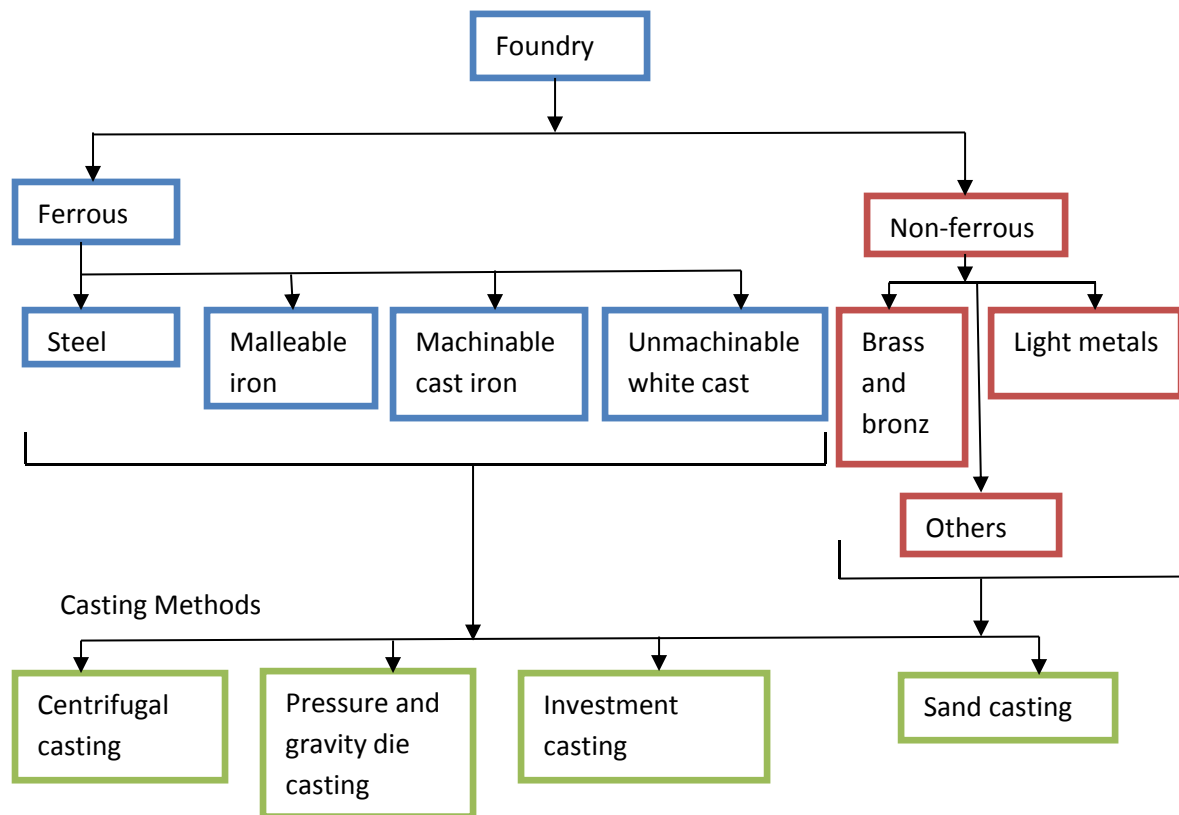


Fig.1.4: Classification of Foundry

1.6 Casting Output

As indication of the size of the ferrous and non-ferrous sectors of the foundry industry can be obtained by references to Table 1.4. Not shown in the table are the inputs for the USSR, India, Brazil, Korea or Taiwan. It is believed that the output of castings in the USSR exceeds that in the USA and that China would rank third in the world league table.

Since the data in Table 1.4 was presented, so many changes have taken place both politically and economically. USSR has ceased to exist and have split into different countries. China and India have multiplied their outputs. The figures in Table 1.5 are more realistic. Worldwide casting shipments in 2009 fell to 80,343,048 tons, down 14% from 2008, according to modern casting census of world casting production. Of the 34 countries participating in the production survey in 2009 only five reported growth- China, India, Korea, Portugal and South Africa. The average percentage decreased in shipments for the remaining countries with declining production was 30%. The 44th census of world casting production

reported that the global casting market experienced a marked contraction in 2009, with overall shipments decreasing 14% from 2008. The global metal casting market was worth US\$158.4 Billion in 2019.

As a result, production per plant decreased, as well. Germany still has the most production per plant, but it fell from 9639 tons per metal casting company in 2008 to 6481 tons in 2009. China's production improved from 1117 tons to 1357 tons per plant as shipment volume increased and the number of casting facilities decreased. Seven of the top 10 casting – producing nations shifted up to down in the rankings in 2009, reflecting the fluctuating markets during the recession. Brazil, which had been one of two top-10 countries to show growth in 2008, experienced a 31.5% decrease in shipments from 2008 to 2009 the biggest drop of any top-10 nations during that time period. India was the fastest growing top -10 nation, increasing its casting tonnage by 9%. The top-10 nations produced a total of 70,476,338 tons, 88% of the global total. The year 2009 marked the fourth year in a row the U.S has reported a reduction of casting volume. It was the first year it has been surpassed in production (by 35,000 tons) by India, which became the second-largest casting producer by volume. The data reported in the 44th census of world casting production is supplied by each nation's metal casting association or similar representative. Countries that did not participate were Denmark, the Netherlands and Thailand. These countries remain listed according to the last year they participated. New to the list are Bosnia and Herzegovina, Mongolia and Serbia.

Table 1.4: Casting Output for 1986

Country	Tonnage (Ferrous Sector)		Output (Non-ferrous sector)	
	Tonnes (x 1000)	Tons (x 1000)	Tonnes (x 1000)	Tons (x 1000)
Austria	166.6	163.9	34.1	33.6
Belgium	194.9	191.8	14.2	14.0
Finland	90.9	89.5	6.2	6.1
France	1,798.0	1,769.2	249.4	245.4
Holland	212.2*	208.8*	17.3	17.0
Italy	1459.5	1,436.1	-	-
Japan	5,563.1	5,474.1	940.4	925.4
Norway	82.2	80.9	4.6	4.5
Portugal	78.4	77.1	6.2	6.1
Spain	703.5	692.2	88.8	87.4
Sweden	292.0	287.3	45.0	44.3
Switzerland	196.0*	192.9*	19.3	19.0
UK	1,078.0	1,060.8	142.5	140.2

USA	9,922.3	9,763.2	3,188.7	3,137.7
West Germany	3,451.5	3,396.3	587.4	578.0
* excludes steel casting source: Clegg, A.J. 1991				

Table 1.5: World Casting Census

Country	Gray iron	Ductile	Malleable	Steel	Cu-base	Aluminum	Mg	Zinc	Other-non-Fe	Total
Austria	29200	89700 ^A	na	19800	2203	87698	4676	10191	na	243468
Belgium	49100 ^B	500 ^A	na	28100	na	1582 ^C	Na	530	na	78812
Bosnia/Herzegovina	8567	1100	na	3826	na	3176 ^D	Na	na	na	16669
Brazil	1365030	525971	26850	166382	12075	194569	3233	2806	na	2296916
Canada	458850	Na	na	111720 ^E	17656 ^E	146879	Na	na	na	735105
China	17000000	8700000	600000	4800000	600000	3350000 ^C	Na	na	250000 ^F	35300000
Croatia	22107	17375	na	1313	459	11652	Na	230	661 ^G	53797
Czech Republic	138838	40678	1881	52392	888	34772 ^C	Na	1368	144	270970
Denmark ^E	32367	48020	na	na	1433	Na	Na	6	5778 ^D	87604
Finland	28041	31363 ^A	na	9413	3052	3612	Na	260	na	75741
France	562000	869000 ^A	na	59500	18818	205924	Na	19513	1949	1736704
Germany	1806480	1191786	31273	182435	76720	540444	19859	51193	1475	3901665
Hungary	25834	15221	11	5695	1442	8010	Na	3738	262	132304
India	5050000	800000	60200	880,000	na	653000 ^D	Na	na	na	7443200
Italy	566068	372449 ^A	na	65283	14386	549400	6700	49000	45516	1668802
Japan	1653901	1364644	37235	198248	75284	1025507	6280	20563	4336	4385998
Korea	1020600	607600	38500	153500	24500	279100	Na	na	11200 ^C ^F	2135000
Mexico	693975	53010	na	70815	126530	539990	98	906	na	1485324
Mongolia	2000	120	100	12000	60	180	Na	na	240	14700
Netherlands ^H	78241	6209	438	na	na	na	Na	na	na	84888
Norway	15200	48400 ^A	na	2700	2177	4058	Na	na	na	72535
Poland	570000 ^I	Na	na	na	na	200000 ^D	Na	na	na	770,000
Portugal	30995	60165 ^A	na	8803	10800	15800	Na	480	na	127043
Romania	29485	1471	712	22955	1814	31163	1750	535	9 ^G	89894
Russia	1740000	1200000	60000	700000	90000	340000	35000	15000	20000	4200000
Serbia	43150	2320	1460	25040	995	1420	Na	500	14260	89145
Slovenia	74,000	14900 ^A	na	27900	2976	18144	495	2079	na	140494
South Africa	95565	68832	114276	147235	17220	47364	Na	2730	na	493222
Spain	274000	461300 ^A	na	65200	6791	86212	Na	8084	491	902078
Sweden	113300	27700	na	15300	8400	24600	1300	4000	na	194600
Switzerland	17600	31000 ^A	na	1806	1807	14613	Na	1308	na	68134
Taiwan	343854	175902	na	50849	33166	230059	5159	74629	1065	914683
Thailand ^J	70000	30000	30000	28600	28600	100000	Na	16900	na	304100
Turkey	456000	352000	2000	98000	12500	96500	Na	13500	na	1030500
Ukraine	640000	40000	na	275000	na	45000 ^D	Na	na	na	1000000
United Kingdom	102000	137000 ^A	na	56000	8000	78000	2000	6200	700	389900
United States	2409483	2553725	35380	686,739	178715	11911345	66224	166922	119748	7408069
Totals	37615831	19939470	1040316	9032549	1379467	10237431	152774	473170	472056	80343064

Note: All data given in metric tons. A) includes malleable iron B) includes ductile iron C) includes mg D) All nonferrous E) 2008 data F) includes zinc G) Lead castings H) 2004 data I) All ferrous J) 2006 data

Source: modern casting, 2010.

Table 1.6: Top-10 Casting Producers (last year's rank in parentheses)

1. China (1)	35.3 million tons		6. Germany (5)	3.9 million tons
	Gray iron	17 million tons		Gray iron 1.8 million
	Ductile iron	8.7 million tons		Ductile iron 1.2 million
	Steel	4.8 million tons		Steel 180,000
	Nonferrous	4.2 million tons		Nonferrous 690,000
2. India (4)	7.4 million tons		7. Brazil (7)	2.3 million tons
	Gray iron	5.05 million tons		All iron 1.9 million
	Ductile iron	800,000 tons		Steel 170,000 tons
	Steel	900,000 tons		Nonferrous 210,000
	Nonferrous	650,000 tons		
3. U.S. (2)	7.4 million tons		8. Korea (10)	2.1 million tons
	Gray iron	2.4 million tons		Gray iron 1 million
	Ductile iron	2.6 million tons		Ductile iron 610000
	Steel	690,000 tons		Steel 150000 tons
	Nonferrous	1.7 million tons		Nonferrous 310000
4. Japan (6)	million tons		9. France (9)	1.74 million tons
	Gray iron	1.7 million tons		Gray iron 560,000
	Ductile iron	1.4 million tons		Ductile iron 870,000
	Steel	200,000 tons		Steel 60000 tons
	Nonferrous	1.1 million tons		Nonferrous 250,000
5. Russia (3)	4.2 million tons		10 Italy (8)	1.67 million tons
	Gray iron	1.7 million tons		Gray iron 570,000 tons

Ductile iron	1.2 million tons	Ductile iron 370,000 tons
Steel	700,000 tons	Steel 65,000 tons
Nonferrous	500,000 tons	Nonferrous 665,000 tons

Source: modern casting/December 2010

Annual global casting production has shown continued growth in 2012 since exceeding prerecession levels in 2011. 47th census of world casting production industry statistics capacity census facilities forecasting market survey tonnage trends iron ductile. See fig. 1.5

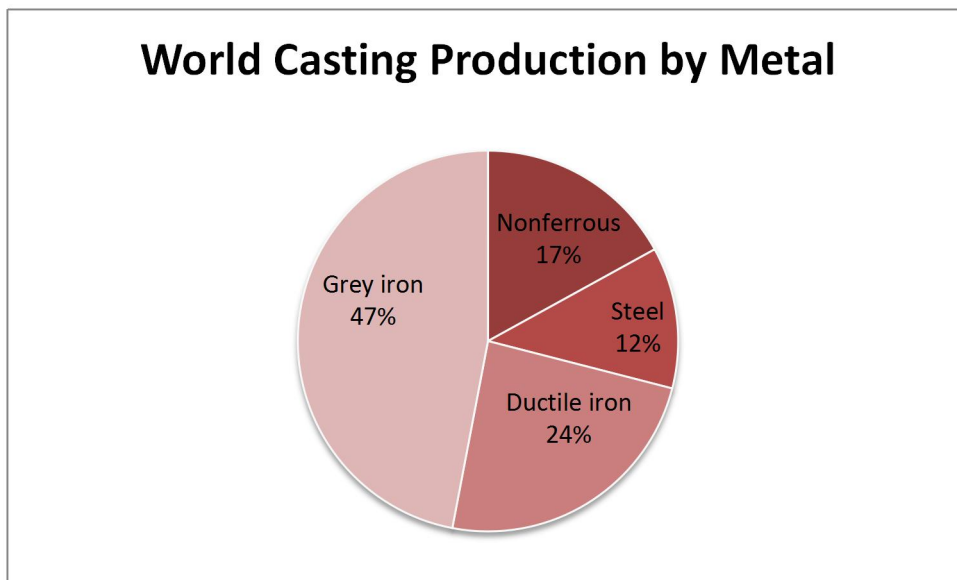


Figure1.5: World Casting Production by Metal

Grey iron 47% = 38.16 million tons, ductile iron 24% = 19.4 million tons, Steel 12% = 9 million tons, nonferrous 17% = 13.6 million tons

While gray iron continues to make up the largest piece of the global production pie, its slice is growing smaller. Since 1999, gray iron production has increased 9.3%. Compare that with a 39.6% increase in ductile iron production, 50% growth in steel production, and a 41.1% increase in nonferrous production.

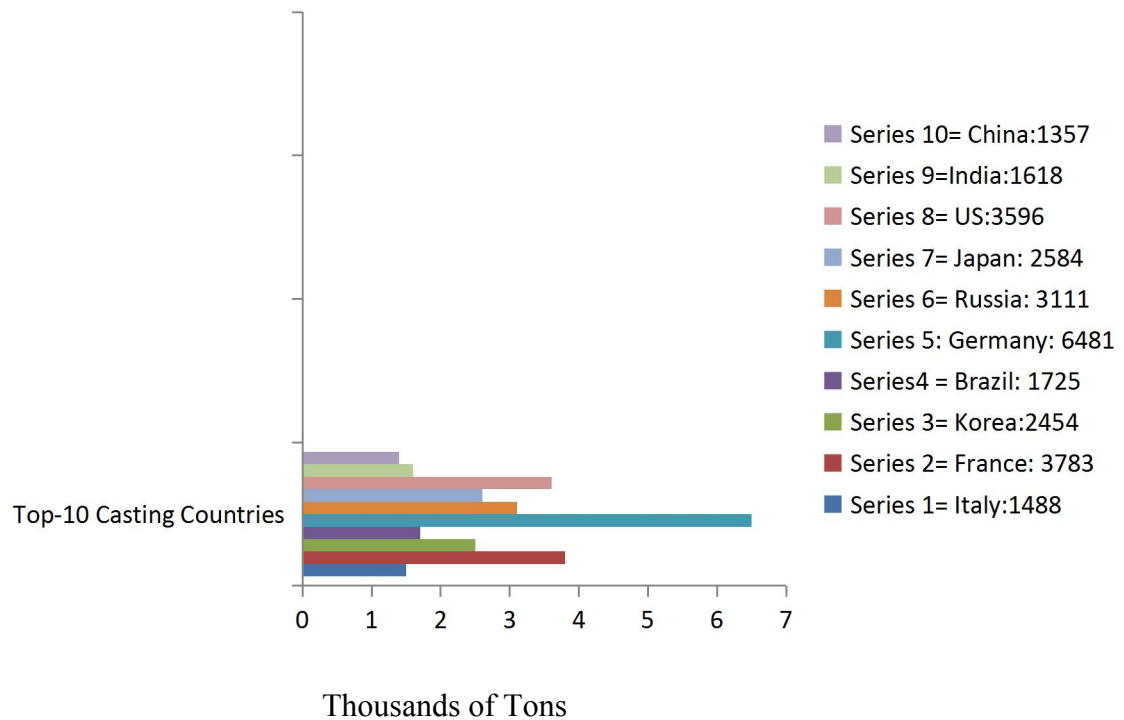


Figure 1.6: Top-10 Casting Countries per Plant

Production per Plant

The average production per metal casting plant for the top 10 nations decreased across the board likely due to plant operating at lower capacity during the 2009 recession. China and Korea, which showed increases in casting shipments from 2008 to 2009, improved their productivity. See fig. 1.6. Table 1.7 shows metal casting plants by nation.

Table 1.7 Metal Casting Plants by Nation

Country	Iron	Steel	Nonferrous	Total
Austria	29	4	39	72
Belgium	16	7	8	31
Bosnia/Herzegovina	5	2	4	11
Brazil	552	191	588	1331
Canada	41	29	115	185
China	17000	4700	4300	26000
Croatia	15	3	24	42
Czech Republic	84	34	62	180
Denmark ^A	7	0	10	17
Finland	14	6	16	36
France	103	37	319	459
Germany	205	53	344	602
Hungary	62	31	97	190
India	-	-	-	4600
Italy	157	44	920	1121
Japan	456	75	1166	1697
Korea	508	142	223	873

Mexico	181	162	350	647
Mongolia	24	15	3	42
Netherlands^B	16	0	5	21
Norway	8	3	11	22
Poland^C	185	0	245	430
Portugal	47	6	39	92
Romania	53	45	71	169
Russia	-	-	-	1350
Serbia	14	8	16	38
Slovenia	8	3	16	27
South Africa	88	51	117	256
Spain	60	32	50	142
Sweden	32	13	73	118
Switzerland	18	4	43	65
Taiwan^C	478	40	330	848
Thailand^D	230	26	220	476
Turkey	741	72	433	1246
Ukraine^E	400	233	437	960
United Kingdom	230*	-	220	450
United States	659	416	985	2060

*includes iron and steel facilities. A)2008 data B)2004 data C)2007 data D)2006 E)2002 data

Gray Iron Versus Ductile Iron

Globally, 65% of iron castings produced are in gray iron, compared to 35% produced in ductile iron. But this type of disparity is not present in every country. Among the top five casting nations, the U.S. produces more ductile iron castings than gray iron, while Russia and Japan show closer gaps between the two materials than do China and India.

New to the List

A few new countries have been added to this year's census of casting producers and another have been updated after seven years of incomplete data.

Ukraine: before this year, the most recent production data from Ukraine dated to 2002, when the country was producing 974,170 tons of castings a year. Not much has changed. The foundry association of Ukraine reports the country produced about 1 million tons of castings in 2009. Ferrous castings makes up the lion's share of production (95.5%), but nonferrous casting has improved 42.9% since 2002.

Serbia: for many years, this country has been in turmoil, with much of the casting activity shut down or severely hampered. From 1990 through 1990, its economy was cut in half. Since then, Serbia has been making up ground. In 2008, the Serbian Foundrymen Society was formed. The country's casting industry is 81% ferrous and 19% nonferrous by tonnage produced. Production per plant is 2345 tons.

Mongolia: more than two-thirds of all of Mongolia's exports go to China, its neighbor to the south. Its largest casting market is steel, which makes up 81.6% of total production.

Economic Woes

With the exception of a few nations, the global casting industry reported a dip in production in 2009. But some countries fared worse than others.

Russia: from 2007 to 2009, Russia's production decreased by 46.2%, from 7.8 million tons to 4.2 million tons. The third largest casting producing nation in 2007. Russia has since fallen behind India and Japan. It saw a reduction of 300 metalcasting facilities in 2009.

Finland: in one year, Finland's casting production was cut in half, from 152888 tons to 75741 ton. Casting production value decreased 46% to \$350 million. Zero metalcasting facilities closed, according to the European Foundry Association, but employment in the industry constricted by 700- 15.7% of the workforce.

Czech Republic: the nation's production fell 49.5% from 536789 tons to 270970 tons. Productivity dropped from 2684 tons/ plant to 1505 tons/plant

Casting Industry-Casting Production Worldwide by Country 2017

This statistic represents global casting production worldwide in 2017, with a breakdown by major country. In 2017, the production of castings in India's foundries amounted to around 12 million metric tons. See Table 1.8.

Table 1.8: Casting Production in million tons 2017

Country	Million tons
China	49.4
India	12.06
USA	9.67
Germany	5.48
Japan	5.45
Russia	4.22
Mexico	2.91
Korea	2.6
Italy	2.24
Brazil	2.22

Source: Statista 2020

Top 20 Steel-Producing Countries 2019 (million tonnes)

Table 1.9 World Steel in Figures 2020

Position	Country	Quantity (million tonnes)
1	China	996.3
2	India	111.2
3	Japan	99.3
4	USA	87.8
5	Russia	71.9
6	South Korea	71.4
7	Germany	39.7
8	Turkey	33.7
9	Brazil	32.2
10	Iran	25.6
11	Italy	23.2
12	Taiwan, China	22.0
13	Ukraine	20.8
14	Vietnam	20.1
15	Mexico	18.5
16	France	14.4
17	Spain	13.6
18	Canada	12.9
19	Poland	9.0
20	Saudi Arabia	8.2

Source: www.worldsteel.org

Table 1.9 shows the world steel figures in 2020, the table reflects the figure produced by each country, unfortunately no African country is able to make the list of first 20 leading steel producing countries in the world. A healthy economy needs a healthy steel industry, it is therefore not surprising that you hear of countries like Turkey in the news always supporting warring countries with arms. None of the countries mentioned in the table above is doing badly economically. China is literally trying to buy off Africa; there is hardly no country in Africa that has not benefitted from Chinese loan or is not indebted to China. China is the world leading producer of steel, some of this steel is used to produce different steel castings used in the production of different machineries. The fact is this, the longer Nigeria dilly dallies with the development of her iron and steel sector the longer we are going to delay our industrial development and also remain a dependent country. Remember this, steel makes the future possible, without it, all the space travel and the missiles launched around the world would have been a mirage.

Precision of Metal Casting Processes

Precision of casting is considered by many to mean dimensional accuracy of the cast product. By this they mean the casting should conform to the specifications as stated by the customer. In a precision casting attributes like consistency, surface smoothness or good surface finish, ability to produce thin sections are important attributes sought after in a precision casting. This is a feature not generally attributed to sand castings but expected in precision castings. The ability to produce intricate shapes and reproduce fine details is expected of precision

castings. Whilst the metal casting process is generically capable of producing complex shapes, the replication of fine detail is the province of the specialist precision casting processes. This capability for detail can be extended to the provision of as-cast holes, not necessarily round, which in the best of the precision casting processes may be produced without the need to resort to machining. The final expectation of a precision casting is that it should demonstrate the attribute of metallurgical integrity. The casting should be free from shrinkage and gas porosity, non-metallic inclusions and other casting defects. It should demonstrate, as a consequence, improved mechanical properties and performance in service.

Factors Influencing the Attainment of Precision in Casting

Several stages are involved in the production of a casting, each of which can exert an influence on precision. These include tooling, mould production, mould materials, mould location, pouring stage, casting contraction and casting finishing. The nature of these activities is such that if they are not practiced with care they can impair the precision of the castings.

Measures Available to Improve the Precision of Castings

Clearly, attention to detail in respect of each of the aforementioned factors will maximize the potential for improving the precision of a casting, independently of the process chosen. However, it is generally recognized that special measures must be taken to optimize precision and some of these measures are introduced are

- Green sand moulding: improvement is through the understanding of the inter-relationship between clay and moisture content, mould compaction and dimensional accuracy. Moulding machines have been developed which achieve consistently high mould densities and this has resulted in an improvement in dimensional accuracy and consistency. Substitution of silica by zircon is practiced to a limited extent in the shell moulding process and the Cosworth process, with improved dimensional accuracy as a benefit. However, zircon sand is expensive and this has prevented its widespread use.
- Cold setting processes (inorganic and organic): the hardening of the sand in contact with the pattern, a major feature of these processes, improves the conformity of the mould to the pattern and consequently dimensional accuracy and consistency. Hardening of the sand in contact with the pattern is also a feature of the shell moulding process.
- The elimination of silica sand as the mould material is a feature of the plaster mould, investment casting, ceramic mould and die casting processes, so that these processes can be expected to demonstrate improved precision. Precision is improved still further in the investment casting process because an expendable pattern is used and there is no mould joint line. With the exception of die casting, these processes also use very fine refractory particles and so provide improved casting surface finishes.
- Mould preheat, as an aid to improved metal fluidity and mould or die filling characteristics, is featured in investment casting and is an option in the ceramic mould

and plaster mould processes, where it improves thin section capability and detail replication.

- The maintenance of the pressure difference during solidification of the casting enhances casting soundness and this is used to advantage in such processes as low pressure die casting, the counter pressure process, the Cosworth process and the Hitchiner CLA and CLV processes.
- Vacuum melting and casting is an essential requirement for the production of nickel-base superalloy castings. Under the condition of vacuum, oxidation and gas absorption are eliminated, with a consequent improvement in metallurgical integrity
- It can be seen from the foregoing comments that there are a number of measures which can be adopted by metal foundries to improve the precision attainable in castings.

Cost Implication of Precision Casting

Precision castings are invariably more expensive than standard castings. This is because of the more expensive plant and processes required to produce precision castings and through the need for improved standards of process and quality control. The reader can get more information on precision casting from the book rewritten by A.J. Clegg titled precision casting processes.

Near Net Shape Capability

Manufacturing processes that produce components to net or near net shape and size with the minimum number of processing steps and with as little waste as possible have the potential to reduce manufacturing costs and improve manufacturing efficiency. This concept is being applied in metal forming processes such as flashless forging and fine blanking, and in the powder metallurgy route. The metal casting process has an inherent near net shape capability and the precision casting processes can produce castings which come close to meeting net shape and size requirements. With the continuing process development and improved process control, castings are being produced closer to shape and size to the benefit of the industry's customers.

Review Questions for Chapter One

1. What is your own understanding of foundry? List the advantages of casting process over other shaping processes.
2. Write a brief history of the Nigerian Foundry industry
3. Briefly explain the basic steps in the sequence from design to finished product of a sand casting foundry using a flow diagram.
4. Write short notes on the Engineer and the foundry industry.
5. Analyse the trend in countries' production of castings in terms of growth and decline in growth from 2009 to 2014.
6. What do you understand by precision casting

7. List some improvement measures for precision casting.
8. Outline key factors influencing the attainment of precision in casting.

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CHAPTER TWO

SOLIDIFICATION OF METALS

2.1 Introduction

It is the purpose of this chapter to consider the major fundamental problem in connection with the solidification of foundry alloys. Before doing so, however, it will be helpful to review briefly some of the important factors involved in solidification.

If attention is confined for the time being to binary alloy systems, it is apparent immediately that solidification proceeds:

- i. At constant temperatures (pure metals and eutectic alloys)
- ii. Over a temperature range (solid solutions)
- iii. By a combination of solidification over a temperature range followed by constant – temperature freezing (Pro-eutectic-plus eutectic-type freezing).

According to Taylor (2000) metals consist of atoms. Most metals in common use are solid at room temperature (mercury is a familiar exception). If we heat a piece of metal in a crucible until it is molten, we find that it can no longer retain its original shape. This is because the atoms of metal in the molten state move about freely and can easily be separated one from another so that the metal has no strength. It has all the familiar properties of a liquid and it takes on the shape of the crucible. If the metal is allowed to cool, a specific temperature is reached at which the atoms begin to align themselves one to another and, in doing so, they give up energy in the form of heat. This temperature is the temperature of solidification. There are a number of important consequences of solidification which we need to consider.

Contraction

The first point to consider is that metal contracts during cooling. This contraction is the sum of three contractions:

- i. In the liquid state: hot liquid metal contracts as it cools.
- ii. During solidification: most metals contract 3 to 7 per cent by volume. An exception is bismuth which expands.
- iii. During cooling in the solid state.

An immediate consequence of contraction in the solid state is that we must make our moulds slightly bigger than the castings we require at room temperature. The pattern-

maker overcomes the problem by using a measuring rule in which an allowance for this contraction is made automatically.

Solidification occurs by the nucleation of minute grains or crystals which then grow under the influence of the crystallographic and thermal conditions that prevail. The size and character of these grains are controlled by the composition of the alloy and by the cooling rate. Growth closes when all the available liquid metal has solidified.

Other changes are also taking place during the freezing process. Heat is being extracted from the molten metal as soon as the metal enters the mould. This heat is often referred to as superheat, since it represents that which must be removed before solidification can begin. The latent heat of fusion is also evolved. This must be transferred to the surrounding mould before complete solidification can be achieved. Finally, the solid metal transfer heat to the mould, and then to the atmosphere as it cools to room temperature.

During the three stages of cooling i.e, liquid, liquid-solid, and solid, shrinkage is also occurring. Thus the metal contract as it losses superheat, as it transform to the solid, and as the solid cools to room temperature. There are, therefore, major points for considerations when a casting solidifies:

- a. Growth of the solid grains
- b. Heat evolution and transfer
- c. Dimensional Changes

Additional variables are present which add to the complexity of the process. These include the effect of the mould material and its thickness, the mould geometry, the metal thickness and such metal properties as its thermal conductivity and solidification temperature range, heat transfer from the mould to the atmosphere, control of grain size by the use of inoculants or vibration, and others. Since these variables operate through their effect on the solidification process, major attention is given to the process itself. The effect of the variables is considered secondarily, or can be deduced from the discussion. The relationship of other properties, such as fluidity, hot-tearing tendencies, and gas evolution, to the solidification process is also covered in this chapter.

2.2 Intrinsic and Extrinsic Factor

The process of solidification, the change of liquid to solid metal after pouring into the mould, is the defining event in the life cycle of a casting. The times involved in this activity may be as short as seconds or as long as hours depending upon the casting process and the size of the casting. The chemical composition of the metal being cast, the manner in which solidification occurs, and the subsequent solid state treatment determines the ultimate microstructure and therefore properties (mechanical and physical) of the casting. It is the duty of the metal casting engineer to control the solidification event to the best of his/her

ability so that the microstructure of the final product can be controlled to optimize the properties desired. The ultimate physical and mechanical properties of the cast metal will depend upon both intrinsic and extrinsic factors present in each casting event and in the processing events subsequent to casting. These terms and what they mean for the casting and its properties are defined in the accompanying Table 2.1 below:

Table 2.1: Intrinsic and Extrinsic Factors

Intrinsic Factors	-Chemical Composition -Cooling Rate during solidification -Heat and Mechanical Treatment after solidification	These factors determine the ultimate microstructure and properties of the casting
Extrinsic Factors	-Metal cleanliness -Additives for microstructure control. -Casting Design -Riser and Gating Design -Solidification Rate Control -Temperature Control subsequent to solidification	These factors represent an attempt by designers, metal casting engineers and other processing engineers to control the processes to attain the ultimate properties promised by the intrinsic factors.

Illustration of the significance of intrinsic and extrinsic factors in determining the tensile properties of a casting (ultimate tensile strength and percent elongation) is shown below:-

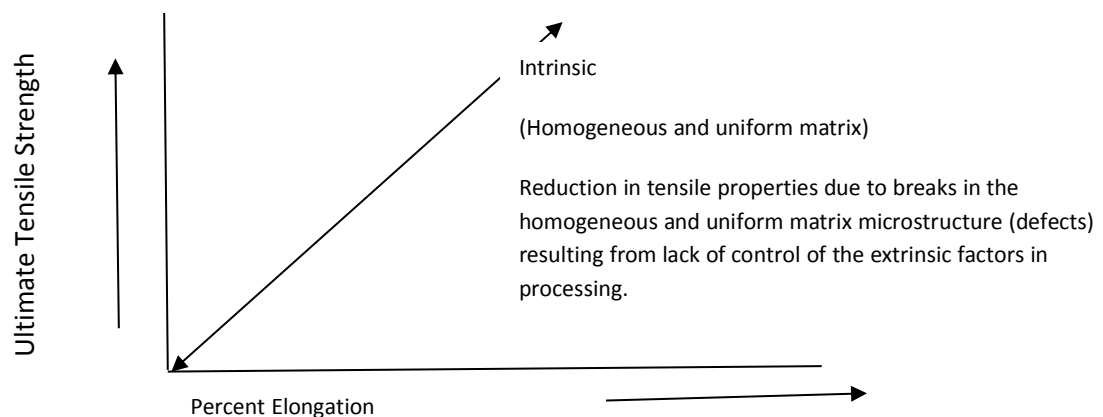


Figure 2.1 Illustration of the significance of intrinsic and extrinsic factors in determining the tensile properties of a casting.

It can be seen in this schematic illustration that the ultimate goal is to produce a casting with a matrix microstructure which is homogeneous and uniform throughout, departure from homogeneity and uniformity results in reduced strength and ductility (Rundman, 2000).

Shragger in his work (1969) gave a concise explanation of the process of solidification of a metal thus, the transition of a metal from the liquid to the solid state takes place in two stages. In the first stage a few atoms arrange themselves in the geometrical pattern characteristic of the metal, and as they solidify give up to their surrounding a part of the energy which made it possible for them to move freely through the liquid. These atoms therefore become relatively stable and serve as the crystal nuclei to which other atoms become attached in the same geometrical pattern to form crystals. During the second stage of crystal growth the crystals feed upon the molten metal by attracting other atoms to their space lattices, and throw out arms into the surrounding liquid. Other arms grow from these first arms and form branches, which in turn throw out spines of their own. This method of growth results in the formation of crystal skeletons which resemble pine trees, and which therefore are called dendrites. The dendritic system occurs in space within the liquid as trees grow in a forest, but during the formation of the crystal skeletons, trunks extend in all directions, not only upward as in the case of trees. The breadth of the normal crystalline grain in a metal is between 0.010 and 0.020 cm. This is equivalent to approximately 520,000 atoms in a row. Dendrites frequently can be seen with the naked eye on the surface of slowly cooled steel. Eventually adjacent crystals meet and interfere with each other. As a result of this mutual interference on every side the external form of the crystals after completion of solidification is geometrically irregular. Process is illustrated below in fig.2.2

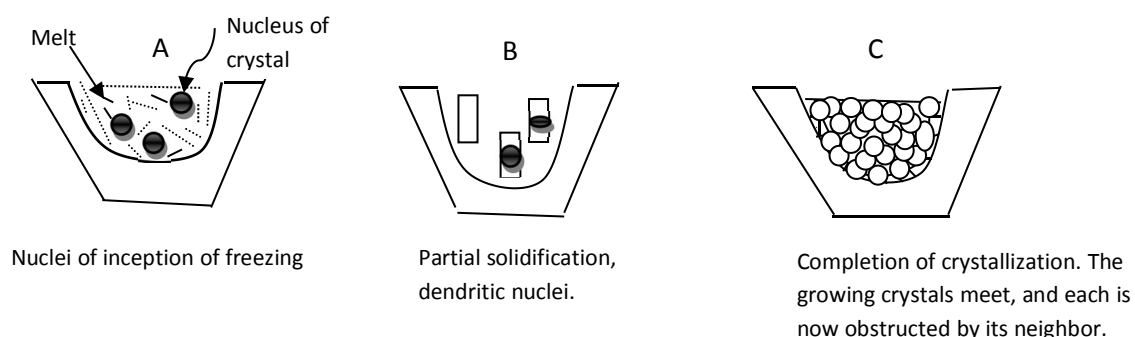


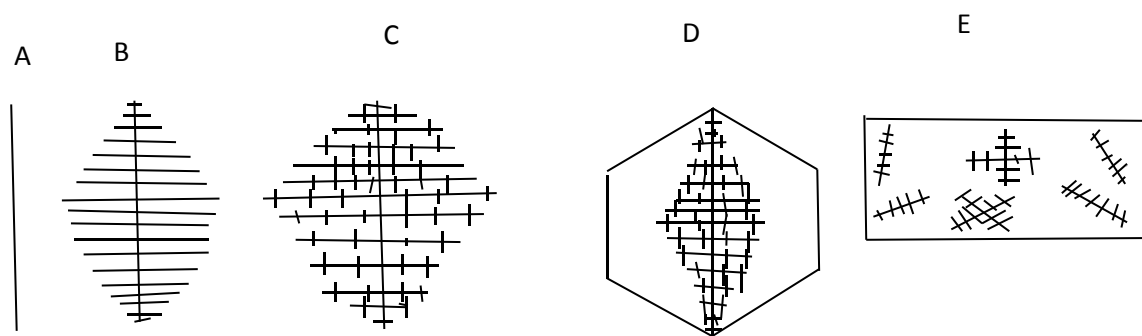
Fig. 2.2 Stages of crystallization (Shragger, 1969)

2.3 Crystallization from the Melt

Matter in the crystalline state exhibits long range order, being characterised by regularity of atomic spacing over considerable distances, metallic crystals deposited from the melt, although possessing internal symmetry, are commonly of irregular external form as a result

of uneven growth rates and mutual constraint in the last stages of freezing. The allotriomorphic grain is thus the normal crystalline unit in the cast structure, although in the case of the eutectic grain or cell two or more separate crystal structures are associated through the simultaneous growth of separate phases. Although the practicing metallurgist has little occasion to distinguish between crystals and grains, there is technically a difference. A crystal is a homogeneous solid of regular geometrical structure peculiar to the element, compound, or isomorphous mixture of which it is composed; within each crystal the atoms are spaced in characteristic pattern. A grain is a larger structure built both by accretions from the molten metal and by the uniting of crystals. Although each of the particles which compose a grain has a definite geometrical form, the external shape of the grain is usually not symmetrical because irregular surfaces are formed by the mutual interferences of adjacent crystals during crystallization.

This distinction is illustrated by the solidification of bismuth. If molten bismuth is cooled rapidly, each individual solid particle which appears has the regular cubic form which is characteristic of bismuth; each such particle is a crystal. As the crystals combine with or attach themselves to other crystals the larger structures known as grains are formed. Steel and most other industrial metals do not occur as regular crystals, but as aggregations of irregularly shaped grains. In each grain there is a single and continuous orientation of the array of atoms. The orientation in adjacent grains obviously must be different, however, because otherwise the grains would merge. Steel differs from most other metals in that it can exist in any of several types of lattice structures, and there are wide variations in the size, shape, and constitution of the grains of different varieties of steel. The characteristic properties of steel and of other metals and alloys are determined by their grain structures. See fig.2.3.



A Primary axis forms first.

B Primary and secondary axes follow, quickly.

C Primary, secondary, and tertiary axes follow quickly.

D Completed dendrite and boundary after interstices are filled up.

E Dendritic segregation in steel.

Fig.2.3. Formation of a dendrite.

Since the crystal lattice usually represents a more closely packed state of matter than the liquid, freezing is almost invariably associated with volume contraction. The reduction in molecular motion is also accompanied by liberation of energy in the form of latent heat of crystallization, which exerts a marked effect upon the rate and mode of crystal growth. Latent and specific heat values for some common metals are given in Table 2.2.

Table 2.2: Specific Heats and Latent Heats of Fusion of some Metals.

Metal	Specific heat	Latent heat of fusion
	Cal/g deg C	Cal/g
Iron	0.176	65.0
Nickel	0.157	72.1
Copper	0.118	48.9
Aluminium	0.259	92.7
Magnesium	0.333	85.6
Zinc	0.115	26.3
Lead	0.036	5.7
Tin	0.062	14.2

Source: Beeley: 1982 *(1 Cal /g = 4.1868Kj/kg)*

Crystallization from a metal melt involves the successive stages of nucleation and growth. The location and relative rates of these two phenomena within the liquid determine the final structure of the solid and establish the extent to which freezing is directional or occurs in a discrete manner throughout the liquid.

2.3.1 Nucleation

Nucleation is the appearance at points in the liquid of centres upon which further atoms can be deposited for the growth of solid crystals. Such nuclei can be produced in two ways. Homogeneous nucleation is the occurrence, during the general movement within the liquid, or ordered groups of atoms forming small zones of higher than average density. These embryonic crystals are ephemeral and unstable, but some reach a critical size at which they become stable and grow.

General nucleation theory explains this in terms of the change in free energy resulting from the precipitation of a particle. This change is compounded of changes in both volume and interfacial free energies.

The formation of solid from liquid results in a negative free energy change directly proportional to the volume transformed.

Thus, for a spherical particle,

$$\Delta G (\text{Volume}) = -\frac{4}{3} \pi r^3 \Delta G_V \quad (2.1)$$

Where r is the radius of the particle and ΔG_V the bulk free energy change per unit volume.

The creation of a new interface however, requires a local gain in free energy proportional to the surface area of the particle. In this case, for the spherical particle,

$$\Delta G (\text{interface}) = 4\pi r^2 \gamma \quad (2.2)$$

(Interface)

Where γ (Gamma) is the interfacial free energy per unit area for a spherical surface. The sum of the respective free energy changes is found to be positive for very small values of r but becomes negative at higher values of r (Figure 2.4)

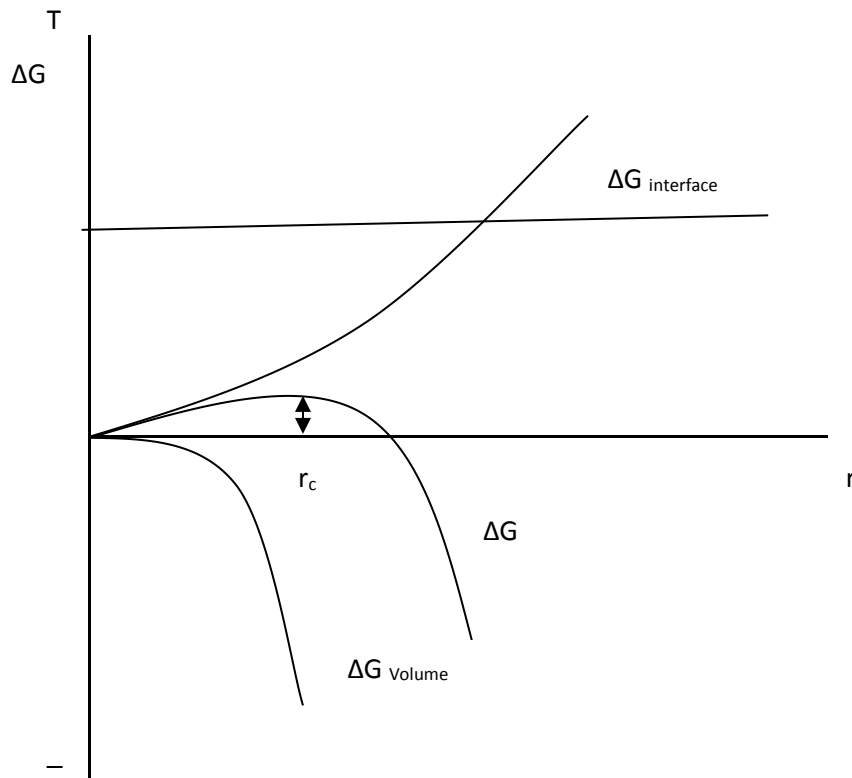


Figure 2.4: Free energy changes in homogeneous nucleation

The peak positive value of ΔG corresponds to the critical radius above which growth can take place with a decrease in free energy. These conditions constitute an energy barrier inhibiting nucleation: however, the critical size of the nucleus diminishes with falling temperature and increases the probability of homogenous nucleation occurring.

In heterogeneous nucleation the initial growth interface is provided by a foreign particle included or formed in the melt. For a second phase to act as a nucleus in this way it must be capable of being wetted by the metal, forming a low contact angle, and must possess some structural affinity with the crystalline solid (Becky, 1982).

The nucleation and growth of crystals occurs below the equilibrium freezing temperature. Because conditions are initially unfavourable to the survival of small nuclei considerable under cooling is necessary to produce homogeneous nucleation. In practice, however, some foreign nuclei are always present in the form of impurities having their origin in the metal, the walls of the mould and the atmosphere. Further foreign nuclei may be deliberately added to encourage a particular mode of crystallization. Solidification under foundry conditions thus occurs with little under cooling.

Once the initial nuclei are established, two possibilities exist for further crystallisation. More solid may be deposited upon the first nuclei, for fresh nucleation of the same or of a different phase may occur in the liquid.

The most effective site for the precipitation of a phase being an existing mass of the same phase, growth might be expected to predominate over further nucleation. In practice, however, barriers to growth result from the evolution of the latent heat of crystallisation and, in alloys, from the change in composition of the adjacent liquid through differential freezing. The influences of these phenomena upon growth will now be further considered.

2.3.2 Growth

The growth processes which follow nucleation determine the final crystallographic structure of the solid. The mode of growth, both of individual grains and of the general mass of solid, depends upon thermal conditions in the solidification zone and the constitution of the alloy.

The freezing of a pure metal presents the most straight forward case. If the temperature were capable of being lowered in a completely uniform manner, random nucleation might be expected throughout the liquid. Under practical conditions of heat flow, however, temperature gradients produce initial nucleation at the relatively cool mould surface, growth proceeding directionally towards the centre of the casting (Figure 2.5). Such growth tends to be associated with a preferred crystallographic direction: favourably oriented crystals grow more rapidly than their neighbours in a temperature gradient.

At a stage depending upon the number of effective nuclei and the initial growth rate, lateral growth becomes restricted by the mutual constraints of neighbouring crystals. An approximately plane interface then advances by the progressive deposition of atoms to join the lattice of one or other of the existing crystals. This growth actually takes place by the edgewise extension of close packed atomic planes, producing a minute terraced structure on the growth interface, but this interface is macroscopically smooth and, in most metals, non-crystallographic. Such is a typical sequence leading to the production of the characteristic columnar structure often observed in ingots and castings, with the individual grains elongated in the general direction of heat flow.

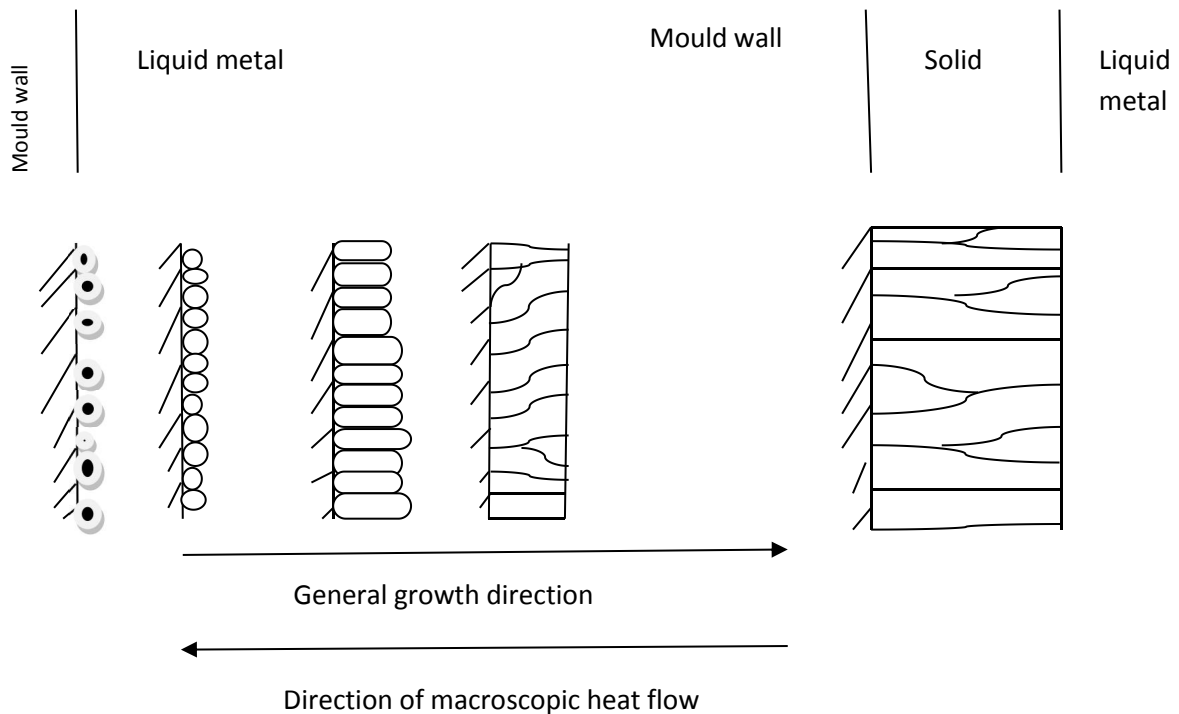


Figure 2.5: Development of columnar grain structure (schematic)

One set of thermal conditions producing such a structure is illustrated in Figure 2.6. This case assumes the existence of the interface advancing progressively as the growth temperature T_G is reached at points deeper inside the casting. Freezing can occur in this manner when the latent heat of crystallisation is insufficient to reverse the direction of the heat flow in the liquid adjacent to the interface. It is only under these conditions that the latter approximates to a flat plane, a mode of growth promoted by slow cooling and a steep temperature gradient.

In many conditions, however, although heat transfer from the casting to the cooler mould produces a positive gradient on a microscopic scale, local evolution of latent heat is sufficient to reverse the temperature gradient at the interface. Thermal conditions in this case are represented in Figure 2.7. Since the minimum temperature in the liquid is no longer adjacent to the interface, growth by the general advance of a smooth solidification front gives way to other modes of growth in which deposition can occur in regions of greater undercooling. Microscopic heat flow can thus be a major factor in the formation of cast structures.

Before proceeding to examine these alternative modes of growth, brief consideration will be given to the alloys which freeze to form solid solutions. These exhibit differential freezing, which again promotes growth in a manner other than by the advance of a smooth interface.

In the binary alloy system illustrated in Figure 2.6, the solid initially deposited from the alloy C_0 is of composition C_1 , so that the residual liquid

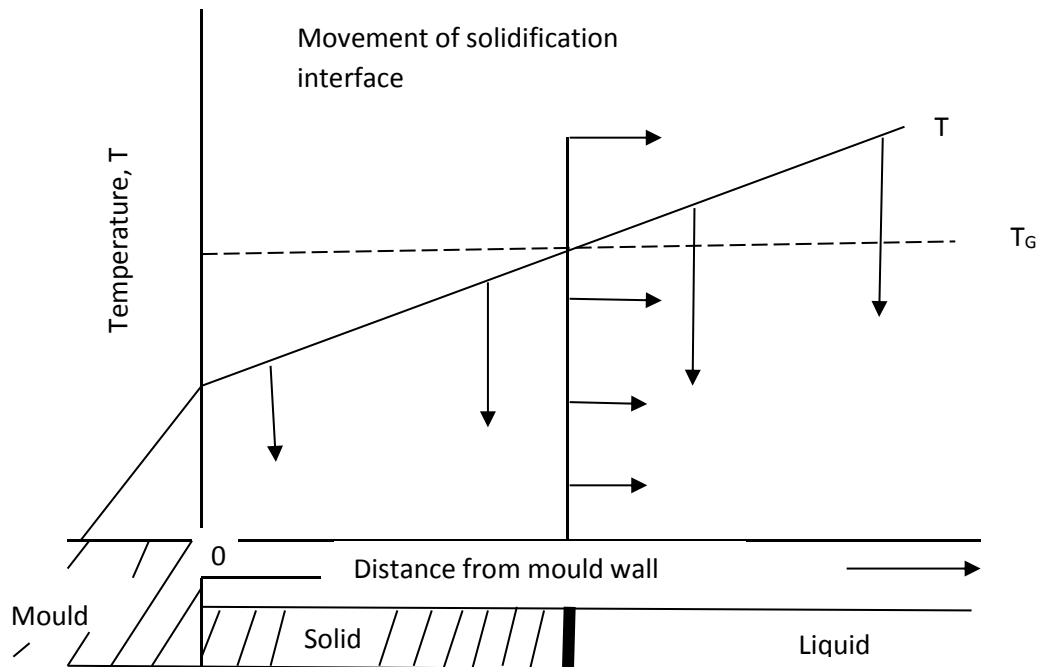


Figure 2.6: Schematic representation of temperature distribution in plane front solidification.

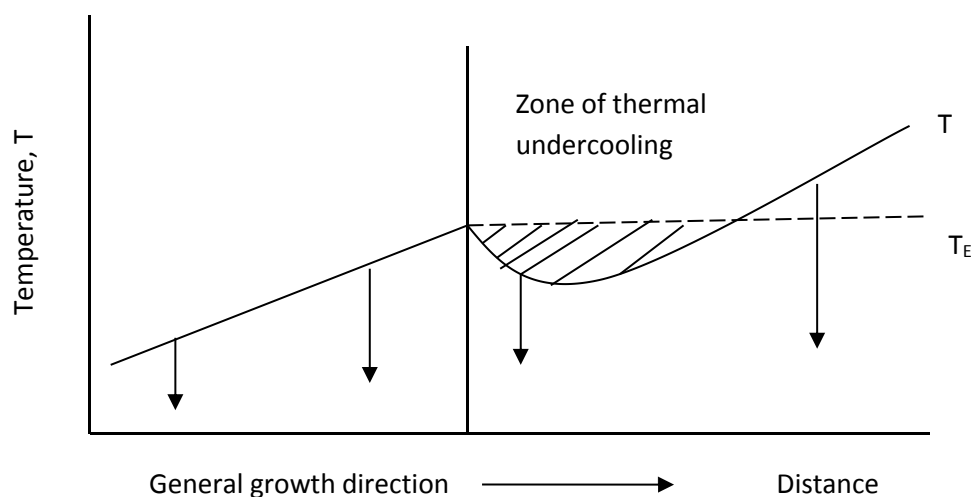


Figure 2.7: Thermal conditions with reversal of temperature gradient in liquid adjoining interface.

becomes slightly enriched in the solute element B. Solid formed during further cooling being similarly deficient in element B relative to its own parent liquid, this element is continuously rejected into the liquid phase throughout freezing.

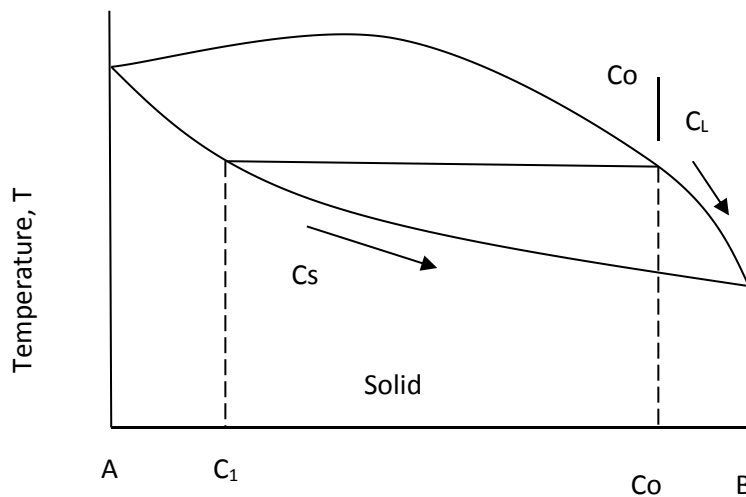


Figure 2.8: Thermal equilibrium diagram for two metals forming a continuous range of solid solutions

The unidirectional freezing of a small element of such an alloy can now be considered, where the system is allowed to reach equilibrium at any intermediate stage, the situation could be defined by a diagram of the type shown in Figure 2.9, with completed homogeneity of the solid and liquid phases. Under dynamic conditions, however, a non-equilibrium situation prevails.

The change in composition of the whole of the liquid is brought about by solute rejection at the interface, so that a compositional gradient must exist in the liquid, its profile being determined by the rate of solute transport relative to the rate of crystallisation.

This compositional variation, illustrated in Figure 2.10a, introduces a corresponding variation in freezing temperature as shown in Figure 2.10b. Each composition on the solute distribution curve has its own characteristic equilibrium freezing temperature, below which a particular amount of undercooling will produce further crystallisation.

If the freezing temperature curve is related to the actual temperature gradient existing in the liquid, as shown in Figure 2.11, it can be seen that before the general temperature level falls sufficiently to produce fresh deposition solid at the interface, considerable

undercooling may exist at points further within the liquid, i.e there may be a band of liquid within which conditions are more favourable to freezing than at the interface. This condition is frequently termed constitutional undercooling, its importance was appreciated many years ago by Hultgren, Genders and Bailey, Northcott and others and its influence upon the mode of crystallization has been subject to much further examination in recent years, in (Becky, 1982). The interaction of the temperature and compositional gradients in the liquid can thus be regarded as the most important single factor influencing the structure of a casting. Both grain and substructure depend upon this factor.

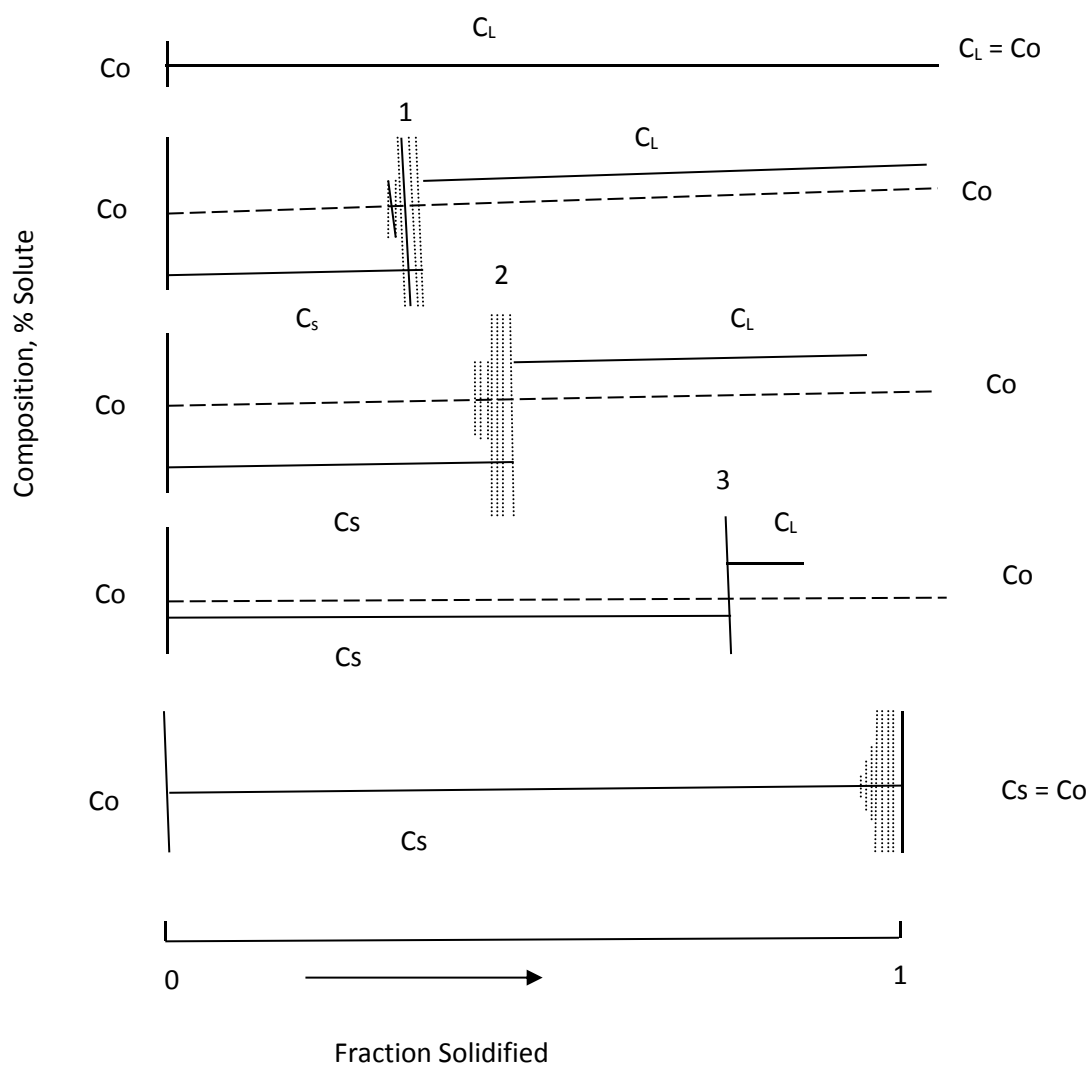


Figure 2.9: Equilibrium distribution of solute between solid and liquid phases at successive stages of unidirectional freezing: C_0 = mean composition before and after freezing, C_s and C_L = compositions of liquid and solid fractions at successive static positions of interface.

Dendritic Growth

When undercooling occurs in the band of liquid adjoining the interface, any existing protuberance on the solid face tends to become stable and to act as a Centre for preferential growth. Whilst general advance of the interface is retarded by the latent heat or solute barrier, such local growth Centres can probe further into the zone of undercooling.

These are favourable conditions for dendritic growth, with its characteristic tree-like form. This is the type of growth most commonly encountered in the freezing of commercial casting alloys forming solid solutions. The primary axis of the dendrite is the result of preferred growth at an edge or corner of an existing crystallite. The projection develops into a needle and subsequently a plate following the general direction of heat flow; this growth direction is usually associated with a particular crystallographic direction.

Lateral growth of the primary needle or plate is restricted by the same latent heat or solute accumulation as inhibited general growth at the original interface, but secondary and tertiary branches can develop by a similar mechanism to that which led to the growth of the primary stem (Figure 2.12). According to Rundman (2000) most solidification events involve the production of dendrites followed by the precipitation of a second phase or phases in between dendrite arms. The reasons why dendrites form is defined by the kinetic and thermodynamic factors which allow atom rearrangement in a convenient way in an acceptable period of time. The exact distribution of alloy elements segregated into and external to the dendrites, and the magnitude of the SDAS (Secondary dendrite arm spacing) is determined precisely.

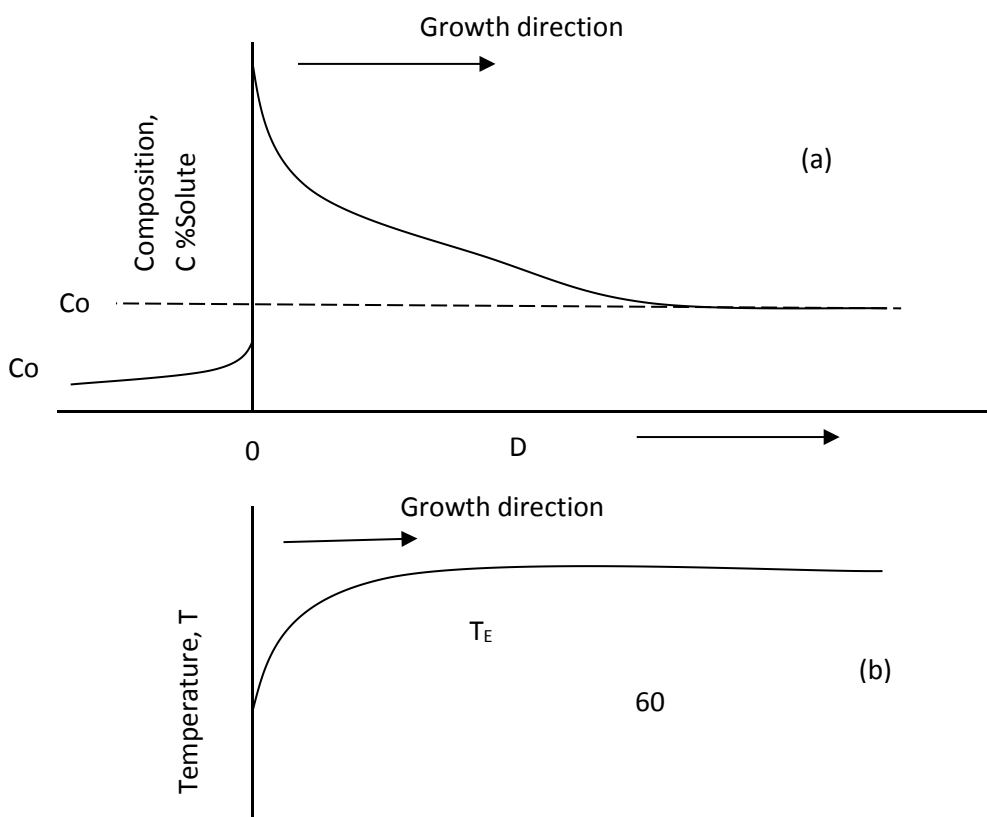




Figure 2.10: Concentration of solute in liquid ahead of advancing interface – nonequilibrium conditions. (a) solute distribution C_L (b) equilibrium liquidus temperature T_E corresponding to solute content at distance D from solidification interface.

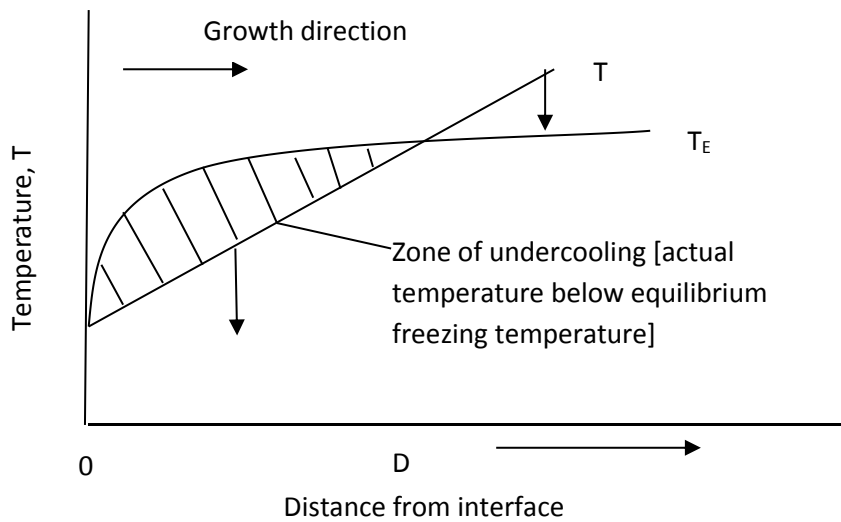


Figure 2.11: Relation of temperature gradient in liquid to equilibrium freezing temperature profile.

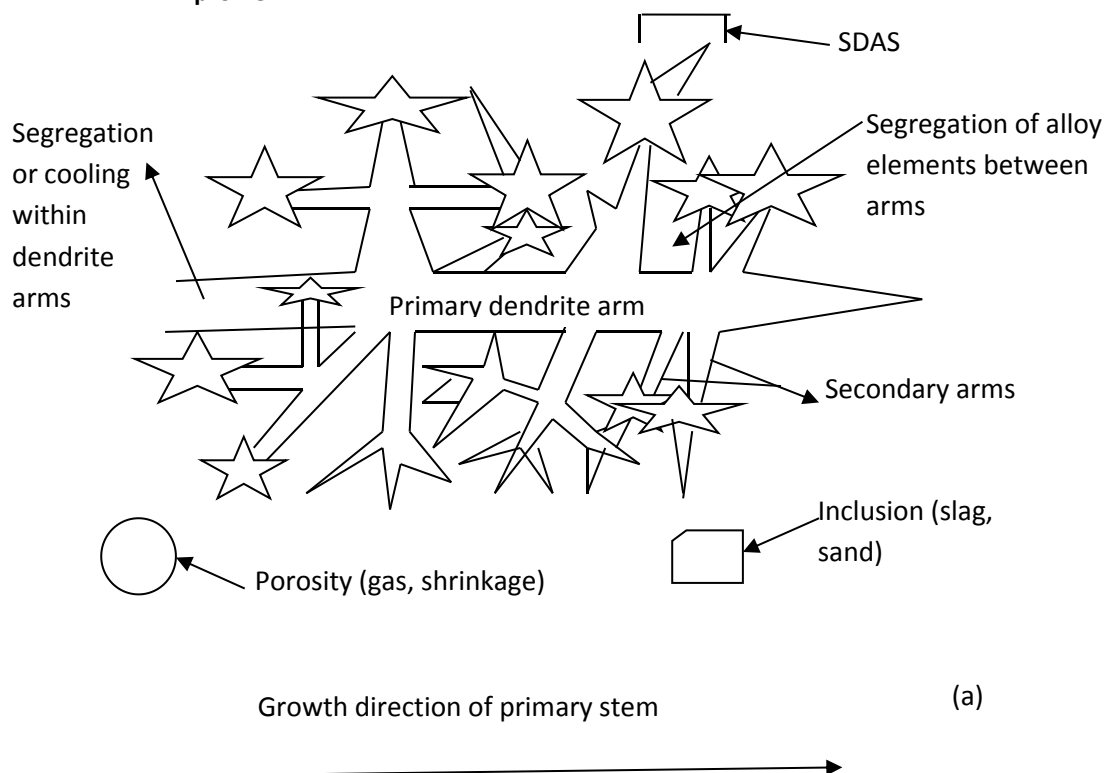




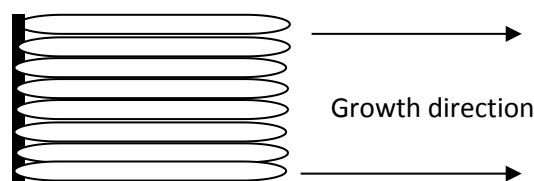
Figure 2.12: Dendritic growth (a) classical concept of a dendrite (b) dendritic microstructure in Al – 0.5% glass particulate composite x 100.

by the alloy composition and the rate at which the heat is removed from the

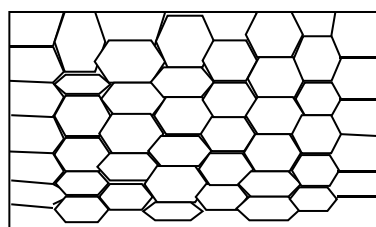
solidifying volume. Once the alloy composition and the size of the casting and mould material is selected, the solidifying material produce a base into which other phases or reaction products may be interspersed (eutectics, peritectics, inclusions, porosity, etc) (Rundman, 2000).

Dendritic growth in a pure metal can only be detected by interrupted freezing and decantation, but is evident in alloys through the persistence of compositional differences, revealed on etching as the characteristic cored structure. Differential freezing process normally results in coring which leaves the centres of the dendrites deficient in solute relative to the interdendritic zones. The resulting compositional gradient can only be eliminated by high temperature diffusion in the solid state, time for which is not normally available during cooling from the casting temperature.

Dendritic growth in alloys is preceded, with less marked undercooling, by the formation of a highly distinctive cellular substructure, direct evidence for which has been obtained by the examination of interfaces from which the liquid has been decanted. This structure (see figure 2.13) is produced as a cluster of hexagonal rods which grow into the liquid and reject solute to their boundaries, on attaining a certain level of undercooling the cellular gives way to the dendritic mode of growth by the preferential development of a limited number of cells. Intermediate rod-like structures have been described by Flemings as 'fibrous dendrites' (Becky, 1982).



(a)



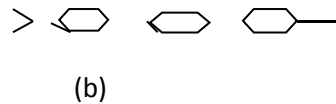


Figure 2.13: Cellular substructure formed by undercool. (a) Structure in growth direction, (b) hexagonal cells on growth interface (nickel base alloy. X 120) Becky 1982.

Independent Nucleation

When freezing occurs under a shallow temperature gradient or at a very rapid rate, the undercooling may be sufficient to promote fresh nucleation at points distant from the main interface. Under these conditions, further solidification produces equiaxed grains, such as are frequently present in the central zone of both castings and ingots. The degree of undercooling at which this will occur will depend upon the potency of the nuclei present and will later be shown to be affected by other conditions. Figure 2.14 summarizes the effect of the increased undercooling produced by varying the temperature gradient, upon the mode of growth.

In sand casting, although the tendency is towards an extremely steep temperature gradient in the mould, the temperature gradient in the casting is comparatively shallow; the entire structure is consequently often equiaxed. This is especially the case in alloys of high thermal conductivity, in which a high degree of temperature uniformity is maintained during freezing.

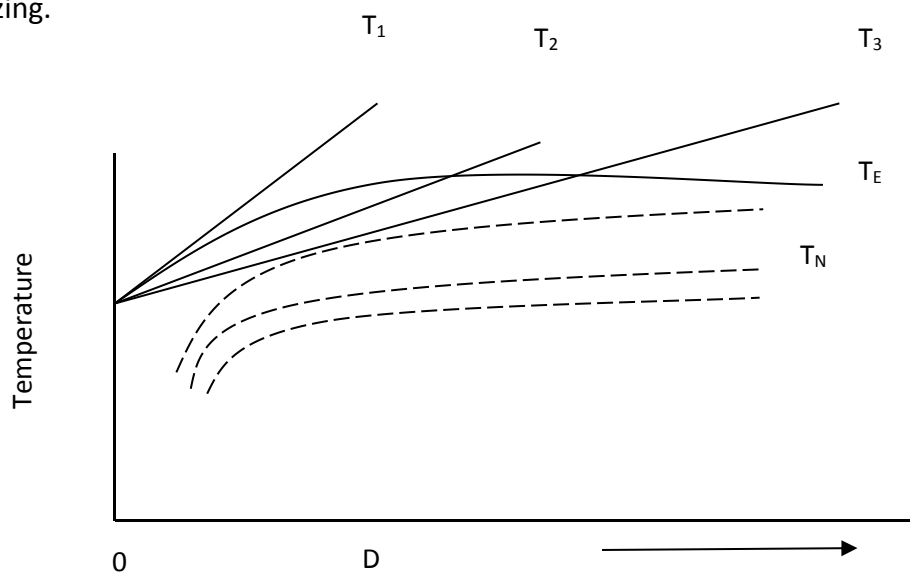


Figure 2.14: Influence of temperature gradient in liquid on crystallisation. T_E = equilibrium freezing temperature. T_N = Nucleation temperature, depending on nature of heterogeneous nuclei, T_1 , T_2 , and T_3 = temperature gradients. Producing increasing undercooling and associated changes in morphology:

Planar → Cellular → dendritic → independently nucleated

Eutectic Freezing

Many casting alloys are either of approximately eutectic composition or contain appreciable amounts of eutectic constituent. Typical conditions for eutectic crystallisation are represented by the binary equilibrium diagram in figure 2.15, in which an alloy of composition E freezes at a single temperature to precipitate a mixture of two phases, α and β , compositions x and y.

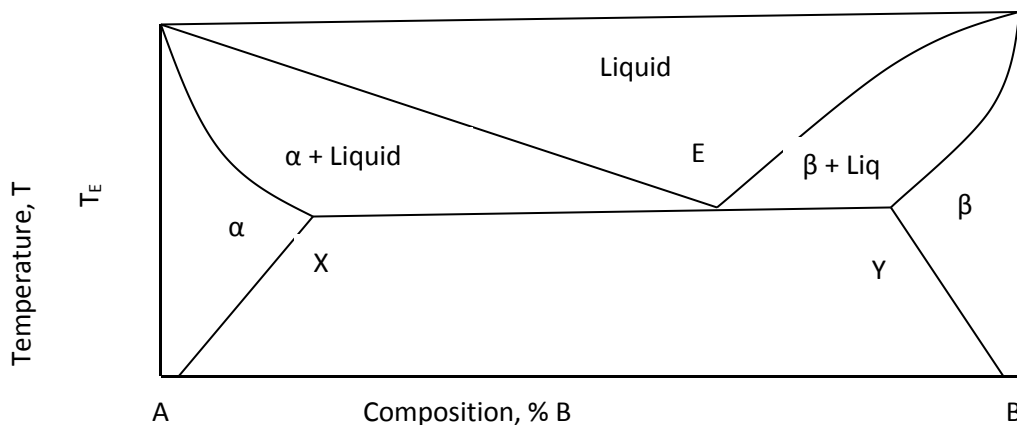


Figure 2.15: Thermal equilibrium diagram for two metals forming a eutectic

Unlike the dendritic growth of grains of solid solution, each eutectic 'grain' is formed by the simultaneous growth of two or more separate phases in close association. The resulting structure may consist of alternate lamellar of the two phases, or may feature rod-like or globular elements of an apparently discontinuous phase in a matrix of the second.

The growth of a lamellar eutectic commences with the nucleation of one of its phases. The solute concentration in the liquid increases until nucleation of the second phase occurs at the interface, after which the growth of both phases proceeds with an orientation relationship between the two. It was originally postulated by Tiller in Becky (1982) that additional lamellae could be produced either by fresh nucleation or by a process of bridging.

Growth of the eutectic grain as a whole takes place by the simultaneous edgewise extension of the plates of both phases. It has been appreciated in recent years that each eutectic grain in the final structure is the product of associated growth from a single centre to form a

microscopically distinct unit. Such units may be equiaxed in form, analogous to the equiaxed grains in single phase systems (see figure 2.16) although it is also possible to grow columnar eutectic structures by controlled unidirectional freezing (Ihom *et al.*, 2014).

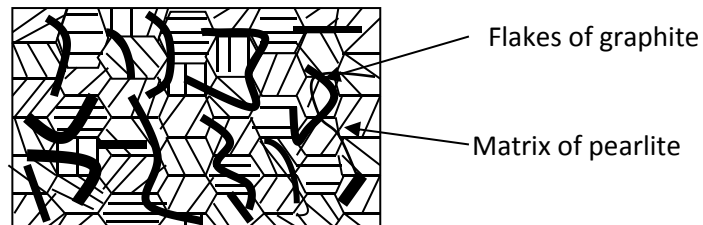


Figure 2.16: Eutectic grain structure in grey cast Iron
(Courtesy of Ihom *et al.*, 2014).

Peritectic Reactions

Solidification involving peritectic reactions is represented in the portion of a binary equilibrium diagram shown in Figure 2.17. In this case the equilibrium freezing of alloys of compositions between X and P involves the precipitation

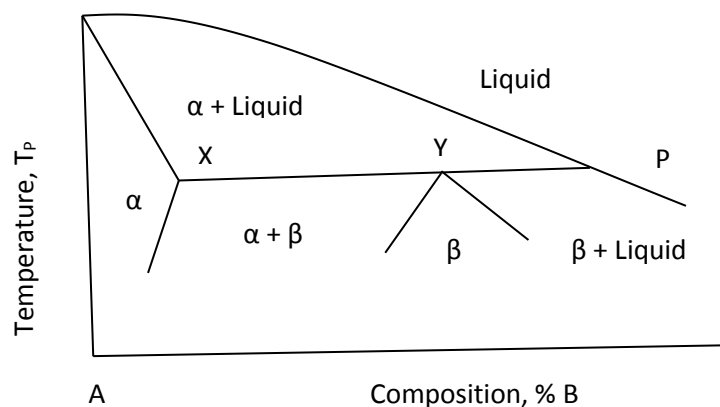


Figure 2.17: Section of thermal equilibrium diagram involving a peritectic reaction

of primary crystals of solid solution α and their subsequent reaction with residual liquid at temperature T_p to form a second solid solution β of composition Y. For alloy compositions to the right of point Y the whole of the α of composition X reacts with a proportion of the liquid of composition P to form β and freezing of the remaining liquid is completed at lower temperatures by the precipitation of additional β . In alloys to the left of point Y the whole of the liquid is consumed in reaction with part of the α and the structure on completion of freezing consists of two solid phases.

Peritectic reactions do not proceed readily to equilibrium since the initial reaction product forms a layer surrounding the primary solid phase; the subsequent reaction rate is controlled by diffusion through this layer and a compositional gradient persists in the final solid. Non-equilibrium residues of primary α thus tend to be retained even in alloys to the right of point Y. In experiments with silver – zinc alloys Uhlmann and Chadrick in Becky (1982) have confirmed the presence of primary α dendrites together with the β phase in all alloys between the extreme points of the peritectic horizontal. The two phases under these conditions are precipitated over separate and successive ranges of temperature.

THE STRUCTURE OF CASTINGS

In the foregoing section the processes of nucleation and growth have been considered in relation to the principal alternative features of crystal structure in cast metals. So far this structure can be seen as an outcome of three major influences:

- i. **Alloy Constitution:** Metal composition governs the basic mode of crystallisation and determines whether the structure will consist of single phase or eutectic grains or both. The alloy composition is also characterized by particular distribution and diffusion coefficients for solute in liquid and solid phases and thus established the relative tendency to constitutional undercooling.
- ii. **Thermal Conditions:** The temperature distribution and rate of cooling in a casting are derived from the initial temperature conditions and the thermal properties of metal and mould.
- iii. **Internal Nucleation and growth Conditions in the liquid:** The relative possibilities for nucleation and growth depend upon foreign particles or solutes present in the liquid, whether as trace impurities or as deliberate additions.

This topic further explains the solidification process in castings and it is more of a summary of what has been discussed above.

Considering firstly the alloys forming a continuous range of solid solutions, it has been shown that the mode of crystallisation is governed by the interaction of temperature and compositional gradients in the liquid.

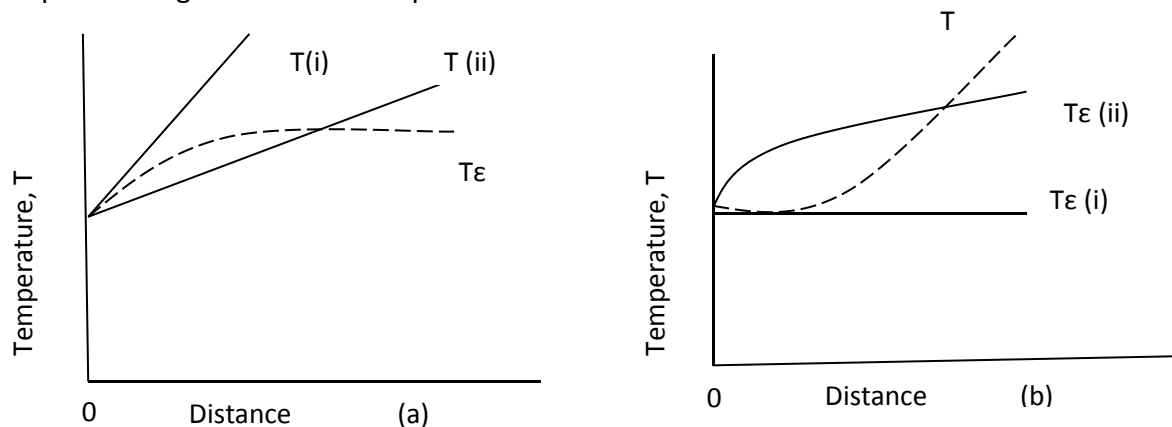


Figure 2.18: Interaction of temperature and compositional gradient in determining structure, (a) influence of temperature gradient (T) (b) influence of liquidus temperature profile ($T\epsilon$) (i) Condition favouring plane front solidification (ii) condition producing undercooling.

Columnar growth from the mould wall towards the centre of the casting is favoured by the existence of a steep temperature gradient, since this increases the probability that renewed growth at the interface will occur before undercooling is sufficient to bring about further nucleation elsewhere (Figure 2.18a). Columnar growth is also promoted by slow cooling which allows more time for solute transport in the liquid, diminishing the concentration gradient at the interface Figure 2.18b). Slow cooling is moreover, associated with an inherently low rate of nucleation relative to rate of growth in all processes of crystallisation.

The influences of foundry variables upon structures must accordingly be determined by their effects upon the temperature gradient G and the rate of freezing R , and it follows that the ratio G/R is a significant parameter with respect both to mode of growth and to final grain structure in solid solution alloys. The effect of this ratio may now be summarised. Progressive change in the parameter from a high to a low value is accompanied by successive transitions in the mode of crystallisation as the effect of undercooling becomes

more pronounced. These successive stages are illustrated schematically in Figure 2.19 and the associated thermal conditions in Figure 2.20. With a very high ratio, columnar growth takes place with the advance of a plane interface, which first gives way to the cellular growth form previously described. Diminishing values of G/R bring about

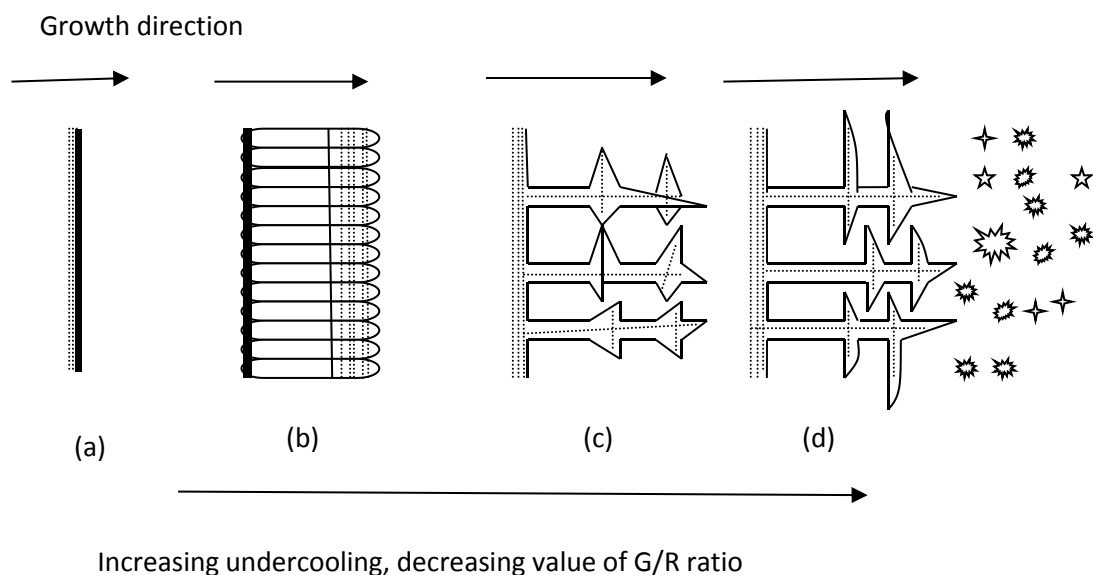


Figure 2.19: Influence of undercooling on interface morphology and mode of growth (a) planar interface, (b) cellular interface, (c) dendritic growth, (d) independent nucleation.

the cell → dendrite transition with columnar growth now occurring on probes of solid some distance ahead of the main interface. At still lower values of G/R , heterogeneous nucleation in the undercooled zone brings about the growth of new grains in positions remote from the existing interface; these grains may themselves undergo dendritic growth, although there is some evidence that the radial growth of independent grains begins with spherical morphology analogous to the plane interface condition in unidirectional freezing.

These successive transitions to cellular, to dendritic and thereafter to independently nucleated crystal growth, can be quantitatively represented in the manner of Figure 2. 20, derived from experimental observations under controlled thermal conditions. From these types of relationship it can also be seen that alloys containing more solute become progressively more susceptible to growth forms associated with undercooling. The actual relationships between G , R and C_0 for the successive transitions are not identical.

The planar → cellular transition is characterized by a clear linear relationship between G/R and C_0 , but evidence suggests that there is no simple relationship between G/R and C_0 for either cellular → dendritic or columnar → equiaxed transition. Under most conditions, columnar and equiaxed dendritic structures predominate in production castings in this type of alloy system. Dendrite morphology is thus of great practical importance (Beeley, 1982).

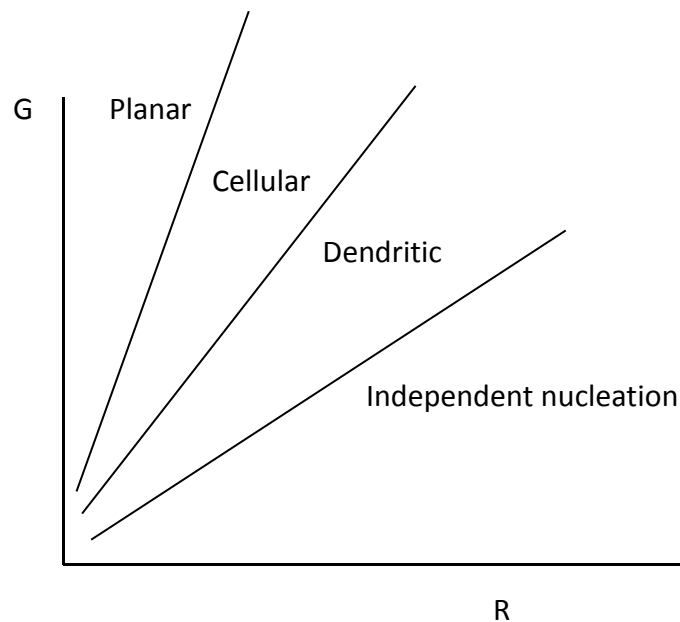


Figure 2.20: Influence of temperature gradient G and freezing rate R on solidification morphology of a given alloy.

Grain Boundaries

The grain boundary is a layer only a few atoms thick which constitutes the zone of contact between adjacent grains having differently oriented space lattices. As a result of the interference between differently oriented grains during the process of solidification, the atoms of the grain boundary are not arranged in the geometrical pattern that is the space lattice characteristic of the metal. The metal in the grain boundary therefore has characteristics different from those of the metal in the grain.

At moderate temperatures the material of the grain boundary is harder than that of the grain. At high temperatures, however, the effect of this difference in constitution becomes important because the atomic bonds which hold the disarranged atoms are the first to loosen. The disarranged atoms acquire freedom of motion as the bonds

loosen, and the metal tends to creep or flow when placed under stress. Under these conditions the grain boundary becomes the weakest part of the metal.

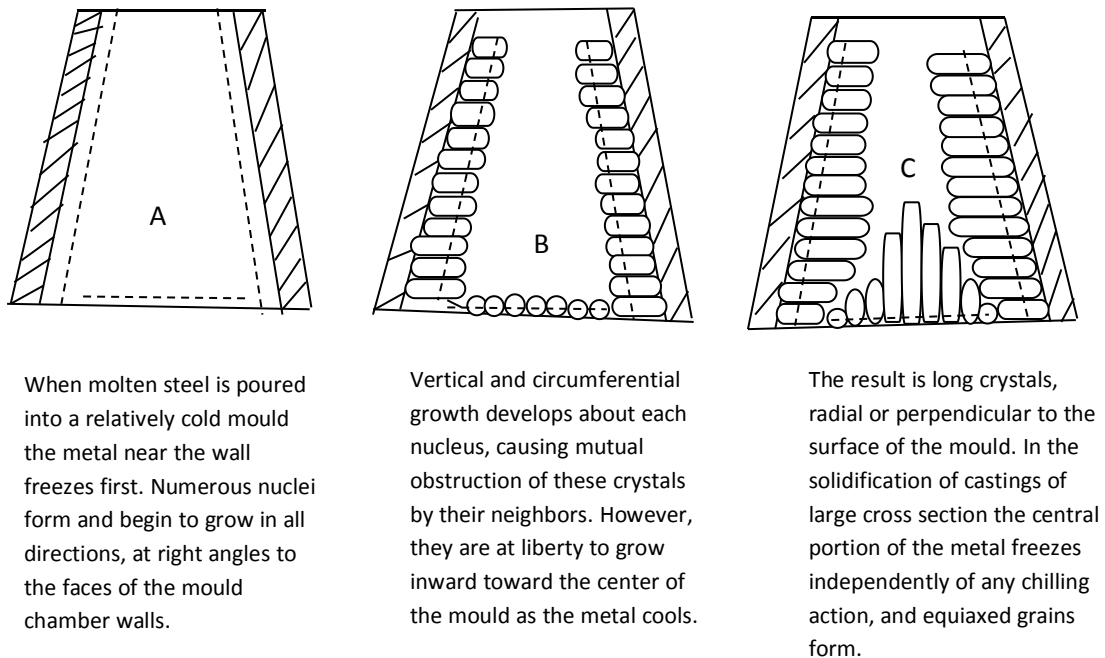


Fig. 2.4 Crystal formation in a chill mould (Courtesy Shragger, 1969)

Effect of Cooling Rate on Grain Size

The rate of cooling is of great importance because it governs the size, shape, and arrangement of the grains of a metal casting. In sections that are cooled slowly through the solidification range, grains that start on one side increase in size until they meet other grains that have started from the other side, and the resulting structure is coarse grained. If cooling is rapid, as in the case of thin sections, or if the metal is poured into chill moulds, solidification starts at a greater number of different points and a larger number of grains develops, producing a finer grain structure. If further control of grain size is required, a foreign material such as alumina may be added to the melt to provide additional nuclei for crystallization.

The significance and Practical control of Cast Structure

The principal factors governing the final metallographic structure of a casting may now be listed. They are:

1. Constitution and thermal properties of the alloy;
2. Casting design and dimensions;
3. Thermal properties of the mould;
4. Superheat and final casting temperature;
5. Conditions for heterogeneous nucleation;
6. Conditions affecting motion during solidification;
7. Subsequent heat treatment.

Thus, although the structure of a casting is in the first instance a function of alloy composition and casting geometry, it is also sensitive to measures taken in founding. These include preliminary treatment of the liquid metal and variation of the cooling rate within the mould. It would, however, be true to say that manipulation of the freezing process in castings has been more usually directed at the problems of feeding than at structure.

The importance of structure in cast alloys lies mainly in the structure sensitive properties which can be utilised in engineering. These properties are determined primarily by the influence of the microstructure on the behaviour of dislocations in the lattices of the individual crystals. Unlike wrought materials, in which further opportunities exist for changing both structure and dislocation density, the initial microstructure is frequently the main vehicle for the control of properties, although subsequent heat treatment plays this role in some cast alloys.

In examining the critical characteristics of cast structures, two types of metallographic features can be conveniently considered:

1. Grain structure (size, shape, and orientation): the boundaries of primary grains formed during freezing are normally visible on macroscopic or microscopic examination, although their detection may be complicated by solid state transformations occurring on further cooling to shop temperature. In a structure consisting largely of eutectic grains, however, boundaries may be more difficult to distinguish unless highlighted by the segregation of impurities.
2. Substructure: important features include the distribution and state of division of alloy components and microconstituents, including solutes, second phase networks or particles, and the separate phases within the eutectic grain. Dendrite substructure too falls in this category.

Cast structure can be complicated by the presence of shrinkages, holes and macroscopic segregation. Control of cast structure may take either of two directions. Most widely established are measures directed towards refinement of grain and constituent size. Special treatments for this purpose are a well- established feature of the production of light alloys and cast irons, whilst more recently there has been increasing attention to grain size control in cast steels and other alloys. The second form of structure control has received only limited attention and involves the manipulation of grain shape and crystallographic orientation to produce anisotropy of structure and properties.

Although structure control is primarily of interest for its effect upon properties of the alloy, this aspect cannot in practice be wholly divorced from the task of producing a sound casting. Thus refinement or columnar growth, for example, may be sought, not necessarily as a step towards superior mechanical or physical properties, but for the suppression of hot tears or for benefits to be derived in feeding. Both aspects must be considered when assessing the most appropriate structure. This partial interdependence of structure and soundness also means that the structure sensitivity of properties varies both with alloy and with solidification conditions. In a work carried out by Ihom (1990) the author pointed out that mould conditions and cooling rate do have great effect on castings structure and properties.

Heat Loss from Castings

For the purpose of riser design it is important to know the rate of heat removal through the wall of the mould. Risers act as a reservoir of liquid metal above the casting and supply liquid metal to the casting throughout its solidification period.

Rate of heat flow per unit area = $\frac{k(\theta_1 - \theta_2)}{\sqrt{\pi d}}$ and quantity of heat passing through mould metal interface $Q = \frac{2Ak(\theta_1 - \theta_2)\sqrt{t_s}}{\sqrt{\pi d}}$

where k = thermal conductivity of the mould material

θ_1 = is the initial mould temperature and θ_2 is the Mould/metal interface temperature (assumed constant during solidification),

t_s = time required to solidify a plate of surface area A

d = thermal diffusivity of the mould.

Q = Considering the amount of heat which must be lost to produce solidification

$$= \rho V[L + c(\theta_p + \theta_1)]$$

where ρ = density of metal,

V = volume of metal, ,

L = latent heat of fusion of metal

θ_p = pouring temperature

c = specific heat capacity of metal

$$\therefore \frac{2Ak(\theta_1 - \theta_2)\sqrt{t_s}}{\sqrt{\pi d}} = \rho V[L + c(\theta_p - \theta_1)]$$

or $t_s = \left[\frac{\rho[L + c(\theta_p - \theta_1)]}{2k(\theta_1 - \theta_2)} \right]^2 \pi d (V/A)^2 = C \left(\frac{V}{A} \right)^2$, where C = Mould constant. This time for solidification of a plate is proportional to $\left(\frac{V}{A} \right)^2$. It can also be shown that the time needed to

solidify to a given depth is proportional to the square of the distance from the mould metal interface.

Solidification Time

During the early stages of solidification, a thin solidified skin begins to form at the cool mould walls, and as time passes, the skin thickens. With flat mould walls, this thickness is proportional to the square root of time. Thus doubling the time will make the skin $\sqrt{2} = 1.41$ times or 41% thicker. According to Chvorinov's rule, the solidification time is a function of the volume of a casting and its surface area.

$$\text{Solidification time} = C \left(\frac{\text{Volume}}{\text{Surface area}} \right)^2$$

where C is a constant that reflects mould material, metal properties like latent heat, and temperature. For sphere, cube, and cylinder, the solidification times are as under:

$t_{\text{sphere}} = 0.043C$, $t_{\text{cube}} = 0.028C$, $t_{\text{cylinder}} = 0.035C$, i.e cube shaped casting will solidify the fastest and the sphere-shaped casting will solidify the slowest.

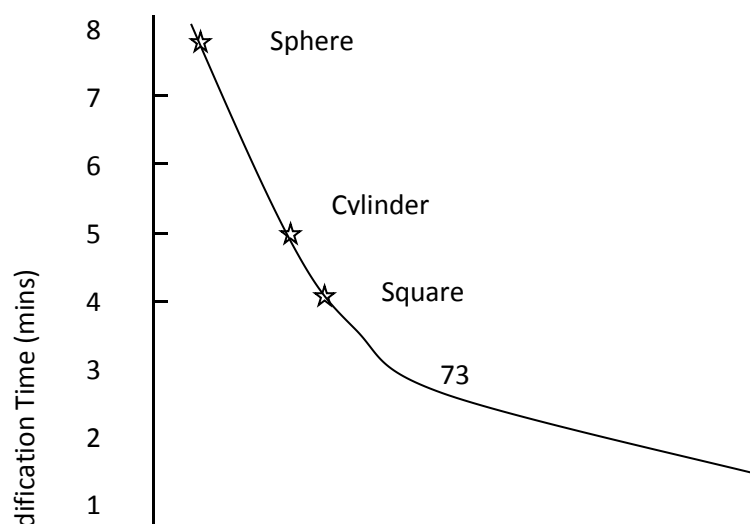
The solidification rates for various cases are as under.

- (i) in the case of a large casting in an insulating mould (sand casting),

$$\text{Solidification time} = C \left(\frac{V}{A} \right)^2$$

where V = total volume of the casting, A = cross-sectional area of the mould-metal interface (approximately surface area of casting). In case the metal-mould surface is convex in place of plane surface, the heat flow is more divergent and the rate of heat transfer will be more and freezing time less. Reverse is true for concave metal-mould interface.

- (ii) When heat flow is controlled significantly by the thermal resistance of the mould-metal interface (as in permanent mould casting and die casting), solidification time $= \frac{\rho L}{h(\theta_1 - \theta_2)} \frac{V}{A}$; where h = film heat transfer coefficient of the interface, ρ = density of metal, θ_1 = temperature of liquid metal, θ_2 = temperature of mould surface. Fig.2.5 shows how solidification time varies with change in Area/volume ratio for various shapes.



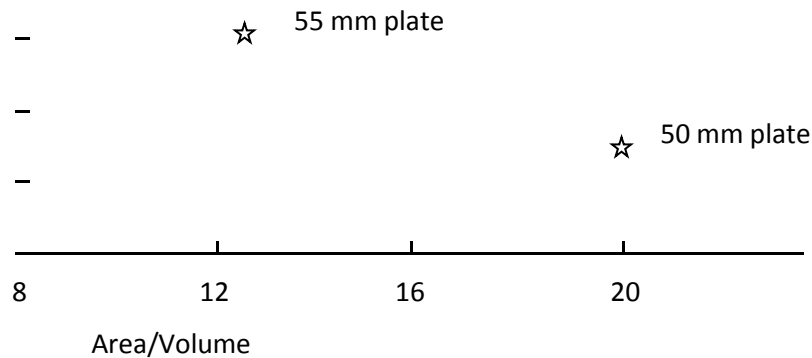
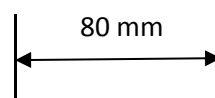
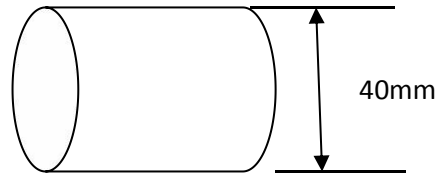


Fig.2.5 Solification Time versus Change in Area/volume

Review Questions for Chapter Two

- 1a. Explain the process of solidification in cast metals
- b. What are the important consequences of solidification?
2. What are intrinsic and extrinsic factors and why do you think the ultimate physical and mechanical properties of cast metals depend on these factors.
3. What is a crystal? Differentiate between a crystal and a grain.
- b. Explain the process of dendrite formation from the nucleation stage to growth. Do this with mathematical and graphical illustrations.
4. How does independent nucleation occur during metal solidification?
5. Explain eutectic freezing in metal solidification with a diagrammatic illustration
6. What is peritectic reaction? Explain with the aid of a diagram for clarity
7. List and explain three major influences on the structure of castings
8. What is the effect of the ratio of temperature gradient to cooling rate (G/R) on casting structure of metals?
9. What do you understand by grain boundaries?
10. Explain the effect of cooling rate on grain size
11. List seven principal factors governing the final metallographic structure of castings
12. Explain how castings structure can be controlled.
13. What is the formula for the quantity of heat (Q) passing through a mould metal interface?
Calculate the solidification time for the casting shown below, if the value of C is 0.51.





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CHAPTER THREE

FURNACES, MEASUREMENT AND CONTROL IN THE FOUNDRY

INTRODUCTION

The metallurgical integrity of a casting is a function of casting design and the methods used to gate and feed the casting. It is also a function of the metal or alloy quality. The metal melting stage exerts a fundamental influence on the quality of the metal. The chemical composition of an alloy is specified to a close tolerance and the first objective of melting is the attainment of the specified alloy composition. Adjustments to the composition may be necessary and can include refinement, to reduce specific element levels, and/ or additions to increase levels. Adjustments of this nature require the availability of analytical facilities to provide rapid data on the chemical analysis of the melt (Clegg, 1991). Also appropriate metal melting facilities i.e. furnaces must be considered.

Whilst they are molten, certain alloy are susceptible to gas absorption and /or the loss of volatile or reactive elements. Special treatments, such as degassing or vacuum melting and casting, may be required to overcome such problems. Careful control of the metal temperature is essential as these problems are exacerbated by higher temperatures. Furthermore, high metal temperatures will accentuate shrinkage problems and increase the likelihood of metal mould reactions. It is, of course, necessary to superheat the metal to provide sufficient fluidity for casting. This explains why temperature measuring devices are used to monitor temperature in the foundry.

The opportunity also exists at the metal melting stage to treat the metal in order to modify the structure and, consequently, the mechanical properties of the casting. These treatments are usually carried out at the point of dispensation of the metal from the furnace and include deoxidation, grain refinement, modification and inoculation. It is the purpose of this chapter to review furnaces used in the foundry, and also review measurement and control procedures for quality melt and castings. Produced castings must meet customer specifications and this requires properties measurement and physical dimension measurement for quality standard to be met (Ihom, 2012).

Furnaces

A furnace is a device in which the chemical energy of fuel or electrical energy is converted into heat which is then used to raise the temperature of material, called the burden or stock, placed within it for that purpose. Furnaces operating at low temperatures are often called ovens depending on their

purpose (Gupta, 2008). There are also others used for higher temperatures for different purposes. When associated with the ceramic industries they are called kilns. Glass is melted in tanks and other special terms often occur, suggesting the purpose, such as sintering machine used in metallurgical ore dressing, foundry furnaces etc.

Furnace Selection

Furnaces are designed for effective heat transfer and also for overall economics of melting operation. Some of the factors considered in furnace selection include the following:

1. Capital depreciation and degree of utilization: this has to do with the service requirement of the furnace and the scale or level of production envisaged by the user.
2. The operating cost: this includes the maintenance cost, labour as well as fuel and power, this costs are very critical in the selection of a furnace. The furnace with the least associated costs will in most instances be preferred.
3. Alloy type: the type of alloy to be melted also determines the type of furnace to be selected. This will take cognizance of the melting temperature of the alloy and other properties of the alloy.
4. The metallurgical factors in the choice of melting equipment, relate to the tendency of the charge to react with the surrounding affecting compositional control, impurity level and metallic yield.

In summary furnace selection is determined by, cost, metal quality, production requirement, and alloy type.

3.1 Classification of Furnaces

The classification of furnace can be done as:

- Batch type - Continuous type
- Direct heating type - Indirect heating type

Different metallurgical furnaces are:

- Crucible furnace
- Hearth furnace (e.g. open hearth furnace)
- Shaft furnace (e.g. blast furnace)
- Converters (e.g. Bessemer, side blown or top blown LD)
- Muffle furnace
- Soaking pits
- Reheating furnaces
- Annealing furnaces

Other Types of Furnaces

- Rotary kiln (e.g. cement kiln)
- Tunnel kiln
- Boiler furnace
- Electric furnaces (three phase or single phase)

- a) Heating by metallic resistors,
- b) Heating by induction,
- c) Heating by electrode arc

For practicing foundry men, furnaces are classified as heating and melting furnaces. Heating furnaces are of lower heat capacity and hardly exceed 1200°C. They are mainly used for heat treatment operations. The melting furnaces are usually of a higher heat capacity. They are used for the melting of metals and alloys. Temperatures in the range of 1600 -1700°C and above can be attained in some melting furnaces, e.g. the electric arc furnaces.

Furnaces are further classified based on various factors as below:

Classification Based on Type of Fuel used:

- Solid fuel fired furnace (coal fired boiler)
- Liquid fuel fired furnace (rotary kiln)
- Gaseous fuel fired furnace (coke oven, sinter furnace, soaking pit, re-heating furnace etc)
- Multi-fuel fired furnace (captive power plant boiler)

Classification based on use of heat saving appliances

- Regenerative furnace (e.g. coke oven)
- Recuperative furnace (e.g. soaking pit, reheating furnace)
- Waste heat type furnace (e.g. rotary lime kiln)

Classification based on draft control system

- Natural draft furnaces (e.g. B.F. stoves, coke oven etc)
- Forced draft furnaces
- Induced draft furnaces
- Balances draft furnaces (most large combustion furnaces come under this category)

Some of the above classified furnaces e.g. batch furnace, continuous furnace, recuperative furnace and regenerative furnace have been shown in Fig.3.1, Fig.3.2, Fig.3.3, Fig.3.4 respectively.

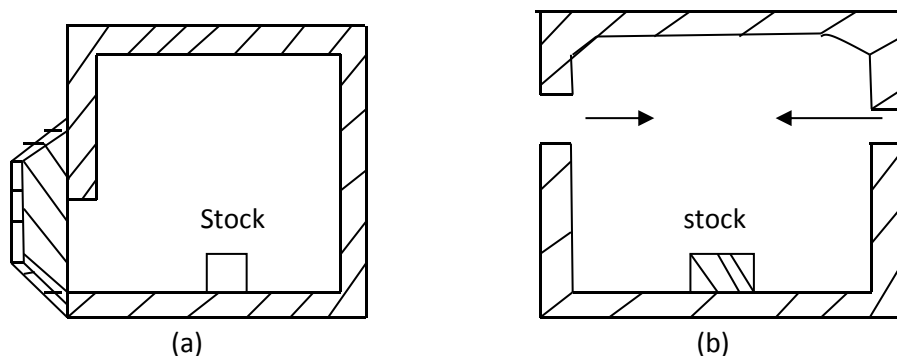
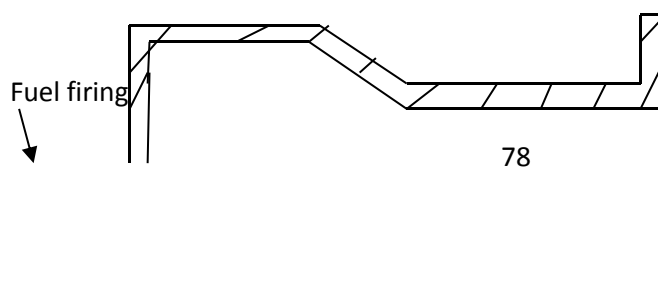


Fig. 3.1 Batch furnaces



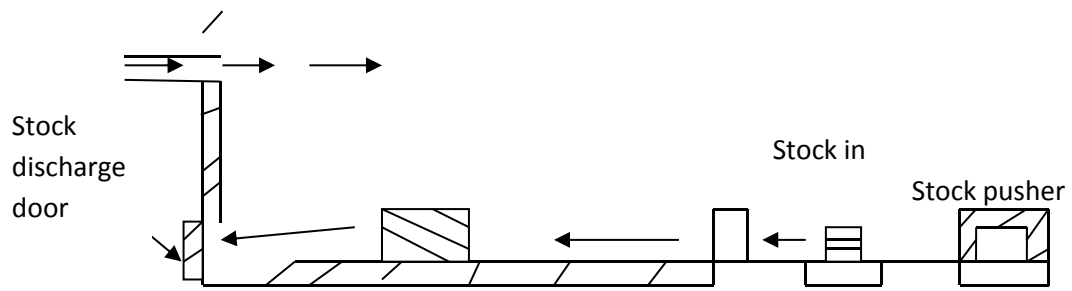


Fig 3.2 Continuous furnace (end discharge)

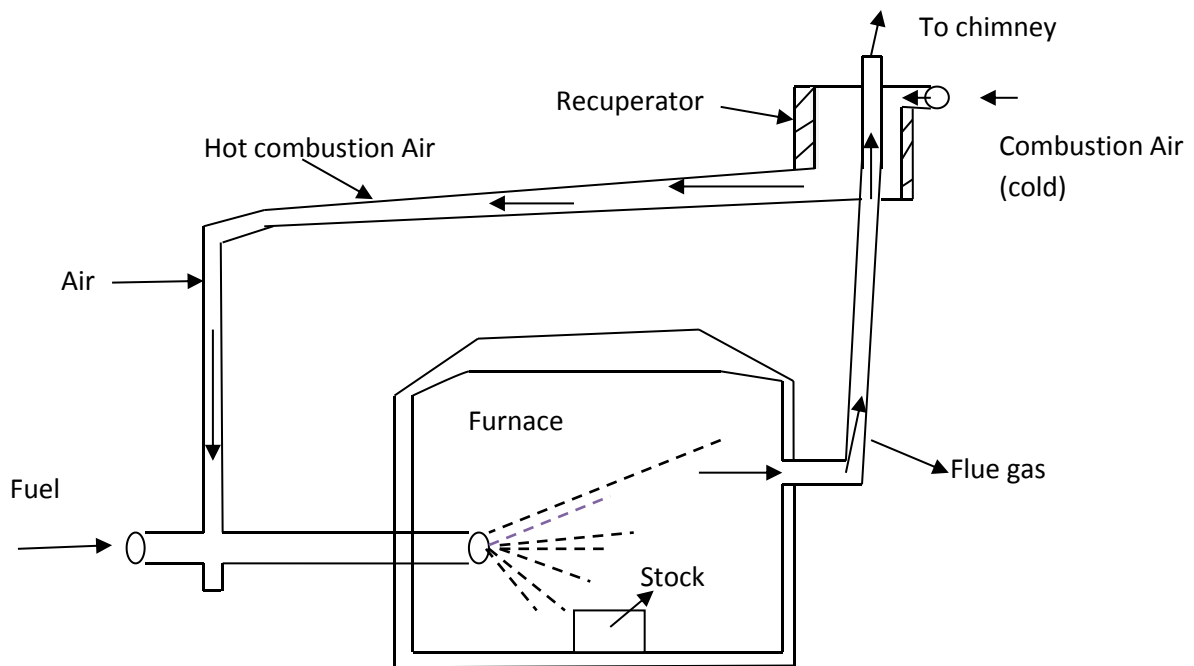
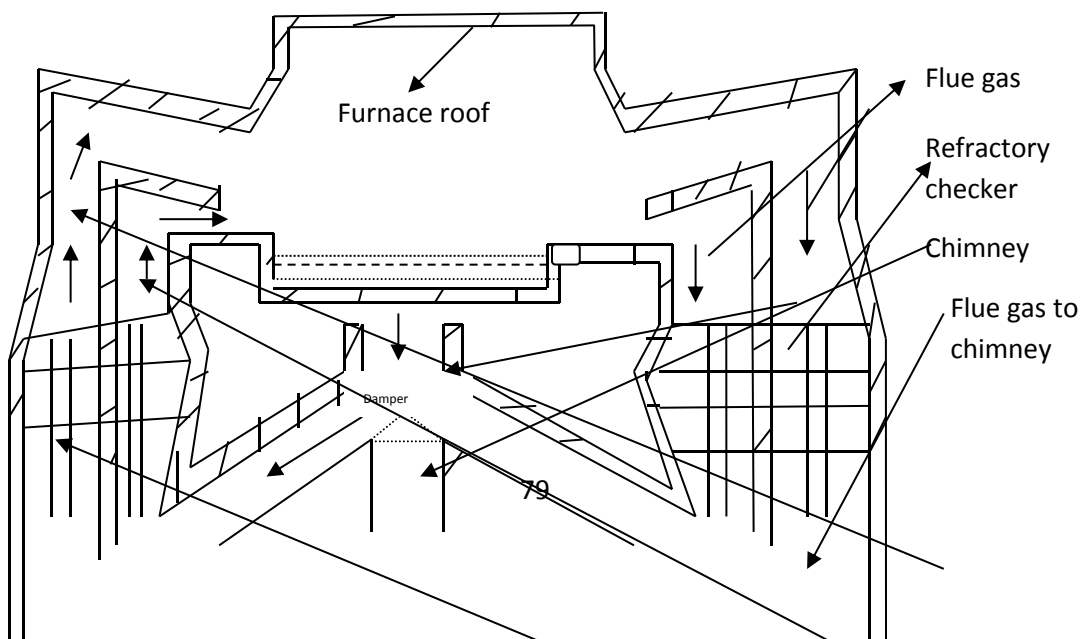


Fig .3.3 Recuperative furnace



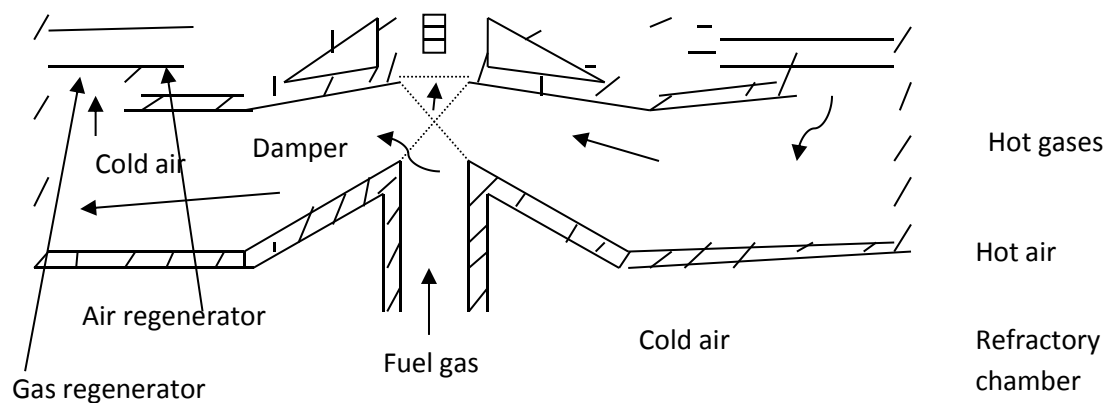


Fig. 3.4 Regenerative Furnace

In a batch furnace, the stock to be heated is charged in the furnace and is heated for a predetermined period to achieve the required temperature. The heated stock is then taken out of the furnace and the fresh cold stock is again charged. This furnace can be put off as and when needed.

In a continuous furnace, the stock enters or is pushed in from one end (i.e, charging end) of the furnace and it travels countercurrent to the hot flue gases to the other end (i.e discharge end). Its speed is so controlled that it gets heated up to the required temperature by the time it reaches the discharge end. It is then discharged out of the furnace and another cold stock may be charged. This process of stock charging and discharging goes on continuously.

In a recuperative furnace, waste heat recovery is done from the flue gas in a metallic or ceramic (tile recuperator) by preheating the combustion air and or fuel gas (if permissible) before it is exhausted out through the chimney.

In a regenerative furnace, waste heat recovery from flue gas is done by a matrix of refractory checker work/ bricks which gets heated up during the passage of hot flue gas through it for a predetermined time (usually 20-30minutes). In the next reversal cycle, cold combustion air and / or cold fuel gas (provided its preheating is permissible) is routed through the hot checker work /bricks of the regenerator which preheats them. Again when the hot regenerator bricks lose their heat and become cool, the passage of the hot flue gas and cold air and cold fuel gas is reversed through the reversal damper/ valve. That is why two sets of regenerators are provided for each furnace so that while one set of regenerator is being heated by hot flue gas, the other set of already heated hot regenerator is losing its heat to the cold combustion air and/or cold fuel gas for preheating them. And after a fixed interval (called reversal cycle usually of 20-30 minutes), regenerators duty is interchanged/ reversed.

Furnace Auxiliaries

The important furnace auxiliaries are: damper, fan (forced draft and induced draft), control valve, and burner.

Damper: the function of a damper is to regulate draught and is a prime instrument for furnace economy. Damper is located just after the furnace and before the stack. In modern

furnaces, damper is made to work in auto mode and its opening gets automatically adjusted depending upon the draught required in the furnace (positive or negative draft).

Fan: in a furnace, a fan is usually used to provide combustion air and is known as forced draught fan. Sometimes a fan is provided before the stack to remove flue gas from the furnace. This is called induced draft fan. A furnace having both forced draft fan and induced draft fan is said to have a balanced draught system.

Control valve: control valve regulates the amount of fuel entering the furnace. For each furnace there is an ideal rate of heat consumption or fuel for the particular heating operation. Any departure from the correct setting of valves results in waste of fuel. These control valves can be regulated automatically depending upon the heat load of the furnace. All control valves should be cleaned, checked and adjusted regularly to ensure their good working.

Burner: burner is a device which produces flame/ heat for heating the stock in the furnace. It must mix the fuel and an oxidizing agent (air) in proportion that are within the limits of flammability for igniting as well as for steady combustion. Thus the essential function of a burner is to mix fuel with the combustion air and introduce the mixture into the furnace in such a way that desired flame shape and penetration is obtained. Basically there are two types of burners i.e, premix and direct (outside mix) type. In the premix burner, the fuel and the air oxidizer are mixed prior to ignition and in the direct type, fuel and the combustion air is mixed at the point of ignition.

A general view of furnaces has been given, however furnaces used for melting within the foundry industry are here presented, with classification being primarily according to shape. Table 3.1 shows furnaces for foundry melting. The Table shows the energy type used, the basic shape of the furnace, name of furnace, the means of melting in the furnace and the main field of application of the furnace.

Crucible Furnaces: furnaces of this type are widely used for melting small batches of ferrous and non-ferrous metals and alloys. The charge is melted in a refractory container, the crucible, generally by an external heat source. Heat may be provided by solid, liquid or gaseous fuels, or by electricity. Example of crucible furnace type is shown in Fig.3.5.

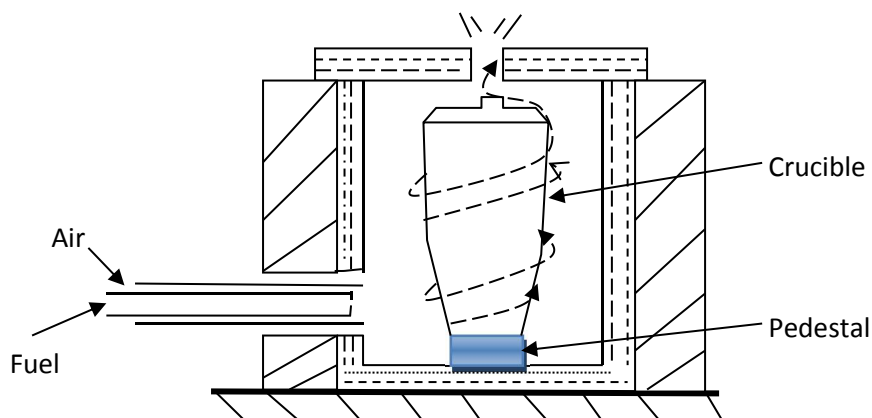


Fig. 3.5 An oil or gas fired crucible furnace

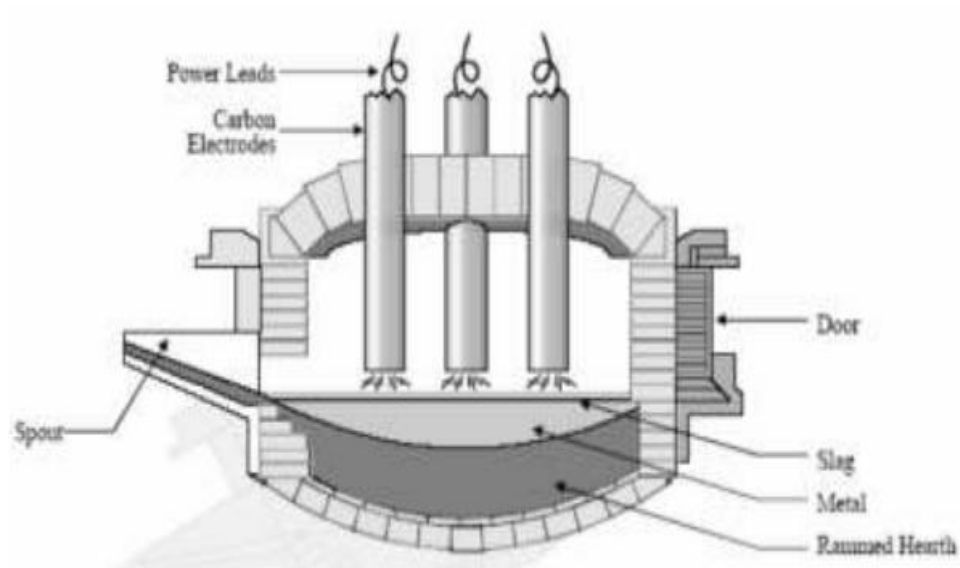
Hearth Furnaces: in this type of furnace the charge usually resides on the floor of the furnace and is heated from above by the energy source. As the mechanism of heat transfer is primarily by radiation, a relatively large melt surface area is required. This may be a disadvantage because it increases the opportunity for oxidation and gas absorption, but is advantageous if refining of the melt is necessary because it maximizes the contact area between the melt and the refining slag cover. One example of this type of furnace is the direct arc furnace (Fig. 3.6), in which the current from the electrodes passes through the slag to the metallic charge, forming three large arcs of plasma with temperatures of several thousand degrees centigrade. A second type is the single phase, indirect arc furnace (Fig.3.7), in which the arc is struck between two carbon electrodes with the energy being radiated to the charge directly and by reflection from the furnace roof. Rotating or rocking motions are often employed to improve heat transfer to the melt and prolong furnace refractory life. Schematic diagrams of hearth furnaces are shown in Fig.3.2



a) Electric arc furnace (NMDC, 2011)

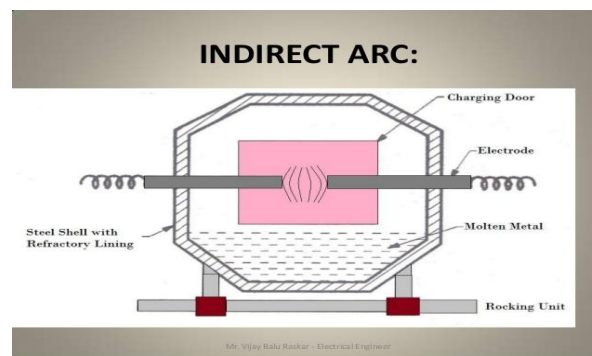


b) Refractory lining of an electric arc furnace (NMDC, 2011).

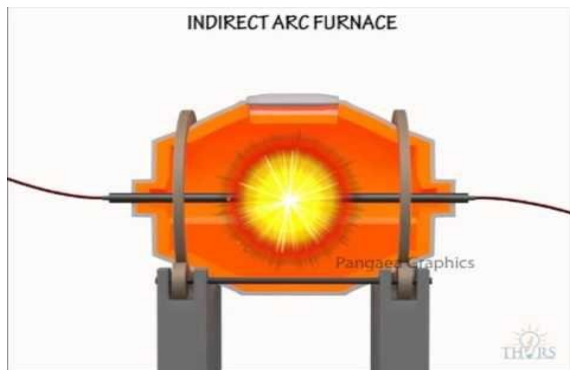


c) Schematic view of an electric arc furnace

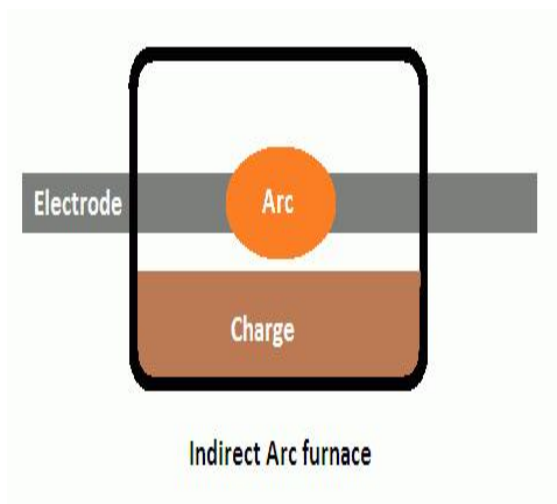
Fig.3.6 Electric arc furnace the direct type



a) Schematic diagram of an indirect arc furnace



b) Illustration of the electric arc in an indirect arc furnace producing plasma temperatures between two electrodes



d) Schematic illustration of indirect arc furnace

Fig. 3.7 Indirect arc furnace (www.Instrumentationform.com, 2020)

Shaft Furnaces: the principal example of this type of furnace is the cupola, which is still used extensively in the production of cast iron. Similar in principle to the blast furnace, the cupola is heated by the combustion of coke, with the ascending heat transferred to the descending charge. Superheating of the melt occurs as the metal trickles through the incandescent coke to collect in the well, from which it is tapped. A schematic diagram of this furnace is shown in Fig.3.8.

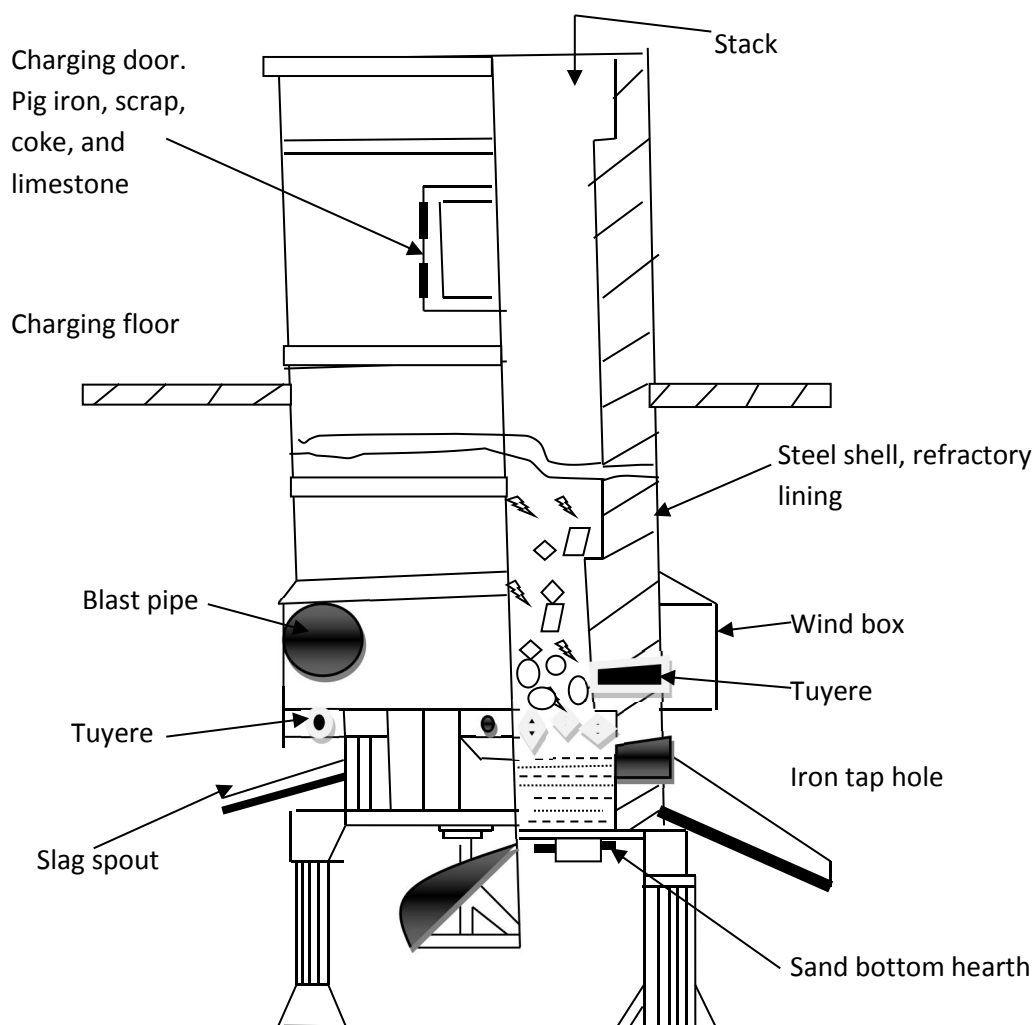


Fig.3.8 Schematic cutaway representation of a Cupola Shaft Furnace

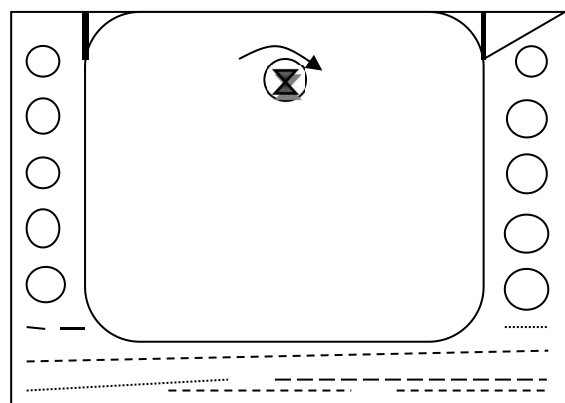
Induction Melting: the principle of induction heating can be applied to the melting of both ferrous and non-ferrous metals and alloys. This method of melting has grown in popularity because of the

excellent metallurgical control it provides, combined with improved productivity and relatively pollution-free operation. The system is designed so that the magnetic field produced by the coil interacts with the charge, which is held in some form of container. Although there are two types of induction melting furnace, coreless and channel, it is the former which is most widely used for metal melting. Fig.3.9 shows the coreless induction furnace used at National Metallurgical Development Centre, Jos Foundry shop, it has two melting units of 500kg each making a total capacity of one ton.

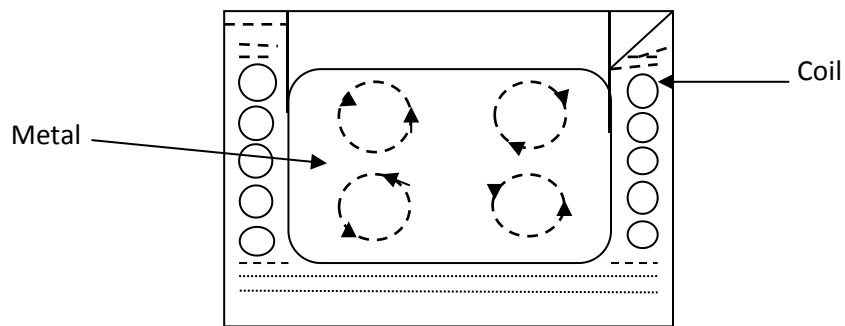
The Coreless Induction Furnace: furnaces are available with a capacity of a few kilogrammes (pounds) to more than 100 tonnes (tons) and are operated at frequencies between mains frequency and 10kHz. The coils are constructed from hollow copper tubing, to permit water cooling, and the loops are insulated from each other with tape. The furnace unit is constructed as a rigid structure to withstand both the electrical and mechanical forces which arise during operation. For maximum efficiency the gap between the coil and the metal charge should be as small as possible. To achieve this, rammed monolithic linings or thin preformed crucibles are used. The coil and lining are mounted on a refractory base and supported using a steel structure. In order to minimize the induced current heating of the steel structure, packs of low-loss laminations are arranged around the structure to divert the flux.

When the furnace has been loaded the power is switched on and current is induced in the charge. The nature, shape and size of the charge material will determine the frequency required. It is difficult to start furnaces operating at mains frequency from cold and it is usually necessary to leave a molten metal 'heel', equivalent to 15 to 20% of the furnace volume, in the furnace. This is clearly only acceptable when consecutive melts are of similar composition. Furnaces can be started from cold at medium frequencies, up to 1 kHz, providing that finely divided charge material is not used.

Once melting is well under way the currents in the melt give rise to mechanical forces which produce stirring, see Fig.3.9. These may be beneficial to melt homogeneity, but can impair refractory life and expose the melt surface to atmosphere. The stirring action is proportional to the power input and inversely proportional to the frequency. The actual shape of the furnace, in terms of length to diameter ratio, is important both from the view of stirring action and power transfer. A ratio of 3:2 would be typical. The number of turns required on a coil varies inversely with frequency. However, because of insulation and cooling requirements, the coil design is limited to around 80 Ampere-turns/mm (2000 Ampere-turns/in) height of furnace.

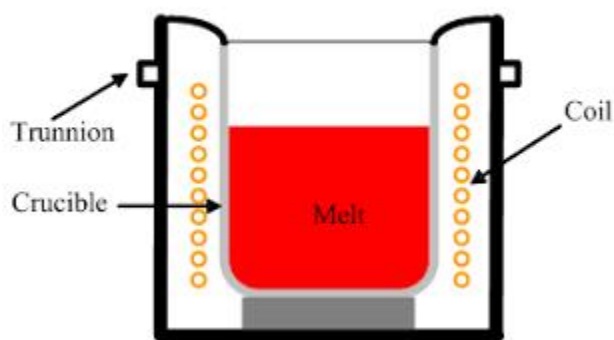


a) Induction furnace

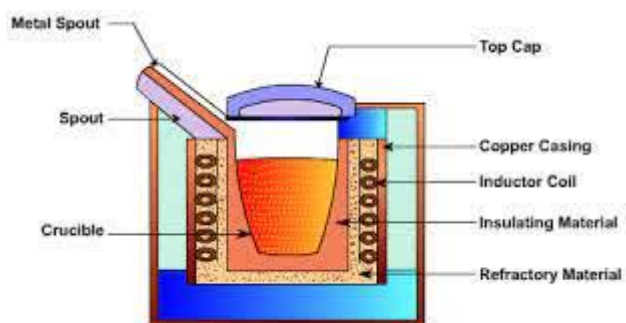


b) Stirring effects associated with induction melting

Coreless induction furnace



c) Schematic of coreless induction furnace



d) A further diagram of another coreless induction furnace

Fig. 3.9 Crucible induction furnaces of different types

Coreless induction furnaces have the advantages of high melting rates, reduced melt loss, freedom from contamination, low running and maintenance costs, and high quality output. Induction melting may also be conducted under vacuum conditions, which further improves melt quality.

Table 3.1 shows the classification of furnaces used in foundry for metal melting. The Table shows the means of melting and main field of application.

Table 3.1 Furnaces for Foundry Melting

Energy	Basic Type	Furnace	Means of Melting	Main Field of Application
<i>Fuel fired</i>	Shaft	Cupola	Coke, charge in direct contact with fuel. Continuous melting.	Cast iron, steel
	Hearth	Reverberatory (air)	Gas, oil, solid fuel	Non-ferrous alloys, cast iron e.g malleable iron
	Open hearth	Gas, oil		Steel (heavy)
	Rotary (rotating or rocking)	Gas, oil, pulverized solid fuel		Nonferrous alloys, cast iron, e.g. malleable, and the duplex holding
	Crucible	Crucible, lift-out, or oil.	Gas, oil, solid fuel.	Most alloys, except steel.
		Tilting	Gas, oil, solid fuel	Except steel
		Bale -out	Gas, oil	Light casting e.g die casting.
<i>Electric</i>	Hearth arc	Direct arc	Arc to charge	Steel melting, cast iron.
		Indirect arc (rocking)	Radiant arc	Nonferrous alloys, high alloy steel, and special irons.
	Crucible (resistance)	Resistor (static or rocking)	Radiant resistor rod.	Steel, cast iron, copper alloys.
		Resistance	Element (shroud or immersion)	For nonferrous alloy, holding for die casting

	Melting channel(induction)	Coreless induction	High frequency induction	Steel e.g alloy steel and small tonnage nickel based alloy steel
		Cored induction	Low frequency induction	Cast iron
			Low frequency induction	Nonferrous alloys, holding for die and light casting.

Furnace Design

In general the closest control of composition, minimal losses and a high standard of cleanliness are achieved in those furnaces which the charge is isolated from the combustion processes and their attendant dangers of contamination with gaseous elements and sulphur. In this respect crucible furnaces offer an advantage over hearth furnaces whether of the static or rotary type since the modern crucible is highly impermeable to contamination. This comparison is to some extent varied even in the case of electric melting, since electric arc melted metal is subject to contamination from the atmospheric gases under the influence of the arc. Induction melting by contrast is analogous to other crucible processes. Where slag –metal reaction is sought the thermal condition in the hearth furnace are preferred since the top heating effect promotes refining. In a special case, for example in the melting of cast iron, direct contact of fuel and charge can be a positive advantage. Since the coke exercises the dual function of fuel and carburizing agent in this case the cupola is unique. Apart from the question of melting condition there is a size limitation on crucible furnaces. For tonnage melting a hearth with a substantial thickness supported by a metal shell is required. Conversely, the crucible is a high convenient and flexible unit for handling small quantities of metal.

Provision of heat for melting and superheating involve increasing cost, this is because more energy is utilized in raising the temperature above the melting temperature. There is a gradual change from the solid and liquid fuel to the successively more controllable form of heating with gas and electric power. These are more expensive successes of energy when compared with the former. However technical advantages are the close control available to justify their higher cost in many cases.

Temperature Measurements

Measurement and control in modern day foundry is very important it is responsible for the high quality of castings produced which are used in critical areas like nuclear power stations, thermal power stations, turbines etc. Among the many controls that are important during melting is temperature. This parameter is measured using thermometer, thermocouples, and pyrometers. The accuracy with which temperatures are measured and controlled will determine the successful operation of some metallurgical processes such as casting, smelting, refining, and heat treatment. It

will also have a profound effect on the strength properties of many metals and alloys. Casting techniques like Rheocasting and Thioxcasting are temperature dependent just like many other melting processes the operation of this techniques depend on accurate monitoring of temperature.

Temperature Scales

In scientific research and in most foreign countries, the standard temperature-measuring scale is the centigrade scale. Here in Nigeria the centigrade scale is commonly used. However in American industrial plants, the Fahrenheit scale is used almost exclusively. Conversion from one scale to the other may be made by the following equations:

$$^{\circ}\text{C} = 5/9 (^{\circ}\text{F} - 32) \quad (3.1)$$

$$^{\circ}\text{F} = 9/5 (^{\circ}\text{C} + 32) \quad (3.2)$$

Furnace Temperatures

An important auxiliary to a furnace is some method of measuring its temperature, because the successful heat treatment of steel depends on close adherence to the correct temperature. There are methods used for this, a simple one being to put in the furnace some substance which melts at the temperature it is desired to verify. The substances used for this are moulded in the form of cones from mixtures of kaolin, lime, feldspar, magnesia, quartz and boric acid, with their melting temperatures arranged in steps from 600°C to 2000°C. When a furnace temperature is required, several of these cones, covering a range of melting temperatures within which the temperature of the furnace is judged to lie, are put in and observed. The temperature is then judged from which cones collapse, and which remain unaffected by the heat of the furnace. For example, to verify a temperature judged to be 810°- 820°C, cones having melting points of 790, 815 and 835°C might be put in, the temperature then being estimated from their condition after sufficient time had elapsed for them to be affected. These cones are called Seger Cones or Sentinels and Fig.3.10 shows how they appear after a test.

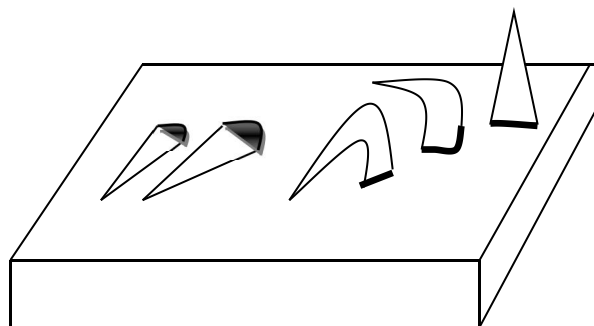


Fig. 3.10 Seger Cones or Sentinels for Temperature Measurement (Chapman, 1972)

In order to understand the effect of thermal treatment on the properties, it is necessary to have some knowledge of how temperature is measured (Avner, 1974). *Pyrometry* deals with the measurement of elevated temperatures, generally above 950°F (510°C), and instruments used for this purpose are known as *pyrometers*.

Thermometry deals with the measurement of temperatures below 950°F (510°C), and instruments for this purpose are known as *thermometers*.

Temperature Measurement by Colour

One of the simplest methods of estimating the temperature of a metal is by noting the colour of the hot body. There is an apparent correlation between the temperature of a metal and its colour, as shown by Table 3.2.

Table 3.2 Variation of Colour with Temperature

Colour	Temperature °F
Faint red	950 (510°C)
Dark red	1150 (621.1°C)
Dark cherry	1175 (635 °C)
Cherry red	1300 (704.4°C)
Bright cherry	1475 (801.7 °C)
Dark orange	1650 (898.9 °C)
Orange	1750 (954.4 °C)
yellow	1800 (982.2 °C)

Except when applied by an experienced observer, this method will give only rough temperature estimates. The principal difficulty is that judgment of colour varies with the individual. Other sources of error are that the colour may not be uniform and may vary somewhat with different materials.

If a continuous indication or recording of temperature is required, then the instruments in use may be divided into two general classifications:

- (1) Mechanical systems that deal essentially with the expansion of a metal, a liquid, a gas or vapour; and
- (2) Electrical systems which deal with resistance, thermocouple, radiation, and optical pyrometers.

Metal –expansion Thermometers

Most metals expand when heated, and the amount of expansion will depend upon the temperature and the coefficient of expansion. This principle is incorporated in the bimetallic strip which is used in the common thermostat. The bimetallic strip is made by bonding a high-expansion metal on one side with a low-expansion metal on the other. As a result of small temperature changes, the strip will curve and therefore make or break an electrical circuit which will control the heating of a house.

When it is use as an industrial temperature indicator, the bimetallic strip is usually bent into a coil, one end of which is fixed so that on expansion a rotary motion is automatically obtained (Fig.3.11)

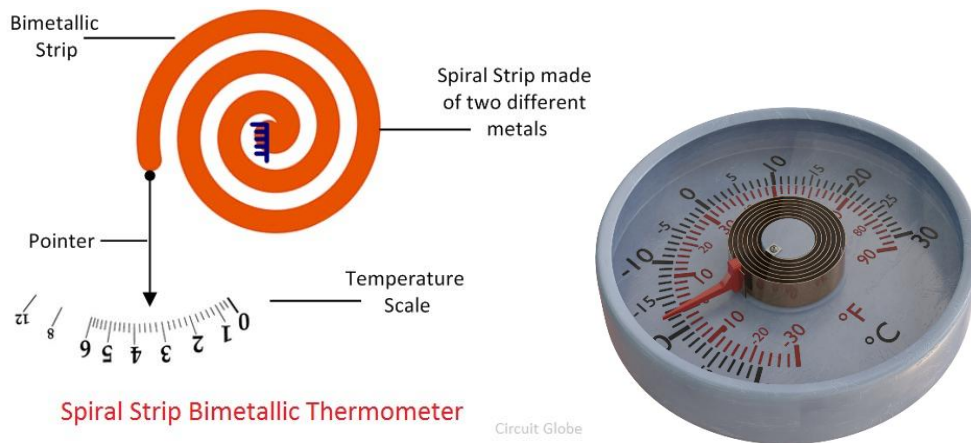


Fig .3.11 Industrial temperature indicator with a helical bimetallic element (Avner, 1974 p2)

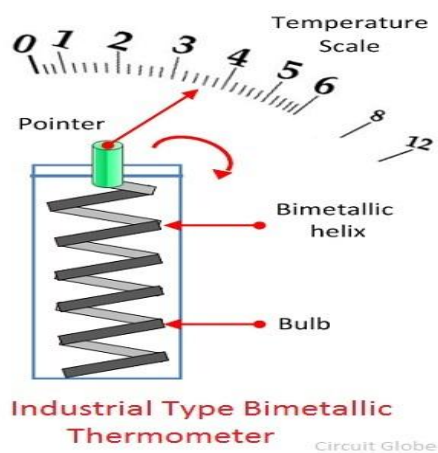


Fig.3.11b simple thermal system for industrial temperature measurement (Avner, 1974,p3)

Most bimetallic strips have invar as one metal, because of its low coefficient of expansion, and yellow brass as the other metal for low temperatures or a nickel alloy for higher temperatures. They can be used in the range of -100 to 1000 °F, they are very rugged, and require virtually no maintenance. Their main disadvantage is that, owing to the necessity for enclosing the element in a protecting tube, the speed of response may be lower than that of other instruments.

Liquid –expansion Thermometers

The remainder of the mechanical systems temperature-measuring instruments, whether liquid-expansion or gas or vapour-pressure, consist of a bulb exposed to the temperature to be measured and an expansible device, usually a Bourdon tube, operating an indicating pointer or a recording pen. The bulb and Bourdon tube are connected by capillary tubing and filled by a suitable medium (Fig. 3.12). The liquid-expansion thermometer has the entire system filled with a suitable organic liquid or mercury. Changes in bulb temperature cause the liquid to expand or contract. Temperature changes along the capillary and at the case also cause some expansion and contraction of the liquid, and

some form of compensation is therefore required. Figure 3.12 shows a fully compensated liquid – expansion thermometer using a duplicate system, less bulb, arranged so that motions are subtracted. Some of the liquids used and the temperatures covered by them are:

Mercury	-35 (-37.22) to 950°F (510 °C)
Alcohol	-110 (-78.9°C) to 160°F (71.1°C)
Pentane	+333(167.2°C) to +85°F (29.4°C)
Creosote	+ 20 (-6.7°C) to +400°F (204.4°C)



Fig. 3.12 a fully compensated liquid-expansion thermometer (Avner, 1974)

Gas–vapour-pressure Thermometers: in the vapour-pressure thermometer, a volatile liquid partially fills the bulb. Different temperatures of the bulb cause corresponding pressure variations in the saturated vapour above the liquid surface in the bulb. These pressure variations are transmitted to the Bourdon tube, the pressure indications acting as a measure of the temperature in the bulb. By suitable choice of volatile liquid, almost any temperature from -60 to +500°F can be measured. Some liquids used are methyl chloride, ether, ethyl alcohol, and toluene.

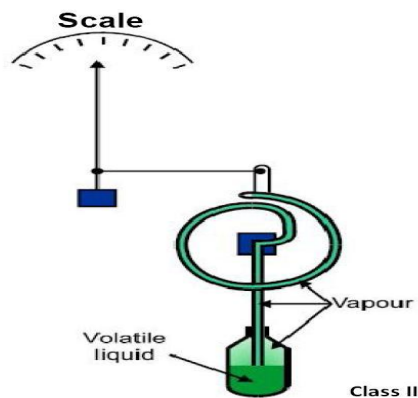


Fig.3.13 Gas–vapour-pressure thermometers (<https://slideplayer.com>, 2020)

The gas-pressure thermometer is similar to the vapour-pressure thermometer except that the system is filled with a gas, usually nitrogen. The range of temperature measured by the gas-pressure thermometer is from -200 to $+800^{\circ}\text{F}$.

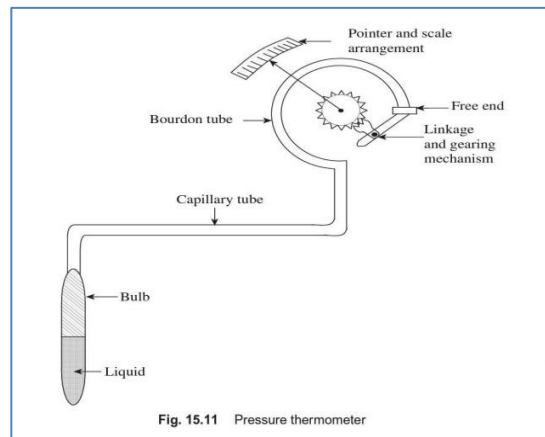


Fig.3.14 Gas-pressure thermometer

Filled-system thermometers are used primarily for low-temperature applications such as plating and cleaning baths, degreasers, cooling water and oil temperatures, and subzero temperatures in the cold treatment of metals. These instruments are relatively inexpensive but are not used where quick repair or exceptionally high accuracy is required.

1. Liquid Pressure Thermometers.

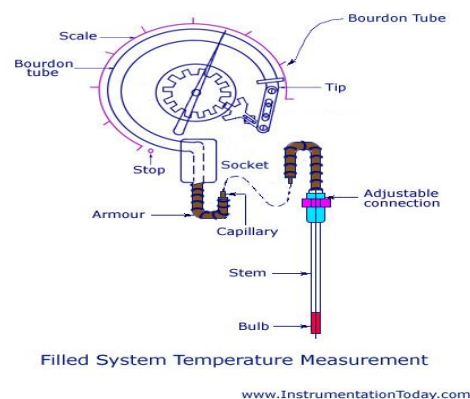
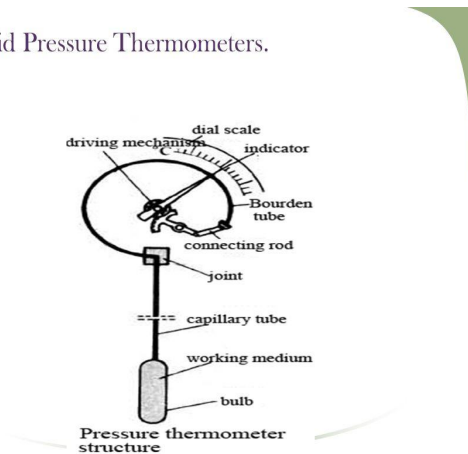


Fig.3.15 Filled-system thermometer (<https://instrumentationtoday.com>, 2020)

Resistance Thermometer

The principle of the resistance thermometer depends upon the increase of electrical resistance with increasing temperature of a conductor. If the temperature-resistance variations of a metal are calibrated, it is possible to determine the temperature by measuring its electrical resistance. The

resistance coil is mounted in the closed end of a protecting tube and the leads are extended to a suitable resistance-measuring instrument, usually a wheatstone bridge.

Resistance coils are usually made of copper, nickel, or platinum. Nickel and copper are most satisfactory for temperatures between 150 and 500°F, whereas platinum may be used between -350 and +1100°F. The resistance thermometer is very accurate and is of great importance in the laboratory. However, its industrial use is limited because it is fragile and requires many precautions in use.

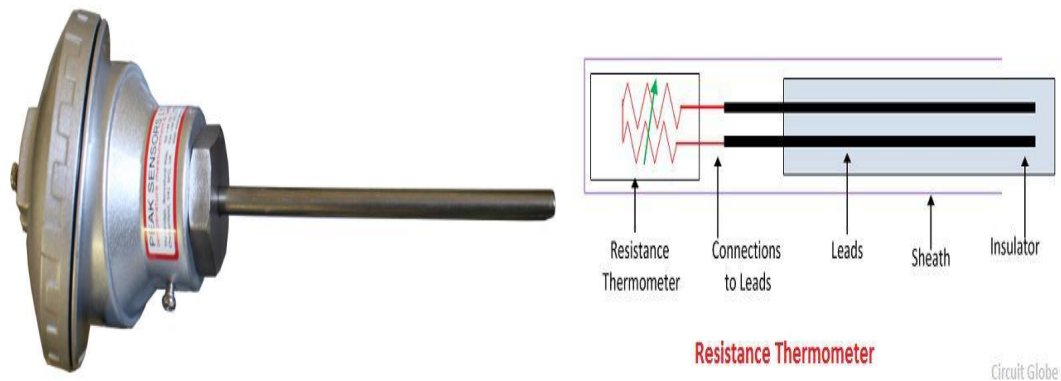


Fig.3.16 Resistance thermometers (<https://circuitglobe.com>, 2020)

Thermoelectric pyrometer

This is the most widely used method for foundry and metallurgical temperature measurement and control; it will perform satisfactorily up to about 3000°F.

The simple thermoelectric pyrometer, shown in Fig 3.17, consist of the following units:

1. The thermocouple, composed of two different metals or alloys
2. The junction block, just outside the furnace
3. The extension leads
4. The indicating instrument or recorder

The operation of this pyrometer is based upon two principles:

Peltier Effect: if two dissimilar metallic wires are brought into electrical contact, an EMF will exist across the point of contact. The magnitude of the EMF developed will be determined by the chemical composition of the wires and the temperature of the junction point.

Thompson Effect: if there is a temperature difference between the ends of a single homogeneous wire, an EMF will exist between the ends of the wire. The magnitude of the EMF developed will be determined by the composition, the chemical uniformity of the wire, and the temperature difference.

The total EMF in a thermoelectric pyrometer, sometimes called the *seebeck effect*, is therefore the algebraic sum of four EMF's, two peltier EMF's at the hot and cold junctions and two Thompson EMF's along each of the wires.

The cold junction, or reference junction, must be kept at a constant temperature. This is usually 0°C, or 32°F. At the indicating instrument this is usually done by means of a cold-junction compensating coil which changes its resistance with fluctuations in ambient temperature, always keeping the instrument at 32°F. If the cold junction, or reference junction, is kept at constant temperature, then the measured EMF in the pyrometer circuit will be a definite function of the temperature of the hot junction. By suitable calibration, it is possible to determine an exact relationship between the developed EMF and the true temperature of the hot junction (Table 3.3). Another useful thermoelectric law states that, if a third metal is introduced into the circuit, the total EMF of the circuit will not be affected if the temperature of this third metal is uniform over its entire length.

The purpose of the extension leads is to move the reference junction to a point where the temperature will not vary. Thermocouple wires are usually not long enough nor well enough insulated to run directly to the instrument. The extension leads are usually made of the same material as the thermocouple wires and are placed in a duplex cable with the individual covering colour-coded for identification.

Copper extension leads may be used in some cases but then the cold junctions are at the junction block instead of the instrument and may be more difficult to maintain at constant temperatures.

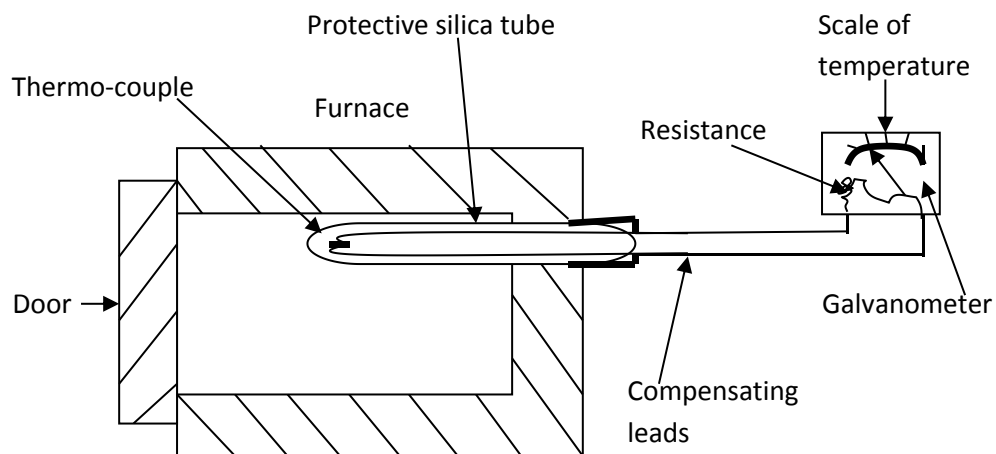


Fig. 3.17 A Simple Thermoelectric Pyrometer

Table 3.3 Temperature versus Electromotive Force

Emf in millivolts; cold junction 32°F

TEMP, °F	PT + 10%RH VS PLATINUM	CHROMEL VS ALUMEL	IRON VS CONSTANTAN	COPPER VS CONSTANTAN
32	0.0	0.0	0.0	0.0
100	0.221	1.52	1.94	1.517
200	0.595	3.82	4.91	3.967
300	1.017	6.09	7.94	6.647
400	1.474	8.31	11.03	9.525
500	1.956	10.57	14.12	12.575
600	2.458	12.86	17.18	15.773

700	2.977	15.18	20.25	19.100
800	3.506	17.53	23.32	
900	4.046	19.89	26.40	
1000	4.596	22.26	29.52	
1100	5.156	24.63	32.72	
1200	5.726	26.98	36.01	
1300	6.307	29.32	39.43	
1400	6.897	31.65	42.96	
1500	7.498	33.93	46.53	
1600	8.110	36.19	50.05	
1700	8.732	38.43		
1800	9.365	40.62		
1900	10.009	42.78		
2000	10.662	44.91		
2100	11.323	47.00		
2200	11.989	49.05		
2300	12.657	51.05		
2400	13.325	53.01		
2500	13.991	54.92		
2600	14.656			
2700	15.319			
2800	15.979			
2900	16.637			
3000	17.292			

Source: Avner, 1974

Thermocouple Materials

Theoretically, any two dissimilar metallic wires will develop an emf when there is a temperature difference between their junction points. Industrially, however, only a few combinations are actually used for thermocouples. These were chosen primarily for their thermoelectric potential, reasonable cost, grain-size stability, linearity of the temperature-emf curve, and melting points higher than the temperature to be measured. The first material in the combination is always connected to the positive terminal.

Chromel –Alumel : chromel (90 percent nickel, 10 percent chromium) vs Alumel (94 percent nickel, 3 percent manganese, 2 percent aluminium, 1 percent silicon) is one of the most widely used industrial combinations. It has a fairly linear calibration curve and good resistance to oxidation. It is most useful in the range from 1200 to 2200°F

Iron –Constantan: constantan is an alloy containing approximately 54 percent copper and 46 percent nickel. This combination may be used in the range from 300 to 1400°F. The primary advantages are its comparatively low cost, high thermoelectric power, and adaptability to different atmospheres.

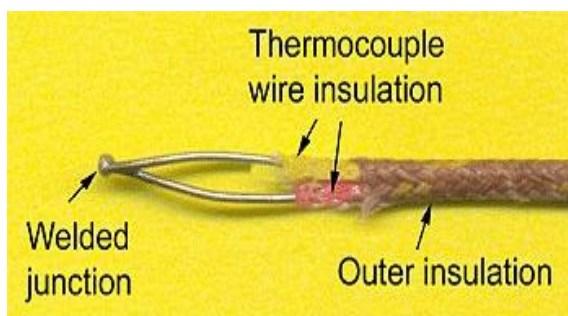
Copper-Constantan: the constantan alloy used with copper differs slightly from that used with iron and may contain small amounts of manganese and iron. This combination is most useful for measuring low temperatures, down to -420°F . The upper limit is approximately 600°F . The above combinations are known as base-metal thermocouples.

Platinum, 10 percent Rhodium-Platinum: this is a “noble –metal” thermocouple. It is used for measuring temperatures which are too high for base-metal thermocouples and where radiation or optical pyrometers are not satisfactory. It is suitable for continuous use in the range from 32 to 3000°F but deteriorates rapidly in a reducing atmosphere.

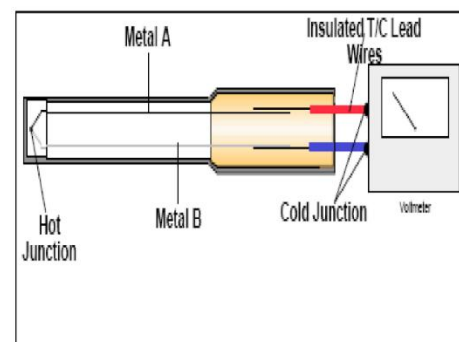
Thermocouples are manufactured by cutting off suitable lengths of the two wires; the ends are carefully twisted together for about two turns, or sometimes butted together, and welded to form a smooth well-rounded head (Fig.3.18a).

The thermocouple wires should be in electrical contact only at the hot junction, since contact at any other point will usually result in too low a measured emf. The two wires are insulated from each other by porcelain beads or ceramic tubes (Fig.3.18b).

In most cases, thermocouples are enclosed in protecting tubes. The protecting tubes may be either ceramic or metallic materials. The tube guards the thermocouple against mechanical injury and prevents contamination of the thermocouple materials by the furnace atmosphere. A variety of metallic protecting tubes are available, such as wrought iron or cast iron (up to 1300°F); 14 percent chrome iron (up to 1500°F); 28 percent chrome iron, or Nichrome (up to 2000°F). Above 2000°F , porcelain or silicon carbide protecting tubes are used.



(a)



(b)

Fig. 3.18 (a) Examples of properly welded thermocouples. (b) Different types of porcelain separators.

(www. Thermocouples.com, 2020)

Measurement of EMF

The temperature of the hot junction is determined by measuring the emf by measuring the emf generated in the circuit. A potentiometer is one of the most accurate instruments available for

measuring small emfs. Essentially the emf developed by a thermocouple is balanced against a known emf and is measured in terms of this standard. The slide-wire scale may be calibrated in millivolts or directly in temperature. In the latter case, the instrument should be used only with the type of thermocouple for which it is calibrated. This information is usually stamped on the dial face of the instrument.

A simple direct-indicating potentiometer circuit is shown in Fig. 3.19. Current from the dry cell is passed through a main circuit consisting of a slide-wire and an adjustable resistance R . The slide-wire AB is a uniform resistance wire which may be considered as divided into an equal number of divisions. With the polarity of the dry cell as shown, there is a drop of potential along the slide-wire from A to B , the magnitude of which depends upon the current flowing through it from the dry cell. Since the slide-wire is of uniform resistance, there are equal drops of potential across each division. In order to standardize the drop between A and B to correspond to the fixed markings on the indicating dial, a standard cell of known and fixed voltage is connected into the circuit by moving the switch to the standard cell (S.C.) position. Notice that the polarity of the standard cell is such that the current flowing from it opposes the current flowing from the dry cell. The resistance R is adjusted so that these currents are made equal, with the result that no current flows through the circuit—as indicated by zero deflection of the galvanometer. The circuit is now standardized so that the potential drop across each division of the slide-wire corresponds to a definite amount of millivolts.

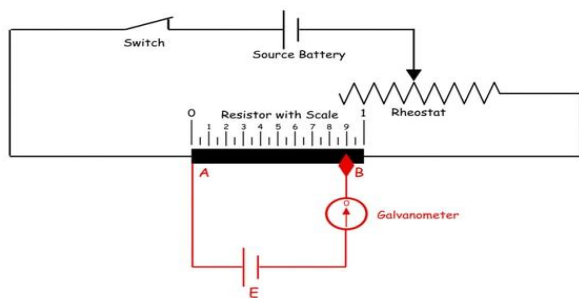


Fig.3.19 A Simple Direct-indicating Potentiometer (Avner, 1974).

When the emf of the thermocouple is to be measured, it replaces the standard cell in the circuit by moving the switch to the thermocouple (T.C.) Position. The thermocouple must be properly connected so that the current flowing from it opposes the flow of current from the dry cell. The circuit is balanced, not by adjusting the resistance R , but by adjusting the resistance of the portion of the slide-wire which is contained in the thermocouple circuit. This adjustment is made by turning the indicator dial until the galvanometer reads zero. At this point, the drop of potential through the slide-wire up to the point of contact is equal to the emf of the thermocouple, and the millivolts may be read directly on the slide-wire scale. Reference to a suitable calibration table, such as Table 3.3, for the particular thermocouple being used will allow the conversion of millivolts to temperature, or the temperature may be read directly if the dial is so calibrated.

Since the cold junction at the instrument is usually higher than the standard cold junction (32°F), it is necessary to compensate for this variation. The compensation may be made manually, or automatically by a temperature-sensitive resistor called a cold-junction compensator. In contrast to

most materials, the cold-junction compensator has a negative temperature resistance coefficient. This means that its resistance decreases with increasing temperature. It will, therefore, maintain the cold junction at a constant temperature by balancing any change in resistance as the instrument temperature varies.

Recording and Controlling Pyrometer

In most industrial installations, the instrument is required to do more than simply indicate temperature. The pointer of the potentiometer may be replaced by a pen that moves over a traveling chart to obtain a complete record of the temperature. This is called a recording pyrometer. The instrument, through the use of electric circuits, may also be used to control the flow of gas to the burners or electricity to the heating elements, and thereby maintain a constant predetermined furnace temperature. This is called a controlling pyrometer. It is possible to design the instrument to record and control the temperature from one or more thermocouples.

Radiation Pyrometer

Shrager (1969) said a radiation pyrometer is a tube containing a thermocouple, and a lens that focuses upon the thermocouple the heat rays radiated by the object, the temperature of which is to be measured. The temperature is measured by any of the methods ordinarily used with thermocouples. Radiation pyrometers are suited particularly for reading surface temperatures of roofs, walls, ducts and linings of a furnace, or of the work in the furnace (Shrager, 1969).

The basic principles of the operation of the radiation pyrometer involve a standard radiating source known as a blackbody. A blackbody is a hypothetical body that absorbs all the radiation that falls upon it. Such a body radiates energy at a higher rate than any other body at the same temperature. Radiation pyrometers are generally calibrated to indicate blackbody or true temperatures. The Stefan-Boltzman law, which is the basis for the temperature scale of radiation pyrometers, shows that the rate of radiant energy from a blackbody is proportional to the fourth power of its absolute temperature.

$$W = KT^4 \quad 3.1$$

Where W = Rate at which energy is emitted by a blackbody

K = proportionality constant

T = absolute temperature of blackbody

The apparent temperature measured from non-blackbody materials will always be lower than the true temperature. This is due to the emissivity of the material, which is defined as the ratio of the rate at which radiant energy is emitted from the non-blackbody material to the rate of that emitted from a blackbody at the same temperature. Hence

$$W = k_e T_a^4 \quad (3.2)$$

$$\text{Or } T_a^4 = e_t T^4 \quad (3.3)$$

Where T_a = apparent absolute temperature of non-blackbody measured by pyrometer

e_t = total emissivity of non-blackbody

Therefore, knowing the total emissivity of the material, the indicated pyrometer temperature may be easily corrected to the true absolute temperature that would be read by the pyrometer under blackbody conditions. Figure 3.20 shows a cross section of a mirror-type radiation pyrometer. Radiation from the target passes through window to mirror and is focused to form an image of the target in the plane of the internal diaphragm. This image is then focused by another mirror upon a group of thermocouples called a thermopile. By viewing hole through the lens it can be determined whether the image of the target is sufficiently large to cover the hole and whether the pyrometer is properly aimed. The rise in temperature of the thermopile is approximately proportional to the rate at which radiant energy impinges on it, and the emf is therefore proportional to T^4 . In actual practice, however, not all the radiant energy reaches the thermocouple since some will be absorbed by the atmosphere and optical parts of the instrument. Therefore, the Stefan-Boltzman law is not followed very closely, and the relation between the temperature of the radiating source and the emf of the thermocouple may be expressed empirically as

$$E = K T^b \quad (3.4)$$

The constants K and b must be determined experimentally by calibration at two standardization points.

The radiation pyrometer does not require direct contact with the hot body and therefore the upper temperature ranges are not limited by the ability of the pyrometer itself to withstand high temperatures. By using suitable stops in the optical system there is no upper temperature limit. The lower temperature limit is approximately 1000°F.

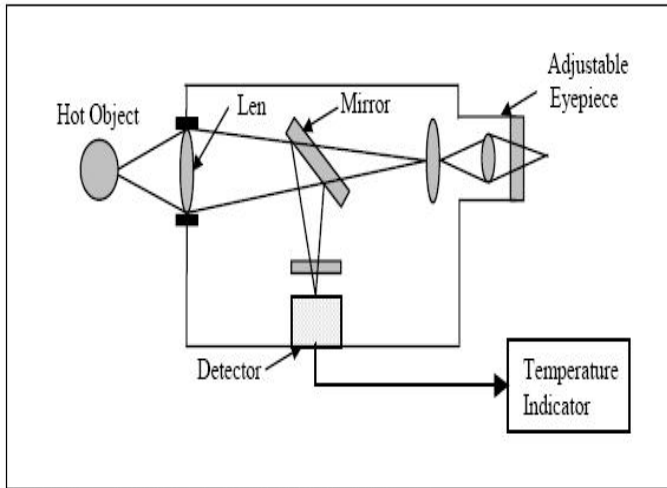


Figure 7-21. Block diagram of radiation pyrometer

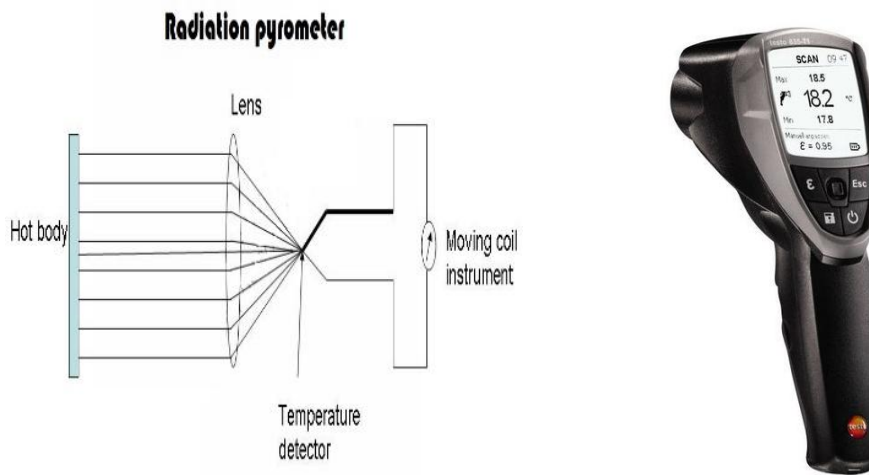


Fig. 3.20 A Mirror Type Radiation Pyrometer (www.slideplayer.com, 2020)

Optical Pyrometer

The instrument described in the previous section which responded to all wavelengths of radiation is known as a total radiation pyrometer. While the general principles on which the optical pyrometer is based are the same as for the radiation pyrometer they differ in that the optical pyrometer makes use of a single wavelength or a narrow band of wavelengths in the visible part of the spectrum. The optical pyrometer measures temperature by comparing the brightness of light emitted by the source with that of a standard source. To make the color comparison easier a red filter is used, which restricts the visible radiation to only the wavelength of red radiation

The type most widely used in industry is the disappearing-filament type. This pyrometer consists of two parts a telescope and a control box. The telescope contains a red-glass filter mounted in front of the eyepiece and a lamp with a calibrated filament upon which the objective lens focuses an image of the body whose temperature is being measured. It also contains a switch for closing the electric circuit of the lamp and an absorbing screen for changing the range of the pyrometer. The control box contains the main parts of the measuring circuit shown in Fig. 3.20. These include dry cells to provide

the current to illuminate the lamp a rheostat R to adjust filament current and a potentiometer slide-wire with associated standard cell and galvanometer to measure the filament current accurately. This current is manually adjusted by rotating R_1 until the filament matches the brightness of the image of the object sighted upon and the filament seems to disappear (Fig.3.20c). Accurate balancing is then obtained by rotating p_1 until the galvanometer reads zero. This indicates that the temperature of the filament has been made equal to that of the object to be measured. By means of a circuit incorporating a potentiometer, the indication of filament current on a meter is balanced, and the temperature is read on the potentiometer dial, which is calibrated to read directly in temperatures.

The temperature range of the optical pyrometer described is from 1400 to about 2400°F. This upper limit is due partly to danger of deterioration of the filament at higher temperatures and partly to the dazzling effect on the eye of the brightness at elevated temperatures. The temperature range may be extended upward by use of an absorbing screen between the objective lens and the filament thus permitting brightness matches to be secured at lower filament temperatures. The pyrometer can then be calibrated for the higher temperature range by using the lower filament temperatures. Thus by using various absorbing screens the upper limit of the optical pyrometer can be extended to 10000°F or higher. Shrager (1969) also agrees that for measurement of temperatures between 1400°F and 2250°F, readings are compared directly; for higher temperature measurements an absorption screen is interposed between filament and object to reduce the apparent brightness of the object, and temperature is read on another scale.

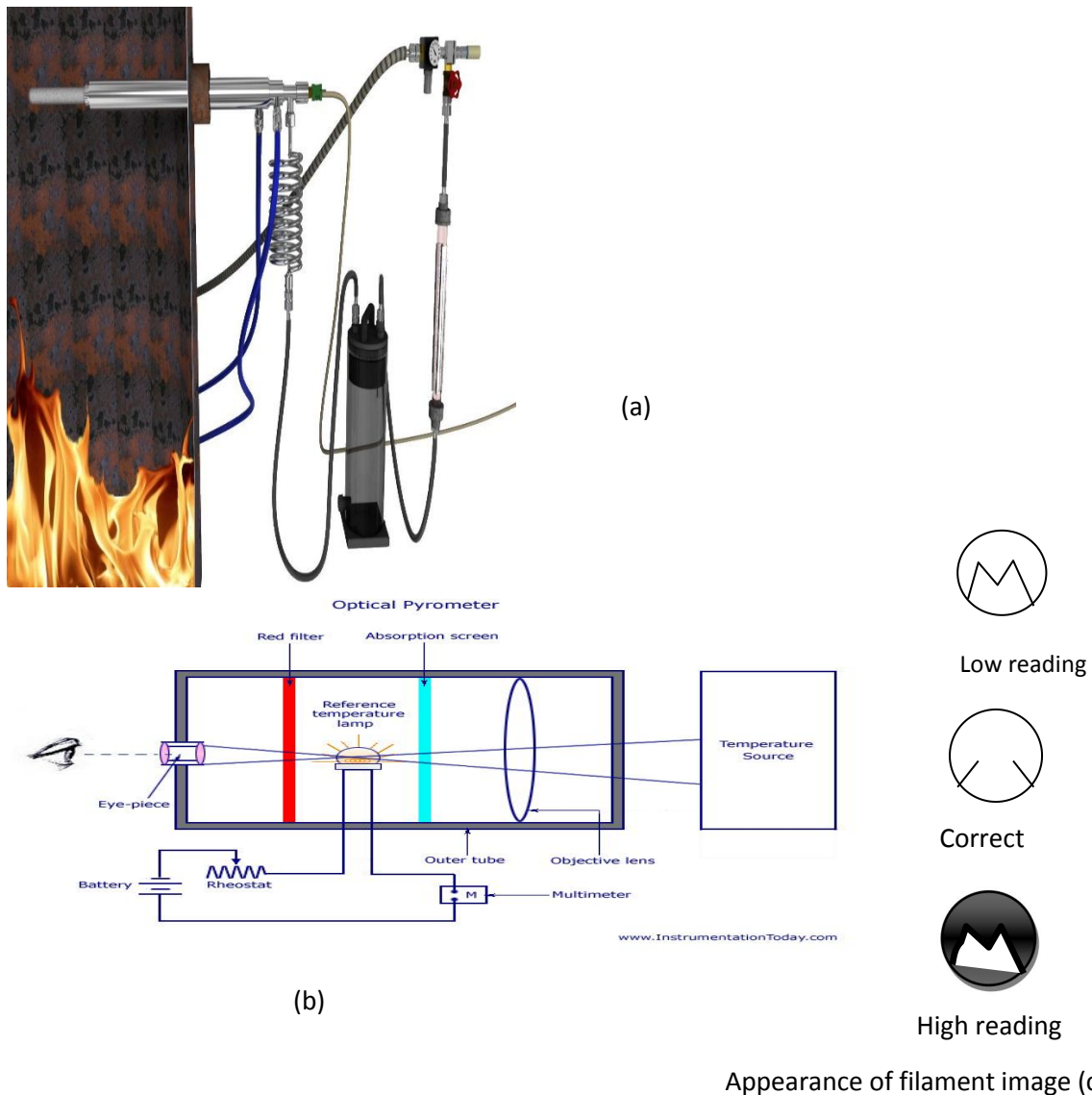


Fig. 3.20 The Disappearing-Filament Type of Optical Pyrometer. (a) Connected to a furnace (b) schematic circuit diagram (c) filament appearance. (Source: www.instrumentationtoday.com, 2020)

Some advantages of the optical and radiation pyrometers are:

1. Measurement of high temperature
2. Measurement of inaccessible bodies
3. Measurement of moving or small bodies
4. No part of the instrument is exposed to the destructive effect of heating

The principal disadvantages are:

1. Errors introduced because the photometric match is a matter of individual judgment.
2. Errors introduced by smoke or gases between the observer and the source.
3. Uncertainty as to the amount of departure from blackbody conditions.

Photoelectric Measurement and Control

Photoelectric measurements are made by use of a light-sensitive cell of chemical nature or by a special type of vacuum tube; in either case, flow of electric current through the cell varies directly, but not necessarily proportionately, with the intensity of light falling upon the cell. An example of the application of the photoelectric cell to metallurgical processes is the determination of the end point of the blow in the Bessemer process of making steel. The process is one that is largely automatic until the end point of the blow is reached, when the converter must be tilted down promptly. Some optical pyrometers incorporate a photoelectric cell that provides readings on the dial of a meter. Such instruments are more accurate than the comparison type using an incandescent filament, and can be used by inexperienced operators.

Magnetic Test for Carbon Content of Steel

The magnetic permeability of steel decreases with increased carbon content provided the alloy content of the steel and its heat treatment remain the same. This fact provides a basis for determination of the carbon content of a sample of steel drawn from the furnace, within a period of about 2½ minutes, and with an accuracy of about ± 0.02 percent. Determinations are made with a Leitz-Blosjo carbon meter, a simplified wire diagram of which is shown in Fig.3.21. the standard is a steel bar of low carbon content and high permeability permanently installed in the meter. In making a test, a sample of the steel is drawn from the furnace, is deoxidized by adding aluminium, is cast into a mould of the required size, and is quenched in water after solidification, all in accordance with a detailed procedure stated in the directions accompanying the carbon meter. The sample is then wiped to remove any water, and is inserted in the meter and tested. For use with alloy steel, the carbon meter must be calibrated over the full range of expected carbon content by making simultaneous chemical analyses and carbon meter tests on identical samples. A curve is then drawn. Typical calibration curve for Blosjo carbon meter is shown in figure 3.22.

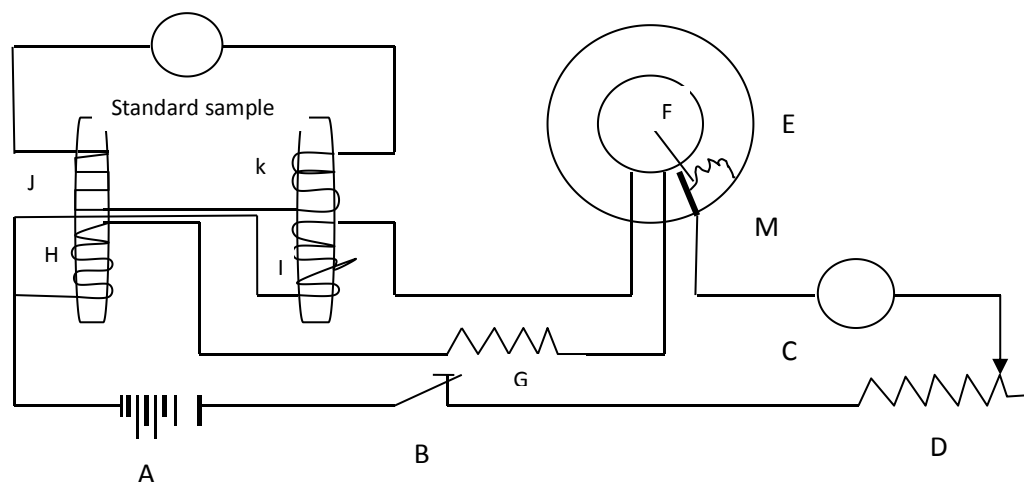


Fig. 3.21 Typical calibration curve for Blosjo carbon meter (Shrager, 1961).

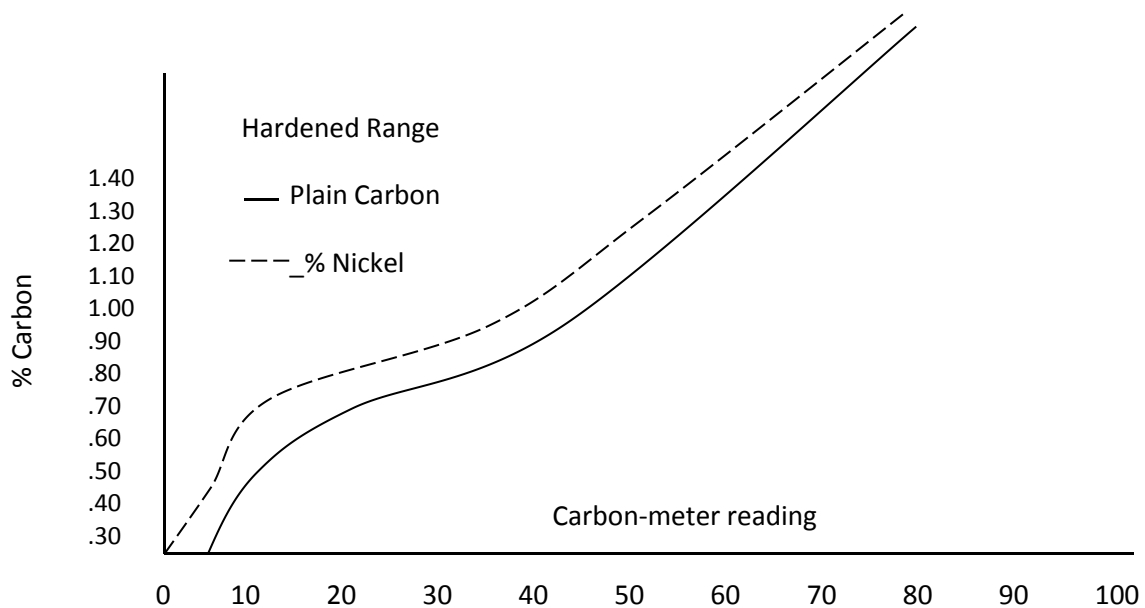


Fig.3.22 Typical calibration curve for Blosjo carbon meter (Shrager, 1961)

Mechanical Properties Testing

Castings are produced according to specifications, and one of the specification is mechanical properties of the casting. The foundry engineer is expected to deliver on castings that meet customer specifications on mechanical properties like hardness, tensile strength, compression strength, fracture resistance, toughness, wear resistance, etc. to achieve these; tests like hardness tests, impact tests, wear resistance tests, strength tests etc. are often carried out on castings. Most mechanical tests fall into the category of tests often referred to as destructive test. This is because the test specimen cannot be used again. Details on this can be found in Shrager, (1969); Higgins (1985), and Bolton, (2000).

Dimensional Measurements

Castings have specified shape and size and the target is to meet this specification during their production. The foundryman cannot rely on the previous dimensions of the pattern that produced the castings, this is because during the casting process, so many changes occur from the mould, and solidification of the liquid metal, which have the potential of affecting both the shape, size, and surface finish of the castings. This explains why the dimension (shape and size) of the casting have to be measured using foundry steel ruler, protractors, angle gauge, Vernier callipers, gauges, etc. The surface finish is also measured using standard comparison pattern for surface finish and stylus profilometer and others. Once these measurements are taken, they are the basis for which machining and surface finishing decision of the castings are made in order to meet customer casting specification.

Identification of the Constitution and Structure of Metals

Various tests methods have been developed for identification of both the chemical constitution and the physical structure of metals and alloys. In industrial plants and foundries it is necessary for example to determine readily the alloy content of metals for the purpose of classification and sorting. Metals frequently must be tested also to determine the microstructure produced by work or heat treatment in order to ascertain their suitability for stated applications or to learn whether a given treatment has been effective. Another important application of testing methods is to research work. The microstructures of metals are examined and studied, and the course of experimental work being performed to improve or develop a given metallurgical process is guided by the information so obtained.

Tests which may be classified as identification tests include a range from the simple spark tests used in the shop to the precise x-ray diffraction tests performed in the laboratory. The study of structures of metals by use of such tools as the metallographic microscope, x-ray diffraction equipment, the spectroscope and spectrograph, and equipment designed for magnetic analysis constitutes the science of metallography. A few of these tests are here under explained.

Examination by x-ray Spectrometry

X-ray spectrometry is used for rapid x-ray diffraction analysis a Geiger counter is substituted for the photographic emulsion and charts are produced automatically by associated electronic apparatus. This simplification and elimination of film processing make the procedure suitable for routine checking of materials by relatively unskilled personnel.

Spectrographic Examination

When a chemical element is volatilized in an arc or in an electric spark the individual atoms are caused to emit visible radiation that is characteristic of the element. If the radiation is directed through a spectrograph and is recorded on a photographic emulsion one or more lines appear each of which represents a single wave length of the spectrum. By comparing the spectrum so produced by an unknown substance with standard spectra of various elements the coincidence of lines provides identification. Quantitative analysis for elements is accomplished by measuring with a densitometer the density of the spectral lines recorded on the film. In industrial production testing by this method a spark is struck on the surface of the metal under test and the photographic record of the resulting spectrum is used for analysis. The National Bureau of Standards supplies a set of spectrographic standards for a number of steels for steels not included in this set or for other metals standards are easily made.

Magnetic Analysis inspection

Equipment used for magnetic analysis testing includes an oscillator adjustable to any frequency with a range of about 2000 to 200000 cycles per second and a test coil that forms part of the oscillating circuit. The apparatus can be calibrated to indicate differences in chemical composition or physical structure stresses produced by cold work or heat treatment and the like.

Details on the above mentioned control test methods can be gotten from Shrager's book on Metallurgy and Metallography, (Shrager, 1961).

Review Questions for Chapter Three

1. Using your own words justify why measurement and control is important in foundry practice.
2. What is a furnace, and what informs furnace selection in the foundry?
3. Out of the many classifications of furnaces, what is the common classification of furnaces used by foundrymen.
4. List and explain the important furnace auxiliaries
5. Give examples of crucible and hearth furnaces, also write brief notes on them
6. Mention one type of shaft furnace use in the foundry. Draw and label its major parts.
7. Explain stirring action in electric induction furnace with schematic illustration
8. Tabulate the furnaces used in foundry, indicating the means of melting and their areas of application
9. What is the equivalent of 900°C in °F? List some five temperature measuring method in the foundry.
10. Explain Peltier effect and Thompson effect
11. Explain photoelectric measurement principle in detection of end point.
12. How can you determine the carbon content of steel drawn from the furnace?
13. Write and clearly elaborate on the importance of mechanical properties testing and dimensional measurement in castings production in the foundry.
14. List and explain some methods used in the identification of the constitution and structure of metals

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CHAPTER FOUR

MOULDING MATERIALS PROPERTIES, PREPARATION, AND TESTING.

Introduction

The commonly used casting technique is sand casting. The technology is well developed and is mechanized for large scale production. It is simple to practice and the equipment involved are not capital intensive. In a country like Nigeria sand casting is predominant, whereas casting operations that were based on die casting machines are no longer in operation in the few places where they were operated up to the year 2000. Nigeria as a country has experienced technology set back with bad government policies which saw a lot of companies closing down including foundry companies most of which were servicing the spare-parts need of the textile companies which themselves closed down. This chapter will examine moulding materials, testing of the properties of moulding materials and cores, types of moulding, core and coremaking, and various binders and additives used in the foundry.

Moulding Materials

Asuquo (2015) said "by moulding materials, we mean those materials that possess the necessary structural strength and hot interfacial properties that enable them to withstand the severe thermo-chemical and hydrostatic forces accompanying melt lodgement into a mould. Such compositions embody what are known as moulding sand, binders and auxiliary materials. Musa (2010) said "the major foundry raw material used for moulding and cores is sand and one of the difficulties confronting both small and medium foundry units at present is finding the right quality and quantities of moulding sand. Until recently, mould sands and binders were still freely imported and used by notable foundry companies across Nigeria like DICON, Kadunna, Nigerian Railways Corporation, etc. these are being progressively substituted by locally available materials.

Functional Requirements of Moulding Materials

A foundry moulding mixture passes through four main production stages, namely preparation and distribution, mould and core production, casting, and cleaning and reclamation. The property requirements of the materials are determined by moulding and casting conditions; the preparation and reclamation stages will however also be considered, with particular reference to integrated sand systems.

The principal properties required at the moulding stage are flowability and green strength: the former is a measure of the ability of the material to be compacted to a uniform density. The ideal balance of these property depends largely upon the intended method of compaction, which may vary from hand ramming with tools to jolt and squeeze ramming on moulding machines and high velocity delivery on sandslingers and coreblowers. High flowability is particularly necessary in the case of the non-selective ramming action of the moulding machine, where the energy for compaction must be transmitted throughout the sand mass.

The need for green strength arises when the pattern is withdrawn and the mould must retain shape independently without distortion or collapse

Refractoriness is the ability for moulding materials to withstand high temperatures without fusion or other major physical change. This property is of greatest importance in the manufacture of high melting point alloys, especially steel; for alloys of lower melting point, refractoriness can be subordinated to other requirements

Dry strength is another requirement of the moulding material particularly during hot metal pouring. The mould must withstand erosive forces and pressure of the liquid metal.

Hot strength to withstand distortion and the capacity for deformation to yield to the contraction of the casting is also a requirement for moulding material.

Collapsibility determines the readiness with which the moulding material will breakdown in knockout and cleaning operations.

To provide a path for the escape of gas, permeability is an essential property, of the moulding material giving protection against surface blows and similar defects.

Fineness is required for the prevention of metal penetration and the production of smooth casting surfaces.

Other qualities include bench life; the ability to retain moulding properties on standing or storage, and durability; the capacity to withstand repeat cycles of heating and cooling in integrated sand systems.

It is thus evident that the qualities required in a moulding material cannot readily be defined in terms of simple physical properties. For complex aggregates bulk properties are of greater significance and some of these can be measured directly by simple tests upon sand compacts. Other qualities are represented in specially developed empirical tests designed to reproduce conditions encountered in the foundry. These tests in conjunction with the direct measurement of more fundamental characteristics such as mechanical grading and chemical composition, provide the basis for the control and development of moulding material properties.

The principal ingredients for sand moulding are silica sand, clays and water or moisture. Clays and moisture provide the bonding during moulding.

FOUNDRY SANDS AND BINDERS

Nigeria is blessed with foundry sand the distribution of which cut across the country every part of Nigeria has sufficient sand for foundry work. According to Musa (2010) research has indicated that silica, zircon, and ilmenite are abundantly available in Nigeria. Studies at the National Metallurgical Development Centre, Jos has shown that each of the six geographical regions in Nigeria has foundry sand. The centre has conducted extensive work on the characterization of sands from different part of the country and has a data bank on foundry sands in Nigeria. In the days of expatriate engineers working in our foundries we were made to believe that Nigerian sands were not good for foundry work. In those days Defense Industries Corporation of Nigeria were importing foundry sand from Germany, likewise the Nigerian Railways Corporation foundry were importing sand from European countries and

Indian. The believe that Nigerian sands were not good for foundry work was proved wrong by some Nigerian engineers working with the Nigerian Railways at Enugu who decided to experiment with the Enugu sand. They discovered that they were getting the same result with the imported sand, ever then the sand has been in use. The Enugu sand has a red colour and AFS clay content % of 25.94%. Sands like Bacita sand, Gombe sand, river Benue sand, Azare sand, Aba sand and Kano sand have been fully characterized at NMDC. So much research work has been done on the characterization of Nigerian sands by so many individual researchers (Ihom, 2007, NMDC, 2008, Yaro, *et al*, 2009). Table 4.1 shows the physical properties of some sand deposits in Nigeria. A lot has been done in the area of raw material development for the foundry in Nigeria today. Clay deposits have been identified and their suitability for foundry work has been investigated at NMDC and many other researchers including the author. Both fireclays and bentonite clay deposits have been investigated; in one of the works by the author, Ameki Bende clay from Abia state which is a calcium based bentonite was processed and activated using sodium carbonate to improve on its foundry properties. The country has so many clay deposits like the Benue clay, Giru clay, kankara clay, Nsu clay, Kwi clay, Onibode clay, Oza-Nagogo clay just to mention a few. Table 4.2 shows some clay deposits in Nigeria their mineralogical composition, chemical composition and physical properties (Ihom, 2002, Ihom, 2005, NMDC, 2008). The combination of properties required in the moulding material depends upon the weight and composition of the casting and upon the moulding practice to be adopted, itself partly governed by quantity and quality requirements. Properties are developed by blending sands or other refractories with bonding materials, water and special additions.

Table 4.1 Physical Properties of Some Sand in Nigeria

S/N	Aperture (mm)	BSS. NO.	Enugu sand (AR)	Ijebu ode (AR)	Katsina (AR)	Birnin Kebbi (AR)	Bacita (AR)	NMC Jos (AR)	Zircon Jos (AR)	ZKS sand Kano (AR)	40%Enugu 60%Bacita (AR)	Kal go sand (AR)	Ughelli sand (AR)	Ilmenite sand	Enugu sand (W)	Udi sand (AR)
1	1.40	14	0.00	0.01	0.00	0.00	0.04	0.08	0.00	0.00	0.06	0.00	0.01	0.00	0.00	0.41
2	1.00	18	0.08	2.99	0.16	0.00	0.10	0.36	0.00	0.28	1.03	0.03	0.15	0.01	0.41	2.71
3	0.71	25	0.23	7.34	2.22	0.01	0.18	3.79	0.00	0.94	2.56	0.93	1.61	0.82	1.79	7.86
4	0.50	35	1.04	11.23	3.27	0.02	0.65	36.46	0.07	0.95	4.70	3.98	6.60	7.27	2.90	13.09
5	0.355	45	8.01	13.40	5.14	0.03	3.76	33.77	1.13	1.24	8.56	14.08	20.47	11.93	4.87	18.57
6	0.250	60	40.83	26.76	56.82	0.73	25.00	20.70	31.74	1.98	17.59	22.72	35.03	19.13	8.12	25.07
7	0.18	80	30.16	18.15	17.03	27.37	36.31	3.21	32.76	3.57	24.89	22.04	28.45	24.27	8.56	19.06
8	0.125	120	13.90	11.24	9.96	53.89	28.30	1.26	27.90	33.49	29.15	20.92	6.98	30.70	6.62	9.62
9	0.09	170	2.86	3.56	4.08	15.74	4.00	0.27	5.54	4.44	8.10	10.42	0.47	5.44	2.25	2.14
10	0.063	230	0.66	1.97	0.51	1.64	0.69	0.08	0.44	2.25	1.84	3.33	0.06	0.10	0.74	0.90
11	0.063	-230	0.30	2.89	0.33	0.38	0.20	0.02	0.13	0.51	1.12	1.55	0.04	0.30	0.70	0.36
12	Grain Fineness Number (AFS)		55.90	55.60	54.50	85.19	71.63	34.42	64.55	82.65	66.67	68.01	48.36	61.28	60.66	47.03

13	AFS Clay Content %	25.94	23.00	14.46	6.64	1.14	0.88	0.01	19.40	11.2	14.06	0.72	4.64	n.d	16.06
14	Permeability at 3½ % H ₂ O	160	150	152	56	130	290	170	140	190	220	290	180	185	260
15	Visual grain shape	SA-R	SA	SA-R	R	R	SA	R	nd	nd	Nd	nd	nd	nd	nd
16	Fine %	0.96	4.86	0.84	2.02	0.89	0.10	0.59	2.76	2.96	4.88	0.10	0.40	nd	1.26
17	Colour	Dark red	Dark red	Red	Pinkish red	Light yellow	Yellowish white	Dark brown	nd	nd	Nd	nd	nd	nd	nd

Table 4.1 Continued

15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Udi sand (W)	Abasand (AR)	Abasand (W)	Nigerian metal fabrication kano sand	NMF Kano	NMF (Imported silica sand) (AR)	MT high silicaceous sand	Jos Larantoso sand	Olympic technical Abagana sand	Lokoja sand (AR)	Itobesand (AR)	Itobesand (AR)	Lokoja sand (W)	Bacitasa sand (W)	MF (A) Sand (AR/W)	MF (B) Sand (AR/W)	Ola-ofuochadamu sand (W)	Ola-ofuochadamu sand (W) C ₃
0.06	0.03	0.00	0.04	0.01	0.00	0.23	0.00	0.00	0.00	0.46	0.31	0.00	0.05	0.22	8.54	0.00	0.00
1.38	2.73	0.04	0.83	1.40	0.32	0.41	0.57	0.04	0.00	0.09	0.02	0.00	0.07	0.18	13.77	4.00	2.14
5.70	6.46	0.16	5.46	4.62	4.54	0.94	2.28	0.19	0.00	0.18	1.75	0.00	0.28	0.19	19.26	10.97	8.10
9.14	11.15	0.94	8.75	4.84	7.08	2.27	3.80	0.45	0.07	0.21	0.12	0.07	0.71	0.81	17.42	16.04	13.54
12.58	16.71	6.74	29.75	6.02	6.40	6.66	7.72	1.60	0.50	2.23	2.05	0.96	2.63	5.04	17.64	23.35	20.16
19.92	28.34	38.40	35.34	11.72	5.74	16.68	14.91	29.01	19.43	8.63	7.12	19.54	11.44	14.89	12.91	24.26	24.92
19.88	20.45	30.80	7.53	11.75	4.16	22.37	13.12	41.41	48.15	10.69	11.02	47.89	14.16	18.99	4.87	12.70	13.14
10.38	7.18	16.66	7.55	40.37	7.14	24.29	18.99	22.95	26.60	38.82	39.10	25.68	9.98	12.77	0.95	1.75	3.14
3.10	3.20	3.62	3.28	13.13	7.76	9.06	12.56	3.11	2.99	25.88	26.61	2.85	2.82	10.26	0.44	0.42	0.90
1.36	1.31	0.84	0.98	4.44	17.08	8.88	9.99	0.55	0.77	8.85	7.08	1.05	2.10	8.02	0.06	0.32	1.10
0.51	1.67	0.34	0.18	1.49	39.24	7.99	15.90	0.55	0.39	3.70	3.63	0.54	76.97	95.16	30.16	41.73	47.92
54.21	Nd	Nd	46.34	75.93	145	87.94	102.7	63.20	65.64	97.13	95.64	65.81	2.74	64.50	39.18	4.50	-
nd	1.50	Nd	Nd	nd	Nd	nd	20.62	1.96	1.66	4.64	4.64	1.66	60	152	400	270	-
140	Nd	Nd	22	90	34	50	52	150	148	45	38	140	R	SA	SA-A	nd	nd
nd	Nd	Nd	Nd	nd	Nd	nd	nd	nd	nd	nd	nd	nd	4.94	18.28	0.50	0.74	230
nd	Nd	Nd	1.16	5.93	56.32	16.87	25.89	1.10	1.18	12.55	10.73	1.59	Light yellow	Grey	Grey	Light yellow	SA
nd	Nd	Nd	Nd	nd	Nd	nd	nd	nd	nd	nd	nd	nd					200
																	Light brown

33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
Sand (A R) C ₁	Sand (W) C ₁	Sand (A R) C ₂	Sand (W) C ₂	Sand (A R) A ₁	Sand (W) A ₁	Sand (A R) A ₂	Sand (W) A ₂	Sand (AR) D ₁	Sand (W) D ₁	Sand (A R) B ₁	Sand (AR) B ₁	Sand (W) B ₂	AB Sand	Road bus h dig gin g sand	Wu ya river sand	Lanzu river sand	Kuchin sand
1.03	1.36	0.20	0.26	6.95	2.50	9.42	1.50	0.05	0.02	0.23	0.64	0.38	2.37	6.42	2.44	1.26	2.01
3.19	4.88	2.37	1.68	8.26	6.44	23.15	7.46	0.10	0.06	1.17	1.71	1.20	4.26	10.78	3.86	4.51	4.65
7.29	11.62	5.71	4.36	9.83	8.50	21.80	7.60	0.16	0.08	3.55	3.21	2.50	5.79	11.37	5.88	9.90	7.86
15.31	18.64	11.01	8.32	10.97	10.38	16.91	9.84	0.27	0.20	7.12	6.87	5.48	9.35	11.87	9.02	18.45	8.97
23.71	21.24	19.51	13.72	12.08	10.16	11.83	12.06	0.74	2.36	14.25	19.85	17.16	12.52	11.73	13.48	30.64	11.89
25.41	21.02	25.84	22.30	13.02	11.56	7.79	12.52	4.92	13.88	24.30	35.08	36.34	18.96	12.11	19.02	19.47	13.24
11.96	9.00	17.45	17.24	8.67	8.56	3.77	8.44	18.24	35.14	23.91	22.21	23.62	15.30	8.00	14.06	8.11	12.96
3.00	2.28	3.53	5.54	5.95	6.86	1.02	4.94	41.06	19.94	19.52	9.18	9.86	16.18	9.78	13.90	4.49	15.81
1.30	1.10	0.73	1.42	5.22	1.72	0.58	3.48	23.22	7.70	4.58	1.10	1.72	6.56	6.26	7.15	1.79	9.48
0.57	1.84	0.91	1.28	7.70	17.72	0.79	11.08	0.98	3.48	0.76	0.27	0.52	4.26	6.00	5.80	0.71	7.72
45.47	44.33	50.96	57.53	64.19	83.68	28.24	73.23	10.24	nd	0.99	0.32	0.78	4.24	5.33	4.97	0.44	4.91
								Med ium fine									
nd	1.80	Nd	7.52	nd	5.42	nd	11.90		99.48extrafine	nd	57.25standard	48.28	51.39	64.18	67.01	39.15	71.14
230	260	250	190	120	110	50	420	100	48	nd	120	200	180	108	230	290	100
SA	SA-A	SA-A	SA-A	Nd	SA	SA-A	nd	SA-A	nd	SA-A	SA-A	nd	nd	nd			
Lig ht bro wn	Pal e bro wn	Pal e bro wn	Red	n. d	Grey	nd	Dar k bro wn	nd	Light yellow	nd	red	Lig ht yell ow			cre am	Brown	Brow n

51	52	53	54
Idoko (towards sat)	Salipeed sand	Mata tuga +	Mata tuga +

sand		bentonite	molasses
3.78	6.29	0.27	18.33
11.03	9.14	1.21	8.79
10.60	10.02	2.01	17.27
10.80	10.22	4.65	20.64
11.37	11.26	15.35	20.00
11.94	12.93	30.89	10.77
9.14	8.79	24.12	2.91
11.07	11.24	15.40	0.81
7.39	7.88	4.24	0.08
6.85	5.05	0.99	0.02
5.03	6.61	1.19	0.20
62.75	63.71	57.00	25.6
5.18	3.65	32.38	46.00
46.00	46.88	Nd	Nd
160	140	130	520
Nd	Nd	Nd	Nd
11.88	11.66	2.09	0.22
Red	Red	Nd	Nd

Source: NMDC DATA BANK, 2008

Key: SA – Mostly subangular; R- Mostly rounded; ND - not determined; AR - As received; W - Washed; BSS - British Standard Sieve No.

Table 4.2 Some Clay Deposits in Nigeria and their properties

S/ N O	Depo sit	Chemical composition (%)								Mineralogical composition (%)				Physical properties before firing						Refrac torine ss (°C)
		Al 2O 3	Si O 2	Fe 2O 3	Ca O	M g O	K 2 O	N a 2 O	L O	Kao linit e	mont morilo nite	ili t e	Qu art z	De nsi ty (g/ cm 3)	App are nt por osit y (%)	B. D (g/ cm 3)	DS (m Pa)	Dryin g shrin kage %	Plas ticit y ind ex	
1	Giru (kebbi state)	38 .5 0	43 .6 3	0. 67	0. 02	0. 10	0. 03	0. 04	14 .1 6	92	3	3	2	2.6 0	81	1.8 2	3. 42	3.23	0.4 2	1750
2	kanka ra (katsi na state)	36 .4 0	46 .4 8	1. 09	0. 73	0. 87	0. 08	0. 10	14 .3 1	90	1	8	1	2.5 9	22. 07	1.7 3	4. 03	5.80	3.1 9	1700
3	Nsu (Imo state)	35 .7 2	49 .5 7	1. 72	0. 61	0. 43	0. 06	0. 09	11 .7 9	n/a	n/a	n / a	n/ a	2.6 0	37	1.8 0	6. 19	7.19	6.0 3	1710
4	Kwi (plate au state)	31 .6 9	37 .6 3	14 .4 8	0. 02 5	0. 12	0. 06	0. 12 0	12 .4 0	89	4.6	4 .1	2	2.5 9	38. 00	1.5 6	5. 13	6.00	0.6 8	1660
5	Onib ode (ogun state)	35 .0 0	48 .0 0	1. 70	0. 2	0. 3	0. 12	0. 05	13 .1	93	2.7	3 .2	1	2.6 1	36	1.7 8	5. 90	6.81	6.5	1730
6	Ozub ulu (Ana mbra state)	34 .1 0	47 .2 1	1. 85	0. 61	0. 43	0. 07	0. 12	11 .0 3	n/a	n/a	n / a	n/ a	2.6 0	35. 73	1.9 3	3. 06	4.68	5.7 1	1737

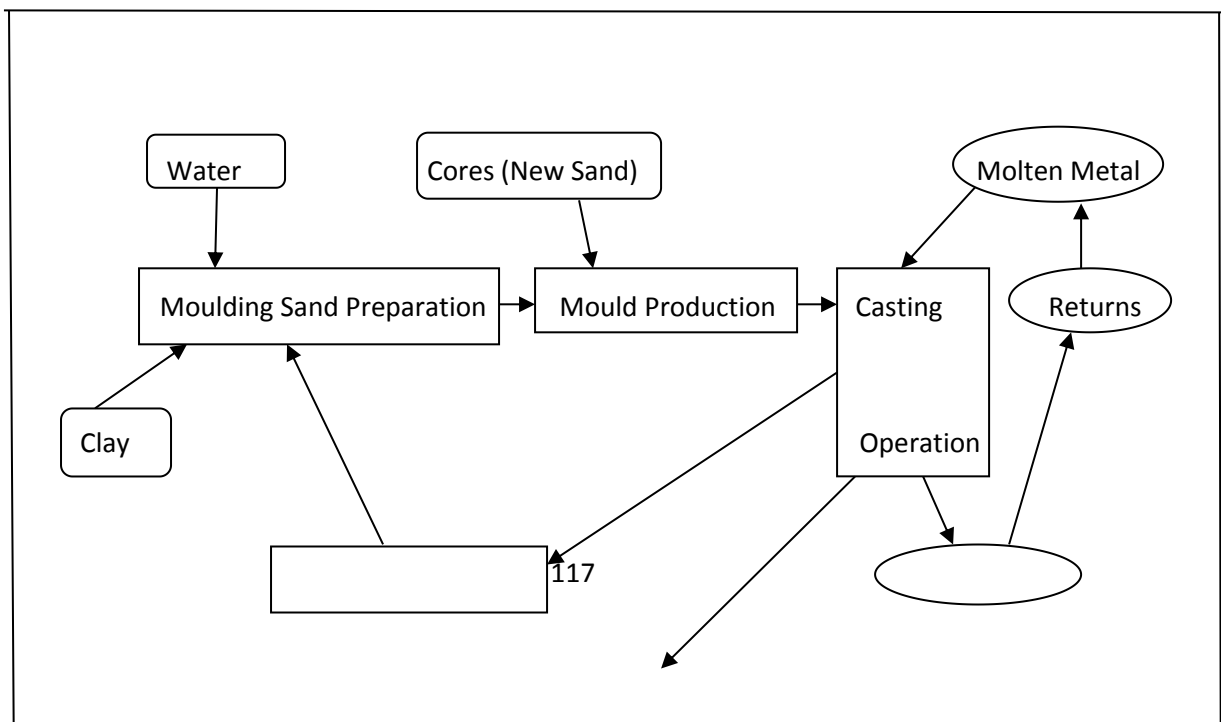
7	Ozanagogo (Delta state)	38.07	46.00	0.78	0.14	0.09	0.07	0.02	13.70	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	36.00	1750
8	Ijapo (ondo state)	38.07	47.00	0.49	n/a	n/a	n/a	n/a	14.70	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	>1600
9	Olo (Enugu state)	21.5	43.3	12.3	Trace	0.91	P ₂ O ₅ 0.27	n/a	15.45										
					Ca + Mg O														
10	Ukpor (Anambra state)	33.2	48.0	1.20	0.73				12.10										
11	Enugu	24.71	53.00	2.32	1.95				16.35										1750
12	Orin (Ekiti state)	34.5	50.50	2.05	1.10				15.50										1730
13	Oshiele (ogun state)	28.30	53.40	1.35	0.88				15.00										1730
14	Werron (plateau state)	36.12	45.16	2.30	0.85				14.40										1760
15	Alkale (Bauchi state)	25.43	54.50	1.05	1.00	15.73													1740
16	Sabon gida (plateau state)	25.88	56.83	13.10	3.20	15.36													1620
17	Ifon (ondo state)	36.80	47.90	0.67	1.11	12.32													1730
18	Okpe (Edo state)	4.30	53.29	1.45	1.30				16.86										1650

Source: PD/CE NMDC, 1999 and NMDC DATA BANK, 2008.

Foundry Sands

Foundry sands account for the production of the major quantity of castings. Sand is used in the ratio of as much as 10 tons of sand per ton of metal to as little as ¼ ton of sand per ton of metal depending upon the type and size of casting and the moulding method employed. The majority of castings are made in green sand moulds, moulds whose major components

are sand (usually silica, SiO_2), clay such as bentonite, and water. The clay-water combination is responsible for the binding action between the sand grains, and can be present in various amounts from 5 to 50 percent by weight. A typical green sand might contain 6% clay and 3% water, materials which are replenished as the moulding sand is reconstituted and reused again and again. In the ideal world, the sand grains would be reused forever. In actual fact the sand grains themselves suffer some attrition due to mechanical, thermal, and chemical attack in the course of their use and so must be replaced on a consistent basis, usually through the production of cores (Rundman, 2000). This "flow" of sand in a green sand foundry is illustrated below together with the flow of metal.



Used Sand Moulds

solid metal



Fig. 4.1 Sand and Metal Flow

Clearly in a foundry which is at steady state (produces the same weight castings day in and day out) the amount of new sand added in cores must equal the spent sand and dust lost due to attrition or for other reasons. In fact in most foundries, perfectly good sand is landfilled every day so as to balance the flow of material into and out of a facility. In Michigan in 1991, approximately 1000,000 tons of sand was landfilled to produce about 1,000,000 tons of cast product. A little reflection by the reader will bring the realization that what comes into a volume (the plant) must also leave; otherwise it is likely to get very crowded in a hurry (the law of continuity on a large scale).

Silica sand grains are very important in molding as they impart refractoriness, chemical resistivity, and permeability to the sand. Sands are specified according to their average grain size the finer the grains the more intimate will be the contact and the lower will be the permeability. The shape of the sand varies from round to angular. The grains are classified according to their shapes.

1. Round grains: These grains have the least contact with one another in a rammed structure thereby making the sand highly permeable to gases. Sand having round grains however lacks strength.
2. Sub-angular grains: These grains however have low permeability and greater strength than the rounded ones.
3. Angular grains: these grains have defined edges and surfaces are nearly flat, produce higher strength and lower permeability in the mould than the subangular, grains.
4. Compound grains: some grains are cemented together such that they fail to separate when screened. They may consist of round, angular or subangular grains or a combination of the three.

Table 4.3 Properties of Silica Sand for Foundry use

Chemical purity

SiO ₂	95-96% Min	The higher the silica the more refractory the sand
Loss on ignition	0.5% max	Represents organic impurities
Fe ₂ O ₃	0.3% Max	Iron oxide reduces the refractoriness
CaO	0.2% max	Raises the acid demand value
K ₂ O, Na ₂ O	0.5% Max	Reduces refractoriness

Acid demand value to pH4 6ml max High acid demand adversely affects acid catalysed binders

Source: Brown (1994)

Characteristics of Sands

The characteristics of moulding sands include the following:

1. Its refractory nature : it can withstand the high temperature nature of molten metal without getting fused
2. Sand has good chemical resistivity: it does not chemically react or combine with molten metal and can therefore be used time and again.
3. Sand has a high degree of permeability as it allows gases and air to escape from the mould when molten metal is poured without interference with the rigidity and strength of the mould. The degree of the strength, hardness, and permeability can be adjusted as desired by varying the composition of the ingredients of the sand.
4. Hot strength; after the moisture has evaporated, the sand may be required to possess strength at some elevated temperature, above 212 F. Metallostatic pressure of the liquid –metal bearing against the mould walls may cause mould enlargement, or if the metal is still flowing , erosion, cracks, or breakage may occur unless the sand possesses adequate hot strength
5. Green strength: the green sand, after water has been mixed into it must have adequate strength and plasticity for making and handling of the mould
6. Dry strength: as a casting is poured, sand adjacent to the hot metal quickly losses its water as steam. The dry sand must have strength to resist erosion and also the metallostatic pressure of the molten metal, or also the mould may enlarge.
7. Thermal stability: heat from the casting causes rapid expansion of the sand surface at the mould metal interface. The mould surface may then crack, buckle, or flake-off (scab) unless the moulding sand is relatively stable dimensionally under rapid heating.
8. Flowability : the sand should respond to moulding processes
9. Produces good casting finish
10. Collapsibility : heated sand which becomes hard and rock like is difficult to remove from from the casting and may cause the contracting metal to tear or crack
11. Is reusable
12. Offers ease of sand preparation and control
13. Removes heat from the cooling casting. This list by no means includes all the properties which might be desirable. Obviously, the most important characteristics of a moulding sand is that it facilitate the economic production of good castings. Sands with the above characteristics are said to be suitable for moulding work (Ogo, 1989)

Size Distribution

The size distribution of the sand affects the quality of the castings coarse grained sands allow metal penetration into moulds and cores giving poor surface finish to the castings. Fine –grained sands yield better surface finish but need higher binder content and the low permeability may cause gas defects in castings. Most foundry sands fall within the following size range.

Grain fineness number	50-60 AFS	Yields good surface
Average grain size	220-250 microns	finish at low binder levels
Fineness content, below 200 mesh	2%	allows low binder level to be used
Clay content below 20 microns	0.5% max	
Size spread	95% on 4 or 5 screens	Gives good packing and resistance to expansion defects

Acid Demand

The chemical composition of the sand affects the acid demand value which has an important effect on the catalyst requirements of cold-setting acid-catalysed binders. Sands containing alkaline minerals and particularly significant amounts of sea-shell will absorb acid catalyst. Sands with acid demand values greater than about 6ml require high acid catalyst levels; sands with acid demand greater than 10-15ml are not suitable for acid catalysed binder systems.

Typical Silica Foundry Sand Properties

Chelford 60 sand sand commonly used in the UK as a base for green sand and for resin-bonded moulds and cores:

Grain shape:	rounded, medium sphericity							
Bulk density, loose:	1490kg/m ³ (93lb/ft ³)							
GF specific surface area:	140cm ² /g							
Angle of repose:	33°							
Chemical analysis:								
SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	K ₂ O	Na ₂ O	CaO	TiO ₂	Cr ₂ O ₃	LOI
97.1	0.11	1.60	0.73	0.15	0.10	0.06	15ppm	0.3

Table 4.4 Chemical Analysis of River Benue Sand

Composition	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	K ₂ O	Na ₂ O	CaO+MgO	TiO ₂	Cr ₂ O ₃	LOI
%	96.25	0.17	1.78	-	-	0.04	-	-	0.67

Acid demand (number of ml 0.1N HCl)

To: pH3 PH4 pH5 pH6 pH7

MI: 2.0 1.8 1.4 1.0 0.8

Table 4.5 Gives Size Grading of Typical Foundry Sands Used in Foundry in Nigeria (Bacita sand)

Aperture size (microns)	BSS Mesh no.	% Weight Retained
1400	14	0.04
1000	18	0.10
710	25	0.18
500	35	0.65
355	45	3.76
250	60	25.00
180	80	36.31
125	120	28.30
90	170	4.0
63	230	0.69
-63	-230	0.20
Grain fineness number (AFS)		71.63
AFS Clay content %		1.14
Permeability at 3 ½ %H ₂ O		130
Visual shape		round
Fineness %		0.89
Colour		light yellow

Source: NMDC databank (2008)

Classification of Moulding Sands

Moulding sands are classified into:

1 Naturally bonded sands

2. Synthetic sands

3. Special sands

Naturally bonded sands are simply those in which the refractory sand grains is associated in its deposit with clay needed for moulding such sand. Such sand often develops good moulding properties with the addition of water. But this has a disadvantage because the high clay content reduces refractoriness and permeability.

Synthetic sands are based on silica sand containing little or no binder in the natural state. The strength properties being developed by separate additions.

Advantages of Synthetic Sands

1. It gives greater freedom in the control of properties

Special Sands

While silica is the moulding media which is used in largest quantity, other sands are also utilized in the foundry for special applications, including chromite, olivine, garnet, carbon sands (petroleum cokes) and other refractory materials that can be obtained with a reasonable cost.

Special Sands are ideal for achieving special characteristics which are not otherwise possible `with silica sand, they include zircon, olivine, chamotte, chromite, and chrome-magnesite.

Zircon Sand

Zircon: zirconium silicate (ZrSiO_2) has the following characteristics:

- 1 Low thermal expansion 1/6 of that of silica sand. This strengthen the mould against thermal and mechanical stress and helps in producing accurate castings
- 2 Chemical inertness to the action of molten metal which enhances the finish of casting while protecting them from sand burns, a property use for high alloy steels. It has high heat conductivity almost double that of silica sand.
- 3 It has greater density than that of silica sand which prevents metal penetration
- 4 It has high sintering temperature and refractoriness this helps casting of high melting point metals.
- 5 This aids the casting of high melting point metal. Zircon sand can be used for casting of this metals.
- 6 It is used for facing sand for those high temperature metals

Clay

Clay imparts the necessary bonding strength to the moulding sand so that after ramming the mould does not loss its shape. As the quantity of clay is increased the permeability of the mould is reduced. Clay is defined as those particles of sand under 20 microns in diameter, those particles of sand that fail to settle at a rate of 25 mm/min when suspended in water. Clay consists of 2 ingredients fine silt and true clay. Silt is a foreign matter of mineral deposit and has no bonding power. True clay

provides the necessary bonds. True clays are made up of extremely minute aggregate of crystallite particle called clay mineral and the clay mineral are composed of flaked shaped particles of about 2 microns in diameter which lie flat on one another. Clays take the general structural form of minute plates in the approximate particle size range 0.01-1micron in breadth, and plasticity and bond are developed by the addition of water. Nigeria has a lot of clay deposits table5 shows some of the clay deposits. In the natural moulding sands the clay occurs in association with the sand grains, whilst the synthetic sands are bonded with selected clays from separate deposits. Net attractive forces are generated between charged hydrated clay particles or micelles and between these and the quartz surfaces. The strength of the ionic bond is a function of the total surface area of the particles and is strongly influenced by adsorption of exchangeable cations at the free surfaces: these modify the balance of local forces between the particles.

On drying, loss of adsorbed water produces shrinkage of the lattice and further strengthening of the bond, so that clay binders are effective in both green and dried condition. Hydration is reversible to temperatures well above the drying range: thus moulds may be dried or cast and the bond regenerated by addition of water after each cycle. Heating to progressively higher temperatures, however, removes chemically combined water and causes permanent loss of bonding capacity. The temperature at which this occurs varies with the particular clay but the loss begins at approximately 400oc and is in all cases complete at 700°C. At still higher temperatures the clays undergo drastic mineralogical changes involving crystallization of alumina and cristobalite and the formation of mullite.

The principal mineral constituents of clays are kaolinite, montmorillonite, and illite. Kaolinite corresponds to the general formula $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$ and is relatively plentiful as the major constituent of china and ball clays and fireclays. Their relatively high alumina content makes these clays reasonably refractory, but irreversible dehydration occurs in the temperature range 400-650°C. The bonding properties are not so high as those of some other clays so that a higher binder content is required, often in the range 10-20%.

Montmorillonite has the basic formula $\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$ but a proportion of the Al^{+++} ions are replaced by Mg^{++} ions in isomorphous substitution. This gives capacity for absorption of exchangeable cations, for example Na^+ and Ca^{++} to which the properties of the clay are particularly sensitive: the typical formula can be represented in the form $\text{M}^{+}_{0.33} \cdot (\text{Al}_{1.67}\text{Mg}_{0.33})^- \text{Si}_4\text{O}_{10}(\text{OH})_2$. Montmorillonite is the principal mineral constituent of the bentonites. These clays have a high capacity for water absorption and exceptionally favourable bonding characteristics: strength properties can therefore be derived from additions as low as 3-5%. Maximum swelling power is obtained in the sodium or sodium treated bentonites: these are notable for the high level of dry strength which they confer, whilst the calcium bentonites give maximum green strength. Many bentonites retain their capacity for water absorption up to 550-700°C and can be thus regarded as thermally more stable than alternative clays, with a potentially longer life in closed systems. Large deposits of bentonite clays have been identified in various parts of Nigeria. However, the occurrence of pure bentonite (Wyoming bentonite) has not been confirmed but there are reports of occurrences of highly montmorillonitic clays in Borno/Yobe, Adamawa, Abia, Anambra, Edo, Imo, Ebonyi, Akwaibom and Cross-River States of Nigeria (Ihom, *et al*, 2006). Some of these deposits are believed to contain montmorillonite as high as 80% even though their reserves have not been estimated. Sodium based bentonite deposits are few in Nigeria, however there are a lot of calcium based bentonite deposits in

Nigeria. Ameki Bende clay deposit in Abia state is one of such deposit this clay has high quantity of iron oxide and other impurities which tend to low its binding and refractory properties. This clay was processed to remove the impurities after which it was activated using sodium carbonate the properties of the clay improved and compared very well with those of sodium bentonite after the processing and activation. See Tables 4.6-4.11

Table 4.6 Chemical Compositon of Unprocessed Bende-Ameki Bentonite Clay Deposit

Composition	percentage (%)
SiO ₂	52.69
Al ₂ O ₃	17.07
Fe ₂ O ₃	9.98
CaO	0.70
MgO	1.41
LOI	15.34
Na ₂ O	0.19
K ₂ O	0.02

Source: Ihom, *et al*, 2006

Table 4.7 Chemical Composition of Processed Bende-Ameki Bentonite Clay Deposit

Composition	Percentage (%)
SiO ₂	60.30
Al ₂ O ₃	12.38
Fe ₂ O ₃	8.78
CaO	0.84
MgO	0.60
LOI	12.15
Na ₂ O	0.16
K ₂ O	0.01

Source: Ihom, *et al*, 2006

Table 4.8 Chemical Composition of the Soft Reddish Brown Residue

Composition	percentage (%)
SiO ₂	43.20
Al ₂ O ₃	15.25
Fe ₂ O ₃	19.16
CaO	0.56
MgO	0.40
LOI	13.75
Na ₂ O	0.16
K ₂ O	0.01

Table 4.9 Some of the Physical Properties of Bende-Ameki Clay and the Imported Bentonite Clay

Property	Activated Processed clay	Residue (soft rock)	Processed	Unprocessed clay	Baroid Bentonite
pH	10.5	4.5	4.60	4.30	9.60
Moisture content					
%	-	-	-	12.60	12.80
Colour	light brown	reddish-brown	light-brown	reddish-brown	light-green
Na ₂ O/CaO ratio	-	0.29	0.19	0.23	-

Table 4.10 Sodium Carbonate (Na₂CO₃) Activation of Laboratory Processed Bende-Ameki Clay

S/NO	%Na ₂ CO ₃	Swollen wt.(g)	Dried wt. (g)	vertical height of Hydrated clay 24hrs (cm)	swollen wt./Dried wt. (swollen Index Ratio)
1.	0	13.00	3.0	5.0	4.33

2.	6.67	13.20	3.2	7.8	4.13
3.	20.00	13.60	3.6	6.9	3.77
4.	26.67	13.80	3.8	6.5	3.63
5.	40.00	14.20	4.2	6.7	3.38
6.	66.67	15.00	5.0	6.5	3.00
7.	93.33	15.80	5.8	6.9	2.72
8.	100.00	16.00	6.0	7.1	2.67
9.	Bentonite from Baroid of Nigeria ltd			8.1	4.33

Table 4.11 Typical Chemical Composition of Standard Bentonite Clay

Compound	percentage (%)
SiO ₂	44-58
Al ₂ O ₃	16-23
Fe ₂ O ₃	2.5-5.0
CaO	0.5-3.5
MgO	3.0-3.8
LOI	12-20
Na ₂ O	0.1-0.8
K ₂ O	0.1-0.3

Source: Ihom, *et al*, 2006

Raw Materials Research and Development Council, Abuja has worked on bentonite in their technical brief on bentonite (1999) the agency reported that bentonite as defined by Shannon is a rock composed essentially of a crystalline clay-like mineral formed by devitrification and the accompanying chemical alteration of glass igneous material, usually a tuff or volcanic ash. The agency added that bentonite defined strictly along this line has not been reported in Nigeria. Volcanic tuff occurs in the Benue trough and around the Jos Plateau, but none of these is known to be associated with appreciable bentonite formation.

Grin however redefined bentonite along a more general line, as a clay body consisting essentially of montmorillonite minerals, regardless of origin or occurrence. This is an industrially more meaningful definition in that it is based strictly on the chemical composition of the rock not origin.

Bentonite is usually found as beds in marine and non-marine strata within the cretaceous, tertiary, and Jurassic to pleistocene age. Bedded bentonite can also occur as small lens shaped bodies with a limited lateral. A less common occurrence is as irregular shaped bodies that grade into unaltered

host rocks. It is a fine –grained clay consisting essentially of smectite minerals. Its properties are controlled by the proportion of montmorillonite.

Bentonite also contains variable proportions of feldspar, mica, and quartz. Impurities such as calcite, gypsum and cristobalite, which may affect the performance of the bentonite clay, can also be identified.

The industrial usefulness of bentonite especially in the petroleum industry is based on its swelling and gel forming capacity when water is added to it. Bentonite having sodium (Na⁺) as either the dominant or as an abundant exchangeable ion typically has very high swelling capacities and forms gel-like masses when added to water. Bentonite in which exchangeable calcium (Ca⁺) is more abundant than other ions has much lower swelling capacities than sodium varieties. Intermediate calcium-sodium bentonites, the so-called mixed types tend to swell moderately and form gel of lesser volumes than that of equal masses of the sodium type.

CLASSIFICATION OF BENTONITE

The various ways of classifying bentonites are:

- Bentonite with (Na⁺) sodium ion as dominant exchangeable ion has very high swelling capacity and is referred to as high swelling or sodium bentonite. It is also referred to as Wyoming or western type.
- Bentonite with (Ca⁺) calcium ion as dominant exchangeable ion has very low swelling capacity and is referred to as low swelling or calcium bentonite. It is also called southern bentonite
- Another type is hectorite, which is a high swelling, lithium-bearing variety of smectite
- There is also the potassium type: K- bentonite or metabentonite, which consists mainly of illite and mixed layer minerals.

Physical and Chemical Properties

The most common smectite group mineral found in economic bentonite deposits is montmorillonite, which is a fine particle sized hydrous aluminum silicate with chemical formula $5Al_2O_3 \cdot 2MgO \cdot 24SiO_2 \cdot 6H_2O$ (Na₂O/CaO).

Bentonite ranges in colour from white to yellow, olive green, brown, and blue. It has a characteristic soapy texture and a wavy appearance. Weathered sodium bentonite has a distinctive “pop corn” texture, while calcium bentonite weathered to an “alligator skin” texture. It is greasy when touched, and swells in water, creating a thixotropic gel as a consequence of interlayer water adsorption.

The major mineral constituent of bentonite, and the mineral that gives bentonite its unique physicochemical properties is smectite. Smectite is the general term given to a group of clay minerals that include beidellite, montmorillonite, montronite, saponite and hectorite. Each of these minerals shares a similar structure but each is chemically distinct. Structurally, they are made up of stacked units, comprised of a layer of octahedrally coordinated ions which are sandwiched between two layers of tetrahedrally coordinated ions. They are divided into two structural groups depending

on whether all the three octahedral sites are occupied (tri-octahedral) or two out of the three are occupied (di-octahedral) smectite.

The great number of flakes and their extreme thinness contribute to many of the industrial uses of bentonite. Their separation by water molecules causes the well-known expansion in volume of the mass called swelling and creates bellying viscosity properties which are necessary in oil well drilling mud. The great surface area promotes adhesion and bond strength when mixed with inert materials as in sands.

Smectite is characterized by exchangeable cations. The most common exchangeable cations are sodium, calcium, magnesium, hydrogen and potassium. The amount and type of exchangeable cations influence the clay surface chemistry and charge, which determines how the clay particles will interact in aqueous suspension. The total exchangeable ions approach 100 million equivalent per 100 grams of sodium based bentonite.

Bentonite absorbs water in a reversible manner up to 550°C. Between 500°C to 600°C, its water of crystallization is lost leading to the production of mullite ($\text{Al}_2\text{O}_3\cdot 2\text{SiO}_2$) and a high temperature form of quartz (SiO_2). At 600°C a hydro-montmorillonite is formed. At 500°C the lattice grouping is intact and destroyed at 1000°C.

The bentonite properties can be classified into the following two headings:

- a) Properties resulting from structure of crystals:
 - Binding power
 - Absorption capacity
 - Dispersivity
 - Filling properties
 - Electrostatic properties
- b) Properties resulting from physic-chemical composition
 - Ion exchange capacity
 - Catalytic properties
 - Capacity to create organo-derivatives
 - Capacity to create new crystalline phases
 - Possibility to produce special chemical matters and building materials

Calcium based bentonites are non-swelling and absorb only slightly more water than kaolinitic clay. Calcium bentonite may be converted into sodium bentonites by the addition of sodium carbonate. Calcium bentonite has lesser dry, baked and hot strengths in sand mixes than sodium bentonite. It swells 2 to 5 times the original volume.

Sodium based bentonite gives better hot strength than calcium bentonite and are referred as moulding sands for steel and iron castings. Sodium base bentonite sand mixtures are also tougher than and not as brittle as calcium base bonded sand mixes. They swell 10-20 times their original volume in water.

Clay mineral studies of the tertiary to recent subsurface in Niger Delta have revealed occurrences of bentonite as well as the other non-swelling kaolinitic clays. Since the Niger Delta opens to the sea,

there is every likelihood that the subsurface Niger Delta bentonite may be enriched in sodium from the saline sea water.

Illite clays are produced by the weathering of micas and form the principal source of bond in the natural moulding sands. They do not swell in the same manner as the bentonites but give reasonable strength properties. Irreversible dehydration occurs in the temperature range 500-550°C. Since the development of bond strength depends upon hydration of the clay, the green strength of a moulding mixture increases with water content up to an optimum value determined by the proportion of clay. Above this value, additional free water causes the green strength to diminish again as illustrated in Figure 4.2. Dry strength, however, continues to increase to much higher original moisture contents, probably due to improved distribution of the binder and the higher bulk densities attainable. Thus by determination of the optimum water content the required strength properties can be obtained with minimum use of clay. A typical combined relationship between clay and water contents and bond strength is illustrated in Figure 4.3.

Compression strength

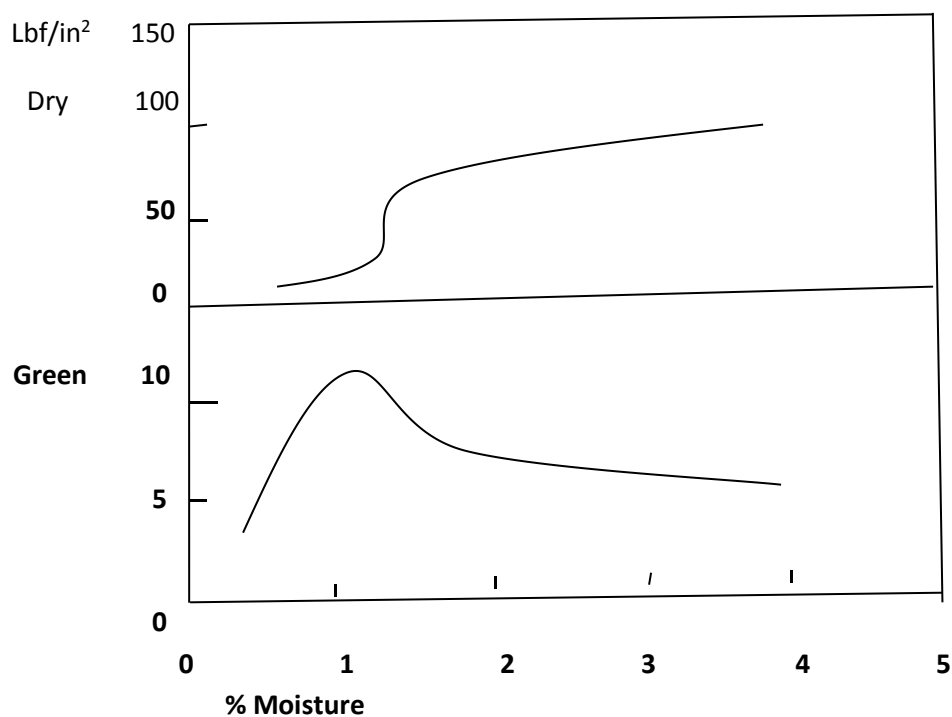
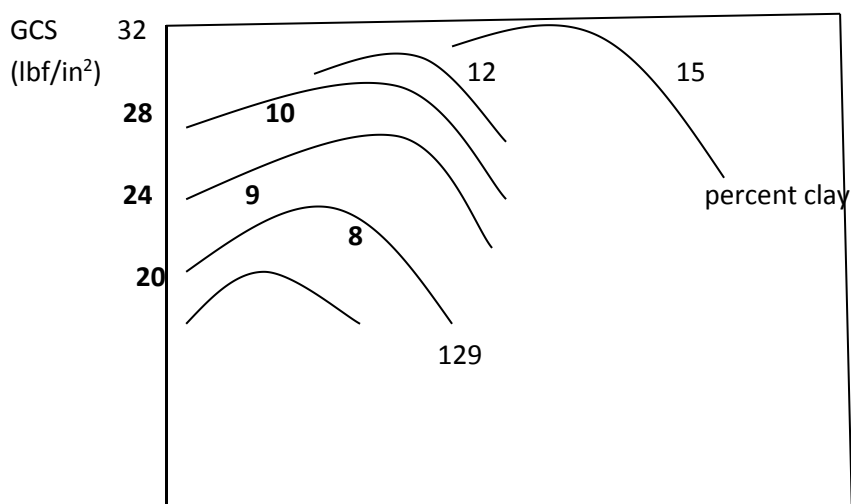


Fig. 4.2 Influence of moisture content on green and dry strengths of moulding sands (bentonite-bonded silica sand)



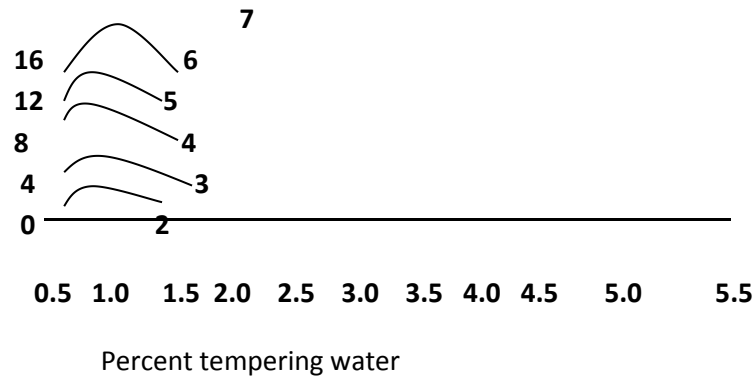


Fig. 4.3 Influence of clay and moisture contents on green strength of moulding sands

Moisture

Clay acquires its bonding action in the presence of moisture. When water is added to clay it penetrates the mixture and forms a surface film which coats the surface of each flake as more water is added the thickness of the film increases up to a certain limit after which the excess water remains in the fluid state. The thickness of this water film varies with the clay mineral and the quantity of clay. The bonding of clay depends on the mixing and the thickness of water film it can contain.

When sand is rammed in the mould the sand grains are forced together the clay coating on each coating acts in such a way that it not only locks the grains in position but also makes them retain that position if the water is added in the exact quantity required to form the films bonding action is best. If water is in excess the strength is reduced and the mould gets weakened. Figure 4.4 illustrates the moisture content variation with green compression strength of Yola natural sand which has a clay content of 26%.

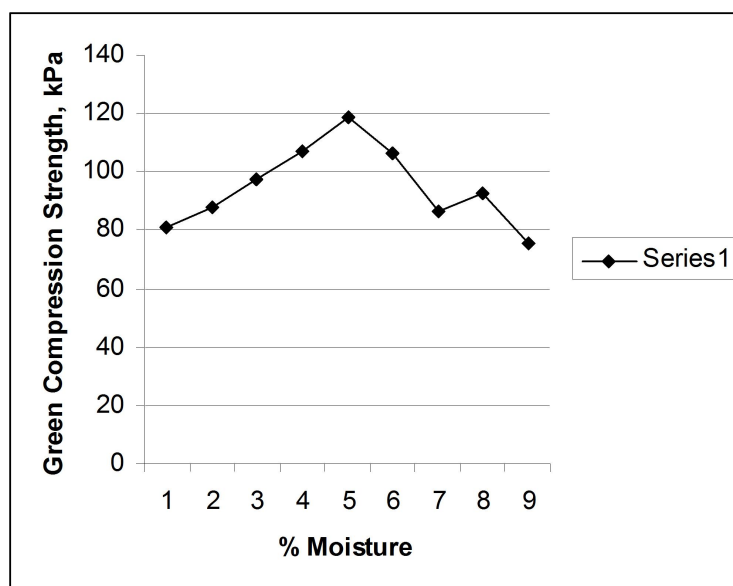


Fig. 4.4 Moisture Content Variations with Green Compression Strength of Yola Natural Sand

Source: Ihom, *et al.*, 2011.

Sand Preparation

Natural bonded Sand

The sand has acceptable texture; preparation is as follows:

Milling for a short time and water is added to attain a moisture content of about 5%. This is in green sand moulding and the sand has the advantage of recycling. Facing sand is also added both for naturally bonded sand and synthetic sand. Plumbago (graphite dust) can be applied to have good finish. Yola natural sand deposit is found in the Northern part of Nigeria by the river Yola basin. The river forms the upper part of the River Benue, which is one of the major rivers that flow through Nigeria. The characteristics of the sand are shown in Table 4.12, the sand does not require the addition of clay only water is added in the preparation of moulding mixture.

Table 4.12 Foundry Properties of Yola Natural Sand as the Moisture Content was Varied from 1- 9%.

Moisture %	1	2	3	4	5	6	7	8	9
Green compression strength kN/m ²	80.67	87.6	97.2	106.9	118.6	106.5	86.2	92.4	75.2
Dry compression strength, kN/m ²	172.4	413.7	1034.3	1327.3	2189.2	2568.4	3033.8	3600	4000
Green permeability (AFS Perm units)	280	290	290	280	310	320	400	420	400
Bulk density g/cm ³	1.65	1.63	1.61	1.63	1.64	1.66	1.68	1.73	1.78
Clay content %	26								

Source : Ihom *et al.*, 2011

Yola natural sand has a Grain fineness number of 88.05 and average grain size of 335.78 microns. Table 4.13 shows the particle size distribution of the Yola natural sand and Table 4.14 shows the average grain size of Yola natural sand from sieve analysis.

Table 4.13 Sieve Analysis of Yola Natural Sand

S/No	ISO Aperture (microns)	Sieve No	Weight Retained (g)	Weight Retained (%)	Cumulative Weight (%)	Product
1.	1400	14	1.8	1.8	1.8	0.00
2.	1000	18	3.0	3.0	4.8	42.00
3.	710	25	4.1	4.1	7.9	73.3
4.	500	35	4.50	4.50	11.40	112.50
5.	355	45	7.00	7.00	18.40	245.00
6.	250	60	17.00	17.00	35.40	765.00
7.	180	80	18.50	18.50	53.90	1110.00
8.	125	120	17.40	17.40	71.30	1392.00
9.	90	170	8.20	8.20	79.50	984.00
10.	63	230	2.90	2.90	82.40	493.00
11.	-63	-230	15.60	15.60	100.00	3588.00
						Σ8805.30

Grain Fineness Number (GFN) = $8805.30/100.00=88.05$ AFS.

Colour: Dark Brown

Grain Shape: Angular

Table 4.14 Average Grain Size of Yola Natural Sand from Sieve Analysis

S/NO	ISO Aperture (Microns)	weight Retained (%)	Multiplier	Product
1.	710	12.8	1180	15104
2.	500	4.15	600	2490
3.	355	6.36	425	2703
4.	250	17.75	300	5325
5.	180	15.76	212	3341.12
6.	125	17.40	150	2610
7	90	6.51	106	690.06
8.	63	3.58	75	268.50
9.	63(pan)	14.18	38	538.84
		Σ98.49		Σ33070.52

Average Grain Size (AGS) = $33070.52/98.49 = 335.78$ microns

Source: Ihom, *et al.*, 2011

Synthetic

The unbonded sand is normally milled and the required percentages by weight (5%, 10%, 12%) of the sand is added of bentonite, 4-5% of water, milled to attain a uniform distribution

Core Sands (Synthetic sand)

The mixtures are many depending on the type of core, and metal, but general purpose core sand can be made with a mixture of 4-5% molasses, (1-1.5%) linseed oil by weight. Molasses provide the green strength. (Green strength is the strength of the mould when it has not yet dried) linseed oil

provides the dry strength. The core is then baked at about 280-300°C 1-2 hours depending on the size and the bulk. Cores are ordinarily made separately from mould in a designated area of the foundry referred to as a core room. They are then transported to the moulding department to be placed in the moulds. Core boxes are required to produce cores (Ihom, 2007). A core must also offer minimum resistance to contraction. This is not necessarily associated with ultimate collapsibility, but rather with short term high temperature deformation.

According to Taylor (1957), cores are usually made of synthetic sand, although clean, natural sand containing only 1 or 2 percent clay can be used. Green sand cores are used occasionally; in this case a strong, highly permeable moulding sand is used. Cores may also be made of green sand used in the dried condition.

According to Heine *et al.*, (1967), core sands may be simply defined as sand mixtures suitable for cores. To satisfy this definition, the sand mixture is expected to have certain properties, such as:-

- (i) Green strength adequate for the operations of core making.
- (ii) Response to core baking so that strength, hardness, and other properties are brought out by the baking operation.
- (iii) After baking, adequate strength for handling, core setting and retention of dimensional accuracy.
- (iv) Resistance to the action of the molten metal, i.e., erosion, fusion, thermal shock, and venting ability to pass off gases.
- (v) Ease of removal from the solidified casting
- (vi) Retention of desirable properties during periods when baked cores are stored.

The above properties pertain particularly to conventional core sands, which are still the most commonly used. Other core sand mixtures such as shell, furan resins, air-set, and silicate sands need not require baking response since they may not be baked.

Core sand ingredients include sand grains, binders for green and cured strength, and other additives used for special properties. Silica is the basis of most sands used for cores, and zircon, olivine, and others are also used. The word sand in foundry terminology may refer to any granular material of 0.05 to 1.0mm average particle size. Core sands are commonly 3-sieve sands because they have higher base permeability. Typical core sands have, % AFS clay content of 0.50% and AFS grain fineness number of 51.3 (Heine *et al.*, 1967).

Binders and Chemically Bonded Moulding

According to Nwajagu (1994), binders are introduced into the moulding and core mixture in order to improve their properties especially the strength. Binders must meet several requirements of which the most important include:-

- (a) To distribute uniformly in the mixture, and ensure the needed total and surface strength in both moist (green) and dry state.
- (ii) To ensure good collapsibility of the mixture, that is, contribute to easy knock out of the core from the casting.
- (iii) To have low gas porosity and hygroscopy.
- (iv) To give the mixture yieldability in green state, and flowability in dry state.
- (v) Not to lower the refractoriness of the mixture
- (vi) To show the least stickiness to the surface of the patterns and core boxes during the production of cores and moulds.
- (vii) To be harmless to the operating personnel, that is to avoid attacking the hands or giving off toxic gases, and
- (viii) To be cheap and easily available in sufficient quantity (non-deficient).

The use of adhesive materials (binders) for holding objects together and particles by surface attachment (adhesion) has been in practice for a very long time (Ihom, 2007). The source of these adhesive materials varied from naturally occurring plants and animals to those produced by

synthesis including the adhesive fish bones. In the plant kingdom adhesive (binders), gums, consisting mainly of polysaccharides and salts of magnesium, potassium and calcium are obtained from trees such as cacia, pine, sheanut tree, cactaceae, manihot esculenta, glycine max, and some vegetable products such as ipomea batatas, zea maize (maize), cocoyam, corn, and tapioca starch (Jideonwo *et al.*, 2006). The main feature of these earlier adhesives and binders is their macromolecular base, a character which led Ihom (2007) to say strong joint can be obtained with any liquid materials which could wet both surfaces to be joined and solidify insitu. Various methods for the modification of materials of plant (starch) and animal (bones) origin for the development of adhesives (binders) have been reported (Ihom, 2007).

Various materials have been known to have been used in the modification of plant (starch), and animal (bones) these include inorganic and organic acids, cements, metallic salts, alkalis like sodium hydroxide and others (Ihom, 2007). These modifications have been carried out with the aim of achieving greater binding strength when the plant extracts were used as binders. Manning and Laitar stated that “foundry sand binders for making cores can be divided into two main chemical classes: organic and inorganic”. Organic binders are produced synthetically from petroleum by-products. Polymers and plastics of different types are used in the production of various types of binders. Organic binders can also be produced from natural organic sources like plants. Carbohydrates and other resins from plants had been known to be good binders and adhesives. According to Rickards (1982), the soundness of castings made through moulding mixtures with cement has been established. The possibility therefore exists that plant binders can be modified or made better with the addition of cement. Cement which has the ability to cold-cure without heating could catalyze the quick self curing of binders made from plants. Cement is thought to be able to achieve cold curing as a result of the formation of strength bonds between the particles, which get stronger with time as tobermorite ‘gel’ is formed. Today’s environmental realities, call for the use of binders that are environmentally friendly (Ihom *et al.*, 2006). Foundry industry is becoming increasingly competitive within the global market place. Foundry technology is improving at a rapid pace and is becoming

very complex. The economic attitude of foundry personnel must centre on improving the quality of finished castings, decreasing core and casting scrap, meeting environmental regulations and reducing costs. Within this framework, decisions on alternative foundry core making processes and equipment must be considered to remain competitive. These decisions must take into account productivity, cost, and applicability within the individual foundry so that quality of casting results (Gilson, 1993, Adamovits *et al.*, 1993). The types of binder system used determine the nature of defects associated with the castings; a fact which has been put across by several authors (Naiyu *et al.*, 1993, Fountaine *et al.*, 1993, Powdrell *et al.*, 1993, and Gilson, 1993).

There is a serious campaign by environmental protection agents for foundries to be using less polluting core binder systems (Adamovits, 1993). According to Hoyt (1994), "due to environmental regulations, foundries must meet strict emission standards, which add significantly to the cost of casting by forcing foundries to install expensive dust and fume collection systems. In addition to the decomposition products that enter the atmosphere, many of these products could enter the casting or the return sand. The higher the LOI or fumes released by the binders of the cores, the higher the danger of poor quality castings. Hoyt (1994), concluded that a reduction of 0.1% binder will reduce binder emissions by 17%".

According to Beeley (1982), cereals binders, mainly starch and dextrin, develop a gelatinous bond with water. The function of the binder is to produce cohesion between the refractory grains in the green or dried state. Since bonding materials are not highly refractory, the required strength must be obtained with the minimum possible addition.

According to Beeley (1982), cereals binders, mainly starch and dextrin, develop a gelatinous bond with water. The function of the binder is to produce cohesion between the refractory grains in the green or dried state. Since bonding materials are not highly refractory, the required strength must be obtained with the minimum possible addition. In the year 2004 a research work was carried out by the foundry section of the National Metallurgical Development Centre, Jos. The raw materials

were cereals (maize, guinea corn, millet, wheat), cassava starch, vegetable oil (soya bean oil) and sand. The binders were air cured as well as heat – cured using the oven.

Table 4.15, showed that for the air-cured samples the highest dry compression strength of 2930.4kPa occurred at a composition of 3% oil, 5% maize cereal, and 92% sand (sample 4 D). The highest dry shear strength of 358.54kPa occurred at a composition of 2% oil, 5% maize cereal, and 93% sand (sample 3 D).

Table 4.16, showed that for the air-cured samples the highest dry composition strength of 2758kPa occurred at a composition of 5% guinea corn cereal, and 95% sand (sample 1 D). The highest dry shear strength of 1034.3kPa occurred at a composition of 1% oil, 5% guinea corn cereal and 94% sand (sample 2 D).

Table 4.17, showed that for the air-cured samples the highest dry compression strength of 2447.7kPa occurred at a composition of 5% millet cereal and 95% sand. The highest dry shear strength of 1172.2kPa occurred at a composition of 5% wheat cereal and 95% sand (sample 1 D).

Table 4.18, showed that for the air-cured samples the highest dry compression strength of 2758kPa occurred at a composition of 5% wheat cereal and 95% sand (sample 1 D). The highest dry shear strength of 1172.2kPa occurred at a composition of 5% wheat cereal and 95% sand (sample 1 D).

Table 4.19, showed that for the air-cured samples the highest dry compression strength of greater than 3223.4kPa occurred at a composition of 5% cassava starch and 95% sand (sample 1 D). The highest dry shear strength of 2240.9kPa occurred at a composition of 2% oil, 5% cassava and 93% sand (sample 3 D).

The above results from Tables 4.15-4.19, has exhibited some common characteristics and salient behaviour worthy of noting. The highest values of dry composition and dry shear strength have all occurred at compositions with 5% cereal binder and cassava binder. 5% of cereal and cassava binder is therefore the best for optimum strength for air-cured cores using these binders.

The strength values of the cores produced using these binders in the air-dried form are high. The addition of some catalyst to the composition could make them dry faster and set within a reasonable time for the cores to be ready for immediate use. Cassava starch seems, so promising from the above results and may likely become a good material for producing self-curing resin binder for core making with more research. The permeability is high enough to allow the escape of gases during casting. Compositions from Tables 4.15-4.19, with oil require baking for them to attain maximum strength.

The recommended baking time for guinea corn from the work was 3hrs at 200°C for optimum strength, and that of millet was also 3hrs at 200°C for optimum strength values. The baking time for wheat cereal binder with oil was 3hrs at 200°C for optimum strength; however, wheat without oil attains optimum strength when it was air-cured for 10hrs. The recommended baking time for cassava starch binder with oil was 3hrs at 200°C for optimum strength, the work however, showed that for cassava starch binder alone the optimum strength was attained when it was air-cured for 10hrs. The result of the work showed that cassava starch binder has superiority in terms of strength over the cereal binders.

Table 4.15 The Characterization of Local Raw Materials as Binders for Core Making (Maize Cereal)

Baking Temperature 200°C

Sample	Green Perm	Green Comp	Dry Compression Strength				Dry Shear Strength				Maize Cereal			
Strength Psi														
			0 HR	1HR	2HRS	3HRS	0HR	1HR	2HRS	3HRS	%OIL	% STARCH		
SAND														
1A	- -	Not Mouldable				- -	-	-	0	2	98			
1B	190 2.2	68 Psi	82Psi	86 Psi	105 Psi	20 Psi	24 Psi	25 Psi	36 Psi	0	3	97		
1C	190	2.5	76 „	425,,	330,,	310,,	32 „	73 „	125 „	95 „	0	4	96	
1D	200	2.7	200 „	465 „	460 „	195 „	38 „	140 „	190 „	140 „	0	5	95	
2A	200	1.9	44 „	90 „	205 „	210 „	8 „	22 „	85 „	100 „	1	2	97	
2B	195	2.6	75 „	120 „	290 „	335 „	10 „	32 „	95 „	120 „	1	3	96	

2C	195	2.7	100 „	160 „	310 „	415 „	15 „	46 „	140 „	165 „	1	4	95
2D	210	3.2	130 „	240 „	465 „	467.5 „	20 „	66 „	150 „	190 „	1	5	94
3A	180	2.3	30 „	210 „	355 „	467.5 „	20 „	62 „	110 „	205 „	2	2	96
3B	185	2.6	67 „	259 „	390 „	467.5 „	23 „	70 „	125 „	240 „	2	3	95
3C	190	2.6	160 „	315 „	445 „	467.5 „	32 „	73 „	160 „	245 „	2	4	94
3D	190	2.7	340 „	400 „	467 „	467.5 „	52 „	160 „	195 „	300 „	2	5	93
4A	190	2.1	38 „	185 „	350 „	467.5 „	6 „	52 „	175 „	210 „	3	2	95
4B	220	2.5	91 „	245 „	380 „	467.5 „	14 „	65 „	150 „	230 „	3	3	94
4C	195	3.2	170 „	295 „	445 „	467.5 „	16 „	67 „	180 „	270 „	3	4	93
4D	200	3.2	425 „	375 „	450 „	467.5 „	18 „	150 „	190 „	305 „	3	5	92

The Recommended Baking Time for Maize Binder Mixtures with Oil is 3 Hours at 200°C. However, for Mixtures with Maize Alone is 1 Hour at the same Temperature for Optimum Strength. **Source:** NMDC, Foundry, (2004)

Table 4.16: The Characterization of Local Raw Materials as Binders for Core Making (Guinea Corn Cereal)

Baking Temperature 200°C

Sample	Green	Green Comp.		Dry Compression Strength				Dry Shear Strength				Guinea Corn Cereal		
		Perm	Strength Psi	0 HR	1HR	2HRS	3HRS	0HR	1HR	2HRS	3HRS	%OIL	% STARCH	%SAND
1A	220	-		Not Mouldable				-	-	-	-	0	2	98
1B	220	1.9	230Psi	220Psi	335 Psi	350 Psi	58 Psi	52 Psi	60Psi	75 Psi	0	3		97
1C	220	2.3	250 „	370 „	390 „	467.5 „	60 „	71 „	90 „	80 „	0	4		96
1D	200	2.6	400 „	467.5 „	>467.5 „	>467.5 „	95 „	170 „	185 „	160 „	0	5		95
2A	260	-		22 „	100 „	200 „	205 „	8 „	19 „	48 „	100 „	1	2	97
2B	230	2.7	59 „	110 „	205 „	295 „	30 „	29 „	60 „	120 „	1	3		96
2C	240	3.2	160 „	165 „	325 „	425 „	50 „	43 „	90 „	130 „	1	4		95

2D	210	3.4	210 „	425 „	460 „	>467.5 „	150 „	67 „	165 „	175 „	1	5	94	
3A	220	2.4	36 „	210 „	250 „	440 „	10 „	69 „	130 „	180 „	2	2	96	
3B	230	2.7	78 „	150 „	270 „	467.5 „	28 „	80 „	155 „	205 „	2	3	95	
3C	180	2.5	92.5 „	270 „	380 „	>467.5 „	53 „	90 „	195 „	235 „	2	4	94	
3D	190	2.6	390 „	280 „	440 „	>467.5„	66 „	110 „	195 „	250 „	2	5	93	
4A	210	2.2	40 „	310 „	320 „	>467.5 „	8 „	115 „	195 „	245 „	3	2	95	
4B	175	2.3	100 „	320 „	325 „	>467.5„	42 „	120 „	200 „	250 „	3	3	94	
4C	200	2.6	150 „	325 „	360 „	>467.5„	46 „	135 „	215 „	280 „	3	4	93	
4D	180	-		215 „	370 „	425 „	>467.5 „	68 „	140 „	310 „	325 „	3	5	92

The Recommended Baking Time for Guinea Corn Should be 3 Hours at 200° C for Optimum Strength. Source: NMDC, Foundry, (2004)

Table 4.17: The Characterization of Local Raw Materials as Binders for Core Making (Millet Cereal)

Baking Temperature 200°C

Sample	Green	Green Comp.	Dry Compression Strength				Dry Shear Strength				Millet Cereal		
		Perm. Strength											
			Psi										
			0 HR	1HR	2HRS	3HRS	0HR	1HR	2HRS	3HRS	%OIL	% STARCH	%
SAND													
1A	-	-	Not Mouldable				-	-	-	-	0	2	98
1B	190	2.1	290Psi	180Psi	175 Psi	180 Psi	330 Psi	82 Psi	110 Psi	115 Psi	0	3	97
1C	190	2.2	320 „	330 „	300 „	410 „	180 „	175 „	160 „	140 „	0	4	96
1D	170	2.5	330 „	390 „	380 „	450 „	150 „	205 „	190 „	155 „	0	5	95

2A	220	2.3	78 „	93.5 „	210 „	280 „	30 „	70 „	125 „	125 „	1	2	97
2B	200	2.4	135 „	17.5 „	230 „	310 „	46 „	75 „	130 „	135 „	1	3	96
2C	180	2.8	260 „	230 „	325 „	465 „	65 „	90 „	140 „	240 „	1	4	95
2D	165	4.1	270 „	250 „	465 „	467.5 „	69 „	140 „	220 „	320 „	1	5	94
3A	230	2.2	50 „	230 „	367.5 „	455 „	28 „	85 „	165 „	180 „	2	2	96
3B	220	3.0	165 „	290 „	380 „	467.5 „	50 „	115 „	190 „	250 „	2	3	95
3C	230	2.8	205 „	350 „	415 „	>467.5 „	95 „	150 „	220 „	295 „	2	4	94
3D	200	3.5	240 „	400 „	>467.5 „	>467.5 „	150 „	170 „	300 „	310 „	2	5	93
4A	220	2.2	62 „	280 „	360 „	>467.5 „	22 „	120 „	190 „	225 „	3	2	95
4B	210	2.4	260 „	350 „	430 „	>467.5 „	48 „	135 „	200 „	250 „	3	3	94
4C	200	2.6	280 „	355 „	455 „	>467.5 „	49 „	160 „	225 „	280 „	3	4	93
4D	200	2.8	355 „	467.5 „	>467.5 „	>467.5 „	130 „	215 „	275 „	290 „	3	5	92

The Recommended Baking Time for Millet Cereal Binders for Core Making is 3 Hours at 200°C for Optimum Strength Values.

Source: NMDC, Foundry, (2004)

Table 4.18: The Characterization of Local Raw Materials as Binders for Core Making (Wheat Cereal)

Baking Temperature 200°C

Sample	Green	Green Comp.	Dry Compression Strength				Dry Shear Strength				Wheat Cereal		
	Perm	Strength Psi											
			0 HR	1HR	2HRS	3HRS	0HR	1HR	2HRS	3HRS	%OIL	% STARCH	%
SAND													
1A	-	-	Not Mouldable	-	-	-	-	-			0	2	98
1B			235Psi	225Psi	225 Psi	200 Psi	95 Psi	90 Psi	61 Psi	65 Psi	0	3	97
1C			300 „	265„	265 „	270„	155 „	150 „	73 „	85 „	0	4	96
1D			400 „	350 „	350„	355„	170 „	170 „	135 „	125 „	0	5	95
2A			50 „	60 „	85 „	150 „	20 „	16 „	11 „	70 „	1	2	97

2B	140 „	135 „	240 „	290 „	70 „	40 „	17 „	90 „	1	3	96
2C	230 „	175 „	315 „	390 „	95 „	58 „	22 „	130 „	1	4	95
2D	240 „	230 „	445 „	465 „	110 „	100 „	30 „	160 „	1	5	94
3A	140 „	300 „	400 „	440 „	42.5 „	100 „	90 „	160 „	2	2	96
3B	152.5 „	310 „	425 „	467.5 „	80 „	110 „	105 „	180 „	2	3	95
3C	240 „	360 „	445 „	>467.5 „	85 „	130 „	115 „	190 „	2	4	94
3D	335 „	430 „	467.5 „	>467.5 „	90 „	140 „	130 „	225 „	2	5	93
4A	132.5 „	310 „	360 „	415 „	50 „	130 „	110 „	175 „	3	2	95
4B	162.5 „	320 „	450 „	465 „	62.5 „	145 „	130 „	200 „	3	3	94
4C	255 „	340 „	455 „	>467.5 „	70 „	155 „	135 „	210 „	3	4	93
4D	300 „	340 „	467.5 „	>467.5 „	95 „	160 „	180 „	250 „	3	5	92

The Recommended Baking Time for Wheat Cereal Binders with Oil is 3 Hours at 200°C, for Optimum Strength; however, Wheat without Oil Attains Optimum Strength When it is Air-Dried. Source: NMDC, Foundry, (2004)

Table 4.19: The Characterization of Local Raw Materials as Binders for Core Making (Cassava Starch)

Baking Temperature 200°C

Sample	Green	Green Comp.	Dry Compression Strength				Dry Shear Strength				Cassava Starch			
			Perm	Strength Psi							% OIL	% STARCH	%	
				0 HR	1HR	2HRS	3HRS	0HR	1HR	2HRS	3HRS			
SAND														
1A	320	-	62.5Psi	34.0Psi	2.5Psi	22Psi	27.0Psi	7.5Psi	22 Psi	26Psi	0	2	98	
1B	330	3.3	352.5	177.5,,	275	352.5,,	73,,	73.5	90,,	115 ,,	0	3	97	
1C	340	3.6	448.5,,	405,,	467.5,,	420,,	161 ,,	175 ,,	160 ,,	152.5 ,,	0	4	96	
1D	-	4.5	>467.5,,	>467.5,,	>467.5,,	>467.5,,	285 ,,	270 ,,	265 ,,	272.5 ,,	0	5	95	
2A	350	-	145 ,,	135 ,,	240,,	445 ,,	73,,	52.5 ,,	122.5 ,,	172.5 ,,	1	2	97	

2B	340	2.7	265 „	230 „	405 „	467.5,,	131 „	90 „	155 „	182.5 „	1	3	96
2C	330	2.8	410 „	335 „	445 „	>467.5,,	190 „	110 „	250 „	270 „	1	4	95
2D	320	2.9	467.5 „	467.5,,	>467.5,,	467.5 „	234 „	140 „	257.5,,	292.5 „	1	5	94
3A	310	2.6	200 „	>467.5,,	>467.5,,	>467.5,,	47 „	235 „	282.5 „	315 „	2	2	96
3B	300	3.2	351 „	>467.5,,	>467.5,,	>467.5,,	160 „	202 „	307.5 „	280 „	2	3	95
3C	290	3.6	467.5,,	>467.5,,	>467.5,,	>467.5 „	220 „	185 „	337.5 „	295 „	2	4	94
3D	290	4.0	>467.5,,	>467.5,,	>467.5,,	>467.5,,	325 „	180 „	357.5 „	315 „	2	5	93
4A	330	2.1	93.5 „	>467.5,,	>467.5,,	>467.5 „	33.5 „	377.5,,	321 „	365 „	3	2	95
4B	300	3.0	350 „	>467.5,,	>467.5,,	>467.5,,	160 „	285 „	350 „	360 „	3	3	94
4C	260	3.2	360 „	>467.5,,	>467.5,,	>467.5,,	130 „	255 „	365 „	317.5 „	3	4	93
4D	-	3.6	380 „	>467.5,,	>467.5,,	>467.5 „	150,,	230 „	>467.5,,	365 „	3	5	92

The recommended baking time for cassava starch binder with oil is 2 hours at 200°C for optimum strength; however it is recommended that for cassava starch binder alone the optimum strength is attained when it is air-dried. having said these in conclusion, despite the fact that the cereals have shown good results, the cassava starch binder still remains superior to them. Source: NMDC , foundry (2004)

Classification of Binders

According to Karl (2000), the three major categories of binders are:-

- (i) Vapour cured (cold Box)
- (ii) No bake, and
- (iii) Heat cured.

Details on each of these three categories are given below:-

I. Vapour Cured (cold box) – resin + Sand + vapor,

The process involves mixing the resin with sand, compacting or blowing it at room temperature around the pattern, the mixture then reacts with gas. The pattern is then stripped from sand. 1-1.5% of the resin is used in preparing the mixture. Examples of vapour cured (cold box) binders include the following:-

1. Sodium silicate + CO₂ gas (mid 50s)
2. Furan + SO₂ gas (mid 70s)
3. Phenolic Urethane + TEA or DMEA gas (early 70s)
(TEA – triethylamine or DMEA – dimethylethylamine)

The advantages of these binders are; no heat, rapid cure, and good dimensional accuracy.

II. Nobake – resin + sand + liquid catalyst

Process – the resin is mixed with liquid catalyst, compacted or blown around the pattern at room temperature, and the pattern is then stripped. Time is allowed for setting to be completed. 1-1.5% resin is used (Borden, 2007).

Examples of nobake binders are as follows:-

1. Sodium silicate + liquid ester
2. Phenolic Urethane + liquid amine
3. Furan + Phosphoric acid

The advantages include; no heating, higher strengths, and good dimensional accuracy.

III. Heat Cured (hot box) – resin + sand + heat

Process – sand is precoated with resin, the sand is blown or dropped onto

hot pattern, and the sand remains for a period of time until resin melts and bonding is completed, then the pattern is stripped. 2-3% resin is recommended. Examples of heat cured (hot box) binders include the following:-

1. Oil Core – linseed oil – late 1600s
2. Shell process – late 40s in Germany
3. Furan and phenolic

The advantages of heat cured (hot box) binders include; higher strength than cold or no-bake, and good dimensional accuracy.

Basically binders are divided into organic and inorganic binders, according to Karl (2000), the drawback of most chemically bonded sands is that they absorb some moisture on the shelf, and become significantly weaker in the process. This is a much greater problem in the summer time than in the winter.

The two to three orders of magnitude difference in tensile strength between green sand and chemically bonded sand can be understood by considering the nature of those bonds. Clay and water is extremely plastic (a result of the weak polar bonds), one sand grain sliding easily over another in response to a shear force. On the other hand, the chemical bond involves very strong directional bonding with the polymeric (or inorganic) chemical, which, has been forced in the reaction. As a result the plasticity of these types of bond is very low compared to the clay – water bond. Of course, these high strengths are absolutely necessary for cores which almost always have much larger static stresses present than is observed in mould; obviously the more intricate and smaller the core, the greater the need for strength.

According to Brown (1994), a wide variety of chemical binders are available for making sand mould and cores. They are mostly based either on organic resins or sodium silicate, although there are

other inorganic binders such as cement, which was the earliest of the chemical binders to be used, ethyl silicate, which is used in the Shaw process and for investment casting, and silica sol, which is also for investment casting.

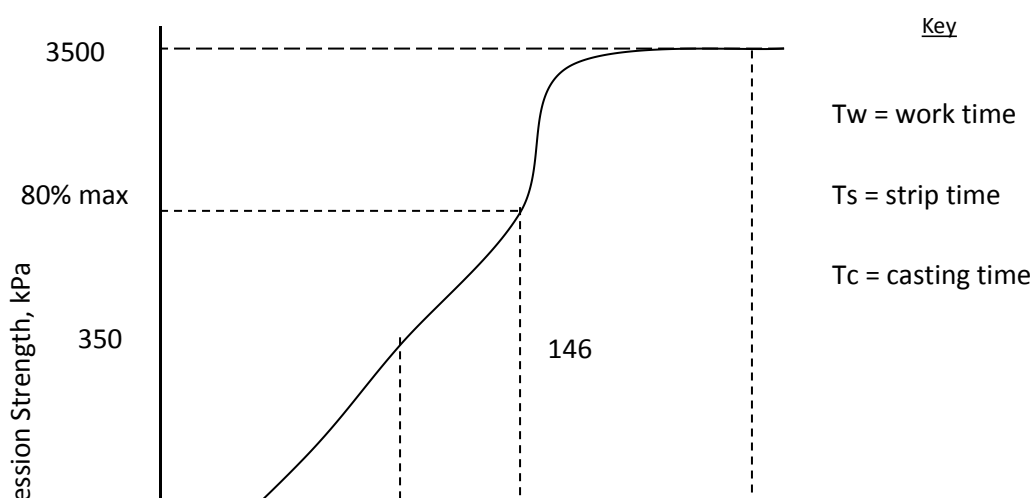
Binders can be used in two ways:-

- I. As self – hardening mixtures; sand, binder and a hardening chemical are mixed together; the binder and hardening chemical are mixed together; the binder and hardener start to react immediately, but sufficiently slowly to allow the sand to be formed into a mould or core which continues to harden further until strong enough to allow casting. The method is usually used for large moulds for jobbing work, although series production is also possible.
- II. With triggered hardening; sand, and binder are mixed and blown or rammed into a core box. Little or no hardening reaction occurs until triggered by applying heat or a catalyst gas. Hardening then takes place in seconds. The process is used for mass production of cores and, in some cases, for moulds for smaller castings (Brown, 1994).

The properties of chemical binders can be expressed in terms of:-

- i) **Work time**:-Which can be conveniently defined as the time after mixing during which the sand mixture has a compressive strength less than 10kPa; at this stage it is fully flowable and can be compacted easily (Morgan, 1973).
- ii) **Strip time**:-Which can be defined as the time after mixing at which a compressive strength of 350kPa is reached. At this value most moulds and cores can be stripped without damage or risk of distortion (Brown, 1994).
- iii) **Maximum time**:-The compressive strength developed in a fully hardened mixture, strength of 3000-5000kPa are often achieved.

It is not necessary to wait until the maximum strength has been achieved before moulds can be cast. The time to allow depends on the particular casting being made; usually casting can take place when 80% of the maximum strength has been reached (Brown, 1994, and Morgan, 1973). Figure 1 is a typical hardening curve for self-hardening sand, it shows the work time T_w occurring at 10kPa, the strip time T_s occurs at 350kPa, the casting time T_c occurs at 80% of the maximum strength and the maximum strength T_{max} occurs at 3500kPa.



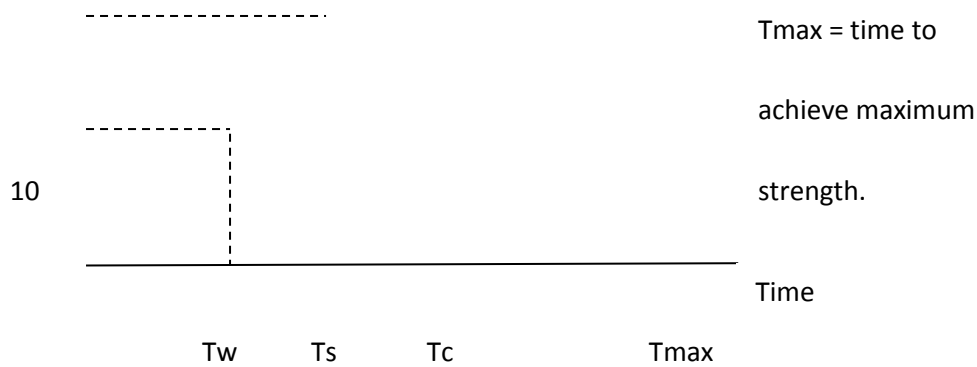


Fig.4.5: Typical Hardening Curve for Self-Hardening Sand. (Source: Brown, 1994).

A Review of Some Methods for Testing Newly Developed Binders

Twardowska and Bambauer (1994) of Ashland Chemical Company, Columbus, Ohio developed a new hot box binder. The authors compared the performance of the new binder with that of the organic binder, considering volatile organic compounds (Vocs), odor, and smoke in the foundry environment during mixing, core making and metal pouring. The researchers tested the new organic binder with sands of different types. As with the majority of sand binder systems, sand variables include sand type, sand moisture, and sand temperature. The researchers tested for the strength performance of the new organic binder system on four different types of sand: three silica sands of varying grain fineness number and a sub-angular lake sand. The binder performed well on all the sands, with the best result observed on finer silica sand. This is typical for most binder systems, whether organic or inorganic. The binder strength performance with respect to sand temperature was also measured, with the temperature of the core box and dwell time kept constant. The bench life of the sand mix was investigated and found to be related directly to loss of moisture from mixed sand. The work also investigated the effect of moisture on the strength of the core. The surface hardness was measured at different time intervals after core-making. The effect of humidity on the hardness was carried out by exposing the core to 99% relative humidity, the result showed a reduction in the surface hardness. The new inorganic binder system was evaluated for hot strength properties using a BCIRA hot distortion tester. Upon heating, the system experienced an expansion or deflection, followed by distortion and breaking of the core sample. This behaviour is very similar to organic binder during hot distortion testing.

A series of test castings were poured using gray iron in Ashland Chemical Company's Metal Applications Laboratory. The test castings included aluminum shake-out, penetration, step cones and erosion wedges. The new inorganic hot box system performed very well in these tests, yielding castings, of high quality with few included core defects. Veining was excellent with good surface finish.

Other tests included core age with respect to scratch hardness, tensile strength versus core age, and shaking-out characteristics. Binder levels were noted in all core preparations for test. The results were graphically represented using bar chart.

In another work titled “Effects of a New In-organic Binder on Green Sand Properties and Casting Results,” Manning and Laitar (1994) ensured that in testing the new binder the compactability of the mould mixes was measured for each moulding mixture prepared. The investigations were in two phases. Phase I, considered the effect of the new binder on green sand properties like, compactability, moisture content, green compression strength, permeability, dry compression strength, LOI, wet tensile strength, AFS clay, and MB clay (Methylene Blue Clay). The normal green sand properties were not affected by the WACGB (Warm Air Cured Glass Binder) sand additions, even at the 30% level.

Phase II studied the effect of WACGB sand additions on green sand properties and casting result made in multiple run green sand mixes and considered the screen analysis of all the sands used in the tests. Three different moulding mixes were prepared, and for each the following properties were determined: compactability, permeability, moisture content, 2 x 2 wt. (gms), green compression strength, dry compression strength, LOI, MB clay and AFS clay content. Seven heats of casting were carried out for the three moulding mixes.

The study took note of the hygroscopic nature of the new binder. The final casting from the seven heats were critically examined for surface finish and the presence of any defects. The conclusions of the work were as follows:- additions of core sands with residual WACGB binders into green sand have no deleterious effects on green sand properties or casting results, despite the hygroscopic nature of the cores up to the levels tested.

Additions of core shake-out sands with residual WACGB to moulding sands showed no loss of green sand properties over 7 cycles. This amounted to a 42% dilution of the green sand by the core shake-out sand.

Casting results showed no loss in surface finish or evidence of defects as compared to castings with no shake-out sand additions.

Additions of ground core sand containing WACGB residues up to 15% had no effect on green sand properties compared to 100% new sand. These include Southern bentonites, Western bentonites and combinations of both.

Additions of 3% ground core sand containing WACGB residues showed some loss in dry compression strength and wet tensile strength, while other properties remain unchanged (Manning and Laitar, 1994).

The review has shown that for a new binder, the work has to be in phases. Phase 1, is the development of the binder, phase II, is the testing of the sands, and core properties and phase III, is the practical application of the cores made with the binder through multiple casting runs. The quality of the castings is assessed, likewise the following:- collapsibility, gas evolution and the nature of the core sand after the casting. In all the works reviewed emissions were only mentioned in brief, although most of the works emphasized the need to reduce environmental pollution by producing odourless and harmless binders. None of the works carried out decomposition analysis of the emissions into the environment.

Binder emissions

According to Tinebra and Wilson (1993), the gas evolution from UFFA-BSA (Furan) binder amounts to 3.8cc/gram and the binder has a residual carbon of 62% after decomposition. Mckinley *et al.*, (1993), said that chemical binder emissions are classified into hazardous air pollutants (HAPS), and Non hazardous air pollutants (Non-HAPS). According to him non- HAPS emissions include:- Ethyl alcohol, carbondioxide, furfuryl alcohol, ammonia, sulphurdioxide, Nitrous oxide, furans, acetones, methyl formate etc. HAP emissions include; formaldehyde, benzene, methanol, toluene, cresole/cresylic acid, phenol, carbonmonoxide, polycyclic-organic matter and cyanide compounds.

Archibald (1993), in his work “Nobake Binder Systems” said that formaldehyde is a potent skin, eye and mucous membrane irritant. It is considered a potential skin sensitizer. Employee exposure to formaldehyde should be controlled to within 1ppm for an eight-hour time weighted average (TWA), per USA regulation. Elwood (1993), said that one of the substances that is in most organic binder system is formaldehyde. OSHA (Occupational Safety and Health Administration) developed a substance specific standard of 0.75PPm threshold limit value (TLV), and called for the monitoring of employees working with the material. OSHA limits are known as permissible exposure limits (PELS).

Materials and OSHA Limits

Formaldehyde = 0.75PPm 8-hr TWA (Time-weighted – average)

Sulphurdioxide = 2.0ppm 8hr TWA

Carbonmonoxide = 35ppm 8-hrTWA

Furfuryl Alcohol = 10ppm 8-hr TWA

Phenol = 5.0ppm 8-hr TWA

Benzene = 1.0ppm 8-hr TWA

Toluene = 100ppm 8-hr TWA

Xylene = 100ppm 8-hr TWA

According to Archibald (1993), air borne emissions of industrial hygiene interest during mould and core production are formaldehyde and furfuryl alcohol, while the decomposition emissions of industrial hygiene interest are carbondioxide and formaldehyde. Geoffrey (1993) also agreed that free formaldehyde, aerated during mixing, is associated with irritation of the eyes, nose and throat. According to the author, low free formaldehyde binders help foundries meet the new OSHA (occupational safety and health Administration) formaldehyde standard and the new EPA (Environmental Protection Agency) emission standard (WTEC, 2005).

Starch binders from manihot esculenta has as their chief emission products water vapour, carbondioxide and a residual carbon of almost 70%. According to Moore and Mason (1981), manihot esculenta (starch) binder has a decomposition temperature of 121⁰C, with volume of gas evolved at decomposition temperature being equivalent to 113.76m³ gas evolved per m³ sand. Urea formaldehyde binder has a decomposition temperature of 163⁰C, with volume of gas evolved at decomposition temperature as 96.48m³ gas evolved per m³ sand. Linseed oil has a decomposition temperature of 427⁰C, with a volume of gas evolved at decomposition as 350.88 m³ gas evolved per m³ sand. Table 4.20, shows the chemical formulae of common binder components.

Manihot Esculenta on Combustion releases carbondioxide and water into the environment. The reaction is shown below

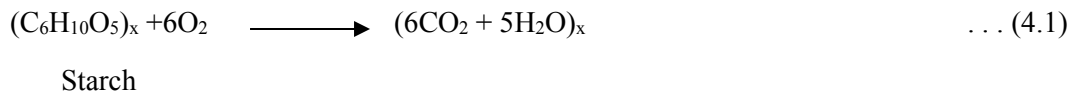


Table 4.20 Chemical Formulae of Common Binder Components

Material	Chemical Formula
Linseed oil	$\text{C}_{54}\text{H}_{98}\text{O}_{16}$
Phenol formaldehyde	$(\text{C}_7\text{H}_8\text{O}_2)_x$
Urea formaldehyde	$(\text{C}_2\text{H}_6\text{O}_2\text{N}_2)_x$
Starch	$(\text{C}_6\text{H}_{10}\text{O}_5)_x$

Standard Test Equipment, and Testing Procedures in Sand Casting

The need for systematic evaluation of the working qualities of moulding materials under foundry conditions has led to the development of a wide range of tests, the work of many committees and individuals. Some of the tests are concerned with basic chemical and physical characteristics, but the majority are designed to measure bulk properties. The bulk properties of an aggregate are sensitive to small variations in mixing conditions and specimen preparation, so that rigid standardization is needed at all stages. Even under these conditions results usually need to be derived from two or more determinations. The reproducibility of tests has been shown to be best in permeability and least in dry strength determinations. In the routine testing of materials taken directly from production batches, great care is also needed to minimize errors by the use of systematic techniques for collection and storage of samples (Beeley, 1982)

Testing Requiring the Use of Standard Test Specimen

Mechanical properties and certain other characteristics are determined on specimens compacted to a bulk density similar to that encountered in a well rammed mould. Many tests utilize the 2 in x 2in cylindrical AFS specimen. Bulk density is closely related to green strength and mould hardness, values for silica sand mixtures ranging from $0.6 - 0.75 \times 10^3 \text{ kg/m}^3$ for unrammed sand to $1.6 - 1.7 \times 10^3 \text{ kg/m}^3$ after prolonged ramming under favourable conditions. Davies determined the influence of a number of major sand characteristics upon bulk density distribution, using an apparatus in which an elongated cylinder of sand is compacted by steady pressure exerted on a ram. The longitudinal bulk density gradient is determined by progressive dismantling of the sectional corebox and the weighing of successive segments of compacted sand. The slope of the bulk density gradient is inversely related to flowability and is found to vary considerably with grain shape, grading and other characteristics

The specimen is prepared by using a standard rammer and specimen tube. The AFS standard specimen is prepared by ramming a known weight of sand mixed with known weight of binder and

water with three blows by allowing a 14lb (6.35kg) weight to fall a distance of 2 in. The exact weight of sand necessary may be found by trial and error, or by using a density attachment. A standard specimen is 2-inch long by 2 inch diameter or 50mmx50mm standard. A stripping post (or pedestal) is used to remove the specimen from the tube, if the testing will not be conducted with the specimen inside the specimen tube. Green strength tests are carried out on newly made specimen, and dry strength tests on specimens baked at 105-110°C. Other specimens of selected shape and sizes are used in special tests e.g in tensile and transverse strength tests (Odetundun, 1993, Ihom and Anbua (2006)). The standard rammer is also used, in conjunction with suitable moulds and rammer head attachments, for the production of specially shaped specimens for the tensile and transverse testing of core sands.



Fig. 4.6 Standard Rammer, pouring hopper and specimen tube for standard Specimen Preparation

(Courtesy, NMDC)

Green and Dry Strength Tests

The principal strength tests measure stress to failure under a constant rate of loading. In the low green strength range, compression testing can be carried out on a simple, manually operated, spring loaded machine of the type shown in Figure 4.7, but most strength testing is carried out on universal machines such as that shown in Figure 4.8. In the machine illustrated, the load is applied by means of a pivoted weight, progressively brought to bear on the specimen as the motorized pusher arm climbs the calibrated rack. The machine is fitted with accessories enabling the lever ratio to be changed for selection of the appropriate strength range; alternative types of specimen holder enable any of the individual strength tests to be performed. For very high dry compression strengths hydraulic machines of higher capacity are usually employed.

Green strength tests are carried out on newly made specimens and dry strength tests on specimens baked at 105- 110°C. Coresand specimens are hardened in a standard manner appropriate to the practice for the particular bonding material.

The universal strength testing machine: is employed for compression, shear, and tensile tests. The cylindrical specimen is axially loaded in compression using flat faced holders' accessories.

In shear test: the compressive loading system is modified to provide or offset loading of the specimen

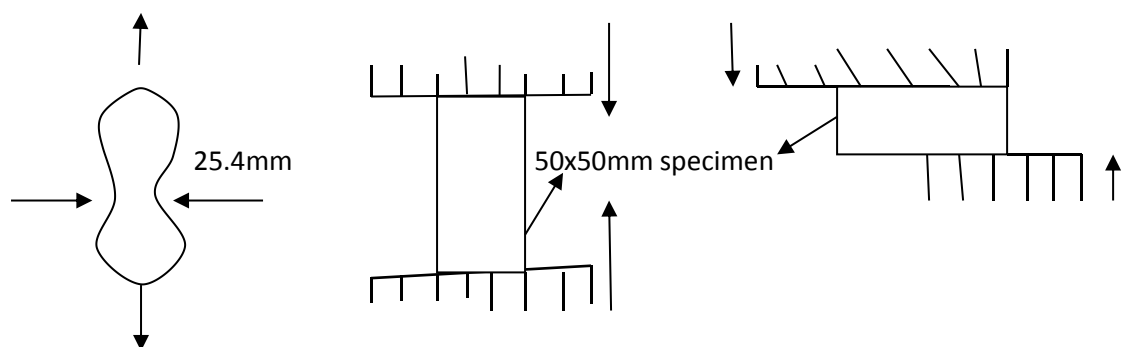
In tensile test: the compressive loading system is replaced with tensile accessories the specimen is then cause to fail in tension. Figure 4.9, illustrate the three tests.



Fig.4.7 Spring Loaded Green Compression Strength Testing Machine



Fig.4.8 Universal Sand Strength Testing Machine (Courtesy NMDC)



(a)

(b)

(c)

Fig.4.9: (a) Specimen failed in tension test (b). Specimen failed in compression test, (c). Specimen failed in shear test.

Compression Strength (CS)

This is obtained by applying a uniformly increasing load on a 2 by 2 inch (50mm x 50mm) sand specimen fixed between two compression heads designed to be self aligning on the universal strength testing machine. The point on the scale at which the specimen crush or squeeze is the compression strength. It is measured in pounds per square inch (lb/in² or Psi). Standardization of the rate of loading is particularly important in the green compression test, since creep of greensand occurs readily under constant load.

Shear Strength (SS)

It is obtained in much the same way as the CS using universal strength testing machine by changing holding devices, so that load is applied on the diametrically opposite halves of the two plane surface of the specimen (i.e. load is applied on the upper half of the specimen at one end and on the lower half at the other end). The point on the scale at which fracture occurs on the specimen is the shear strength of the sand. It is also measured in lb/in² or Psi. It is usually greater at or near a moisture content of best workability or correct temper. For a naturally bonded moulding sand this is 7% moisture (Tokan *et al.*, 2004). Under most conditions the results of shear tests have been shown to be closely related to those of compression tests, although the latter property increases proportionately more at high ramming densities.

Tensile Strength (T.S.)

A modified specimen tube for ramming is used. The special waisted specimen is loaded in tension through a pair of grips. The specimen is then failed using the universal strength testing machine with a special tensile strength accessory attached for holding the specimen. The specimen is specially prepared with a core sand and baked. The tensile specimen has a cross section of 1in² at its centre. The point at which the specimen breaks under tension is the tensile strength of the moulding sand (Dietert, 2000).

Transverse Strength

A plain rectangular specimen is supported on knife edges at the ends and centrally loaded to fracture (Figure 4.9). It is also measured with specially prepared specimen made of core sand, and baked. The specimen is 1in x 8in and is broken between two knife edges 6in apart when a bending load is applied. The specimen has a cross section of 1in x 1in. The point shown on the scale of the machine at which the specimen breaks is the transverse strength of the moulding sand (Dietert, 2000). Tensile and transverse tests are commonly applied to high strength coresands, the conditions being more relevant to the stresses incurred in cores during handling and casting. Both tests, unlike the compression test, provide values well within the working ranges of normal types of universal sand testing machine. Versions of these two tests have been evolved for the evaluation of shell moulding mixtures, being carried out on cured specimens approximating to the thickness of a production shell.

Little is to be gained from routine use of the whole range of strength tests, although each may be useful in individual circumstances. Studies of correlations between various strength properties are particularly valuable and can greatly reduce the volume of testing (Beeley, 1982, Ithom *et al.*, 2006).

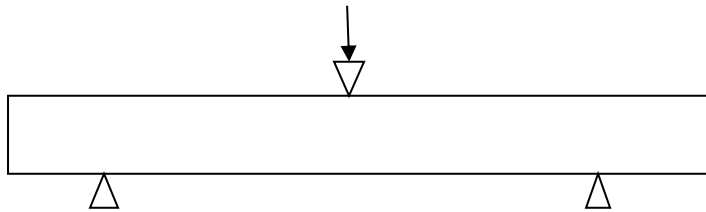


Fig. 4.9 Illustration of Transverse Test

Permeability

Permeability: this is determined by measuring the out flow of air through a compacted specimen under standard condition. The test for green permeability is carried out on AFS standard cylindrical specimen retained in its ramming tube. The permeability meter or electric permimeter is used for the test.



Fig.4.10 Manual and Electric permimeters

Permeability is that property of moulding sand which enables air or gas to escape through the sand it is measured by noting the rate of flow of air under a known pressure through a standard AFS specimen, while it is confined in the specimen tube mounted on the electric permimeter. The air passes into the specimen tube through a selected orifice. The permeability number is read directly on the calibrated scale of the machine. Two different orifices may be used, small (0.5mm) and large (1.5mm), the small one is for permeability lower than 50, while the large one is for permeability above 50. Two types of permeability meter are shown in Figure 4.10, the electric permimeter has just been described. In both cases the test for green permeability is carried out on the AFS standard cylindrical specimen, retained in its ramming tube. The manual type of permeability meter incorporates a graduated bell of 2 litres capacity containing a volume of air over water. A tube from the air enclosure communicates directly with the specimen tube, placed over a mercury seal, so that the air can escape through the specimen as the bell descends. The time for exhaustion of 2 litres of air is determined.

The permeability number P is defined as the volume of air in cm^3/min passing through a specimen of length 1cm and cross-sectional area 1 cm^2 , under a pressure difference of 1 cm water gauge:

$$P = Vh / atp \quad (4.2)$$

Where V = volume of air, cm^3

h = height of specimen, cm

a = c.s.a of specimen, cm^2

t= time, min

p= pressure difference, cm water

Using the standard apparatus and technique, the permeability may be derived directly from the formula

$$P = 3007.2/t \quad (4.3)$$

Where the time t is expressed in seconds.

A more rapid although less accurate measurement of permeability may be made using a modified technique. A standard orifice, of small cross-section in comparison with the porosity of the specimen, is placed between the pressure chamber and the specimen. The pressure between orifice and specimen now lies at a value intermediate between the chamber pressure and atmospheric pressure, depending on the permeability of the specimen. The value is derived directly from this pressure, measured by calibrated water manometer. Dry permeability determinations require a modified specimen holder using a mercury seal between the dried specimen and the walls of the holder.

Permeability is expressed as the volume of air in cubic centimeters that will pass per minute under a pressure of 1 gram per square centimeter through a specimen of sand 1 square centimeter in cross sectional area and 1 centimeter in height.

There are four recognized conditions of permeability

- (a) Based permeability is the permeability measured with a specimen of packed dry sharp sand.
- (b) Green permeability is the permeability measured with a specimen made of moist moulding sand.
- (c) Dry permeability is the permeability measured with a specimen made of moulding sand and dried at 220 to 230°F (99°C to 110°C)
- (d) Baked permeability is the permeability measured with a specimen made of sand with thermosetting binders and baked at some temperature above 230°F (above 110°C) (Tokan *et al.*, 2004, Nwajagu, 1994)

Flowability: of a moulding sand can be defined as its ability to be compacted effectively to a uniform density. Moulding aggregates do not in general possess a high standard of flowability, since the frictional and other forces which assist bonding are correspondingly opposed to freedom of movement of the grains: the property thus tends to bear an inverse relation to strength properties.

Flowability Test

No single method has been adopted for the measurement of flowability, but several tests have been developed and criticized (Beeley, 1982). They include methods based on compaction of the standard cylinder test specimen on extrusion of sand through an aperture in a tube under a standard load and on measurement of hardness differentials on the sloping base of a cylindrical core rammed in a modified tube mould. The property has also been related to the incidence of 'supervoids' in the surfaces of compacted specimens.



Fig.4.11 Flowability Tester

The simplest technique for deriving a numerical index is the Dietert method, based on the movement occurring between the fourth and fifth blows of the rammer head in the production of a standard compression test specimen. An arbitrary scale of values is assigned to this movement, with zero travel corresponding to maximum flowability: this assumes that compaction of a highly flowable material is fully accomplished by the earlier rammer blows. The most comprehensive data on flow properties can be derived from studies of the influence of ramming upon bulk density distribution.

Flowability indicator made by Ridsdale Dietert is suitable for controlling the flowability of moulding sands. Flowability is the property, which enables a sand to flow readily into a mould and fill up the interstices when subjected to ramming. It is influenced by moisture, permeability, grain shape, fineness and clay content. The indicator is a specially constructed dial gauge calibrated to read in percentage flowability, and may be readily attached to the sand rammer. The stem rests on top of the plunger shaft and the movement between the fourth and fifth drop of the weight is registered as flowability. The further the plunger descends, indicating incomplete flow the lower the percentage flowability. When the sand rammer is used for ramming test specimens, the indicator is rotated out of position (Dietert, 2000).

Deformation and toughness test

Deformation or plasticity of moulding sand is determined from decrease in length of the cylindrical specimen during the green compression test. The properties can be related to potential resistance of the moulds to hydrostatic pressure and to casting contraction. The product of deformation and green strength is used as an index of toughness.

$$\text{i.e sand toughness number} = d \times s \times 1000 \quad \dots \quad (4.4)$$

Where, d = deformation, in

s = green compression strength lbf/in²

Shatter test: the shatter index is a further measure of sand toughness that property which aids satisfactory lift during pattern withdrawal. The device is 6 feet tall, when the standard AFS specimen is allowed to fall from a height to a base where it is shattered. The fragments are collected in 0.5 in mesh sieve. The shatter index being that percentage or total weight retained on the sieve. A low value of the shatter index indicates the friability in pattern withdrawal in subsequent handling operations. Too high a value may indicate unsatisfactory moulding quality resulting from excess clay or water content.

The Shatter Index Test

Shatter index tester is the approved Ridsdale design for determining the “mouldability” of green sands. The shatter index test is a simple control test which has been standardized in the United Kingdom by the joint committee on sand testing (JCST). The Ridsdale tester conforms to the specification of this committee. The shatter index is a further measure of sand toughness, that property which aids satisfactory lift during pattern withdrawal.

A standard AFS or DIN green sand test specimen is ejected from a specimen tube and falls 6ft (1.83m) on to a steel anvil mounted in the centre of the 13.2mm mesh British standard Test sieve. Shatter index is defined as the percentage of the total weight of the fractured sand specimen, which remains on the test sieve. A low value indicates friability in pattern withdrawal and subsequent handling operations; too high a value may indicate unsatisfactory moulding qualities resulting from excessive clay or water content. Values of 50-85 have been quoted by Beeley as representing the mouldable range. This value, when correlated with the compression strength test gives a good indication of the

mouldability of sand, i.e. the kind of “lift” which can be obtained when a sand mould is removed from a pattern (Dietert, 1989).



Fig.4.12 Shatter Index tester

Mouldability Index Test

The property of a sand that determines the manner in which a sand will ram into a mould is termed “mouldability”. Mouldability index test is one which measures the amount of temper water required to produce a good moulding mixture, over and above the amount of water required by the components of the moulding mixture. A device known as mouldability tester is used for this test (Odetundun, 1993).

The procedure is to place a representative sample into the opening of the rotary screen, and brush the sample onto the screen. Set the timer on for 10 seconds and allow the rotary screen to riddle the sand for 10 seconds, a catch pan is used to collect the sand passing through the screen. The material that passed through the screen is weighed and divided by 2 to get the mouldability index. Some machines were designed to read mouldability index directly from the scale.



Fig. 4.13 Mouldability Index Tester

Moisture Content Determination

Ridsdale “speedy” moisture tester is a portable and self-contained unit, easy to use anywhere in the foundry for quick determination of moisture in core and moulding material. Two models of this tester have been specially developed for use in the foundry industry, namely model type “C2” measuring 0 – 10% moisture in 0.1% divisions and model “D2”, measuring 0 – 20% moisture in 0.2% divisions. The weighed sample of sand is shaken up with a measured quantity of “speedy” absorbent material (calcium carbide) in the sealed container. The principle being that acetylene gas is evolved in proportion to the amount of moisture in the sand. The gas pressure is

registered on the gauge which is calibrated in percentage moisture (Dietert, 1989). This makes use of the reaction



Other methods include the loss weight method, moisture is readily determined by loss in weight on drying at 110°C. Various rapid aids are employed, including balances directly calibrated to read the moisture content of a standard sample after drying; samples can be dried by the passage of hot air through a filter cloth tray. See Figure 4.14.



Fig. 4.14 Speedy Moisture Tester kit

Surface hardness test: the hardness of a rammed sand surface can be directly determined by indentation test. Surface hardness can be measured to check the ramming density of the actual mould.

Hardness Test for Cores.

Core hardness tester made by Ridsdale Dietert is used for controlling the surface hardness of cores produced by conventional and modern core processes. This is a new designed instrument with four – point penetrator for abrading the surface of the core and is easily operated. The depth of penetration is registered directly on a horizontally mounted gauge and represents numerically the hardness of the core. Hardness measures will indicate errors in the degree of bake or cure and variation in density over a core surface.

Impact Penetration Test

Ridsdale impact penetration tester BCIRA design is used for measuring the sub-surface strength of sand moulds and cores. This instrument was developed primarily for determining the safe stripping time for moulds and cores made from cold self-hardening sand mixture, but it has been found equally useful for measuring the sub-surface strength of CO₂ – silicate moulds and cores and surface dried green sand mould. The probe is readily detachable so that this instrument can be carried in the pocket in the special leather case supplied. The graduated probe is driven into the surface of the mould or core by means of a spring-loaded hammer inside the body of the instrument. The number of hammer blows of equal impact required to drive the probe a given distance into the material indicates the sub-surface strength. The spring load on the hammer is adjustable so that for a given setting it can readily be used as a routine acceptance test for production moulds and cores.

Indentation Mould Hardness Tester

The hardness of a rammed sand surface may be directly determined using an indentation tester. For the measurement of green hardness a spring loaded, spherical indenter is used, the depth of

penetration from the flat reference surface of the instrument corresponding to an empirical scale of hardness from 0- 100 units. Surface hardness can be measured to check the ramming density of actual moulds.

High Temperature Properties

High temperature tests are particularly relevant to foundry conditions, since they enable mould and core materials to be assessed under conditions similar to those existing during casting and cooling cycle (Odetundun, 1993). High temperature tests: they include the following tests

- Hot strength
- Hot deformation
- Collapsibility
- Expansion
- refractoriness

Hot Strength test

The standard hot strength test measures the compressive load required to fracture a $1\frac{1}{8}$ in diameter X 2in cylindrical specimen after a fixed period at the testing temperature. The furnace soaking time, usually 20 minutes is sufficient for considerable changes to occur in clay bonded sands. Due to sintering of the clay bond a marked strength peak is reached at a certain temperature, above which the strength falls again due to the presence of liquid between the sand grains to eliminate the effect of prolonged soaking, a modification was introduced by Parkes using dielectric heating of the specimen, enabling the test temperature to be attained uniformly, and rapidly for strength measurement after a very short time interval. The hot strength test can be modified by delaying application of the load until the specimen has cooled to give a measure of retained strength (Odetundun 1993).

Hot Deformation

Longitudinal deformation of the specimen during the hot strength test is measured, the total deformation to failure being used as the criterion. The hot deformation rate is also employed as an index of behavior at some fixed load below half that producing failure:

$$\text{Rate value} = \text{Deformation} / \text{Load} \times 10^3 \quad \dots\dots\dots (4.6)$$

Refractoriness Test

The standard method for refractoriness determination, using pyrometric cones, is irrelevant to most casting conditions, since unacceptable sintering is obtained well below the fusion temperature. A cone fusion test may, however, be used as a guide to the high temperature behavior of bonding clays. Refractoriness is the ability of the sand to resist fusion from the hot liquid metal. A standard cylindrical AFS rammed specimen is fired for about two hours at 1550°C. A refractory specimen retains its shape and shows slight expansion, whilst excessive sintering and fusion cause shrinkage and distortion, impurities such as metallic oxides, cause a lowering of the fusion point of some moulding sand, and result in sand fused with metal at the casting surface. This property is of greatest importance in the manufacture of high melting point alloys especially steel. Another method of measuring refractoriness described by Nwajagu, (1994) consist of measuring the temperature at which grains of moulding mixture starts to bake. For this purpose specimen from the moulding mixture is placed in a crucible, together with the specimen from the moulding mixture is placed in a crucible. The crucible, together with the specimen is placed in muffle furnace, which allows for gradual heating up to 1500°C.

The furnace is heated preliminary to 800°C and the mixture is tested up to the temperature of 1500°C, at 25°C interval. After each temperature is reached, the specimen is removed from the furnace and the degree of baking verified. The refractoriness of the mixture is taken as the lowest

temperature at which the grains start to bake. The high temperature muffle furnace of George Fisher type (+GF+) is quite convenient for such work. It is equipped with autotransformer, thermostat, and tube for placing the samples. This method is also described by Beeley, according to him the refractoriness of a compacted sand mass may be estimated by observing the appearance and dimensional changes of a standard cylindrical AFS rammed specimen fired for two hours at 1550°C. A refractory specimen retains its shape and shows slight expansion, whilst excessive sintering and fusion cause shrinkage and distortion.

Susceptibility to sintering has also been studied by means of a resistance heated curved platinum strip resting against the periphery of a cylindrical specimen. Significant differences in behavior were observed, but the test was never as widely adopted as the simple firing test (Beeley, 1982).

Collapseability

This is mostly applicable to core, collapseability is related to the speed and degree to which mould or core breaks down after it has served its purpose in shaping the metal. It determines the readiness with which the mould material will break down in knock out and cleaning operations. Chemical resistivity, conductivity, sand durability etc are also properties of sand, though their tests are not important in the determination of good foundry sand (Odetundun, 1993). The hot strength test is unsuitable for organically bonded coresands, since complete decomposition of the binder produces rapid collapse on loading. However, the time to failure under a fixed load can be determined as a measure of the decomposition rate for an organically bonded sand at a particular load and temperature. In a thesis work carried out by the author he observed that the best measure for collapseability is the ease with which the cores breakout during shake-out and cleaning, for good collapseability the shake-out time must be less than 45 seconds (Ihom, 2007).

Expansion

The total longitudinal expansion of the 1^{1/8} in diameter specimen is measured at the test temperature without the application of a significant load: for this test the specimen may be either free standing or confined within a fused silica tube. Expansion behavior is relevant to certain types of sand defect in castings.

Although the above tests can give valuable information on the comparative behavior of moulding materials, the heating conditions are not wholly representative of those met in production. In an actual mould only a thin layer of material attains a temperature approaching that of the casting, whilst the main body of sand remains relatively cool. High temperature properties can be determined under conditions more analogous to those in founding by using gradient heating of the specimen from a single hot surface, and a modification of the normal hot strength test has accordingly been developed. An account has also been given of the use of gradient heating in conjunction with a deformation- time test at constant load. The latter test is particularly relevant to contraction defects in castings, where the time parameter governs the magnitude of stresses developed (Beeley, 1982). In another thermal expansion test, the original length of the standard specimen is taken using measuring gauge before subjecting the specimens to various temperatures. At the end of which each specimen is removed from the furnace and gauged again. The thermal linear expansion is then calculated using thermal linear expansion formula (Musa, 2010).

Composition and Grading Tests

Composition test is carried out to know the chemical content or chemical constituents. Grading test uses mechanical sieve test and after a time, we plot the cumulative grading percent against B.S. Sieve number.

Chemical Analysis

Another very important property of sand is the chemical composition. This is to determine the components of the sand and the amount present. Chemical analysis cannot be over emphasized, since it helps to select a good sand for a particular casting. For example the specification of sand suitable for ferrous foundry work is different from non-ferrous foundry work and chemical analysis gives the clue as to which one is more suitable. It also helps in knowing the amount of additives to be added to sand.

Generally, chemical analysis will give an insight to whether the sand is high silica sand or other types of sand i.e. it is through chemical analysis one detect the type of sand used.

Hygroscopy

Hygroscopy is of interest for core mixtures in dry state. This property enables us to determine the possibility of retaining the cores in the factory store for a long time and also the possibility of placing the core in the mould long time before casting.

Hygroscopy depends on the type of the binder used. It is known that, cores prepared with molasses, dextrin, etc, are more hygroscopic in comparison with those prepared with linseed oil and others. Hygroscopy is determined by the increase in mass in percent of standard dry specimen, after it had stayed in a desiccator above water for 5 hours. The best core mixtures have hygroscopy of 0.1%. Hygroscopy of up to 0.5% is allowable (Nwajagu, 1994)

Gas Determination

Ridsdale gas determinator is used for the rapid measurement of the volume and rate of gas evolved from moulding materials. Services required are electricity, water, drain for cooling water and nitrogen for sweeping the tube free from oxygen. These supplies are connected to the base of the console, which can be operated conveniently on a standard metre high laboratory bench. Comprises special tube furnace with automatic temperature controller, 60mm diameter. Fused silica tube fitted with water – cooled metal closure and spring gun assembly and chart recorder, mounted in one console: complete with 5 charts and 12 copper sample cartridges.

This apparatus includes in one console all the equipment necessary for the determination of the gas content of foundry core sand and moulding materials.

The BCIRA designed special tube furnace, houses a 60mm diameter silica tube, closed hemispherically at one end. The open end is fitted with a water cooled metal closure and a spring gun for injecting thin walled copper cartridges into the hot zone of the furnace.

The furnace is capable of operating at temperatures up to 1100°C and is fitted with a Eurotherm temperature controller, a solid state unit allowing the furnace to be brought to the correct temperature without attention or danger of over heating.

Below the furnace and protected by a heat shield is mounted an Arkon model 63 pressure recorder (0 – 250mm water gauge) which accurately records the pressure rise in the tube due to the gas evolved from the sample. The pressure rise can be converted to gas volume (per gram of sample) by calibrating with known weight of pure potassium hydrogen carbonate (see Morgan and cooper BCIRA journal, 1966 vol. 14 pp 247-251). This calibration can be greatly simplified by using a microcomputer programme developed by the BCIRA (SEE BCIRA Report No. 1536).

This method of determining the gas evolved from moulding materials has a significant advantage over the direct volume method in that it enables the rate of evolution of the gas to be accurately determined. A further advantage is that results are recorded on a chart and hence they are independent of the human element and one person can readily operate the equipment. The standard electrical equipment is for operation on 220/240 volts, single phase, 50 cycle AC supply (Dietert, 1989).

Measurement of Sand Properties

(a) **Acid Demand Value**

Acid demand value is the number of ml 0.1MHCl required to neutralize the alkali content of 50g of sand (Brown, 1994).

The acid demand value is determined by:-

Weighing 50g dry sand into a 250ml beaker and adding 50ml of distilled water. Then add 50ml of standard 0.1M hydrochloric acid by pipette stir for 5 minutes and allow it to stand for 1 hour. Titrate with standard solution of 0.1M sodium hydroxide to pH values of 3,4,5,6 and 7. Then subtract the titration values from the original volume of HCl (50ml) to obtain the acid demand value.

Mechanical Grading

(b) **Calculation of Average Grain Size**

The adoption of the ISO metric sieves means that the old AFS grain fineness number can no longer be calculated (Brown, 1994). Instead, the average grain size, expressed as micrometer (μm) is now used. This is determined as follows:-

- (i) Weigh a 100g sample of dry sand
- (ii) Place the sample into the top sieve of ISO sieves on a vibrator, vibrate for 15 minutes.
- (iii) Remove the sieves and, beginning with the top sieve, weigh the quantity of sand remaining on each sieve.
- (iv) Calculate the percentage of the sample weight retained on each sieve, and arrange in a column as shown in Table 4.21.
- (v) Multiply the percentage retained by the appropriate multiplier and add the products.
- (vi) Divide by the total of the percentages retained to give the average size (see Table 4.21).

Table 4.21: Calculation of Average Grain Size

ISO Aperture (μm)	Percentage Retained	Multiplier	Product
≥ 710	Trace	1180	0
500	0.3	600	180
355	1.9	425	808
212	25.3	212	5364
180	16.7	212	3540
150	19.2	150	2880

125	10.6	150	1590
90	6.5	106	689
63	1.4	75	105
≤63	0.5	38	19
Total	99.6	-	20335

Average Grain Size = $20335/99.6 = 204\mu\text{m}$

(c) Calculation of AFS Grain Fineness Number

By definition, the AFS grain fineness number is the average grain size, and it corresponds to the sieve number whose opening would just pass all the sand grains, if all were of the same size. This number is a convenient means of describing the relative fineness of sand; most foundry sand being from about 240 to 220 microns in average fineness. Most sand properties, however, depend on the size distribution as well as average size. The fineness test makes possible the evaluation of both factors (Heine *et al.*, 1967, Brown, 1994, and Ihom and Olubajo, 2002).

Using either the old BS sieves or AFS sieves, 100g sample of dry sand is weighed and placed into the top sieve of ISO sieves on a vibrator to vibrate for 15 minutes. The quantity of sand remaining on each sieve is then weighed and the percentage retained is then calculated. The results are arranged as in Table 4.22. Each percentage weight is then multiplied by the preceding sieve mesh number and divided by the total of the percentage to give the AFS grain fineness number, (see Table 4.22).

Table 4.22: Calculation of AFS Grain Fineness Number

BBS Sieve Number.	% Sand Retained on Sieve.	Multiplied by Previous Sieve no.	Product
10	Nil	-	-
16	Nil	-	-
22	0.2	16	3.2
30	0.8	22	17.6
44	6.7	30	201.0
60	22.6	44	1104.4
100	48.3	60	2898.6
150	15.6	100	1560.0
200	1.8	150	270.0

Pan	4.0	200	800.0
Total	100.0	-	6854.2

AFS Grain Fineness Number = $6854.2/100$

= 68.5 or 68 AFS

Foundry sands usually fall into the range 150-400 μ m, with 250 μ m being the most commonly used. Direct conversion between average grain size and AFS grain fineness number is not possible, but an approximate relation is shown in Table 4.23, as given by Brown (1994).

While average grain size and AFS grain fineness number are useful parameters, choice of sand should be based on particle size distribution (Brown, 1994).

Table 4.23: Conversion Table for AFS Grain Fineness Number and Average Grain Size

AFS Grain Fineness Number	35	40	45	50	55	60	65	70	80	90
Average Grain Size (μ m)	390	340	300	280	240	220	210	195	170	150

Source: Brown, 1994

(d) **Determination of Particle Size Distribution of Sand**

This is the principal factor controlling permeability and surface fineness and has important influence upon strength and other properties. It controls the texture of the casting. Grading is based principally on the use of standard sieves to separate selected fractions for weighing. This sieve analysis can be performed on the sand in as, received state as well as washed state where the fines (clay and silts) have been removed. Sand grain particles range in size from 53 to 3360 microns. Silt particles range from 20 to 53 microns. Clay particles are less than 20 microns in size. The apparatus for the test include a stack of sieves with mesh numbers 14, 18, 25, 35, 45, 60, 80, 120, 170, 230, and – 230 (pan), shaker device, weigh balance, brushes (Hard and soft) and weighing pan. The procedure is to weigh 100g of the sand sample and place it on top of the top most sieve of the set of sieves already placed on the shaker device. It is shaken for 15 minutes at the end of which the weight of sand particles retained on each sieve is taken, weighed and recorded (Odetundun, 1993)



Fig. 4.15 Nest of Sieves mounted on a Sieve-Shaker and Digital Weighing Balance used for Weighing Retained Sand on Sieves

Testing Chemically Bonded Self-Hardening Sands

Units

Compression strength values may be reported in:

SI Units kPa = kN/m²

Cgs Units = Kgf/cm²

Imperial Units Psi = lbf/in²

Conversion Factors

100kPa (kN/m²) = 1.019Kgf/cm²
= 14.5038Psi (lbf/in²)

1Kgf/cm² = 98.0665kPa
= 14.22Psi (lbf/in²)

1Psi (lbf/in²) = 6.895kPa (kN/m²)
= 0.07032Kgf/cm²

The curing properties (work time, strip time and maximum strength) are measured by composition test using 50mm diameter specimen tubes with end cups, or AFS 2 inches diameter tubes, with a standard rammer. Sand is mixed in a food mixer or small core sand mixer, catalyst being added first and mixed, then the resin is added and mixed (Brown, 1994). Figure 4.16 shows a core mixer.



Fig.4.16 Core Sand Mixer

Measurement of ``Work Time'' or ``Bench Life''

According to Brown (1994), the measurement of work time can be done by mixing the sand as above, when mixing is complete, start a stop watch and discharge the sand into a plastic bucket and seal the lid. After 5 minutes, prepare a standard composition test piece and immediately measure the compressive strength. After further 5 minutes intervals, again determine the compressive strength, stirring the mixed sand in the bucket before sampling it. Plot a graph of time versus strength and record the time at which the compressive strength reaches 10kPa (0.1kgf/cm², 1.5Psi); this is the work time or bench life (Brown, 1994). The Sand temperature should be recorded. For fast setting mixtures, the strength should be measured at shorter intervals, say every 1 or 2 minutes (Morgan, 1973, and Brown, 1994).

Measurement of Strip Time

According to Morgan (1973), measurement of strip time is carried out by preparing the sand mixture, when mixing is complete, start a stopwatch, prepare 6-10 compression test pieces within 5 minutes of completion of mixing the sand. Each specimen is then covered with a waxed paper cup to prevent drying. The compression strength of each specimen is then determined at suitable intervals, say every 5 minutes, and a plot of strength against time is made, the time at which the strength reaches 350kPa (3.6kgf/cm², 50Psi) is recorded as the ``strip time''. The sand temperature should also be recorded.

Measurement of Maximum Strength

According to Brown (1994), the mixtures are first prepared by mixing them. The time of completion of mixing is recorded. 6-10 specimens are quickly prepared and covered with a waxed cup, and the strength determined at suitable intervals say 1, 2, 4, 6, 12 and 24 hours. Plot the results on a graph and read the maximum strength. The sand temperature should be held constant if possible during the test.

Curing Temperature

According to Brown (1994), the optimum curing temperature for most binder system is 20-25°C, but temperatures of 15-30°C are usually workable. Low temperature retard the curing reaction and cause stripping problems, particularly if metal pattern equipment is used. High sand temperatures

cause reduction of work time and poor sand flowability and also increase the problem of fumes from the mixed sand. If sand temperatures regularly fall below 15°C, the use of a sand heater should be considered (Brown, 1994).

Results of the Determination of Curing Characteristics

Tables 4.24-30 shows the curing characteristics of manihot esculenta-cement, manihot esculenta-ammonium nitrate and UFFA-BSA binder systems. The experiments were conducted by the author and the results were used in plotting graphs which were used in determining the bench life, the striping time and the maximum strength. See example in Figure 4.24. Ammonium nitrate was never really a good catalyst for self curing. The samples remained in wet condition without drying, making the samples weak. The samples could only develop strength on heating or baking.

Table 4.24: Bench Life of UFFA-BSA with Washed Rukuba Stream Sand

Time (Minute)	Compression Strength, kPa
9	11.72
12	55.85
13	47.58
14	27.58
16	27.24
19	Finally Set

Source : Ihom, 2007

Resin = 2.7, Catalyst = 60% of Resin

Temperature of Sand = 25°C

Zero Time = 10.41am

Temperature after Mixing = 27°C

Table 4.25: Strip Time of UFFA – BSA Using Rukuba Stream Sand

Time (Minutes)	Compression Strength, kPa
10	20.00

15	565.39
20	644.68
25	406.81
30	575.73
35	120.66

Source : Ihom, 2007

Sand Temperature = 26⁰C

Zero Time = 11.26am

Temperature after Mixing = 30⁰C

Table 4.26: Maximum Strength of UFFA – BSA Using Rukuba Stream Sand

Time (Hrs)	Compression Strength, kPa
1	2000
2.16	4000
3.06	475
22.49	180
23.57	168.93
24.57	588.14
25.57	2999.34

Source : Ihom, 2007

Sand Temperature = 28⁰C

Zero Time = 12.23pm

Temperature after Mixing = 30⁰C

Table 4.27: Bench Life and Strip Time of UFFA – BSA Using River Benue Sand (SP₁)

Time (Minutes)	Compression Strength, kPa
4	7.93
5	23.44
6	50.33
7	620.55
9	630.20
12	320.62
14	289.59

Source: Ihom, 2007

Sand Temperature = 24.5°C

Zero Time = 9.41am

Temperature after Mixing = 25°C

Table 4.28: Maximum Strength of UFFA – BSA Using River Benue Sand (SP₁)

Time (Minutes)	Compression Strength, kPa
8	4400
22	120.00
27	850.00
	169

32	20.00
35	50.00
38	30.00
41	900.00

Source : Ihom, 2007

Sand Temperature = 26°C

Zero Time = 1.45pm

Temperature after Mixing = 32°C

Table 4.29: Manihot Esculenta Resin with River Benue Sand (SP₂)

Time (Minutes)	Compression Strength, kPa
7	13.10
12	11.72
17	11.03
22	11.72
27	12.41
32	11.03
321	137.90

Source : Ihom, 2007

Catalyst used – Ammonium Nitrate

Resin = 3%

Catalyst = 0.2% (Based on Sand)

Temperature of Sand before Mixing = 22°C

Temperature of Sand after Mixing = 23°C

Zero Time = 10.27am

Amount for Standard Specimen = 160g

Table 4.30: Curing Characteristics of Manihot Esculenta Resin Using Cement as the Hardener or Catalyst, and River Bank Sand (SP₄)

Time, (Hrs)	Compression Strength, kPa
0.02	18.62
0.17	18.27
0.25	20.69
0.33	20.69
2.57	158.59
3.57	137.90
4.57	179.27
5.57	237.88
24.17	615.72
25.17	568.84
26.17	4200

Source : Ihom, 2007

Amount for Standard Specimen = 168g

Cement = 1%

Water = 2%

Resin = 5%

Temperature of Sand before Mixing = 19°C

Temperature of Sand after Mixing = 20°C

Zero Time = 10.26am

Visual and Microscopic Observation

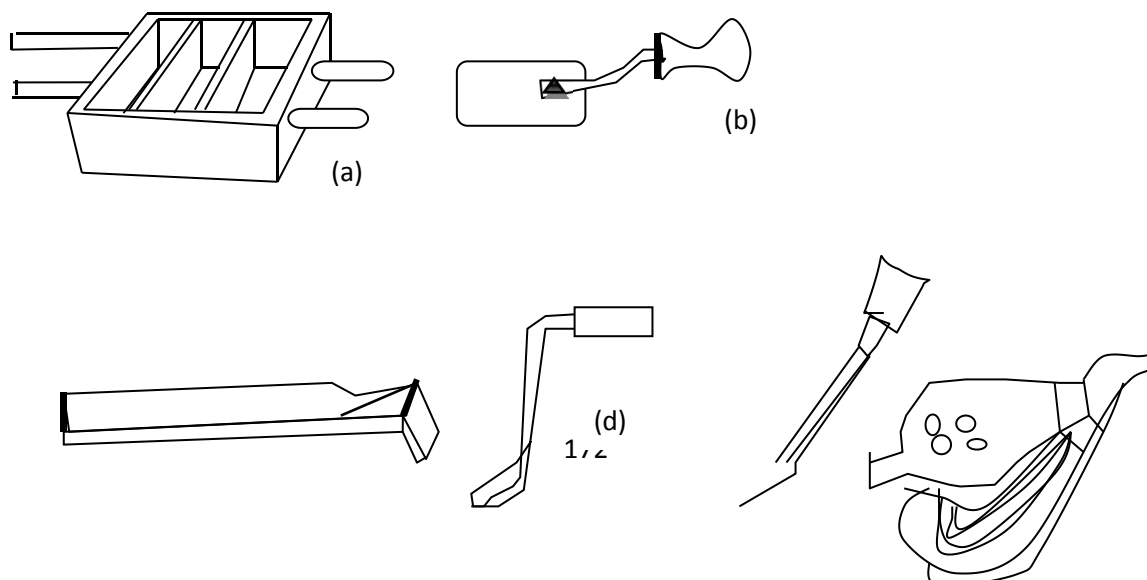
Here the colour and shape of the sand can be observed. Some inferences can be drawn from the colour and the shape of a sand. Sand can be whitish, brownish, reddish, grayish etc. The tests are carried out with eyes or by lens and aided by microscopes (for shape). The shapes can be round, angular, sub-angular or compound. The significance of these observations is that the shape of the sand determined the strength of the mould. Magnifying lens and microscope are also used for viewing defects in castings (Odetundun, 1993).

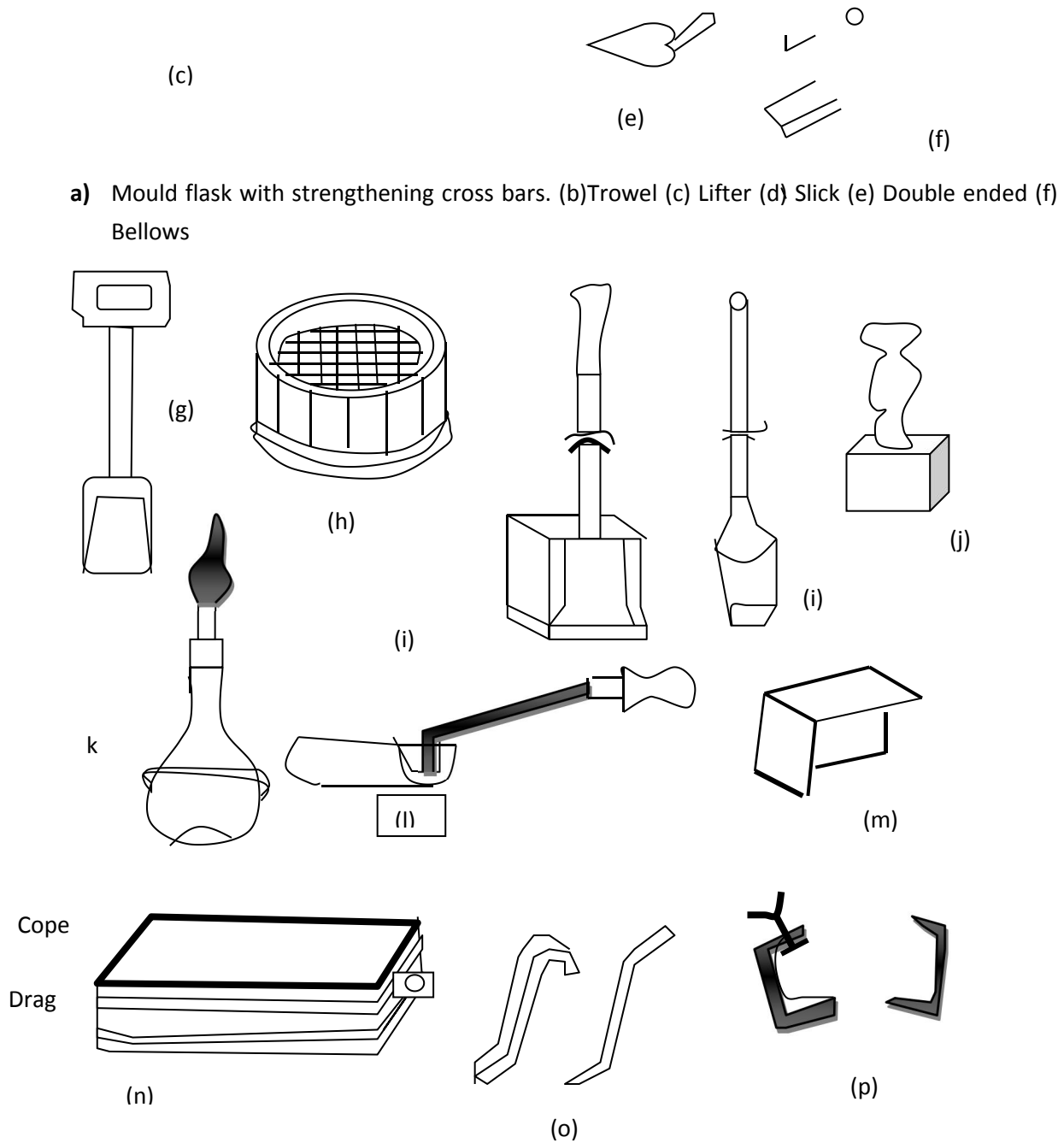
Determination of AFS Clay Content

A 50 gram sample of dried sand is placed in a wash beaker, and washed with a solution of 475ml of distilled water and 25ml of 3% sodium hydroxide solution for five minutes with the aid of a mechanical stirrer in the washing machine. A little water is used to wash into the beaker, the sand particles that sticks to the stirrer. It is allowed to settle for 10 minutes and then the suspension formed as a result of clay is siphoned off. Fresh water is added, allowed to stand for 5 minutes, and again the water, on top is siphoned off. This continues at 5 minutes interval until the water is clear. The sand that remains is dried in the oven at 110°C until it is dried, it is removed and weighed. The difference between the initial weight and the final weight is then multiplied by 2, which gives the AFS clay percentage in the sand. Details on sand testing procedures can be gotten from the book titled "Foundry Raw Materials for sand Casting and Testing Procedures" by Ihom (2012).

Tools and Equipment for Moulding

Small or medium-sized castings are made in flask-a box shaped container without top and bottom which confines the sand moulds. Fig.4.17 shows equipment for moulding.





(g) Shovel (h) Riddle (i) Floor rammers (j) Bench rammer (k) Swab (l) Gate cutter (m) Inside square corner smoother. (n) Box Flask (o) Gagers for reinforcement in moulding boxes (p) Clamps for moulding boxes.

Fig.4.17 Tools and Equipment for Moulding

It is made in two parts, held in alignment by dowel pins. The top part is called the cope and the lower is called the drag. If the flask is made in three parts, the centre one is called cheek. Metal flasks of steel or, cast iron are usually used in production work because of their rigidity and permanence.

A snap flask is a small flask with a hinge on one corner and a snap catch on the other. With its use, moulds can be made repeatedly using the same flask. A moulding board and a bottom board complete the flask. The moulding board is a smooth board on which the flask and patterns are placed when the moulding is started. When the mould is turned over, the function of this board is over. The mould is placed on a similar board called bottom board, which acts as a support for the mould until metal is poured in the mould.

Before any metal is poured into a mould, it is necessary that the flask be clamped in some way to prevent the buoyant effect of the molten metal from lifting up the cope. Small moulds are usually held down by cast iron weights, placed on the top of the moulds. Larger flasks are usually held together by clamps, placed on the side or ends-either U-shaped clamps, held tight by driving wooden wedges under the end, or clamps that can be quickly adjusted to fit the height of the flask.

A gagger is a small L-shaped metallic accessory used in floor moulds to help support hanging bodies of sand in core. It is used only in large moulds having having cross bars. The gagger is first coated with a clay wash and then placed next to one of the cross bars. The lower end should be close to the pattern, and the upper end should extend to the top of mould. The various other tools used are: showel, riddle, rammers, bellows (compressed air), trowel, slick lifter, swab, draw spike or screw, vent wire, gate cutter.

Showel: is used for mixing and tempering moulding sand and for moving the sand from pile to flask.

Riddle or Sieve or Screen: is used to remove bits of metal and foreign particles from the moulding sand. The size of the opening in the mesh indicates the size of the riddle.

Rammers: are used to pack the sand evenly in the mould and for ramming into corners. The hand rammer is made of wood and resembles a handleless mallet with one end flat and the other a blunt wedge. Metal rod with one end round to rectangular shape can also be used as a rammer.

Trowels: are used to shape and smoothen the surface of the mould and for doing minor repairs. These are made of steel and are relatively long and narrow. The end of a trowel may be pointed, round or blunt.

Slicks: are spoon shaped trowels used for repair or slicking (smoothing) a mould surface. They may be leaf shaped but are generally pointed.

Lifters: are long, narrow tools with hooked ends used for finishing work in tight places, doing repair work, or removing loose sand which has fallen to the bottom of the mould.

Draw spikes: are used to remove the pattern from the mould and also for rapping the pattern gently to loosen it from the sand to assure a clean draw.

Swab: it is made of flax or hemp and is used for applying water to the mould around the edge of the pattern. This prevents the sand edges from crumbling when the pattern is removed from the mould.

Rawhide Mallet: it is used to loosen the pattern in the middle so that it can be withdrawn without damage to the mould. A rawhide mallet will not mar or deface the pattern as a metal mallet would.

Gate Cutter: it is a piece of sheet metal used to cut the opening that connects the sprue with the mould cavity. This opening is called 'gate'.

Clamps: these are used to hold the cope and drag of the completed mould together so that the cope may not float or rise when the metal is poured into the mould.

Types of moulding

A large proportion of castings, including the vast majority of those made by machine moulding, are cast in greensand moulds. There is a strong economic incentive to enlarge this proportion still further and greensand castings of several tonnes in weight are no longer uncommon. In some cases, however, there are still compelling technical reasons for drying or hardening the mould.

1. Green sand moulding: this is when the mould is filled with molten metal while the mould is still moist due to the presence of water the mould lacks permeability and strength and this may result in blow holes and pin holes in the casting. The characteristics include:

- The drying operation, with its attendant investment in stoves, running costs and loss of production time, is eliminated
- The rapid turn round of moulding boxes and the smooth moulding and casting cycle are advantageous in mechanized systems
- The sand is readily reconditioned since there is little dehydration of the clay bond
- Greensands, having low compression strength, offer little resistance to attraction, so that the risk of hot tearing is reduced
- Moulds joint closely, leaving little 'flash' for removal by fettling.

Table 4.31 shows the composition of green sand for various purposes.

Table 4.31 Typical Sand Mixtures of Green-Sand Moulds

Purpose	Composition of Green Sand				
	Parts of floor sand	Parts of new dust	Parts of coal sand	Parts of carbon blacking	Parts of talc (French chalk)
Light work	6	1	$\frac{1}{2}$	-	-
General work	8	4	$1\frac{1}{2}$	-	-
Smooth finish	10	4	$1\frac{1}{3}$	$1\frac{1}{2}$	$\frac{1}{2}$

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2. Dry sand moulding: is used when the mould requires greater strength to withstand the weight of a large weight of metal or if a hard surface is required to avoid surface erosion. The mould is prepared with a specially prepared sand and dried in an oven. The water content in the dry sand mix is kept high about 6-8% so that green properties are satisfactory after the mould is ready then its surface is spread with molasses water and the mould is dried in an oven and maintained at about 200-300°C until all the moisture content is eliminated. Dry sand mouldings are more rigid, shrinkage proof and strong. However, the higher cost involved, limits its application to large casting. Characteristics include:

- Drysand moulds offer maximum resistance to distortion under metallostatic pressure and to mould erosion during prolonged pouring. They are therefore suitable for castings of the largest dimensions and can give a high standard of accuracy. In the production of grey cast iron mould rigidity contributes to internal soundness as well as to dimensional accuracy. (greater stability of greensand moulds can nevertheless be achieved by high pressure moulding: the difference between the types of practice is then reduced.)
- The veining problem is reduced in the absence of steam generated from free moisture
- Impervious mould surfaces are readily attainable since sands of lower permeability may be used and thick mould coatings can be satisfactorily dried out
- Moisture control is less critical than in greensand practice, where minor deviations are liable to produce either surface friability or gas defects. At the higher moisture levels used in drysand practice, some moisture may be evaporated on standing without loss of moulding properties.
- Surface chilling is much reduced, facilitating metal flow in thin sections
- Moulds can be allowed to stand for some time before casting without the dangers of drying out and surface friability such as are encountered in greensand practice.

3. Loam moulding: is applied to large castings e.g 100 tons of liquid steel. This is a method of moulding for large size castings where regular moulding in flasks will be too expensive and inconvenient. The loam sand mould is constructed of porous bricks cemented together with loam mortar- a moisture of equal amount of sand and clay (50/50) weighted to the consistence of manual. The inside of the bricks structure forms the rough contour of casting and is faced with a 6-12mm layer of loam sand. It is then swept by strickle to get the required shape eliminating the use of regular pattern.

4. Skin dried mould: only the surface is dried using gas torch and other drying techniques it is intermediate between greensand and full dry sand

Mould Drying

Full mould drying is usually accomplished in stoves operating in the temperature range 200-400°C. Some moulds are, however, only surface dried, the practice being intermediate between green sand and full dry sand. Surface drying can be carried out by gas torch or by using hot air drying hoods or blowers fired with coke, oil or gas: surface hardening can be assisted by prior treatment with sprays

of water or dilute binder solutions. Limited surface drying can, alternatively, be achieved with the aid of inflammable mould coatings.

A further modern compromise between green sand and dry sand practice is the use of the CO₂-Sodium silicate process for mould hardening; in this case strengths equivalent to those of dry sand moulds can be achieved without the need for stoving. Sands based on self-setting organic binders such as the furan resins can be similarly employed for moulds. These techniques extend the effective range of greensand practice without the more complex and costly production cycle involved in full drying.

Sand Moulding Process

The pattern is made of metal or wood. preparation of the sand is done by adding a specific amount of clay and water to obtain a good green strength. The mould box is then placed on a flat surface the pattern is placed in side the box. The prepared mould mixture is packed round the pattern and rammed. The mould box is usually in two halves a cope and a drag. The cope is the upper part while the drag is the lower part. After the moulding process the patterns are removed and the cope and drag are assembled together. If the casting has a hole a separate moulding known as a core is made and placed in the mould box before assembly. Provision is made for feeding of the casting by forming or creating a gating system during the moulding process. To facilitate pouring an enlarged opening called the pouring cup or basin is made channels are cut to allow metal to flow out of the metal cavity thus maintaining a metallostatic head during solidification. The channels are known as risers. The metal is run from the pouring cup down a gate or sprue through runners or cross gates and into the mould cavity through in-gates.

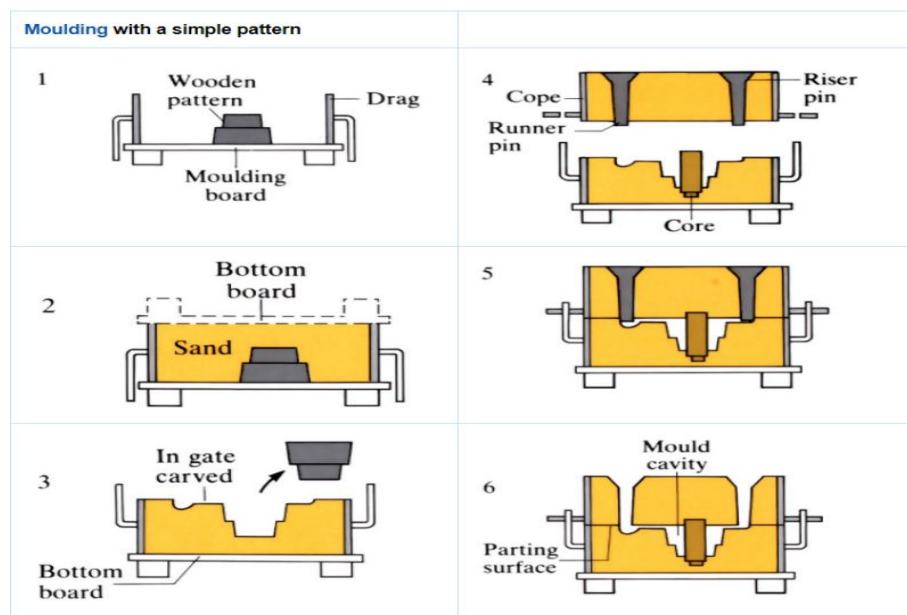


Fig.4.18 illustrates moulding process with a simple pattern

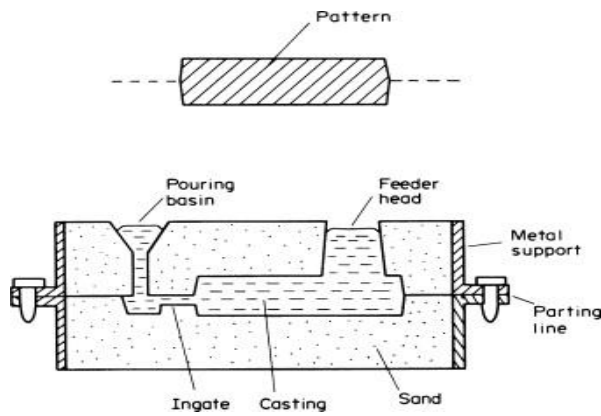


Fig. 4.19 A Poured Moulding Box



Fig. 4.20 Patterns used for making some Automotive Parts

Sand Moulding Methods

1. Bench moulding: Bench moulding is carried out on a convenient bench and the moulds prepared are relatively small. By bench moulding, green sand, dry sand or skin-dry sand moulds can be made. In this, hand ramming with loose patterns is employed and as such it is a slow and laborious method.

Methods of bench moulding: various methods of bench moulding are described below:

- (i) **Two box moulding:** it uses the moulding box made in two parts (upper is called cope and lower one drag). Two parts are fitted with a suitable clamping and locating device. Clamping prevents the cope from lifting due to the pressure of the molten metal while pouring. Locating device enables the two parts to maintain proper alignment at all times. In this method, the drag and pattern are placed on the moulding board and the sand is rammed in drag. The drag is then rolled over the board. The other part of the pattern is fitted over bottom one, and cope is placed over the drag. Sprue-pin and riser pin are placed in position, and sand filled in the cope and rammed. Mould is vented, sprue and riser pins removed. Mould is then parted off, pattern withdrawn, mould cavity cleaned and gate cut in the drag. Core is placed in position and reassembled and clamped to make the mould ready for pouring. See Fig. 4.18 above.
- (ii) **Three-box moulding:** When the pattern is of flanged type, two box moulding becomes inconvenient. To facilitate moulding work in such cases, three boxes are used (middle

box being called 'cheek'). During pouring of metal, all the three boxes are clamped properly. Fig.4.21 shows the various steps involved.

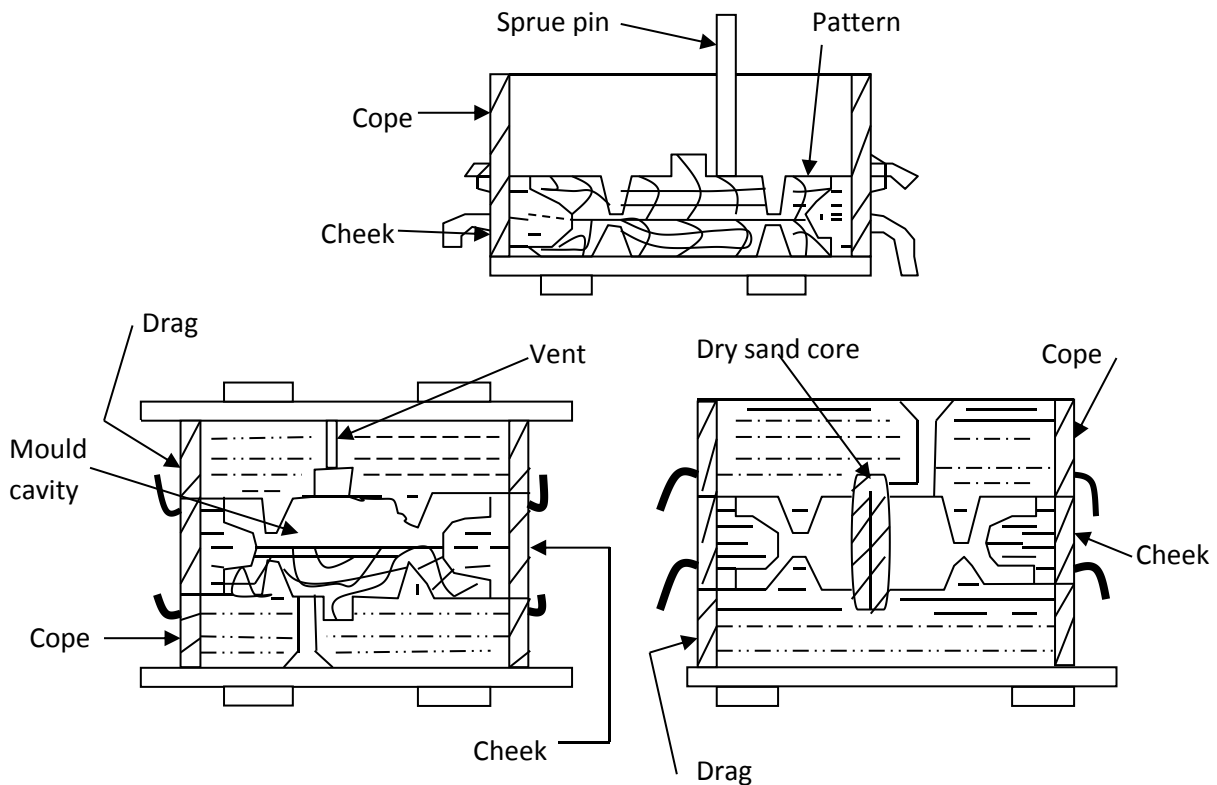


Fig.4.21 Three box moulding procedure

- (iii) **Stacked moulding:** When a large number of small size castings are required, each having one flat surface, this method can be used. Both sides of one half of the mould can be made use of by stacking them as shown in Fig.4.22. There will be a common passage for the molten metal running through the stock of the intermediate boxes. A number of parts can thus be cast in a single pouring operation.

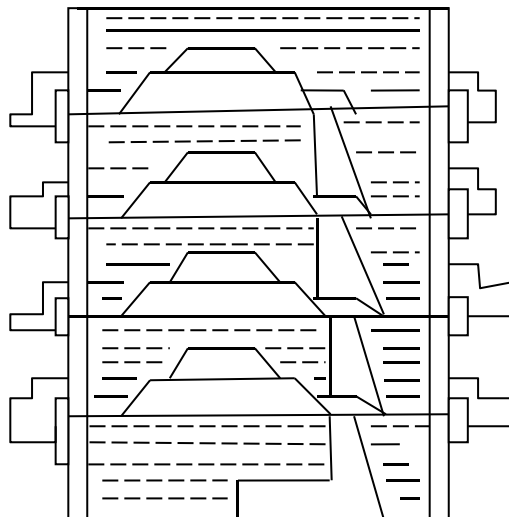


Fig.4.22 Stacked moulding

2. Floor moulding: In this method the moulding of medium and large moulds is directly carried out on the floor. Green sand, dry sand, or skin-dry moulds can be made by this method on the floor with the proper flasks. It is also a slow and laborious method as it requires ramming with loose patterns.

The floor moulding is generally carried out using two part boxes (top and bottom, known as cope and drag). These boxes consist of two stout frames with pins and holes to ensure accurate location. The ground surface is first levelled and half part of pattern placed over it and then box frame is placed around the pattern. Box is packed with sand, and sand is rammed and leveled off. The packed box is then turned over and second box placed on top, ensuring correct location by inserting dowel pins into the holes inside the lugs on the boxes. The other half of pattern is placed over earlier half and sand is filled and rammed in top box and leveled off. Two boxes are then opened and pattern is removed. If any repair is required, same is carried out and gates for pouring metal made. If cores have to be located to form holes, these are placed in position. Boxes are again put back into position and usually clamped to prevent the upper box floating on the liquid metal

4. **Plate Moulding:** the patterns in case of floor moulding are usually constructed of wood and are split on an appropriate horizontal parting-line. The two portions of the pattern have to be located together with dowels. However, in plate moulding, the pattern consists of a flat plate usually of metal instead of wood for long life, with portions of the pattern permanently assembled in alignment on each side. For very large quantity production, and for very heavy castings, two plates may occasionally be used-one to assist in the making of copes, the other for drags. The plate incorporates some locating arrangement for the moulding boxes, which could be pegs in the plate, but more usually consists of holes for locating pegs. The use of a plate normally calls for moulding boxes which incorporate lugs having holes for location. Fig.4.23 shows a typical double-sided plate used for hand or machine moulding, and shows how provision is made for six castings from one pouring. The plate includes runners, gates, part of pourer and part of riser, thus reducing considerably the time to finish the mould after the extraction of the pattern equipment. This method is usually used for large quantity production. The use of a particular plate is restricted to a certain range of moulding boxes.

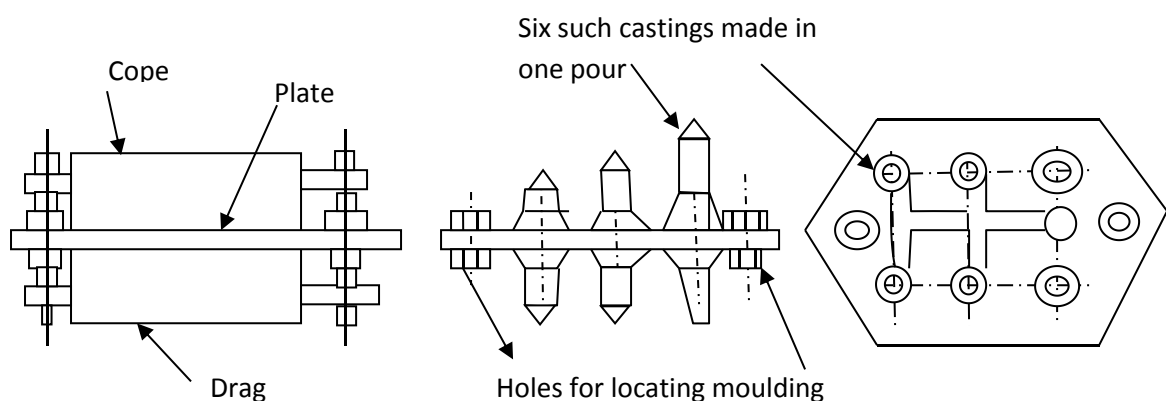


Fig.4.23 Plate moulding

4. **Pit-moulding:** In this method, the moulding is carried out in the pits and generally very large moulds are made, the pit serving the purpose of flask. Generally green sand is used in pit moulding but cement bonded sand sections may also be used. For large moulds, this is the only method of moulding and is quite slow and laborious.

5. **Machine moulding:** a variety of machines are used in this method for carrying out the moulding of small, medium and large moulds. This method is faster and gives uniform mouldings, but requires mounted patterns. By this method also, green-sand, dry-sand and skin-dry moulds can be prepared.

Sand Casting Advantage

1. it has a great flexibility as a process
2. it is simple
3. it is economical
4. it can be used to provide a wide variety of size from a low grain of several tons, there is little wastage of material as the sand can be reconditioned.

Disadvantage

1. sand casting can not be employed for thin sections
2. the dimensional accuracy and surface finish is poor
3. erosion of the mould face by the molten metal causes a lot of problems

Core and Core Making

According to Jain (2009) a core is a pre-determined shaped mass of dry sand which is made separately from mould. It is positioned in a mould to obtain a shape in the casting which can't be readily obtained by the mould proper. Core box pattern equipment, baking equipment and handling facilities are required for making of cores. Core can be eliminated when of small size, particularly, if the hole can be machined. Cores should be of sufficient thickness and free of fragile or overhanging projections which might be easily broken during the necessary handling and transportation involved in production.

A core is used for the following purposes:

- i. To obtain the desired cavities and recesses which otherwise could not be obtained by normal moulding operation.
- ii. In pit moulding, the entire mould is made of cores.
- iii. Sometimes the cores are also used to reduce metal erosion in gates and runners (splash cores),
- iv. to retard foreign matter in the melt(strainer cores),
- v. provide a cup or basin on the top of mould (pouring basin cores)

Core may be defined as that portion of the mould which form the hollow interior of the casting or a hole through the casting. The word core means the mass of dry sand that is prepared separately by baking in the oven and then placed in the mould. The main material of the core is refractory, either a natural or a synthetic sand. The sand-mix used for core making consists of the sand together with a binder which is used to give strength after baking. A natural binder (sometimes called core-gum) is linseed oil. A synthetic binder is a synthetic resin. A recent development is to mix sand with sodium

silicate solution so that the grains are coated and obtain the necessary hardness by 'gassing' with carbon dioxide, causing the sodium silicate to bond the grains together and produce strong core, thus eliminating the baking process.

Characteristics of Cores and Core Sands

1. Core must have sufficient hardness as well as strength in both dry and green state.
2. Core must be permeable to allow the core gases to escape easily.
3. Core should be able to withstand the high temperature of molten metals.
4. Cores when prepared should be collapsible i.e. they should disintegrate and collapse after the metal solidifies if the core does not collapse difficulties may be experienced in removing it from the casting.
5. Core should produce minimum amount of gas when in contact with molten metal.

Core Binder

Since pure sand used for preparing core has no natural bond, binder is used. A core binder is an agent added to sand to produce a good 'green' bond and also hardness after baking. A typical natural binder is linseed oil, a typical synthetic binder is a resin of the thermosetting type.

Generally core oils (composed of 50 to 60% linseed oil, 25% resin and balance mineral oil) are used as they are very economical to produce better cores. In the case of thermoplastic binders (resin and pitch), the powdered binder is mixed with core sand, and on heating the binder liquefies and coats the sand grains. On cooling the dispersed liquid binds the sand grains together to form a united mass. Use of synthetic resins is limited as they are costly. Addition of resin to core oil speeds up drying of core and reduces the volume of core gas. Pitch compounded with dextrin and steam coal is used for large cores.

Phenol and urea formaldehyde thermosetting plastic core binders are becoming common due to their high strength, low gas formation, collapsibility and resistance to moisture absorption.

Molasses adds hardness to the core but lacks in strength. On the core, molasses water may also be sprayed. Protein binders (gelatin, glue, casein etc) are used where collapsibility is the main criterion

Reinforcement of Cores

Excepting very small cores, these are internally reinforced with core wires or grids to help cores retain their shape while damp, for transportation and for strengthening purposes.

Types of Cores

Cores are generally made of green sand or dry sand. The green sand cores have relatively low strength being made of green sand, whereas dry sand cores are made of sand and special binders which develop strength when baked. These could also be classified according to their position or use, according to which these can be of horizontal, vertical, balanced, drop and other types. These four types will be clear from Fig.4.24. Horizontal and vertical cores are used more frequently than other types. In the case of balanced core, the core print should be sufficiently large to support the weight of core which extends into mould cavity from one side only. It should be able to withstand the force of buoyancy of the molten metal surrounding it.

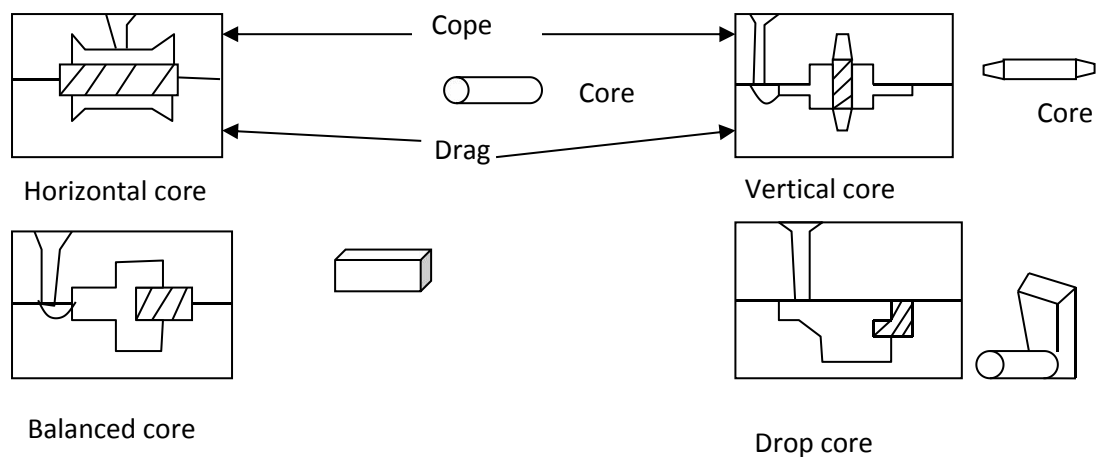


Fig.4.24 Types of Cores

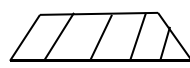
Making of Core

Different types of cores can be made using core boxes. Cores are made separately in a core box made of wood or metal. The various steps in core making are ramming of core sand in the box, venting, reinforcing, removing of core from box, baking, pasting, sizing etc. This work of producing cores can either be done by hand or by some machines designed for this purpose. In machine moulding, the core sand mixture is rammed by jolting, squeezing or blowing by means of suitable machine. Venting, reinforcing and other operations are carried out by hand. Cores of symmetrical cross-section can be produced by extruding core sand mixture through a suitable die opening. The cores by extrusion process are made in lengths and cut to shorter length as needed.

Cores are generally made by core blowing machine for production work, in which the core sand is placed in small hopper over the clamped core box and blown under a pressure of 5 to 8 kgf/cm². The core boxes are of special construction to provide for escapement of air. It requires special drying equipment. Even complex cores can be produced in a few seconds by core blowing method. Core boxes used for core-making are designed in several types which aid in core removal. The most commonly used are of split, rollover and hooked type.

Core Boxes

It can be as simple as possible and can also be complex requiring precision metal assembly capable of long life and under exacting conditions supposing the core of interest are as shown below



(a)



(b)

The core boxes will be as shown below

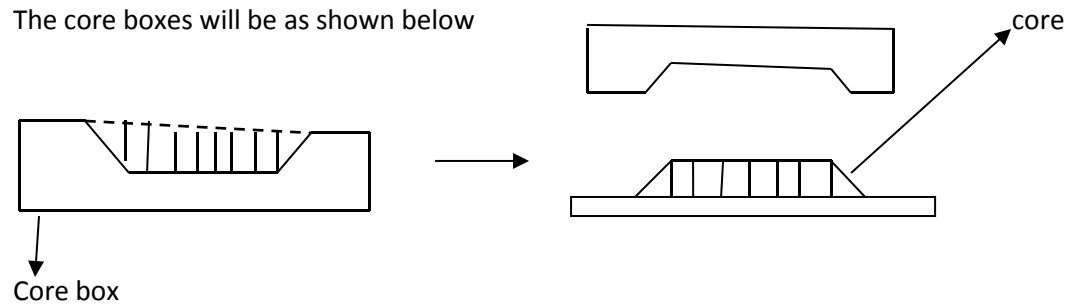


Fig. 4.25 Description of the moulding process for core (a)

For shape (b) the box can be rammed as shown in Figure 4.25b and the core fired to a desirable temperature.

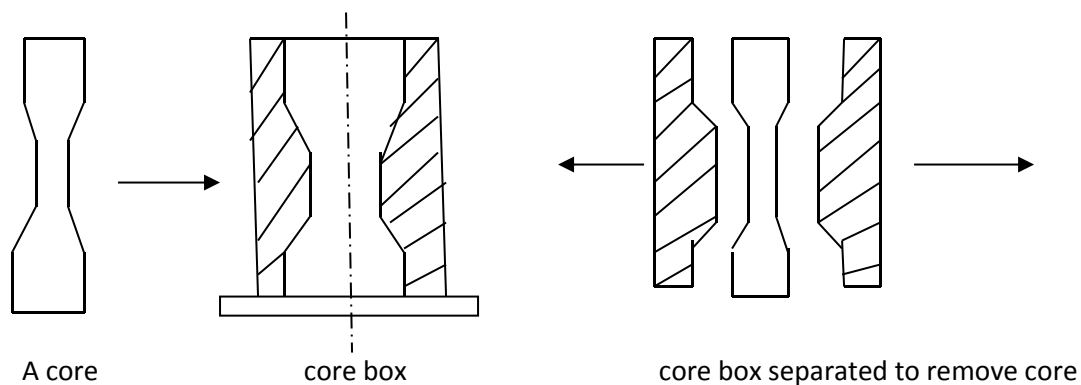


Fig. 4.25b The process for producing core (b)

The (a) type is the one sided core box producing flat walled cores or half core which can be turned out directly unto a flat board or plate for drying. The type of core depend on the type of pattern. Many type of core are designed in separate half for subsequent joining e.g. (b). in some cases the box is always made to split along the planes normal to the flat surface, the core box can then be parted laterally to leave the core standing in (b) on the base plate. One piece core without adequate flat surface and normally produced in split and doweled core boxes of which one half is removed to enable the core to be extracted normally on the pattern plan

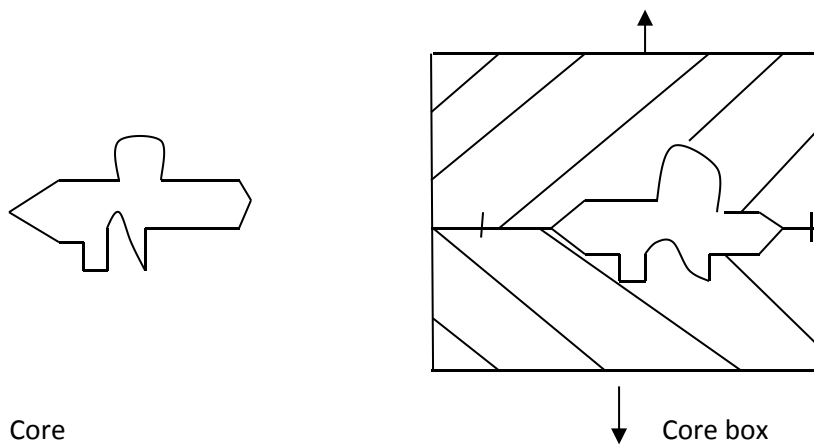


Fig.4.26 one piece core



Fig.4.27 Components of a Core Box for making Core for Vanes of a Water Pump using Cold-Setting Binder

Advantage of Core Box (J)

One of the advantages is that the core can be dried while still in one half of the pattern. When small cores are required in large quantity, production can be done by the use of multi gang core boxes with several core impressions and thus enable a number of core boxes to be rammed or blown or compacted at the same time reducing the time for stripping and reassembling.

Compaction

For compaction we can either use hand or machine. Another thing is the core reinforcements with core irons or metal grids. If the core has fragile design.

Core Venting

Small core can frequently be vented with small holes leaving out through the print surface its purpose is to allow the in trapped gases to escape. Large cores may be moulded round placed metal pipe which serves also to strengthen and conduits for gas.

Core Hardening

Green cores are used in special situations but most often are hardened to comparatively high strength to meet handling and casting conditions. There are many ways we can harden the material.

Separate hardening core making practice: has in the past been based on hardening by the oxidation polymerization of linseed oil or the thermal curing synthetic resin, requiring in either case an appreciable stoving fire. The period depends on the particular core binder, the mass of the core affect the time taken for the center to attain the necessary temperature i.e. the large cores requires more time than smaller cores

Disadvantages of separation (hardening)

1. Possibility of sagging in green state
2. Stoving is time consuming

Hardening with the Mould Box

Three methods are used,

- a) Hot box
- b) Cold set
- c) Carbondioxide process

The advantage of the hardening within the mould box is that it gives high accuracy in dimension, but the possible problem is the extraction of an already hardened core, this requires a high standard of core box construction and finish, and this is why one has to be very careful and don't use a worn out core box.

- a) Hot box:** the hot box was associated with the production of shell mould cores from dry resin bonded mixture. It is the high accuracy of this core that lead to their base outside the field of shell moulding. The core box of steel cast iron or aluminum are provided with vents and injectors as required, and is maintained at temperature in the range of 180-260°C. The core is blown and curing proceeds at a rate sufficient for injection within a fraction of a minute. This is coupled by residual heat in the core. Striping is assisted by periodic treatment of silicon parting fluid. The core box can be heated cyclically through an oven or with the aid of thermal-statically controlled heating element. Generally baking is carried out in ovens equipped with drawers, shelves or other holding devices. The operation is generally continuous and cores are put either in batches or continuously over moving shelves. The heat in oven is produced by burning oil or coke or by electric resistance. Core-making time depends upon the type and quantity of binder used, the amount of moisture used in sand, and size of core. The temperature for baking depends on the core material used. When cores are baked, they are more easily supported on a flat surface which should be incorporated in the design.

Disadvantage

High cost due to the provision of core box, thermal-static and other heating elements.

b) Cold set Process

The basis of cold-set is the condition of acceleration to the binder by addition of a catalyst on dry mixing it with sand, coring begins immediately and continues until the core is strong enough to be strip from the mould box or core box. Hardening is

completed either without external heating or assisted only by a brief stoving at 200°C. Little ramming is needed since the mixture have extremely high flowability.

c) CO₂ Process

This is the most versatile of the core making processes being expanded. Suitable for mass production and jobbing large and small work. And the process is basically simple. The high flowable silica mixture is blown or rammed into the boxes and CO₂ at a pressure of 20lbft/in² i.e. 140KN/m² is diffused through the sand to initiate the hardening reaction which occupies a very short time interval. Various methods can be use to distribute the gas and ensure uniform hardening. This is accomplished by the provision of probes and tubes insert to ensure smooth gas flow and avoid dead zones in the core box.

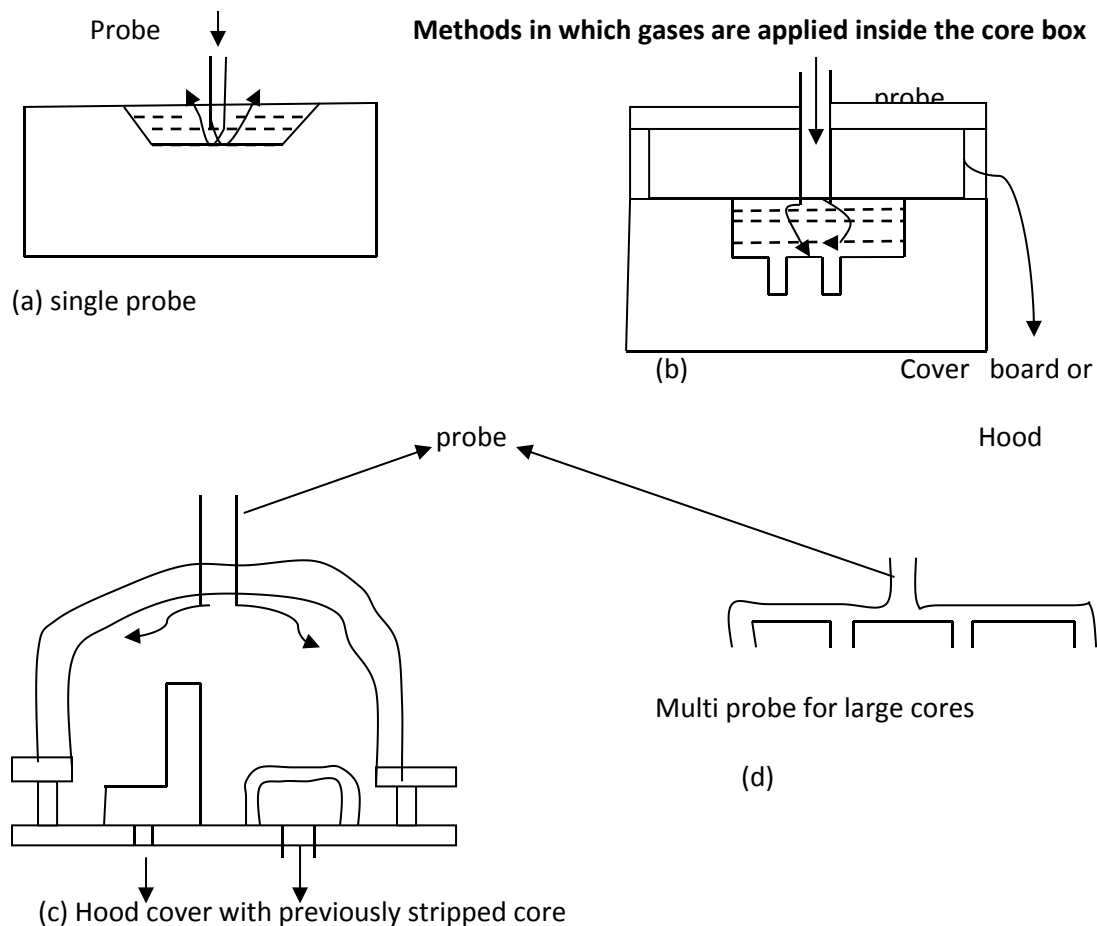
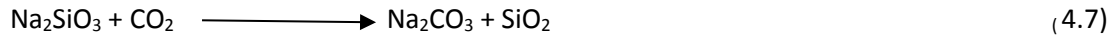


Fig. 4.28 Methods in which gases are applied inside the core box a) single probe, b) single probe
c) and d) multi-probe system.

Multiple probe is used if the core is large. It is not however a must for the core to harden within the core box, in which case a sand mixture requires additional binders to confer green strength. Gassing in such cases are carried out with the aid of hoods and chambers. Besides the methods shown above CO₂ can be applied as a step in core blowing sequence or by passing cores and mould box through a chamber which is alternately evacuated and filled with the gas. The carbondioxide process using Sodium silicate (NaSiO₂) hardened by carbondioxide is used. The system SiO₂ –Na₂O-H₂O forms a

series of substance of widely differing viscosity depending upon the $\text{SiO}_2\text{-Na}_2\text{O}$ ratio. Molecular ratio 1.5 and 3.1 are used in founding. Passing CO_2 through the $\text{Na}_2\text{O-SiO}_2$ impregnated sand produces carbonic acid in the aqueous solution. This causes a rise in the $\text{SiO}_2\text{-Na}_2\text{O}$ ratio and the formation of colloidal silica gel which hardens and forms a bond between the sand grains

Overall equation



Short gassing time have been shown to be most effective in producing strong cores, the hardening process then continues on standing. Over gassing reduces core strength, and the dilution of CO_2 with air assist hardening. The carbondioxide process has the advantage that special core boxes are not needed the process is used widely in moulding, giving conditions equivalent to dry sand mould without need for stoving, capital cost is low, cylinder gas can be used on a small scale. Theoretical gas consumption represent 0.2 and 0.5% of the weight of the sand mixture which is double under practical conditions. Actual consumption figures are greater than 5%.

Core Dressing

Core dressing is the operation of applying a compound to the surface of a core, either in the green state or after baking, for the pupose of providing protection against the scouring action of flowing molten metal and to assist the formation of a smooth surface in a cored hole or cored form.

Core Chaplet

A core chaplet is a metal location piece inserted in a mould either to prevent a core shifting its position or to give extra support to a core. The molten metal melts the chaplet which then forms part of the cast material.

Method of Supporting Cores in the Mould

Generally core prints are provided in cores. These core prints are a sort of projection at the end of core and these support the core in position in a mould. Design should provide space for core prints sufficiently large to locate the core accurately, preventing sagging, and resist the hydrostatic molten-metal pressure. In some cores small metal props (chaplets) are also used which are placed in the mould cavity to support the core and these props fuse and become part of casting. The chaplets, therefore, must be clean, dry and selected of proper material. Sometimes small metal insert hinge tubes are also used to provide support for tiny hole-forming cores. As far as possible chaplets should be avoided as fusing is not always easily accomplished, and it may lead to production of unsound castings.

Some cores are nearly fully surrounded by metal, and a vent then becomes necessary to release the gases generated during pouring. If possible, the hole formed by the vent core should be incorporated as functional part of the design or located where it will do no harm, otherwise welding or plugging would be required.

Review Questions on Chapter Four

1. Define moulding material
2. List and explain the functional requirement of moulding materials. Also mention the principal ingredients for sand moulding.
3. List the various shapes of sand grains and also list characteristics of moulding sands and explain.
4. What is the best Grain Fineness Number range and Average Grain Size range for foundry sand
5. Give three mould sand classification and explain their advantage and disadvantage.
6. Write on clay and its use in the foundry
7. What is "bentonite"? State the various classifications of bentonite.
8. Discuss bentonite properties in accordance with its major two classifications
9. Discuss the effect of moulding mixture moisture content on green mould strength.
10. What do you understand by natural bonded moulding sand mixture?
11. What are the characteristics of core sands?
12. Define binders and state their requirements.
13. List the three major classifications of binders.
14. Write a brief note on binder emissions.
15. List some test equipment used for testing sands and moulding mixtures.
16. Explain some testing procedures in sand testing mentioning the equipment used.
17. List and draw some equipment used for hand moulding in the foundry.
18. List and explain the types of moulding that you know.
19. Describe sand mould process in the foundry. Illustrate the process diagrammatically.
20. List and explain the sand moulding processes that you know. Make your explanation clear with diagram of the mould type.
21. What is a core? List the purposes of a core in a mould.
22. What are the characteristics of a good core? Write a short note on core binders.
23. What are the different types of cores used in the foundry?
24. Describe how cores are made with diagrammatic illustration.
25. Write short notes on the following: core compaction, core venting, core hardening, core reinforcement, core dressing, core chaplet.

26. How is a core supported in a mould?

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CHAPTER FIVE

CASTING DESIGN

Pre-design Considerations in Design of Castings

A good design engineer should consider the following point:

- i). Design should be such that the pattern can be adopted for economical moulding by standard methods.
- ii). Gates, risers and chills should be positioned properly to ensure soundness.
- iii) Section size and shape should not be such as to cause undue stresses in the mould and consequent tearing and cracking.
- iv) Directional solidification be established and controlled. Fig. 5.1 shows example of arrangement to achieve directional solidification.
- v) If casting is of complicated shape, it can be broken down into component parts and the separate castings welded together. For instance, bosses and cumbersome projections instead of casting integral can be welded to make foundry operations easier, cheaper and more dependable.
- vi) To prevent tearing, small tie bars are used in critical areas. To reduce stress slightly, straight members like spokes to wheels may be curved.
- vii) Some thin sections of castings cool and contract much faster than heavier members, and if such members are attached rigidly, high stresses will develop. If members are curved, the small sections will tear to relieve the stresses or deform (warp) plastically without tearing.
- viii) For sound castings, temperature gradients in solidifying castings must be properly controlled. Heavy sections should not be fed through light sections. Designer should attempt to limit junctions to as few as possible. If limiting the number of junctions is not possible, it is advisable to cast in segments and join them together later by other fastening methods.
- ix) If possible sections should be designed to taper towards riser. It must be remembered that the casting soundness obtained by natural solidification is proportional to the degree of tapering allowed.
- x) Since tendency of a casting to warp or tear is proportional to its length and complexity, it is advisable to separate casting into parts and fasten them together by other methods
- xi) Since it is very difficult to obtain horizontal flat surfaces at top because of centre line shrinkage and collection of slag, dross, and other impurities lighter than metal on the upper flat surfaces it is advisable to have curved surfaces on top and incorporate flat surfaces on vertical sides.

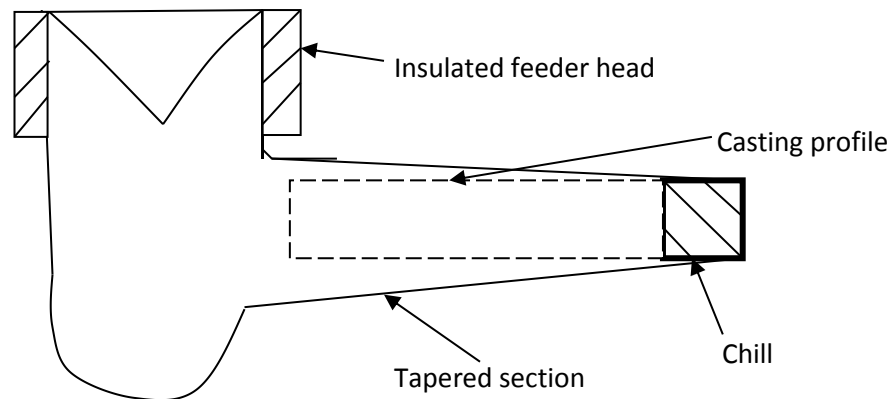


Fig.5.1 Schematic representation of techniques used to promote directional solidification

According to Beeley (1982) the purpose of design is to achieve functional performance of structures at minimum cost in materials and manufacture. Both these factors are involved in the initial choice of casting as the means of production; the individual design is itself usually a compromise between a purely engineering concept based on service requirements and a shape lending itself to high quality, low cost production. Casting design for production is no longer as tedious as it used to be back in the days when design engineers will do sketches with dimensional details and give it to the draughts men for the final engineering drawing. So much time was spent on getting the design but the guarantee was never there that the castings will be defect free. Most a times many trial castings will have to be made before arriving at a perfect design and casting. Today new technologies are solving these problems to a great extent. Layer by layer production or 3D printing, and computer aided design and simulation as well as computer aided manufacturing are today used in the foundry to save production time, cost, reduce defects rate and improve quality of castings. Clegg (1999) said "the design function is the starting point for all manufacturing activity, including the production of castings." A designer must consider a number of issues at the outset. Firstly, a decision will be taken on what material to specify. This will be determine by the mechanical properties of the material, its density and its suitability for the environmental conditions under which the component must operate. Secondly, the functional shape of the component must be determined in order that it can meet its functional objectives. At this stage the designer will be concerned with such aspects as ease of manufacture, sectional properties and aesthetic appearance.

The designer must be aware of the constraints that may be imposed on a design by the founder's ability to produce thin sections, ensure soundness in remote sections and avoid distortions. A knowledge of metal casting processes, their capabilities and limitations, will therefore be invaluable to the designer, as will the opportunity to liaise with a foundry engineer at the design stage. Liaison at this stage will ensure that the most suitable casting process is selected and that the decision on casting orientation in the mould, which affects such factors as joint plane determination and tooling requirements, ensures cost effective production to the benefit of both the founder and customers alike.

Examining the process by which a casting comes to be used, five separate stages can be distinguished:

Preliminary stages:

- I. the decision to use a casting,
- II. detail design,
- III. commercial contact: enquiries, quotations, order;

Production stages:

iv pattern manufacture,

v founding and finishing

In order to be able to use the metal casting process effectively in component design and production, the designer should be aware of the following considerations (clegg, 1999):

- i. the designer should have a thorough knowledge of the casting processes available, their capabilities and limitations.
- ii. Casting is particularly suitable for parts which contain internal cavities that are inaccessible, too complex, or too large to be easily produced by machining.
- iii. Cores should, however, be avoided as far as possible because they reduce the directional accuracy of the mould assembly, increase the production cost of the casting and the fettling problems.
- iv. Complex design details should be modified to simplify production and reduce component costs
- v. The casting process enables the designer to specify walls of varying thickness, bosses, lugs, pads and, strengthening ribs.
- vi. These sections may be desirable, within the limits of strength requirements, for weight saving purposes, but their specification may restrict the choice of casting process.
- vii. Remote thicker sections and junctions locally increase the casting's mass and present the possibility of shrinkage porosity unless access for feeding is possible
- viii. Variations in section thickness result in variations in cooling rate which may, in turn, cause distortion or residual stresses.
- ix. The specification of close tolerance will increase the cost of the casting and must be weighed carefully against potential savings in the cost of machining.
- x. Castings have isotropic properties
- xi. Large complicated castings can often be redesigned to be split into several smaller, less complex castings which can be joined subsequently.

Engineering structures may be produced from metal in the cast, wrought or sintered condition and the final shape may be developed by many different combinations of manufacturing process. Fig.5.2 shows major routes in the production of engineering components. The starting point is with liquid metal using different manufacturing methods, different products can be produced.

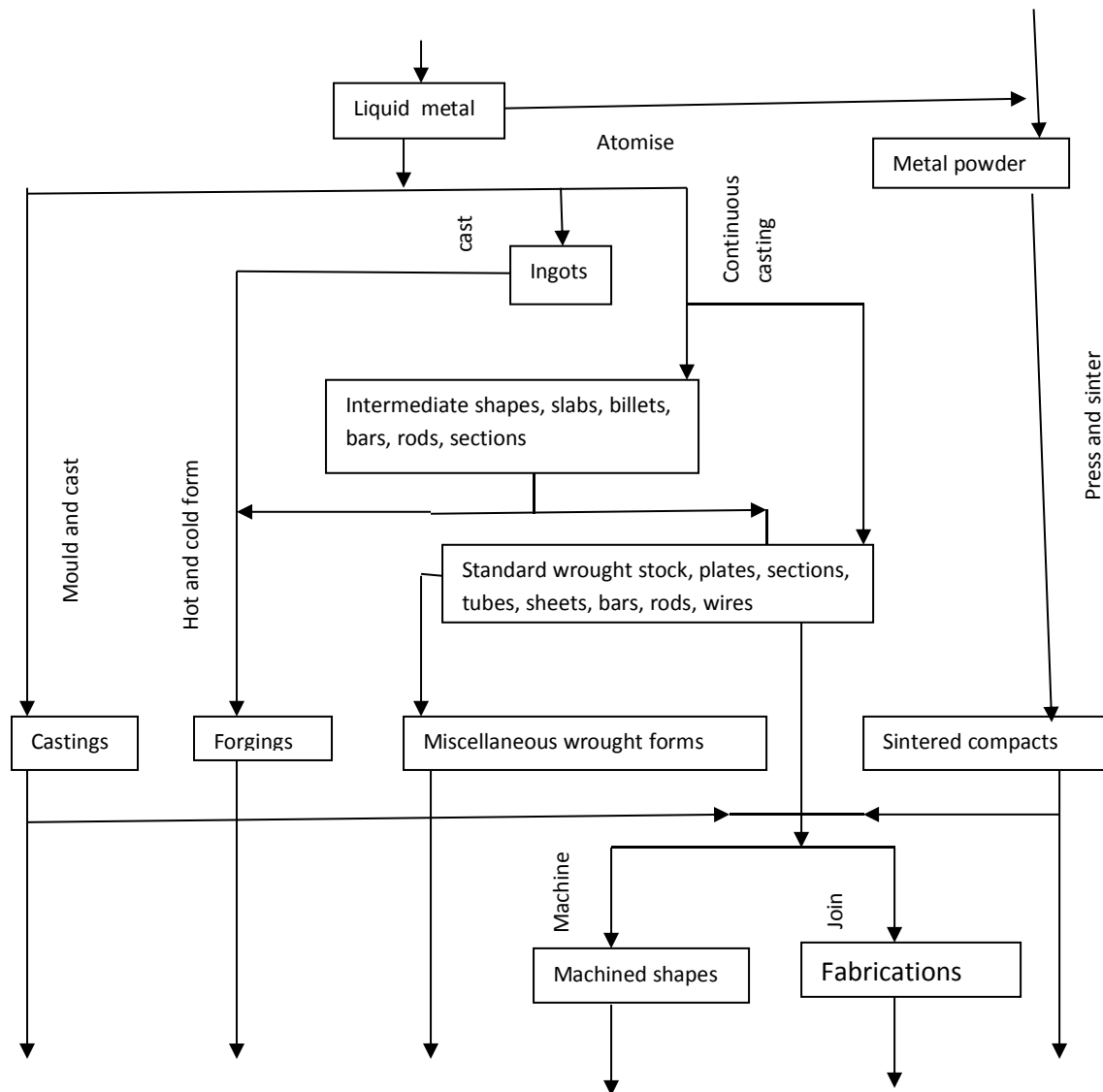


Fig.5.2 Major routes in the production of engineering components (source: Beeley, 1982)

Technical Aspects of Making Sound Castings

1. Tapers must be incorporated in all sections in order to facilitate removal of pattern from moulds, or separate solidified castings from permanent moulds. Taper also induces directional solidification.
2. All corners should be rounded and re-entrant sections must be avoided as far as possible in order to permit free flow of liquid metal. Generous fillets should be incorporated.
3. Pattern maker's shrinkage allowance should be provided to allow for shrinkage of metal from freezing point to room temperature. Thus, depending upon metal, all dimensions are scaled up between 2-5%.
4. Cores must be used to form cavities and re-entrant sections.

5. Shape of component must be carefully examined to determine the location of suitable parting line (position where the opposite halves of the mould meet and where it is broken open to remove pattern or casting). It is not necessary that parting line be a flat plane, it can be stepped also.

6. It must be ensured that part of the shape gets buried or becomes keyed into the mould cavity so as not to damage the mould or casting upon removal.

7). The problems of pattern making should be kept in mind. The number and complexity of cores needed should be minimized.

8). Minimum thickness of cast parts for ease of metal flow should be as under:

Material composition		Minimum thickness
(a)	Very small castings of grey iron, aluminum, magnesium, and copper-base alloys	3 mm
(b)	Large castings of above materials.	4.5 to 6 mm
(c)	Iron with 0.5 to 1% phosphorous used for household goods, stove platos, radiators, etc.	1.5 mm
(d)	Small steel castings.	6 mm
(e)	Large steel castings.	12 mm

9). Very often, by making and studying the model of castings, important casting decisions can be taken. Following this approach, areas of potential shrinkage and tearing can be predicted, the best location of gates and risers determined, casting repairs can be eliminated by incorporating suitable design changes, money saving changes in pattern construction can be spotted before making working patterns.

3D Printing/ Additive Manufacturing

Modern foundries have evolved with great precision in terms of castings produced as a result of the introduction or incorporation of the 3D Printing technology also known as additive manufacturing or rapid prototyping technology at the design and pattern making stage. Castings are designed using computer software like AutoCad, Solidworks and others. The engineering drawings are scanned by scanners and converted into 3 D drawings which are understood by the 3 D Printer which can read the drawing and then print it using plastic ink or metal ink depending on the type of machine used for the prototyping. The emergence of this technology has given rise to accuracy in casting production, time saving in pattern making, and time and cost saving in casting production in the foundry of today. The role played by additive manufacturing in foundry today cannot be over emphasized so it is important to briefly review it here.

A 3D printer is a computer controlled machine used to produce physical parts from a virtual computer aided model drawing of the object. This machine uses additive manufacturing technology to build an object up, one layer at a time to produce a finished product. It can be used to produce a variety of spare parts and industrial prototypes for hobbyists, domestic and industrial applications and can be employed to create prototypes, foundry patterns, architectural models and other parts in the educational, scientific and technological sector.

Additive manufacturing techniques like 3D printing have a lot of advantages over the traditional subtractive manufacturing techniques like milling, lathe work etc. The first advantage is the minimal wastage of material in additive manufacturing, compared to subtractive manufacturing techniques that start from a block of material that produces a lot of waste from the process. The second is the reduction in cost due to the lack of tooling like jigs and fixtures needed in a subtractive manufacturing process. The last advantage is the production of complex patterns that can't be produced by any other manufacturing process

History of 3D Printing

Most 3D printing technologies were used for rapid prototyping. The creation of early stage product mock-ups, of concept models – essentially supporting the design and engineering process. They were used to mimic the results of more traditional manufacturing processes, such as machining, casting, injection molding, etc. Then some bright spark came along and realized that you could use the same layer-based manufacturing processes to, perhaps, build final end use components. Which is called rapid or direct manufacturing. The issue was, as anyone that's worked in the field knows, is that these machines aren't all that rapid. In fact, they're often infuriatingly slow. But this was how it was: Rapid Prototyping versus Rapid Manufacturing. And it was a little secret in the world of design and engineering.

This technology was started by RepRap project at the University of Bath (it gave the basics of many of today's desktop 3D printing devices) and the rise of Brooklyn's Makerbot (now part of the Stratasys empire). Fig.5.3 shows a makerbot 3D Printer prints a cylinder.



Fig.5. 3 MakerBot prints a cylinder, 2010

As their patents began to expire, there was a boom in entry-level rapid prototyping machines. Of course, rapid prototyping is a term that's industry specific and the mainstream media needed a new term. Behold, the term 3D printing was born.

Then those working at the more advanced end of the market wanted to differentiate their solutions that were as different from a two grand ABS extruding machine as chalk from cheese. The folks working with advanced laser sintering machines for both plastics and metals, those working on machines that build parts by fusing together powdered titanium, didn't want their machines confused with an inkjet. This class of vendors have also been pushing the adoption of their machines in the world of manufacturing as an alternative to the likes of CNC machining and injection molding. And so the term Additive Manufacturing was born. "Additive" refers to the successive addition of thin layers between 16 to 180 microns or more to create an object. In fact, all 3D printing technologies are similar, as they construct an object layer by layer to create complex shapes.

Printing with 3D Printer

There are 3 main steps in 3D printing.

The first step: is the preparation just before printing, when you design a 3D file of the object you want to print. This 3D file can be created using CAD software, with a 3D scanner or simply downloaded from an online marketplace. Once you have checked that your 3D file is ready to be printed, you can proceed to the second step.

The second step: is the actual printing process. First, you need to choose which material will best achieve the specific properties required for your object. The variety of materials used in 3D printing are very broad. It includes plastics, ceramics, resins, metals, sand, textiles, biomaterials, glass, food and even lunar dust! Most of these materials also allow for plenty of finishing options that enable you to achieve the precise design result you had in mind, and some others, like glass for example, are still being developed as 3D printing material and are not easily accessible yet (sculpteo, 2020).

The third step: is the finishing process. This step requires specific skills and materials. When the object is first printed, often it cannot be directly used or delivered until it has been sanded, lacquered or painted to complete it as intended.

The material chosen for the project will determine which printing methods are most suitable. Among these, the most commonly used techniques for each group of materials are described next.

Printing with Plastic or Alumide

- **Fused Deposition Modeling (FDM) Technology:** is at the very entry of the market as it is mainly used by individuals. It is probably the most popular printing method due to the number of printers available on the market. FDM is an affordable 3D printing process compared to other 3D printing technologies. This process works by material being melted and extruded through a nozzle to 3D print a cross section of an object each layer at a time. The bed lowers for each new layer and this process repeats until the object is completed. Layer thickness determines the quality of the 3D print. Some FDM 3D printers have two or more print heads to print in multiple colours and use support for overhanging areas of a complex 3D print.
- **SLS Technology :** Laser sintering is a 3D printing technique consisting of the fabrication of an object by melting successive layers of powder together in order to form an object. The process most notably facilitates the creation of complex and interlocking forms. It is available for plastic and alumide. Fig.5.4 shows some items printed using the SLS Technology.



Fig. 5.4 Some objects printed using SLS Technology

Printing with Resin or Wax

The technology needed is the photopolymerisation, a technique that involves the solidification of photo-sensitive resin by means of a UV light. It is used by different 3D printing processes such as:

- **Stereolithography (SLA):** uses a vat of curable photopolymer resin. The build plate descends in small increments and the liquid polymer is exposed to light where the UV laser draws a cross section layer by layer. The process is repeated until a model has been created. The object is 3D printed by pulling the object out of the resin (bottom up), which creates space for the uncured resin at the bottom of the container and can then form the next layer of the object. Another method is to 3D print the object by pulling it downward into the tank with the next layer being cured on the top.
- **Digital Light Processing (DLP)** a projector is used to cure photopolymer resin. This is very similar to the SLA method except that instead of using a UV laser to cure the photopolymer resin, a safelight (light bulb) is used. Objects are created similarly to SLA with the object being either pulled out of the resin, which creates space for the uncured resin at the bottom of the container thus forming the next layer of the object, or down into the tank with the next layer being cured at the top. Sculpteo uses DLP technology for silver and brass 3D printing. We 3D print a wax model first then, we use a lost-wax casting technique: a mould is made around the wax before it is melted and filled with silver, creating your object.
- **Continuous Liquid Interface Production (CLIP)** works by projecting a continuous sequence of UV images, generated by a digital light projector, through an oxygen-permeable, UV-transparent window below a liquid resin bath. The dead zone created above the window maintains a liquid interface below the part. Above the dead zone, the curing part is drawn out of the resin bath.
- **MultiJet printers:** Similar to Stereolithography, the high-quality PolyJet and MultiJet 3D printing processes use a UV light to crosslink a photopolymer. However, rather than scanning a laser to cure layers, a printer jet sprays tiny droplets of the photopolymer (similar to ink in an inkjet printer) in the shape of the first layer. The UV lamp attached to the printer head crosslinks the polymer and locks the shape of the layer in place. The build platform then descends by one layer thickness, and more material is deposited directly onto the previous layer.



Fig.5.5 Objects printed using multijet printers

Printing with Metal

- **DLP:** combined with the lost-wax casting technique allows objects to be printed in 3D. Sculpteo uses DLP technology for silver and brass 3D prints. First, we 3D print a wax model. Then, we use a lost-wax casting technique: a mould is made around the wax before it is melted and filled with silver, thus creating your object.
- **Direct Metal Laser Sintering (DMLS):** uses a laser as a power source in order to sinter metal powder by aiming a laser and tracing a cross section of the object layer by layer. Direct Metal Laser Sintering is similar to the selective laser sintering process.
- **Electron Beam Melting (EBM):** uses an electron beam as the power source instead of a laser to 3D print metal. An electron beam melts metal powder layer by layer within a high vacuum and can achieve full melting of the metal powder. This method can produce high-density metal parts thus retaining the material's properties.

Printing with multicolour

- **Binder Jetting:** is popular since you can create detailed 3D prints with colour. An automated roller is used to spread a layer of powder onto the build platform. Excess powder is pushed to the sides and ensures that the bed is filled with a layer of packed powder. On a fast axis, the print heads apply a liquid binder and colour simultaneously to create a cross section of the object on the powder.
- **Selective Deposition Lamination:** is a 3D printing process using paper. This process is similar to Laminated Object Manufacturing (LOM) rapid prototyping method. The process involves layers of adhesive coated paper (or plastic or metal laminates) that are successively glued together with a heated roller and cut to shape with a laser cutter layer by layer. A roller with the material moves each new sheet of material over the last and repeats the process until the object is completed.
- **Triple-jetting technology (PolyJet)** used in Stratasys Objet500 Connex3, is the most advanced method of PolyJet 3D printing. This technology performs precise printing with three materials and thus makes three-colour mixing possible. To know more about this technology, you can refer to PolyJet & Multijet (Sculpteo, 2020)



Fig.5.6 Objects printed using triple-jetting technology (PolyJet)

Table 5.1 3D Printing Technologies Comparison

Technology	Additive Manufacturing Process		Advantages	Disadvantages	Plastic based material	Metal or Brass	Resin	Multicolour
Fused Deposition Modelling		Material Extrusion	Strong Parts Easy to print yourself	Poorer surface finish and slower Requires support structures	Yes			
Selective Sintering	Laser	Powder Fusion	Bed No support required High Heat and Chemical Resistant High speed	Precision limited to powder particle size Rough surface finish	Yes			
Direct Metal Sintering	Laser	Powder Fusion	Bed High-density components Intricateness	Finishing step is a mandatory		Yes		
Electron Melting	Beam	Powder Fusion	Bed Good printing speed Less distortion	Needs finishing Caution required when dealing with X-Ray		Yes		
Stereolithography		Photopolymerisation	Complex Geometries Detailed parts Smooth Finish	Post-finishing required Requires Support structures			Yes	
Digital Processing	Light	Photopolymerisation	Concurrent production Complex shapes and sizes High precision	Thickness limitation Limited range of materials			Yes	
Continuous Interface Production	Liquid	Photopolymerisation	Concurrent production Complex shapes and sizes High precision	Thickness limitation Large choice of resins simulating different properties			Yes	
Multijet et Polyjet		Material Jetting	Good precision Good surface	Slow Build Process			Yes	Yes

		finish		
		Use of		
		multiple		
		materials		
		and colours		
		No removal		
		of support		
		material		
		Lower Price		
Binder Jetting	Jetting	Enables colour printing	Limited choice of materials Fragile parts	Yes
		High speed		
		Lower Price		
Selective Deposition Lamination	Sheet Lamination	No toxic materials Quick make parts	Less accurate Non-Homogenous to make large parts	Yes

The list of 3D printing technologies and processes continues to grow as 3D printing is always changing. The 3D printing industry continues to innovate its hardware as well as the materials and processes to create objects or parts. Depending on many factors such as budget, design or function, choosing the appropriate 3D printing process as well as the right material is important. 3D printing can create many different 3D printed objects that were previously only fabricated through mass manufacturing methods. It is today a very handy technology in design and production of pattern in the foundry.

Process and Alloy Selection

Casting Processes

At an early stage in design and before proceeding to the detailed determination of shape, the casting process, the alloy and if possible a general outline of the proposed manufacturing method need to be established. One of the first considerations is whether a sand casting, a diecasting or a casting made by some other specialized process will be required. The main processes and the principal factors influencing selection are listed in Table 5.2. once the process has been decided in broad terms, the general approach to the shaping of the component must be considered and at this stage the possibility of using multiple construction and other supplementary techniques arises.

Table 5.2 Process Selection

a. Casting Processes	b. Factors in Process Selection
1. sand casting, including core assembly and close tolerance variations (cold set, CO₂, block moulding, etc) 2. gravity die or permanent mould casting 3. pressure die casting 4. shell mould casting 5. investment casting (permanent and expendable pattern techniques) 6. centrifugal casting	1. suitability for shape and size of product 2. suitability for alloy 3. accuracy and surface finish 4. quantity requirements and overall cost of production

Source: Beeley, 1982 p303

Cast-Fabricated Construction

Although casting is frequently in competition with other methods of forming, a wide field exists within which two or more techniques can be regarded as complementary and the best features of each exploited. A single casting may, for example, be broken down into smaller units to be subsequently fabricated by welding, bolting or other mechanical means; casting may be similarly employed in conjunction with wrought materials such as plate or rolled sections. These assembly techniques can be used either for economic reasons or to simplify the technical problems in the production of larger units. Apart from simplification, structural division enables the best material to be utilized for each section of the design.

Ideal conditions for cast-welded and other types of duplex construction are achieved if the foundry is able not only to influence the design, but to undertake the production of the finished assembly. This is particularly important where welding is involved, since weldability of the alloy and metallurgical effects involving the structure of the component castings must be taken into account.

Multiple construction is more commonly used in conjunction with steel than with cast iron and nonferrous castings. The contraction characteristics of cast iron are such that there is less tendency for tearing and distortion to occur in extended castings, whilst the high fluidity and low shrinkage tendency facilitate the direct casting of thin members. Steel, on the other hand, has good weldability, giving an incentive to circumvent casting difficulties by division. The development of electroslag welding enables relatively thick cast sections to be joined.

Apart from division and subsequent fabrication, several supplementary techniques are available to extend the design potential of cast products; they include the local introduction of special properties by means of inserts, bimetal casting and surface treatment. Such techniques may be employed either as a means of lowering product cost or to achieve otherwise unobtainable combinations of properties.

Inserts

Metal inserts of different composition from that of the casting may be incorporated permanently in the structure by placing in the mould before pouring. Although the ideal is to achieve interfacial adhesion through wetting, inserts should also be designed for mechanical interlocking with the parent casting, for example by undercut grooves or milling.

Bimetal Casting techniques

True bimetal castings of tubular form are produced by sequential pouring of separate alloys in centrifugal casting. The principle is also used in static casting e.g. in the manufacture of rolls by the double-pour technique; a casting is poured in one alloy and the liquid core is subsequently displaced or diluted by a second molten alloy of different properties.

Surface Treatments of Castings

Many processes are used to develop special properties over the whole or part of the casting surface. They are commonly adopted either for enhanced appearance and corrosion resistance or to improve wear or fatigue resistance. The latter can be achieved by surface hardening and by generation of residual compressive stresses in the surface layers: shot peening, carburizing and nitriding owe their beneficial effects to both these mechanisms. Polishing also contributes to fatigue resistance. The principal finishing processes used with castings are classified in Table 5.3. The surface treatments extend the effective range of application of the parent alloy, so that their use must be considered at the outset as an element in alloy selection. This choice must again be made on both technical and economic grounds, including the suitability of the treatment to the bulk material. Thus a decision must often be made between a cheaper material with a surface coating and a more expensive alloy with the intrinsic surface properties required.

Property Criteria in Design

The design of castings may be based upon any of a wide range of cast metal properties, depending upon the service conditions of stress, temperature and environment. The first essential is to define these conditions and to select the right design criteria. The economic use of materials demands that the properties of a given alloy be considered in relation not only to function but to cost, since the strength or rigidity of a component, for example, may be achieved by alternative combinations of material properties and dimensional proportions.

The choice of alloy is also governed partly by production requirements: foundry characteristics, machinability, and weldability need to be considered in relation to the particular shape and application.

Mechanical Properties

The most frequently specified property is tensile strength, although its significance in the design of static structures is less than that of the yield stress or proof stress, which marks the effective limit to the elastic range.

The other essential guide to elastic behavior is young's modulus, the measure of stiffness, or deflection under a given load: this property determines the resistance of a structure to elastic distortion and eventual instability. In many designs rigidity is the critical factor governing dimensions, requiring section thicknesses which are more than adequate from a strength viewpoint. Young's modulus is relatively insensitive to changes in cast structures, being primarily established by composition. In grey cast iron, however, the effective value varies markedly with the graphite content and decreases with an increase in the applied stress.

The tensile properties also give a guide to other properties which are not themselves frequently determined, for example the shear, torsional and compression strengths of the material; in each case there is a consistent relationship with tensile strength for a given class of alloy.

Table 5.3 Surface Treatments for Castings

Primary purpose	Treatment
A. Wear resistance and improved mechanical properties, particularly fatigue resistance	1. flame and induction hardening 2. hard surfacing by alloy weld deposition or plating 3. carburizing and nitriding 4. local chilling (as applied for example to camshafts in cast iron) 5. shotpeening
B. Appearance and corrosion resistance	1. electroplating 2. tinning and galvanizing 3. painting, stove enamelling and associated pretreatments 4. vitreous enamelling 5. anodizing, pickling, and chromate baths 6. chemical and electrochemical polishing 7. mechanical polishing and machine finishing

Source: Beeley, 1982

Tensile strength will also be shown to be relevant to fatigue performance. In calculating strength requirements, stress concentrations at notches must be taken into account; the elimination of stress raising features such as sharp corners is essential in deriving maximum strength from cast components. Notch effects and their predominant influence on strength and the vital importance of fillet radii have been demonstrated by Caine in his major works on casting design (Ihom *et al.*; 2014). In prescribing the mechanical properties of materials to be used in engineering designs, two major uncertainties arise, firstly in respect of the exact distribution of service stresses and secondly in respect of quality and the possible presence of defects or residual stresses.

Nominal properties quoted in specifications are usually those expected from sound cast test bars. To take account of possible errors in predicting the magnitude and distribution of stresses and to allow for the possibility of stress concentration at unseen defects, a safety factor is normally incorporated in the design. A design stress of approximately half the yield stress i.e. a safety factor of 2, is commonly used where static stresses alone are involved, but much higher factors are employed for dynamic stresses and in other special circumstances. Safety factors can be greatly reduced where rigorous non-destructive testing is used to ensure quality; there is also less need for high factors where simple designs increase the accuracy of stress predictions.

Mechanical properties are sensitive to high strain rates and to cyclical stresses, either being being capable of producing failure well below the ultimate tensile stress, especially in the presence of notches or surface imperfections; knowledge of tensile properties is of limited value under such circumstances. Notch brittle behavior under shock loading arises from triaxial stresses which can produce brittle fracture even in alloys showing ductility in tensile testing (Beeley, 1982).

Notched Bar Impact Properties.

Derived from Charpy and Izod tests are relevant under these although such tests cannot be used to provide design stress data since results are dependent on notch geometry and specimen size, which cannot be directly related to other shapes and sections. However, this situation is changing with the advent of the fracture mechanics approach to the design of metal structures. Impact test results are of particular significance where low temperature service is envisaged and where the metal is susceptible to the ductile-brittle transition, commonly encountered in ferrous and other metals with the body centred cubic crystal structure. In such cases impact tests may be used to determine the actual transition temperature or simply to provide comparative fracture energies at a standard temperature. Austenitic steels and nonferrous alloys with the face centred cubic structure are comparatively immune from low temperature embrittlement. Under fatigue conditions materials fail under stresses far below their yield stresses. The selection of materials for melting and casting is normally based on the ability of the alloy and metal to meet service condition and functionality the use of design data and practical is therefore most a times inevitable.

As earlier on mentioned in the chapter the design process has been greatly simplified with the advent of the computer. There are computer programmes today that assists with the casting design right from the gating system design, the casting itself, the positioning of the risers for directional solidification and uniform filling of the casting cavity. After the casting design there are also programmes that can simulate the casting process. These simulation programmes are in a position to inform the casting designer on the state of the final casting. Defective areas will be clearly shown and thereby prompting the designer to effect the correction. Real castings are only embarked upon when the simulation process is perfect.

Computer-aided Method Design

The main input is the 3D CAD model of an as-cast part (without drilled holes, and with draft, shrinkage and machining allowance). The model file can be obtained from the OEM firm, or created by a local CAD agency. Various display options such as pan, zoom, rotate, transparency, and measure are provided to view and understand the part model (Fig.5.7). The cast metal and process are selected from a database. Part thickness distribution is displayed for verifying the model and evaluating part process compatibility (Fig.5.8).

The AutoCAST software developed at I.I.T. Bombay in collaboration with Advanced Reasoning Technologies provides a single integrated easy-to-use environment for casting method design, solid modeling, and simulation (ART, 2008). The latest Release 10 incorporates multi-cavity mold layout, automatic modeling and optimization of method design, and a costing model to compare various layouts. The cast metal and process are selected from a database. Part thickness distribution is displayed for verifying the model and evaluating part process compatibility. The method design involves cores, feeders and gating system (Fig.5.9) Holes in the part model are automatically identified for core design. Even intricate holes can be identified by specifying their openings. The print length is computed based on the core diameter and length (the user can change these if

required), and the entire core model is automatically created. The program suggests the number of cavities depending on the mold size (selected from a foundry-specific library), considering both cavity-cavity and cavity-wall gaps. Then the part model is automatically duplicated in the correct locations as per the desired cavity layout.

To facilitate feeder location, the program carries out a quick solidification analysis and identifies feeding zones. The user selects a suitable location close to the largest feeding zone, and the program automatically computes the dimensions of the feeder using modulus principle (solidification time of feeder slightly more than that of the feeding zone). The feeder model is automatically created; the user can change its dimensions or apply feed aids such as insulating sleeves and exothermic covers. More feeders can be created by specifying their positions.

The gating channels are created semi-automatically. First, the user indicates gate positions on the part or feeder model. Then the sprue position is decided, and it is connected to the gates through runners.

Runner extensions are automatically created. Any type of gating system: horizontal, vertical, investment tree, and direct pouring can be created or modified within minutes. The program also suggests a suitable filling time (which can be changed by the user), accordingly computes the dimensions of the gating channels, and creates their solid model.

Automatic Optimization

The mold cavity layout, feeders, and gating are automatically optimized within minutes based on quality requirements and other constraints (Ravi, *et al.*, 2008). For mould cavity layout, the primary criterion is the ratio of cast metal to mould material. A high ratio such as 1:2 (cavities too close to each other) can reduce the heat transfer rate and lead to shrinkage porosity defects. A low ratio such as 1:8 (cavities too far from each other) implies poor utilization of mould material and reduced productivity. The program tries out various combinations of mould sizes and number of cavities to find the combination that is closest to the desired value of metal to mold ratio.

The gating design is driven by the ideal mould filling time, which depends on the cast metal, casting weight and minimum wall thickness. Fast filling leads to turbulence-related defects (such as mould erosion, air aspiration and inclusions). On the other hand, slow filling may cause defects related to premature solidification (such as cold shuts and misruns). To optimize the gating design, the program simulates the mould filling and computes the total fill time (Fig.5.10). A simplified layer-by-layer algorithm is used, taking into account the instantaneous velocity through the gates (considering back pressure, if applicable), and the local cross-section of the mold cavity. This gives an

accurate estimation of filling time, while being computationally efficient. If the difference between the ideal and simulated filling time is more than a specified limit, the program automatically changes the gating design, creates its solid model, and simulates the mold filling again.

The feeder optimization is driven by casting quality, defined as the percentage of casting volume free from shrinkage porosity. The user indicates a target quality. The program automatically changes the feeder dimensions, creates its solid model, carries out solidification simulation, and estimates the casting quality (Fig.5.11). The solidification simulation employs the Vector Element Method, which computes the temperature gradients (feed metal paths) inside the casting, and follows them in reverse to identify the location and extent of shrinkage porosity (Fig.5.12). This has been found to be much faster than Finite Element Method, without compromising the accuracy of results. The feeder design iterations are carried out until the desired quality is achieved, or the number of iterations exceeding a set limit. The user can accept the results, or reject them and modify the feeder design interactively.

Finally, the cost of the casting is computed in terms of amortized tooling, cast metal, other materials (mold, core, etc.), energy, and labour. The user can carry out 'what-if' analysis and compare different method layouts in terms of manufacturing cost. A detailed method report containing the dimensions of part, mold, core, feeders, gating, various results (yield, quality, cost), and an image of the entire casting is automatically generated, which can be printed or stored for future reference (see Fig.5.13).

The software has been developed for standard Windows XP and Vista computers. The graphical user interface is designed to minimize the learning and operation time, and the user is gently guided through forgotten or wrong steps. Even those without any prior exposure to computers are able to use the software after a single day of training. All steps starting from part model importing to mold, core, feeder, and gating system design, simulation and optimization can be completed within one hour for typical castings. Over 40 foundries regularly use the software today, and many others have engaged consulting services for troubleshooting critical castings in all major metals and processes. Direct benefits include at least 50% reduction in casting development time and shrinkage porosity defects. Other benefits include yield improvement, faster quotations, taking up more complex projects, ready reference and training (Ravi, 2008). Continuous interaction and feedback from industry over the last 20 years has helped evolve the software to its current state in terms of features, applications and benefits to the end-users. For details on this topic reader should read the book "Fundamentals of Foundry Technology" written by Ihom *et al.*, (2014).

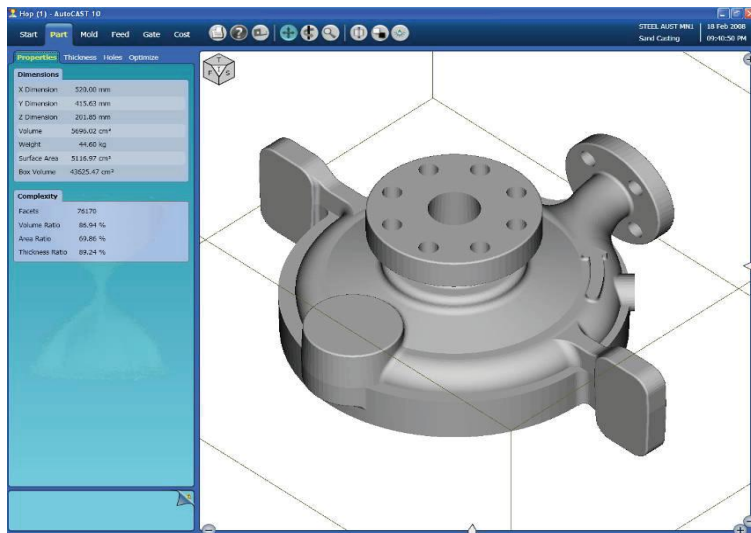


Fig.5.7 Part property computation.

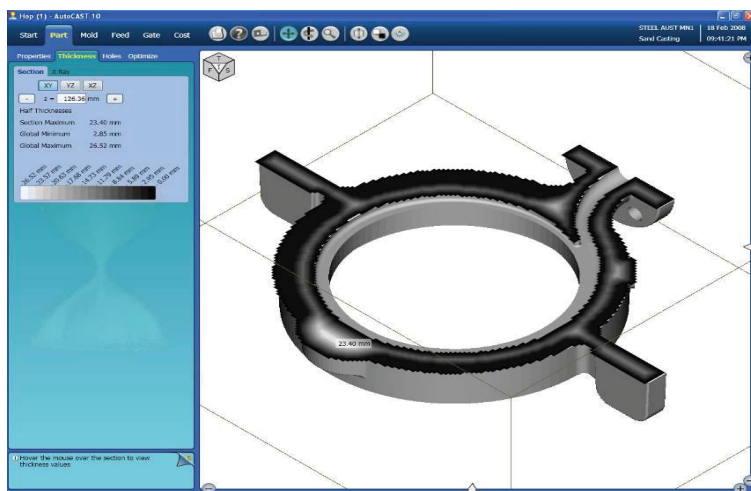


Fig.5.8 Part thickness distribution

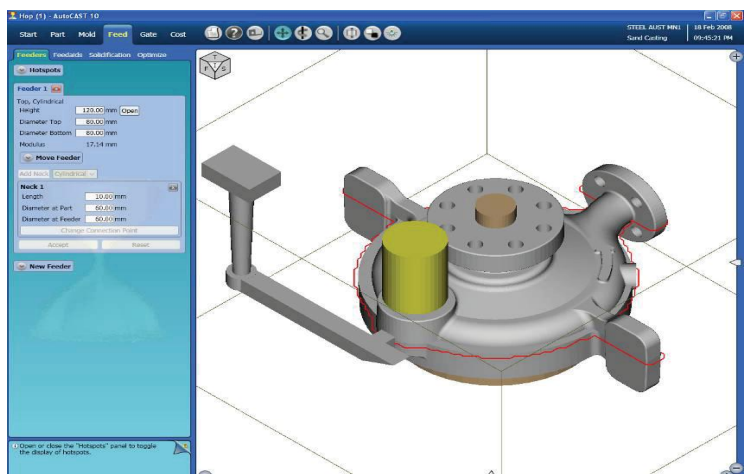


Fig.5.9 Method design and model.

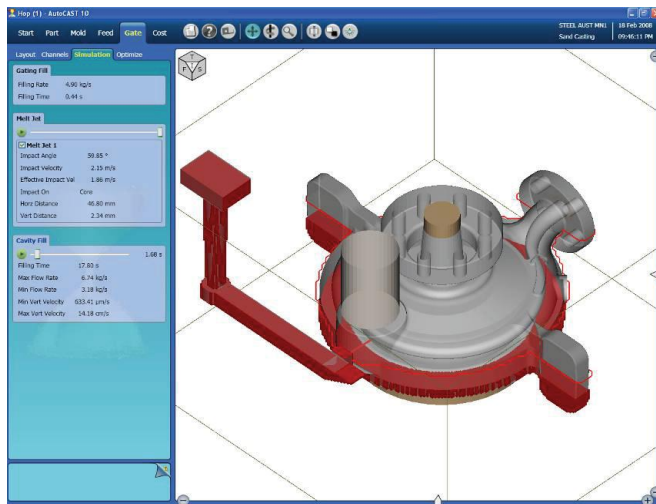


Fig.5.10 Melt jet path and mold filling.

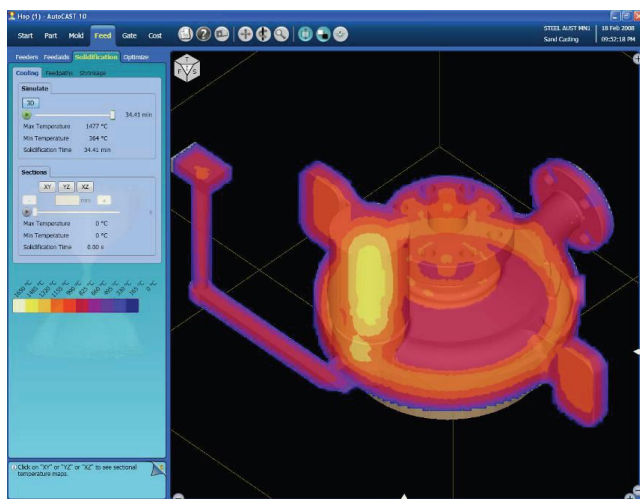


Fig.5.11 Casting solidification simulation.

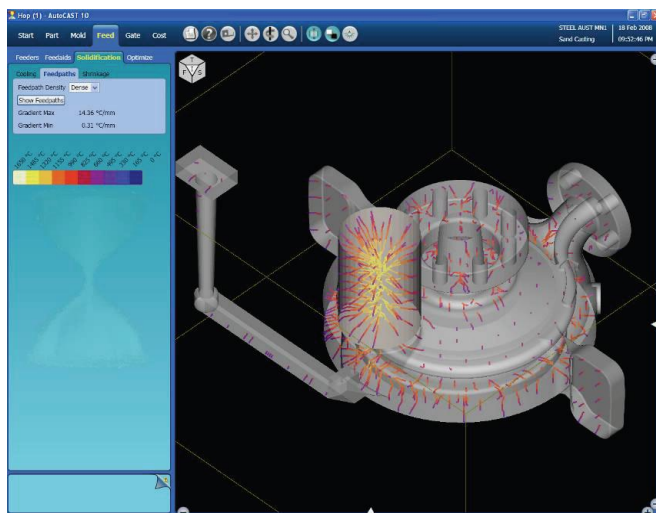


Fig.5.12 Feed metal paths (gradients).

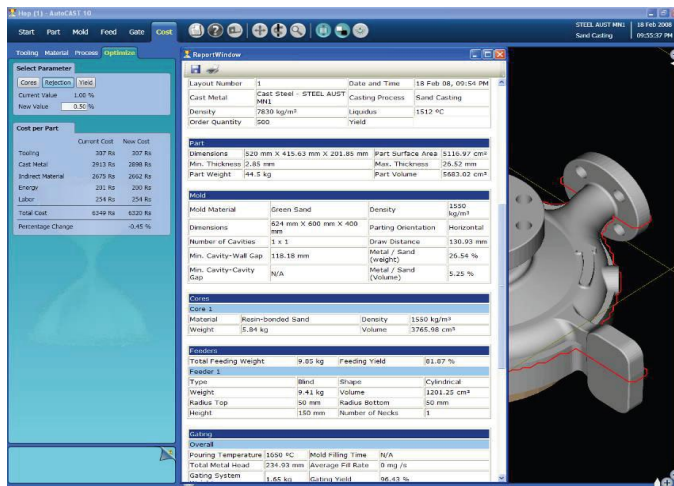


Fig.5.13 Cost analysis and method report.

Review Questions on Chapter Five

1. List five predesign considerations in design
2. Schematically represent techniques used in promoting directional solidification
3. What is the purpose of design in production of castings.
4. List the stages on which a casting comes to be used
5. List some important considerations used by designers of castings
6. Draw and label the major routes in the production of engineering components
7. List some technical aspects of making sound castings
8. What is 3D Printing? How is it applied in foundry technology or production of castings
9. What do we mean by process and alloy selection in design of castings?
10. Explain cast-fabricated construction
11. Write short notes on the following: surface treatment of castings, property criteria in design, and mechanical properties specification in design
12. Explain computer-aided method of design in today's modern foundry using AutoCast software to explain for clarity.

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CHAPTER SIX

POURING AND GATING DESIGN

Feeding of Metal in Sand Moulds

To take care of feeding problems, particularly when casting is complex in size and shape, is the most important aspect to ensure sound castings. Problems are encountered because of slow rate of heat abstraction from a large mass of metal. This results in minimizing temperature gradients and difficulty in obtain solidification in directional manner towards the feeder. While it is easy to obtain directional solidification with alloys which have short freezing range, it is quite difficult with alloys having wide freezing range. Location of feeders and risers, to supply hot liquid to thicker sections which may become isolated during solidification, and to establish temperature gradients initially, is very important. Sometimes temperature gradients can be established artificially by using chills within the moulds, insulating pads and tapered sections. It may be noted that shrinkage cavities are likely to form in sections like T_s and crosses etc. which take longer to solidify because in such cases, volume of metal is more and surface area through which heat can escape is reduced. The solution, therefore, lies in providing shapes in which volume of metal is decreased and the surface area through which heat can escape is increased. In the case of crosses, best results can be obtained either by staggering the location of ribs, or introducing a cored hole at the centre of cross, or using a circular web whose walls are thinner than straight ribs. It must be ensured that last portion to solidify will be fed with metal from feeder. Design, sizing and location of feeders, gates and channels is, therefore, most important. Usually feeding problems are best solved by experience, yet some scientific and empirical rules developed with experience will be found to serve a good guide in tackling this problem.

i.) Heat Transfer Approach (Square Root time effect)

$$\text{Heat transferred per unit area} = cvt \quad \text{.....} \quad (6.1)$$

where t = solidification time, c = mould constant and is a measure of the chilling power of different mould materials. Its value is also dependent upon interface temperature.

$$\text{Also thickness of uniform skin} = \frac{c\sqrt{t}}{L\rho} \quad \text{.....} \quad (6.2)$$

where L = Latent heat of fusion and ρ = density.

ii.) Chvorinov's Rule

According to Chvorinov's rule, thickness of a uniform skin

$$D = \frac{V(\text{Volume})}{S(\text{Shape})} = \frac{c\sqrt{t}}{L\rho} \text{ or } \frac{V}{S} = K\sqrt{t} \text{ where } K = \frac{c}{L\rho} = \text{Constant or } t \propto \left(\frac{V}{S}\right)^2 \quad \text{.....} \quad (6.3)$$

Thus, for any shape where the same interface boundary conditions hold, according to Chvorinov's rule, solidification time is directly proportional to the square of the ratio of volume to surface area.

In order to ensure that metal in feeder solidifies last, $\left(\frac{V}{S}\right)^2_{\text{Feeder}} > \left(\frac{V}{S}\right)^2_{\text{casting}}$

For same volume, solidification time will progressively increase for the following shapes in order because their surface areas for same volumes decrease: plates, bars, cuboids, short cylinders, spheres. Though theoretically sphere takes longest to solidify but is not feasible for feeders. Short cylinder is nearest approached and it is tapered to facilitate moulding.

Design for Soundness

The importance of sand casting is increasing day –by-day as the scientific research has brought about lot of applications and adaptations in the field of casting industry. This is probably the easiest and most convenient way of giving the desired shape to the metal. Sand is the most commonly used material, because it can be easily packed to any shape, has high permeability and resistance to high temperatures. Thus complex shapes can be easily cast by using sand moulds which might not be possible otherwise. In order to secure the optimum cost and quality benefits, the following design details should be given due consideration:

Automated Pouring Systems

In order to achieve the low material and labour costs, increased productivity, better quality and better working conditions, trend is towards automation of complete foundry. Recently attempts have been made for automated induction pouring systems. Automated pouring systems, act as interface between mould-making and melting. These systems hold the molten metal ready for pouring, and pour the molten metal into the mould exactly as required

The induction pouring furnaces, using controlled stopper to pour the molten metal direct to the mould or in dosed quantities into intermediate casting ladles, are used for this purpose and these possess the following characteristics. Keep the temperature and chemical composition of the molten metal constant during holding and pouring; eliminate slag inclusions from the poured molten metal; add inoculates and alloying materials at the right time and in exactly measured quantities; adjust the pouring rate to the intake capacity of the mould; measure the weight of the poured metal exactly, and adjust pouring to the mould transport.

Such a pouring furnace consists of a cylindrical shell with refractory lining, pressure-sealed cover, flanged channel indicator, stopper and a pressure control system. Filling and pouring is through siphon shaped ducts whose bottom ends are located at the base of the furnace, to ensure virtually slagfree pouring. Pressurised gas forces the molten metal into the furnace's pouring nozzle through a stopper. The pressurized gas also keeps the level of the molten in the nozzle constant irrespective of varying quantity of metal in the furnace. The rate of metal pouring is controlled by the movement of stopper (Jain, 2009).

A pneumatic servo-cylinder adjusts the stopper travel continuously in accordance with the pouring program. Since the pouring positions are not always the same, the furnace is able to move in two directions (longitudinal and transverse) relative to the moulding plant. A hydraulic tilting device allows the furnace to be completely emptied. The angled inductor is flanged to the base of the furnace. The flange is water-cooled. Due to the tendency for the hotter metal to rise, the area around the throat is largely free of crust formation, making it accessible for mechanical cleaning. The inductor itself is easily accessible from the outside of the furnace. Because of its relatively low

overall height, the furnace does not have to be placed in a pit, but can be installed on the floor of the foundry.

The filling and pouring siphons are also easy to clean mechanically. The suspended oxide particles produced in the siphon ducts, particularly when the molten metal is treated with magnesium, are deposited on the refractory lining. The upper part of the filling and pouring siphons are therefore flanged for easy cleaning. The induction pouring furnaces eliminate slag inclusions, ensure required pouring rates, measure the weight of the molten metal exactly and keep the temperature of the melt constant during pouring. The molten metal must be poured at a rate matched to the intake capacity of the mould. Among the latest foundry advances is electronic monitoring of the pouring process, which can be either open-loop controlled using the teach-in principle or close-loop controlled by regulating the mould gate level. Productivity can be significantly increased by using intermediate ladles, operated either as tilting systems or with stopper control when special demands are made on the pouring process. Modern, automated pouring systems allow continuous foundry operation by holding the molten metal ready for pouring at all times and ensuring that it is poured into the mould exactly as required.

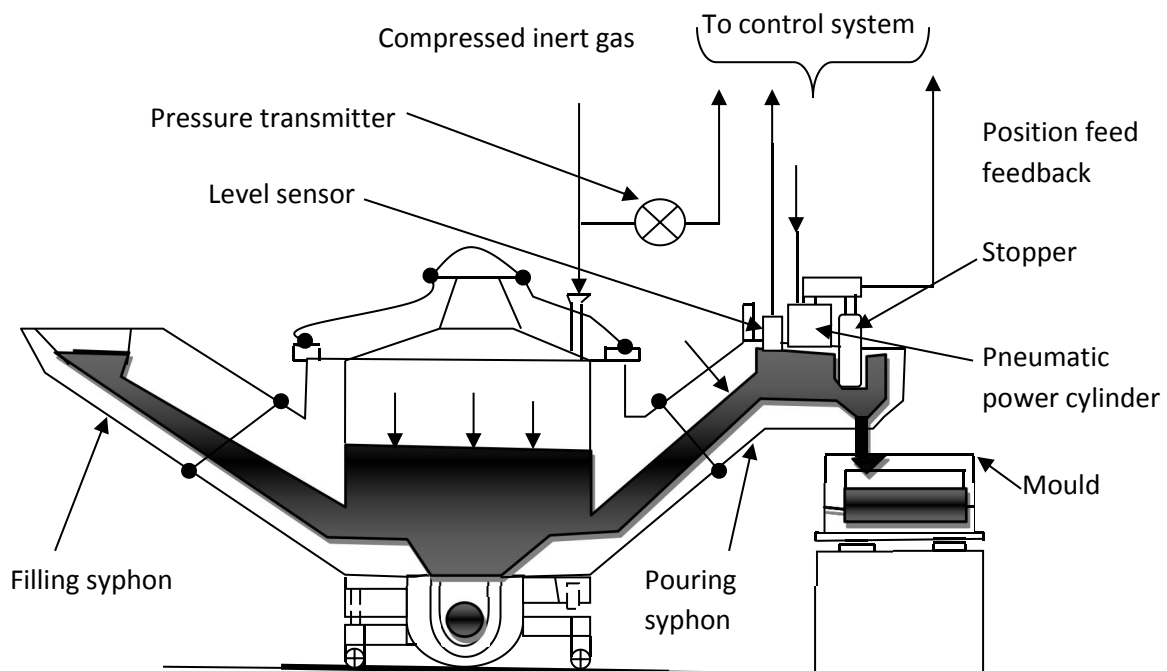


Fig.6.1 Automated pouring system

Gating Provision

A sand casting is produced by pouring the molten metal into the mould through a port called “gate”. It is the conventional practice to locate the gate either at parting line or in the lower most portion of the casting. The gating system (comprising of pouring basin, sprue, runner, gates etc.) achieves the following purposes:

1. It is to make the process of pouring easier
2. It is to avoid turbulent flow

3. It is to avoid washing the sand from the sand mould
4. It is to avoid inclusions or dross

This can be explained further

- i). To direct the molten metal into the mould with minimum turbulence. Excessive turbulence causes aspiration of air and formation of dross.
- ii). To fill the mould system completely. (it should do so with least disturbance, thereby promoting cleanliness and reducing oxidation).
- iii). To distribute the metal with the least disturbance in order to reduce erosion of the mould material and consequent sand inclusions.
- iv). To skim or separate dross or other foreigner matters i.e., as the metal flows through the gating system, loose sand, oxides and slag should be prevented from entering the cavity of mould by providing skimming action. (it is desirable that the appendages which hinder the flow of metal should not be used. Also the thin cores or dividing walls, which might spall when subjected to hot metal be avoided in design). Heavier sections must be fed with sufficient hot metal through heads and risers to compensate for the shrinkage allowance.

According to Clegg (1991) the system of channels in the mould through which the metal passes into the mould cavity is termed the gating or running system and typically comprises the elements shown in Fig.6.2 and Fig. 6.3. Good gating system practice is essential if casting scrap is to be minimized and metallurgical integrity optimized. The importance of the gating system is emphasized by the list of defects which can be attributed to incorrect gating system practice. Casting defects which can be attributed to incorrect gating system practice are as follows:

- i. Sand, slag, dross inclusion,
- ii. Rough surface finish- including metal penetration.
- iii. Entrapped gases,
- iv. Excessively oxidized metal,
- v. Localised shrinkage (pipes in ingate)
- vi. Dispersed or micro-porosity,
- vii. Cold laps-non-fusion of converging streams and,
- viii. Misruns.

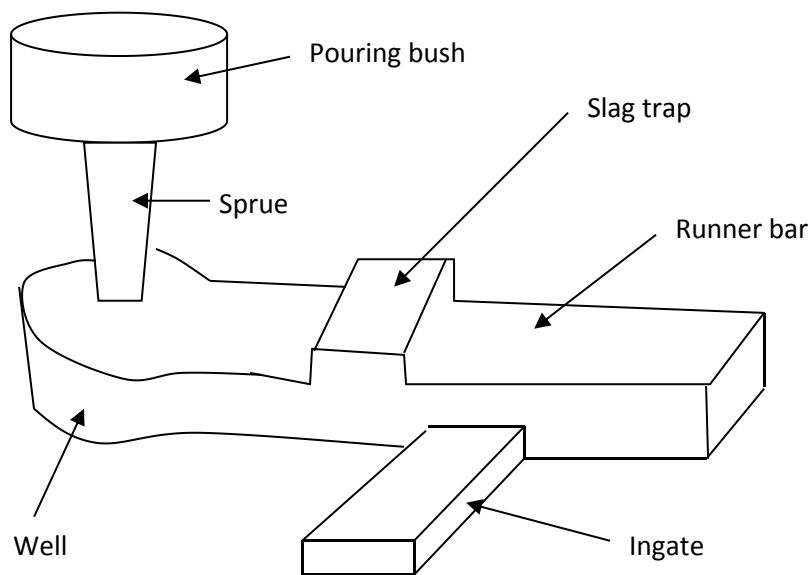


Fig.6.2 Schematic representation of a gating system

Requirements of an Ideal Gating System

As already mentioned gating system includes pouring basin, sprue, runners, risers, and gates. The gating system should promote temperature gradients favourable for directional solidification (Fig. 6.3). Entering velocity of metal should be least and free of turbulence to avoid erosion of the mould and core surfaces. Gating system should be rammed as hard as or harder than the mould cavity. Various parts of the gating system should be rounded, smooth and streamlined to prevent turbulence and erosion. It should avoid the formation of oxides and other dross and kept free of loose sand and prevent their passage on to casting. A runner should be extended some distance beyond the last gate to trap any dross from the first flow of metal. The dross and slag present in the ladle should not be carried to the mould cavity. The gating system should avoid the entrainment or absorption of air/gases into the metal while passing through it. Metal with excessive superheat may increase the gas content of the metal and may produce more dross and adversely influence directional solidification. The gates should lead metal to the heavier sections of a casting, preferably below or through a riser. Finally gate should be practicable and economical to make.

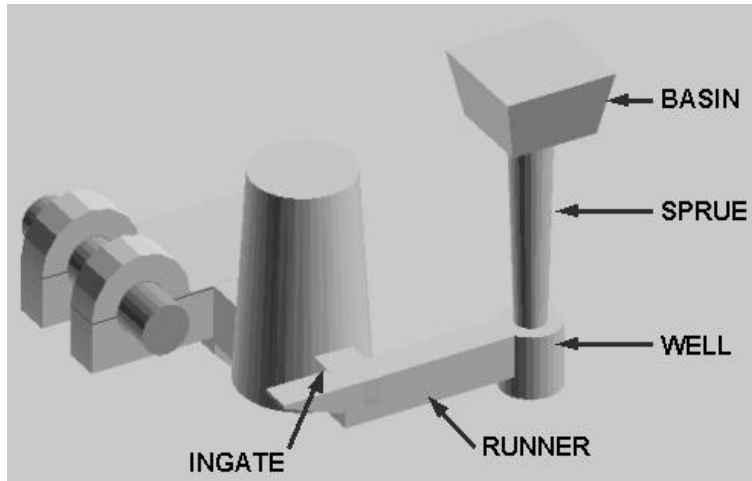


Fig. 6.3 Major Elements of a Gating System (Ihom *et al.*, 2014)

Pouring System

The important points to be considered in the design of pouring system of castings are:

- i). Liquid flow should not damage (erode) the mould walls
- ii). Liquid should not carry sand or gross into the casting
- iii). Aspiration of gases into the stream of molten metal should be avoided
- iv). Pouring of metal with minimum loss of temperature and establishing temperature gradient on the mould surfaces and within the metal to help the directional solidification towards the riser.

All this can be achieved by suitable design of the gating system and proper pouring system. In order that no air is absorbed by the liquid metal on its downward passage in gate, the shape of the gate should be such that the pressure of the liquid at any point in the gate passage is not below the atmospheric pressure. This is possible when sides of the down gate are made hyperboloid in section. Since hyperbolic shape is difficult to produce, taper section with more diameter at top and smaller at bottom can serve the purpose. In actual practice a pouring basin is provided at top and metal is fed via tapered vertical sprue and a short horizontal gate as shown in Fig.6.3. This arrangement minimizes oxidation and reduces the damage to the mould cavity because the force of the incoming metal is reduced.

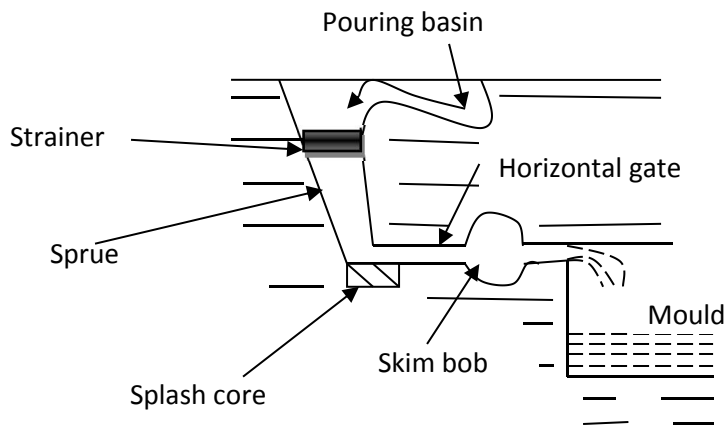


Fig.6.3 Top pouring basin

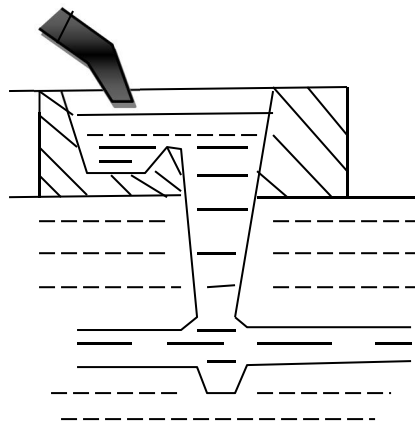


Fig.6.4 Sprue design for negligible aspiration and turbulence.

The sprue cross-section may be circular, square or rectangular. The size of the sprue usually varies from 10 mm square for small castings (below 12 kg) to about 20 mm square for heavy castings. The size of the sprue should be enough so that it is kept full during the entire pouring operation, and the metal does not enter the mould cavity with high velocity causing splattering and turbulence. If the sprue is straight having sharp corners, severe aspiration resulting in turbulence in the metal occurs. Aspiration is negligible with no turbulence, if the sprue is tapered, corners rounded, sprue-well provided and dam type pouring basin made.

Pouring basin also reduces the eroding effect of the liquid metal stream coming directly from furnace and it helps in maintaining a constant pouring head. A ceramic strainer could be placed at the top of the sprue to remove dross. A ceramic splash core could be placed at the bottom of the sprue to reduce the eroding force of the liquid metal stream. A skim bob trap placed in a horizontal gate could be provided to prevent heavier and lighter impurities from entering the mould.

Gating Design

Gate is defined as opening from runner (common passage way to supply metal to number of cavities) to the mould. The size and location of gate should be such as to ensure quick filling of mould, distribution of metal in the mould cavity at a proper rate, without excessive temperature loss,

turbulence, minimum erosion of mould, without entrapping gases and slags, no development of cracks on cooling, and easy removal of gate without damaging casting.

To prevent loose sand and dross from entering the mould cavity and to allow the metal to fall in a small stream, a large size pouring basin is provided on the top of the sprue –cum-riser or a strainer core could be fitted in the pouring basin. If metal is poured very slowly in a mould cavity, then solidification may start while it is not even completely filled up. If poured very fast, high velocity will erode mould surface. Thus optimum pouring velocity is essential. Gates, depending on their position may be top, parting and bottom type. In the case of top gating the molten metal is poured down the head or riser. Thus erosion of mould by dropping metals should be ensured by making hard mould. In this case hot metal remains at top and thus proper temperature gradients are established for directional solidification towards the riser. Top gate may be made to serve as riser.

Top gates are usually limited to small and simple mould or large castings made in moulds of erosion resistant material. Top gating is not advisable for light and oxidisable metals like aluminium and magnesium because of fear of entrapment due to turbulent pouring. In the parting line gating system, the metal enters the mould cavity at the same level as the mould joint or parting line. The sprue is connected to the casting through a gate in a horizontal direction. It is thus possible to provide skim bob or skim gate to trap any slag or sand in the metal. The choke serving as a restriction controls the rate of flow. In the bottom gating system, the molten metal flows down the bottom of the mould cavity in the drag and enters at the bottom of the casting and rises gently in the mould and around the cores. Bottom gates are best suited for large sized steel castings. Turbulence and mould erosion are least in this case. However, time taken to fill up mould is more. Directional solidification is difficult to achieve in bottom gating because the metal continues to lose its heat into the mould cavity and when it reaches the riser, metal becomes much cooler (see Fig.6.5 and Fig. 6.6 for the different gating design types).

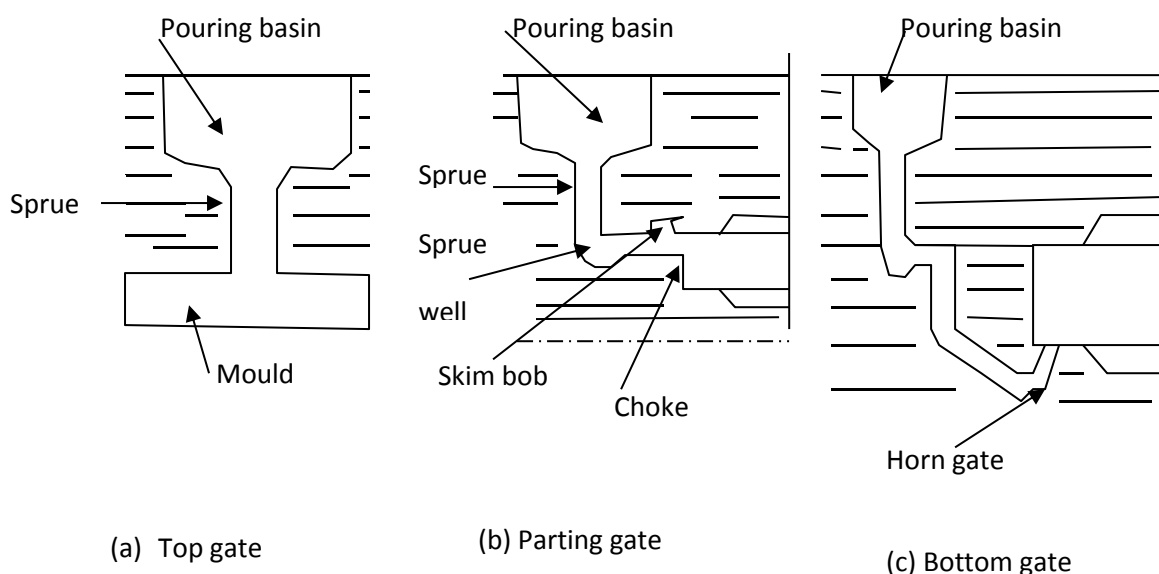
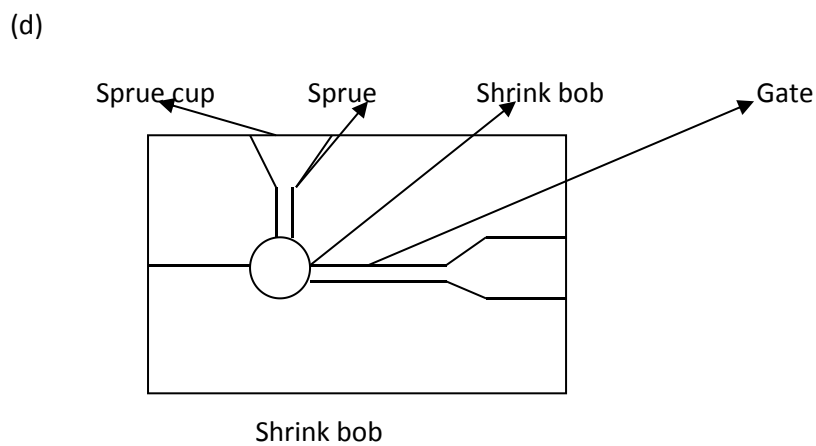
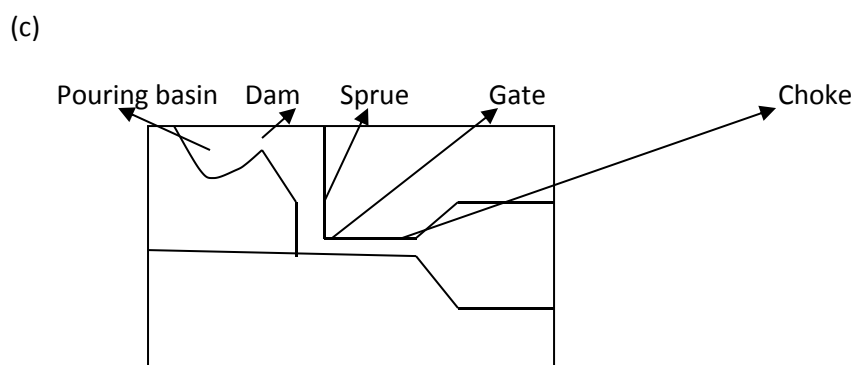
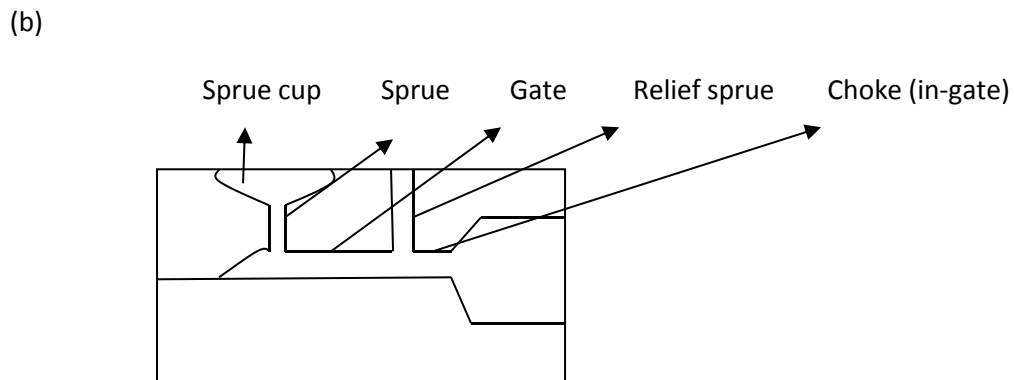
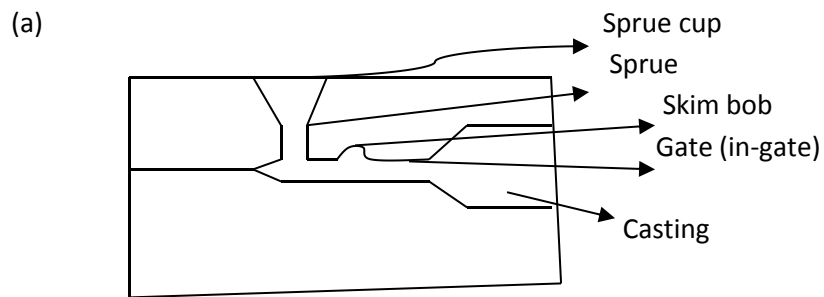
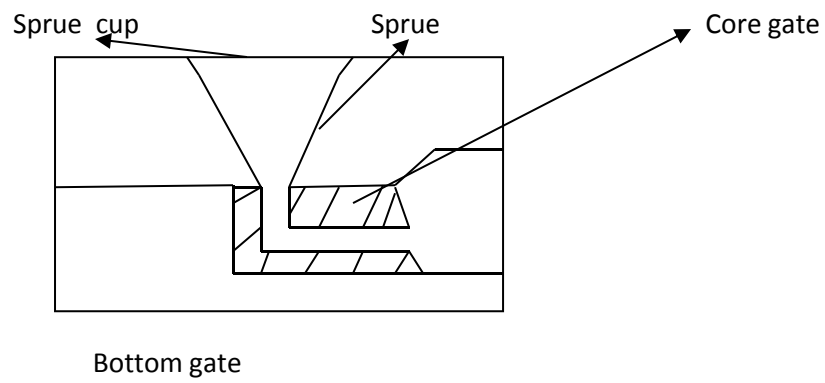


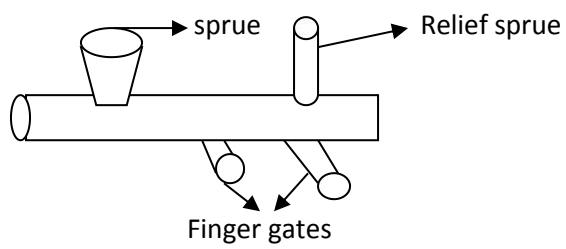
Fig. 6.5 Top gate, parting gate and bottom gate designs



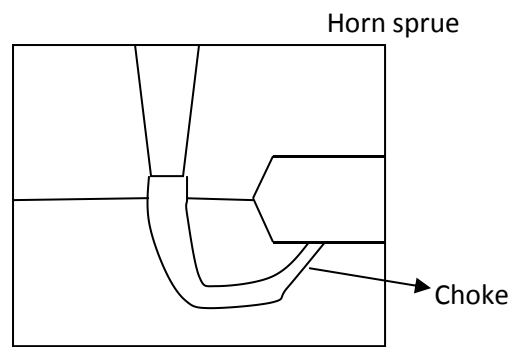
(e)



(f)

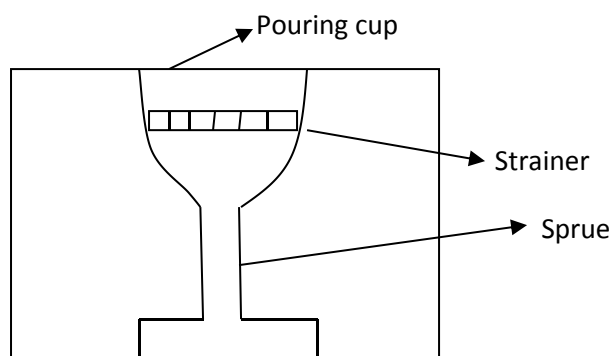


(g)



Bottom type of pouring

(h)



Top pouring

Figure 6.6: Shows various gating designs

The parting line- the line separating the drag and the cope. The metal flows through the sprue to the parting line and it fills the cavity. Skim bob is also called relief sprue, it collects dross or slag that is contained in the melt. The sprue cup depends on the amount of the melt and the pattern. See figure 6.6 (a).

The gate at the choke is smaller this is to produce a greater velocity. Figure 6.6 (b) differs from Fig.6.6 (a) in that the relief sprue comes to the top. Figure 6.6 (d) has a shrink bob which serves the dual purpose of slag and dross collector and metal reservoir to feed the casting as it shrinks. Figure (e) has a bottom gate, the gate enters the casting cavity at the bottom of the drag half of the mould in fact the bottom gate is normally advocated for steel casting in particular to reduce erosion and gas entrapment and to reduce splashing which can result in cold shots. Branch gates are also obtainable see Figure 6.6 (f). the branched gate is design to feed a single casting at several places or points or a number of individual castings. Figure 6.6 (g) shows the horn type of pouring, one objective of this type of pouring is that it has the tendency of fountain effect on casting. It does not require any core. Figure 6.6 (h) shows top pouring or top gating system the disadvantage is in velocity variation, the metal enters the mould from above. It has a strainer core which is designed to break-up the metal stream so that it can enters the mould cavity with minimum turbulence and erosion. Pouring cups are frequently made of baked sand cores and strainer core, splash cups are also made baked. Sand cores since they must withstand considerable amount of erosion from the molten metal and pressure from the flowing molten metal; binders are used to hold the sand particles together. Tars are also used. The strainer core can be made in the form of a filter, sieving is very important.

Aspiration Effect

In a faulty mould design, the metal velocity may be high and thus pressure may fall below atmosphere and the gases originating from baking of organic compounds may alter molten metal stream, producing porous castings. Two cases are possible in moulds where negative pressure may be experience. One is in the sprue design and other where sudden changes in direction of flow takes place. Referring to Fig.6.7 it will be seen that pressure at points 1 and 3 is atmospheric. By Bernoulli's theorem, it will be negative at 2, if sprue is as shown by dotted lines. To overcome this problem sprue should be made tapered, preferably with curve as shown in firm line between 1 and 2. Other condition is shown in Fig. 6.8, where due to change in direction of flow of metal, vena contract effect is experienced. To avoid negative pressure in this region the shape of mould should be as per vena contract profile.

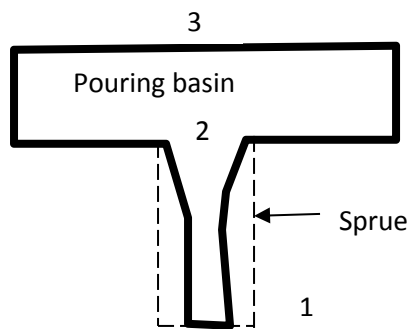


Fig.6.7 Negative pressure in sprue design

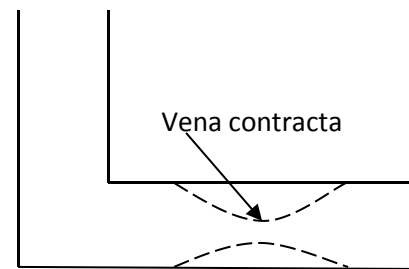


Fig. 6.8 Negative pressure on sudden change in direction of flow

Gating Ratio

Gating ratio is defined as the ratio of sprue area to total runner area to total gate area. A gating ratio of 4:3:2 results in pressurized system. In this system, the proportions of sprue, runner and gate cross-sectional area are so arranged that back pressure is maintained on the gating system by a fluid film restriction at the gates. This system is adopted for metals like steel, iron, brass etc. the pressurized gating system is kept full of metal. The back pressure due to restriction at the gates tends to minimize danger of the metal pulling away from the mould walls with consequent air aspiration. Pressurised systems are generally smaller in volume for a given metal flow rate than unpressurised ones. Thus, less metal is left in the gating system and casting yield is higher. However, severe turbulence may occur at junctions and corners unless careful streamlining is employed. High velocity and turbulence result in entrapment, dross formation and mould erosion.

In case of unpressurised system the primary restriction to the fluid is at or very near to the sprue. The gating ratios like 1:3:3, 1:2:2 will produce an unpressurised system. Such a system is adopted for light, oxidizable metals like aluminium and magnesium where the turbulence is to be minimized by slowing down the rate of metal flow. In the case of unpressurised systems careful design is required to ensure them being kept filled during pouring. Drag runners and cope gates aid in maintaining a full runner, but careful streamlining is essential to eliminate the separation effects and consequent air aspiration.

Directional Solidification

As the molten metal in the mould cools down it solidifies and contracts in volume. Since all the parts of a casting do not cool at the same rate due to varying sections, varying rate of heat loss to adjoining mould walls etc., voids and cavities are liable to be formed in certain regions of the casting. In good casting design these voids are filled up with liquid metal from the portion of the casting which is still liquid. Thus solidification should continue progressively from the thinnest section which solidifies first towards the risers which should be the last to solidify. This process is known as 'Directional Solidification', which is aimed at producing sound castings. Directional solidification can be ensured by designing and positioning the gating system and risers properly, increasing the thickness of certain sections of the casting by the use of padding, using exothermic materials in the

risers or in the facing sand around certain portions of the casting, using chills in the moulds. The impurities can be prevented from travelling into the casting by observing the following:

- i. Provision of pouring basin of adequate size helps in breaking down the eroding force of the stream of molten metal as it is being poured from ladle. A proper design of pouring basin regulates the rate of metal entry, allows the metal to flow into the sprue smoothly and prevents turbulence
- ii. Provision of ceramic strainer in down sprue helps in preventing dross from the ladle entering the casting
- iii. The maximum impact is felt at the bottom of vertical sprue from where sand is likely to be eroded and enter into mould. This can be prevented by providing ceramic splash core at bottom of vertical sprue
- iv. Sharp corners in metal flow path should be streamlined to avoid turbulence and dead pockets (refer Fig.6.5)
- v. Provision of skim bob helps in trapping both heavier and lighter impurities flowing towards the casting

Section Thickness

The minimum section thickness which can be poured for various metals is limited because of differences in solidification temperatures and fluidity. Minimum section thickness which will provide the necessary strength or weight, without requiring excessive temperatures to ensure running must be used. The normal values of minimum thickness for castings of simple design are 3 mm for cast iron, 2.25 mm for malleable iron, 6 mm for steel, 2.25 mm for brass and bronze, and 3 mm for aluminium. If length of flow is more, then larger thickness than values given above have to be provided. The minimum value of thickness for obtaining sound castings will be high if there are intricacies in the mould cavity. There should be as great uniformity of metal section between bosses and lugs and the body of the casting as possible in order to permit adequate feeding of boss or lug.

Fluid Flow

Gating system design is based on the laws of fluid mechanics, although these assume that incompressible fluids are transported through channels with impermeable walls. Despite the fact that liquid metals are frequently transported through permeable channels and are concurrently losing heat, the laws of fluid mechanics can, with certain exceptions, be used as the basis for gating system design. The two laws which provide the basis for gating system design are the Law of Continuity and Bernoulli's Theorem. The former states that the volume rate of flow is constant throughout the system and is a function of linear velocity and cross-sectional area of the flow passage. Thus, if the cross-sectional area decreases, the velocity must increase to maintain the flow rate, or vice versa. Bernoulli's Theorem states that the total energy of a unit weight of fluid is constant throughout a system. This energy is a function of the potential, kinetic and pressure energies, and can be summated for any point in the system. From Bernoulli's Theorem it is possible to derive an expression which relates the velocity of the metal at any point in a gating system as a function of the distance of fall from a datum point, such as the pouring bush.

Consider a liquid metal flowing through a tapered gating system

If the liquid is continuously flowing through the channel, the quantity of liquid passing per second is the same at all sections i.e.

$$Q_1 = Q_2 = Q_3 = \dots \text{ or } a_1 \cdot v_1 = a_2 \cdot v_2 = a_3 \cdot v_3 = \dots \text{ and so on (Khurmi, 2006) } \dots \quad (6.4)$$

Where Q is the discharge at any section (1, 2, 3....), a is the cross sectional area of the channel at any section (1, 2, 3...), v is the average velocity of the liquid metal at any section (1, 2, 3...)

Let us take this example

Liquid metal is flowing through a channel in the gating system of 100 mm diameter with an average velocity of 10 m/s. Determine the rate of discharge of the liquid in litres/s. Also determine the velocity of liquid metal at the other end which is the mould cavity, if the diameter of the cavity is gradually changed to 200 mm.

Solution

Given: $d_1 = 100 \text{ mm} = 0.1 \text{ m}$; $v_1 = 10 \text{ m/s}$ and $d_2 = 200 \text{ mm} = 0.2 \text{ m}$

Rate of discharge

We know that the cross-sectional area of the pipe at point 1,

$$a_1 = \frac{\pi}{4} \times (d_1)^2 = \frac{\pi}{4} \times (0.1)^2 = 7.854 \times 10^{-3} \text{ m}^2$$

$$\begin{aligned} \text{and rate of discharge } Q &= a_1 \cdot v_1 = (7.854 \times 10^{-3}) \times 10 = 78.54 \times 10^{-3} \text{ m}^3/\text{s} \\ &= 78.54 \text{ litres/s Ans.} \end{aligned}$$

Velocity of liquid metal at the mould cavity

We also know that cross sectional area of the mould cavity at point 2 is

$$a_2 = \frac{\pi}{4} (d_2)^2 = \frac{\pi}{4} \times (0.2)^2 = 31.42 \times 10^{-3} \text{ m}^2$$

$$\text{And velocity of liquid metal at point 2, } v_2 = \frac{Q}{a_2} = \frac{78.54 \times 10^{-3}}{31.42 \times 10^{-3}} = 2.5 \text{ m/s} \quad \text{Ans.}$$

The velocity of a metal stream is important for several reasons. Firstly, consider a metal stream leaving a pouring bush to travel vertically downwards through a sprue. From Bernoulli's Theorem we can predict that the velocity of the metal stream will increase as it falls. The law of continuity tells us that the cross-sectional area of the stream will decrease in order that the volume rate of flow remains constant. In consequence, the metal stream will leave the sides of the sprue and, if the mould is permeable and cast in air, air will be aspirated through the mould walls and be occluded into the metal stream, or cause excessive oxidation when turbulence occurs at the sprue base. Tapered sprues are advocated to overcome this problem.

High velocity streams are erosive in nature and likely to dislodge particles of mould material. They are also likely to cause penetration of the metal into the mould material when they impinge upon it. On the other hand, low velocity streams are more susceptible to aspiration and less likely to completely fill the mould cavity. Practical gating systems must take these issues into account. They are most commonly defined by their gating ratio, which is the ratio of the cross-sectional areas of the sprue, runner bar, and ingate. System employing multiple gates present their own problems in respect of balanced flows.

Bernoulli's Equations

The factors that must be recognized when designing a gating system are, gas contamination which include dross or slag, aspiration of gas or sulphur and hydrogen. There are problems concerned with fluid flow and the understanding of fluid flow will help to improve any gating system liquid flow either in stream line, laminar fashion or in a turbulent manner whether smooth or turbulent flow depending upon the velocity of the liquid, the cross sectional area of the flow channel and the viscosity of the liquid the relationship is expressed as the Reynolds number.

Laminar flow of a liquid metal in the mould is when the viscosity of fluid is dominating over the inertia forces. It is also known as a viscous flow. A laminar flow can best be understood by the hypothesis that liquid moves in the form of concentric cylinders sliding one within another.

Turbulent flow: it is a flow, in which the inertia force is dominating over the viscosity. It is a practical flow which comes in contact with the engineers.

Critical velocity: it is a velocity at which the flow changes from the laminar flow to the turbulent flow. It has lower and upper critical velocity.

Prof. Reynold, after carrying out a series of experiments, found that if Reynold's number for a particular flow is less than 2000, the flow is a laminar flow. But if Reynold's number is between 2000 and 2800, it is neither laminar flow nor turbulent flow. But if Reynold's number exceeds 2800 the flow is a turbulent flow. It may be noted that the value of critical velocity corresponding with $R_N = 2000$ is for a lower critical velocity and that corresponding with $R_N = 2800$ is for a higher critical velocity.

Reynolds Number (R_N)

$R_N = \text{mean velocity of flow} \times \text{diameter of tube} \times \text{density of liquid} / \text{kinematic viscosity of liquid}$

$$= \frac{\text{Inertia forces}}{\text{Viscous forces}} = \frac{\rho v^2}{\frac{\mu v}{d}} = \frac{\rho v d}{\mu} = \frac{v d}{\nu} \quad \dots \left(\because \nu = \frac{\mu}{\rho} \right) \quad \dots \dots \quad (6.5)$$

Example 6.4

Liquid metal having kinematic viscosity of 21.4 stokes is flowing through a mould channel of 300 mm diameter. Determine the type of flow, if the discharge through the channel is 15 litres/s.

Solution

Given: $\nu = 21.4 \text{ stokes} = 21.4 \times 10^{-4} \text{ m}^2/\text{s}$; $d = 300 \text{ mm} = 0.3 \text{ m}$ and $Q = 15 \text{ Litres/s} = 0.015 \text{ m}^3/\text{s}$

We know that area of the pipe,

$$a = \frac{\pi}{4} \times (d)^2 = \frac{\pi}{4} \times (0.3)^2 = 0.0707m^2$$

And velocity of liquid metal, $v = \frac{Q}{a} = \frac{0.015}{0.0707} = 0.212 \text{ m/s}$

$$\therefore \text{Reynold's number, } R_N = \frac{vd}{\nu} = \frac{0.212 \times 0.3}{21.4 \times 10^{-4}} = 29.7$$

Since Reynold's number is less than 2000, therefore the flow is laminar. **Ans.**

When Reynolds number reaches a critical value turbulence flow always result for example experience shows that steel always flow under turbulent condition when Reynolds number is greater than 3500. turbulent flow creates such problems as inclusions, dross or slag, aspiration of air into the metal, erosion of the mould wall and roughing of the casting surface. The flow of liquid into a mould is also governed by other variables summed up by the Bernoulli's theorem which says that the sum of the potential energy, the velocity energy, the pressure energy, and the friction energy of a flowing liquid is equal to a constant.

$$Wz + WP_v + \frac{WV^2}{2g} + WF = K \quad \text{..... (6.6)}$$

Where, W is the total weight of fluid flowing in kgs and in tonnes.

Z is the height of liquid in foot, cm, or meter.

P is the static pressure in the liquid in lbf, N/m²

V is specific volume in cm³

g is acceleration due to gravity

V is velocity in ft/sec, etc

F is frictional loss

K is constant.

If all the term are divided by W, we have the dimension of length, considering

1. Potential head (z)
2. Pressure head (Pv)
3. Velocity head ($V^2/2g$)
4. Frictional loss of head (F)

The Bernoulli's theorem is base on the first law of thermodynamics

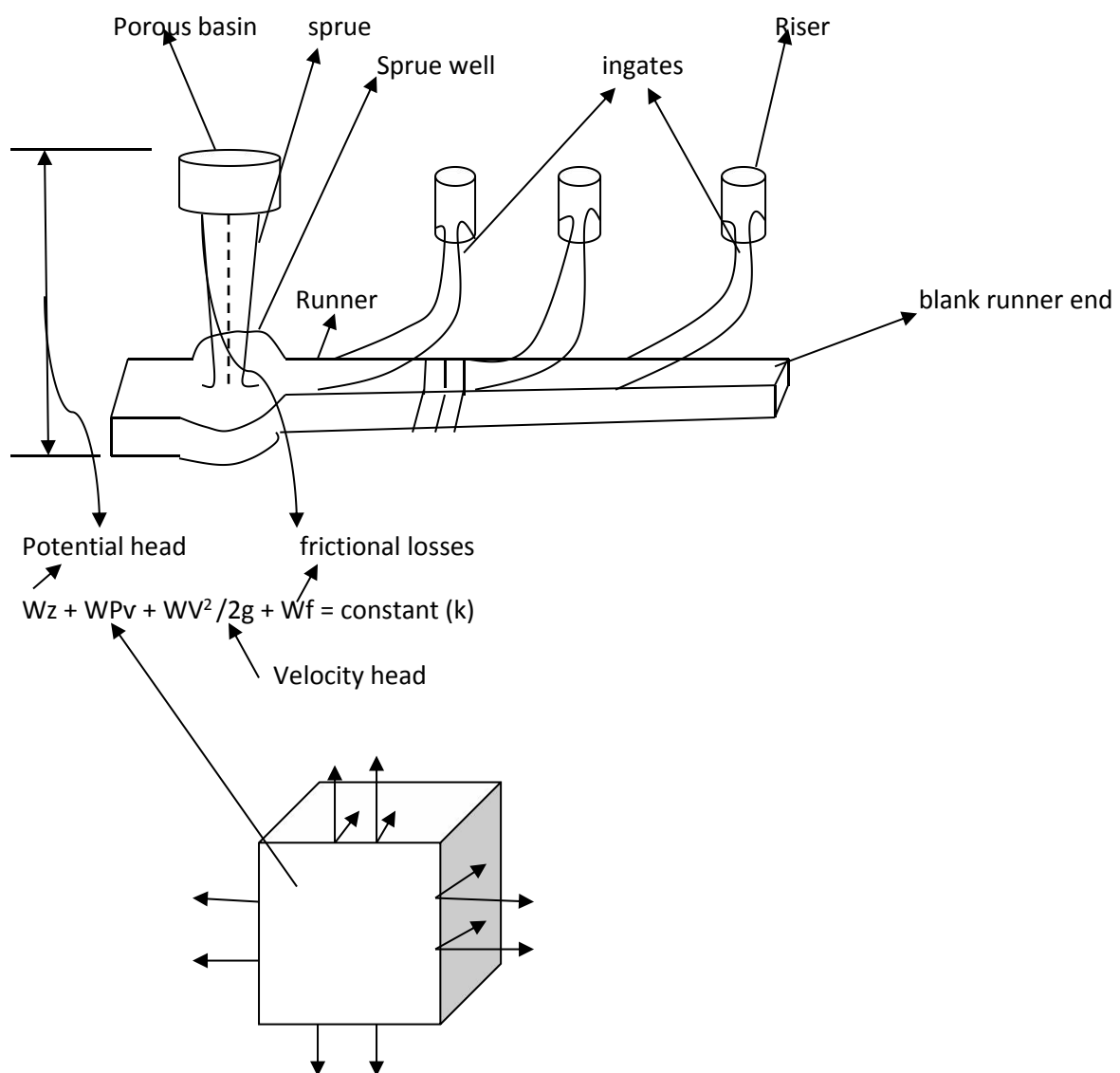


Fig. 6.9. Bernoulli's theorem illustrated in a gating system

The potential energy of the metal can be considered a maximum as the metal enters the pouring cup this form of energy is then rapidly changed to P.E or vel. E and pressure energy as the metal passes through the mould once the flow is established and the potential and frictional head are virtually constant the velocity is high when the pressure is low and vis-visa while the metal is flowing there is a constant loss of energy is the form of fluid friction between the metal and the mould wall. There is also a heat lost that is not represented in the Bernoulli's theorem but which eventually leads to the solidification of the metal.

Example 6.2

Liquid metal is poured through a tapered gating system having end diameters of 150 mm and 50 mm at the in-gate respectively. Find the discharge at the larger end and velocity head at the smaller ingate, if the velocity of liquid metal at the larger end is 2 m/s.

Solution

Given: $d_1 = 150 \text{ mm} = 0.15 \text{ m}$; $d_2 = 50 \text{ mm} = 0.05 \text{ m}$ and $v_1 = 2.5 \text{ m/s}$

Discharge at the larger end

We know that the cross-sectional area of the pipe at the larger end is,

$$a_1 = \frac{\pi}{4} \times (d_1)^2 = \frac{\pi}{4} \times (0.15)^2 = 17.67 \times 10^{-3} \text{ m}^2$$

And discharge at the larger end is,

$$Q_1 = a_1 \cdot v_1 = (17.67 \times 10^{-3}) \times 2.5 = 44.2 \times 10^{-3} \text{ m}^3/\text{s}$$

= 44.2 litres/s **Ans.**

Velocity head at the ingate

We also know that the cross-sectional area of the pipe at the ingate is,

$$a_2 = \frac{\pi}{4} \times (d_2)^2 = \frac{\pi}{4} \times (0.05)^2 = 1.964 \times 10^{-3} \text{ m}^2$$

Since the discharge through the pipe is continuous, therefore

$$a_1 \cdot v_1 = a_2 \cdot v_2$$

$$\text{Or } v_2 = \frac{a_1 \cdot v_1}{a_2} = \frac{(17.67 \times 10^{-3}) \times 2.5}{1.964 \times 10^{-3}} = 22.5 \text{ m/s}$$

$\therefore$ Velocity head at the ingate of the mould cavity is

$$= \frac{v_2^2}{2g} = \frac{(22.5)^2}{2 \times 9.81} = 25.8 \text{ m} \text{ **Ans**}$$

Example 6.3

A circular channel gating system of 250 mm diameter carries a liquid metal of specific gravity 0.8 at the rate of 120 litres/s and under a pressure of 2kPa. Calculate the total energy in meters at a point which is 1 m above the datum line.

Solution

Given: $d = 250 \text{ mm} = 0.25 \text{ m}$; Specific gravity of liquid metal = 0.8; $Q = 120 \text{ Litres/s} = 120 \times 10^{-3} \text{ m}^3/\text{s}$; $p = 2 \text{ kPa} = 20 \text{ kN/m}^2$ and $Z = 1 \text{ m}$.

We know that the area of the pipe,

$$a = \frac{\pi}{4} \times (d)^2 = \frac{\pi}{4} \times (0.25)^2 = 49.09 \times 10^{-3} \text{ m}^2$$

$$\text{And velocity of liquid metal, } v = \frac{Q}{a} = \frac{120 \times 10^{-3}}{49.09 \times 10^{-3}} = 2.44 \text{ m/s}$$

$$\therefore \text{Total energy} = Z + \frac{v^2}{2g} + \frac{p}{\omega} = 1 + \frac{(2.44)^2}{2 \times 9.81} + \frac{20}{0.8 \times 9.81} \text{ m} = 1 + 0.3 + 2.5 = 3.8 \text{ m Ans.}$$

Factors involved in Gating Design

Gating designing is used to produce sound casting. Improper design of the gating system can cause one or more defects like:

1. Sand; slag; dross; or other impurities
2. Rough surfaces;
3. Entrap gases;
4. Excessively oxidized metal
5. Localised shrinkage
6. Dispersed porosity and microporosity
7. incomplete fusion of liquid metal where two streams meet
8. Entrapped globs of pre-solidified metal (cold shots)
9. Unfilled moulds (misruns)
10. Metal penetration in sand mold or core

The gating system is therefore designed to accomplish the following objectives.

1. Fill the mould rapidly without lapse requiring high pouring temperature
2. Reduce or prevent agitation or turbulence and the formation of dross in the mould
3. Prevent slags dross scums or eroded sand from entering the casting by way of the gating system
4. Prevent aspiration of air or mould gases into the metal stream
5. Avoid erosion of moulds and cores
6. Aid in obtaining suitable thermal gradient to attain directional solidification and minimise distortion in the casting
7. Obtain maximum casting yield and minimum grinding cost (fettling; polishing; or cleaning)
8. Provide for ease of pouring utilizing available labor and crane equipment.

Pouring Time

A slight trickle of metal or metal poured too cold is not desirable because metal will freeze too fast to fill up the mould or will develop cold shots. Very rapid filling of the mold also will present such problems as having adequate gating system to handle a large volume of metal in a short time. Erosion of the mould; rough surface; excessive shrinkage and other possible defects there is therefore an optimum pouring rate or range for most casting that must be established by experience. In conventional casting, it is important to establish the optimum pouring rate, once this is done the next step is the proper proportioning and distribution of the various part of the gating system in order to achieve this rate a metal like steel must be poured fast to prevent premature freezing because of its high freezing range compared with other metal like aluminum and magnesium can be poured more slowly. For example for shell moulding ductile iron (vertical pouring) the

$$\text{pouring time (t secs)} = k_1\sqrt{w} \quad (6.6)$$

where $k_1 = 1.8$ for section from 3/8 to 1 inch. 1.4 for thinner sections. 2.0 for heavier sections. For

$$\text{steel casting the pouring time (t) sec} = k\sqrt{w} \quad (6.7)$$

where $k = 1.2$ for 100lb to 100000lb casting for 0.4 section thickness. This is obtained when casting time is plotted out on a log scale

For Brass and bronze 15- 45 seconds casting time is recommended

Greatest at that point and in some instance there may even be a negative pressure existing at some of the first gate leading towards the casting and actual flow of metal out of the mould back into the runner. Additions to proper Proportioning of the Gates are:

1. To develop enlargement in the gating system to dissipate momentum effect.
2. To bend the runner away from the casting
3. To use a tapered runner

Elimination of Dross and Slag

The use of pouring basin, strainer cores and suitable dams in a gating system helps to filter out slag and dross before it enters the mould cavity. In the case of light metals the differences are some what greater than for copper or ferroalloys since there is a little difference in specific gravity between the impurities and the metal. Enlargement in the feeding system to reduce the velocity of flow or special devices such as the relief gate which relieves the dross and slag.

Risers

Riser is a hole cut or moulded in the cope to permit the molten metal to rise above the highest point in the casting. It provides a visual check to ensure filling up of mould cavity (Jain, 2009). The primary function of a riser is to feed metal to the castings as it solidifies. Grey cast iron needs less feeding in

some alloy because of the period of graphitization which occurs during the final stages of solidification which cause an expansion that tends to counteract metal shrinkage. Steel or white cast iron and many of the nonferrous alloy which have an extended solidification range requires an excessive and some time elaborate feeding system to obtain sound casting.

Table 6.1 Table of Materials and their volumetric Shrinkage

Material	Volumetric Shrinkage
Medium carbon steel	2.5-3.0
1% carbon steel	4.0
Pure aluminum	6.0
Pure copper	4.92
Grey cast iron	1.9- negative depending on graphitization composition
White cast iron	4.0- 5.50

Grey cast iron used for intricate castings swells on solidification. Aluminum –silicon alloys does the same thing. The problem of feeding metal during the entire solidification period of the casting involves a number of variables

1. Riser shape
2. Riser size as a function of casting shape
3. Location of risers
4. Riser connection to the casting
5. Use of chills
6. Use of insulators and exothermic compounds

Chills are metals that conduct the heat away so fast that directional solidification is achieved by the use of chills

Riser Provisions

After the mould has been filled up, metal enters the risers. Risers act as reservoir and heat gradient regulator, and provide the necessary fluid metal to compensate for liquid metal and solidification shrinkage. The risers are usually located at the uppermost part of the section being fed. Depending on the metal being cast, their volume is kept between 25 and 55% of the casting. It is important to note that the risers are suitably located so that there is no necessity for excessive removal of metal to produce the finished contour. Risers are connected to the casting by a neck of metal called gate which enables the riser to be removed easily from the casting after solidification.

Riser Design

If no riser is provided during casting, the solidification will start from walls and liquid metal in the centre will be surrounded by a solidified shell and the contracting liquid will produce voids towards the centre of the casting. Further cooling of the solid in centre sets up undesirable stresses in the

casting. Provision of risers overcomes these problems as these supply molten metal for a solidifying casting. For this purpose, the risers must be large enough to remain liquid after the casting has solidified and must contain sufficient metal to provide for the contraction losses. Further these should be so positioned that they continue to supply metal throughout the solidification period.

Riser Size

A casting loses its thermal energy by transferring it to the surrounding by radiation, convection and conduction. Hence the surface area relative to its volume is important in determining the rate of this heat transfer. This concept was expressed mathematically by Chvorinov as solidification time (t) = square of volume / square of Area = $V^2 / A^2 = (V/A)^2$

This equation indicates that for a riser to have a solidification time equal or greater than that of the casting the minimum riser size will be obtained from a sphere, but cylinders are most often used for risers.

Pouring Basin

When a metal enters the sprue such a metal should be flowing under conditions that the whole thing is full. The ideal thing is that when a metal enters the sprue it should be flowing under conditions that are nearly as good as those which are present when full flow has been established and good results are obtained by

1. Stream lining the pouring basin and providing a dam so that constant conditions are established when a metal enters the sprue
2. Use a strainer core in the basin
3. Use of delay screen or sprue plug

Design and Positioning of Risers

The most efficient shape of a riser of a certain size is that which results in a minimum of the heat loss, thus remaining hot and keeping the metal in molten state as long as possible. In other words, a riser should be designed with the minimum possible volume while maintaining a cooling rate slower than that of the casting. The best shape for the general run of castings to achieve above objective is cylinder. The height of the riser should be tall enough so that any pipe formed in it may not penetrate the casting. The ratio of height to diameter usually varies from 1:1 to 3:2.

The optimum riser diameter for a given casting can be obtained by the following rules:

a). **Chvorinov's Rule:** it states that the freezing time of a casting, i.e., $t = \frac{1}{q^2} \left(\frac{V}{A} \right)^2$

where q = solidification constant, depending on the composition of cast metal and the positioning of the mould cavity, viz., along a vertical or a horizontal axis.

$\frac{V}{A}$ = ratio of volume of the casting to its surface area.

Values of $\left(\frac{V}{A} \right)^2$ and freezing time have been found out by actual experiments for different metals and alloys and for different cylinder diameters and are available in standard hand-books.

Best riser is one whose $\left(\frac{V}{A}\right)^2$ is 10 to 15% larger than that of the casting.

(b). Caine's Method: This method is based on the relative freezing time of the casting and the riser. It defines the relative freezing time of the casting and the riser. It defines the relative freezing time to complete solidification as the ratio of surface area of casting divide volume of the casting : surface area of riser divide volume of the riser.

According to Caine, (1) if the casting solidifies infinitely rapidly, the feeder (riser) volume should be equal to the solidification shrinkage of the casting, and (2) if the feeder and casting solidify at the same rate, the feeder should be infinitely large.

Fig.6.10 shows this hyperbolic relationship between the relative freezing time and relative volume.

$$\frac{\frac{A_c}{V_c}}{\frac{A_r}{V_r}} = \frac{a}{\frac{V_r}{V_c} - b} + c \quad \dots\dots\dots \text{..(6.8)}$$

where a = freezing characteristics constant for the metal = 0.1 for steel

b = contraction ratio from liquid to solid = 0.03 for steel

c = relative freezing rate of riser and casting = 1 if same mould material is used around casting and riser.

For a casting of simple shape, the same curve can be plotted between volume ratio and shape factor $\left(\frac{l+w}{t}\right)$ (where l , w and t denote maximum length, width and thickness of casting respectively).

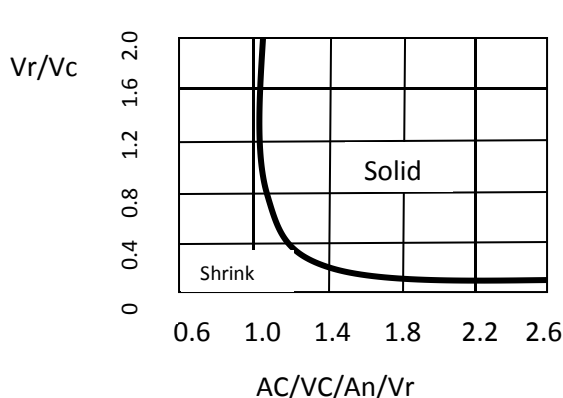


Fig. 6.10 Relative riser and casting geometry for

Obtaining sound steel casting

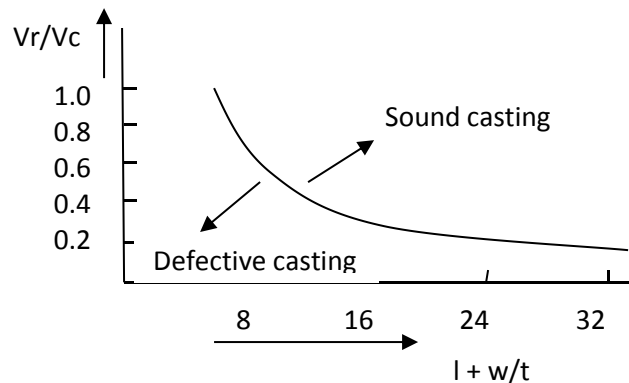


Fig.6.11 Ratio of V_r/V_c to $l + w/t$

Further, for a casting with a low A/V ratio, as in the case of a cube and sphere, one central riser may be able to feed the entire casting. However, when A/V ratio is high, as in the case of a bar and a plate, more than one riser is necessary. Proper location of riser is essential in such a case. For a steel plate of 100 mm thickness, one central riser is adequate if the maximum feeding distance is less

than $4.5t$ from the edge of riser [refer Fig.6.12 (a)]. If more risers are required, distance between two nearest edges of risers should be less than $4t$ [refer Fig. 6. 12 (b)]. For a bar of square cross-section of 50- 200mm side(s), a central riser is good if maximum feeding distance is $30\sqrt{s}$ from the edge and distance between two risers (nearest edges) should be less than $1.2s$.

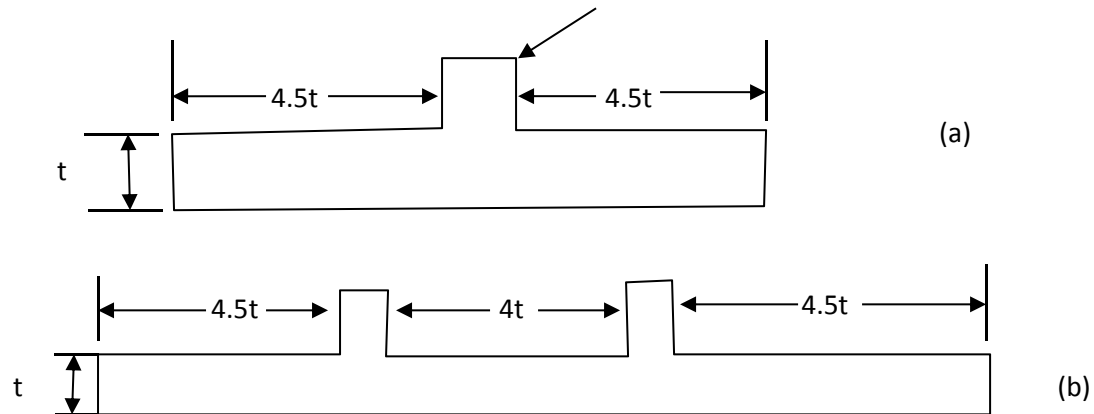


Fig.6.12 (a) Riser location for one central riser and **(b)** riser location for more risers

The feeding distance of the riser can be increased by using chills which provides sharp thermal gradient and decreases feeding resistance. In the case of single riser, chill should be placed at the end and for more than one riser, it should be placed midway between two risers. The proper placement of riser is equally important since it should be able to feed the solidifying casting effectively. If the casting is of cubical or spherical shape, (i.e. of chunky shape having low value of $\frac{A_c}{V_c}$) then a single riser is adequate to feed casting on solidification. However when value of A_c/V_c is high (as in case of bar and plate shaped castings), more than one riser may be required. If only a single riser is used in such cases then the slushy state just prior to solidification may restrict metal flow from a single riser and cause centre-line shrinkage. As a thumb rule it can be said that a single riser is adequate if feeding length is less than 4.5 times the thickness of plate for 12-100 mm thick steel plates. In the case of square bars of size (side) 50- 200 mm, a central riser can be used for distance of less than 6 times square root of bar size. Longer feeding distances than above are possible by use of chills which increase the cooling rate and reduce centre line feeding resistance. In the case of alloys having higher centre-line feeding resistance than steel, chills have to be used to ensure soundness of those parts of the casting requiring the greatest strength.

Exothermic materials are sometimes used in risers for producing directional solidification by creating heat. They consist of oxides of metal like iron, chromium, nickel, or copper and aluminium metal in powder form. These compounds may either be added to the surface of the molten metal in the riser just after pouring, or these may be added to the sand of riser walls. A chemical reaction takes place due to the contact with molten metal producing a large amount of heat. Thus, the metal in the riser gets superheated remaining molten for a longer time. Provision of insulating pads and sleeves around risers helps to conserve heat. Provision of suitable chills at desired locations also helps promote directional solidification.

Solidification Influence

The design of the casting section should be such that it allows the riser to fulfill the needs of supplying hot metal and controlling directional solidification. For example, in Fig.6.13 the molten metal will solidify inward from the metal -mould interface by progressive solidification. With proper conditions of temperature differentials, the intersection of the progressive freezing will move upward into the location of the hottest spot which should be within the riser. This is called directional solidification. If the height of any section is too much in comparison to its cross-section then the progressive solidification rate will exceed the directional solidification, and result in fine centre-line porosity or even a larger or series of large cavities. In order to avoid such a condition it is essential that the cross-section tapers downwards being larger at top and smaller at bottom.

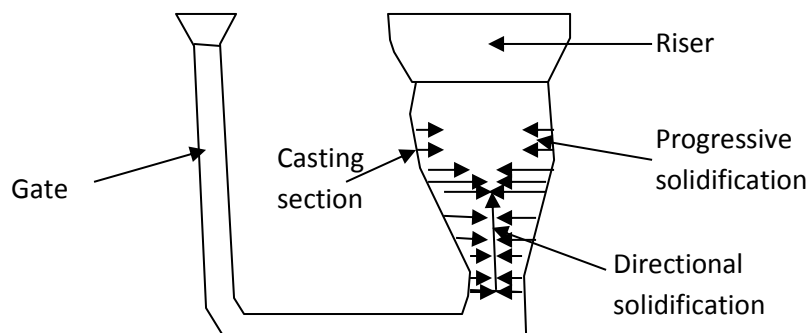


Fig.6.13 Molten metal solidifying inward from the metal-mould interface

Section Proportioning

If the sections can be adequately fed, the limitations of section proportioning are not so critical as the design of the junction. Contraction stresses due to widely differing temperature gradients need to be taken care of. It is ordinarily possible to produce castings without recourse to chills where sections thicknesses are not less than 80% or more than 120% of adjacent section, as regards section variations remote from risers.

Requirements for Feeding

There are four criteria which must be satisfied if the requirements for feeding are to be met, these are (Clegg, 1991):

- i. Heat transfer criterion
- ii. Mass transfer criterion
- iii. Communication criterion
- iv. Pressure criterion

This has been covered in previous sections above but for clarity is here repeated.

Heat transfer criterion: the first requirement is that the feeder head must solidify after the casting. Whilst the laws of heat transfer can be applied to the solidification of castings, the complexity of the problem has led to the development of empirical rules. As shown above using Wlodawer equation which relates solidification time to modulus of the casting. Wlodawer proposes that a safety factor of 1.2 be used because the modulus of the head changes with time as it loses metal whilst feeding the casting.

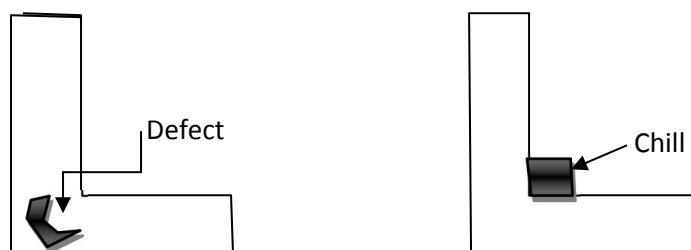
Mass transfer criterion: This criterion recognizes that not all the metal in a feeder head is available to feed the casting because the head is also solidifying at a similar rate to the casting. The mass required to feed a casting is a function of the alloy's specific shrinkage and the casting's volume.

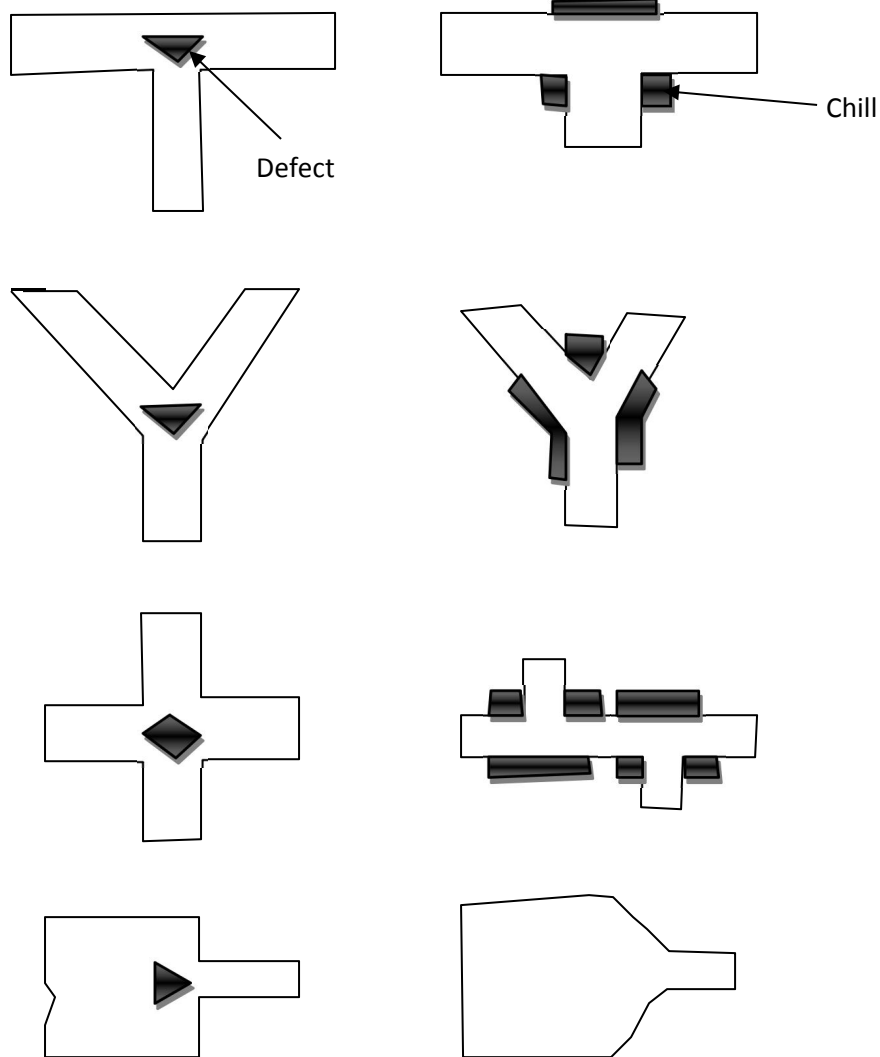
Communication criterion: Extended castings, such as bars or plates, present problems in feeding because for effective feeding to occur, there must be a path through which the liquid metal can travel to reach all parts of the casting. The term feeding distance is used in this respect and experimentally derived rules are available to guide the foundry engineer on this requirement.

Pressure criterion: This criterion recognizes that a pressure difference is necessary to move liquid metal from the feeder head to and through the casting. This pressure difference will consist of the weight of the metal, i.e the metalostatic pressure and atmospheric pressure. This criterion is captured in Bernouilli's equation above.

Junctions and Shrinkage

Junctions between intersecting members are a common feature in castings, they are also a potential source of shrinkage porosity unless they are designed with care. Shrinkage cavities caused by improper directional solidification are most often likely to occur in L, T, Y, X sections and where large sections are joined with small sections abruptly. What happens in these sections is that, there has being a greater mass at the junction point compared to the legs, the junction point area becomes a hot spot with directional freezing progressing towards the hot spot, which in turn feeds the legs and develops the shrinkage cavity. The hot spot can be eliminated by either making the section more uniform or using chills near the cross-section of larger mass [Refer to Fig.6.14]. Although every effort must be made to prevent isolation of heavy sections which can become 'hot spots', sometimes it becomes very difficult. Under such circumstances, it is left to the foundry man to control the freezing by means of: (i) special manipulation of the position of risers in moulds, (ii) controlling the speed of pouring, (iii) utilizing hot metal in the risers, (iv) using mould materials of different thermal characteristics.





(a) Poor Design

(b) Good Design

Fig. 6.14 (a) Poor Design (b) Good Design

Fillets

Adequate fillets at all intersections materially increase the strength soundness of castings. Size of fillets depends on the metal used, shape and thickness of wall section and the size of the casting. Fillet radius should not be more than the section thickness.

Eliminating Hot Tears

In a casting, hot tears result from temperature gradients, establishing different rates of contraction during solidification and thereby inducing stresses due to resistance of the sand of a magnitude

sufficient to cause fracture. These can be minimized by adopting good design, i.e. avoiding abrupt changes in section, sharp angles and non-uniform webs connected to flanges.

Eliminating Gates in Castings

Gases in castings may appear as gas holes, (big holes, few in number distributed at several places in the casting), pin holes (small holes, large in number near the top of casting), pin holes (small holes distributed throughout the casting). Proper riser design and adequate venting of permeable moulds is essential to avoid these defects. Another source of gases is from the dissolved gases in the liquid metal at high temperature, which on cooling are given off. Vacuum melting and vacuum degassing (placing liquid metal in low pressure chamber to remove dissolved gases) can be used to reduce gas in melts.

The Choke Area

The choke area is the smallest in the feeding channel and it controls the velocity of the molten metal into the mould cavity. It also controls the feeding time.

$A = W / d t c \sqrt{2gH}$ where A = the choke area, H = effective height of the molten metal, c = the efficiency factor or nozzle coefficient which is a function of the gating system used, t = the pouring time, d = density of the molten metal, and w = weight of the cast

Sprue Design

As the metal gains velocity in passing through the sprue. It loses its pressure energy or head and this lost of pressure head in the sprue may result in the tendency to form a vortex on the metal in the sprue or a negative pressure effect on the metal column so that gas from the mould is sneaked into the metal stream the remedy is to taper the sprue opening. this also reduce turbulence and mould erosion and also the sprue size is often selected, so that it control the pouring rate that is, the major restriction to the gate system occur in the sprue.

This has the advantage of early establishment of the proper flow characteristics and of reducing the rate of flow of metal entering the mould cavity from the gates an alloy such as aluminum that are subject to drossing, the use of a restricted sprue area to reduce the velocity of the metal may lead to drossing of the metal as it enters the runner. An ideal sprue or gating system to over come this is shown in the figure below

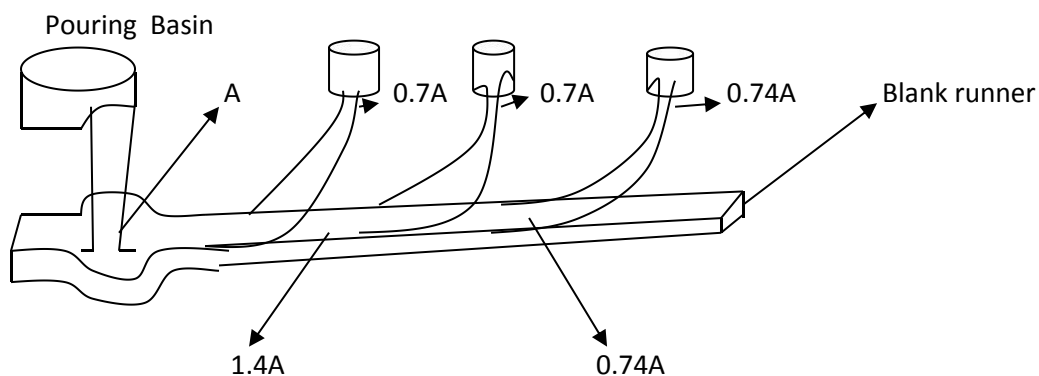


Fig.6.15 Ideal sprue for overcoming drossing of metal

A = Choke area. All the design is based on choke area.

To avoid turbulence and agitation

1. Keep the system filled. From the pouring basin and tapering the sprue.
2. Using sprue base or wells
3. Reducing the metal velocity (it is reduced by enlarged runner and reduced runner and enlarged ingates)
4. Stream lining the system—radius, sprue entrance, and exit, runners and ingates are also radiused

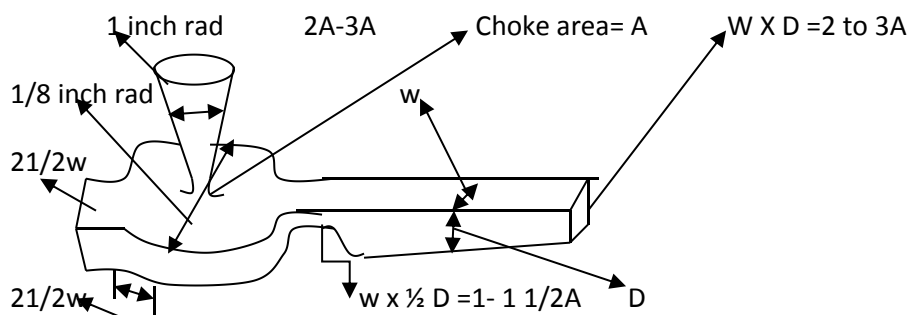


Fig.6.16 Design to avoid turbulence and agitation

Some metals like cast iron and steel are not prone to drossing and therefore these precautions are not necessary. Also since steel is poured at high temperature and chill very rapidly the factors that may determine the sprue design is not drossing and quiet entry of metal into the mould but the need to get metal into the mould fast enough to avoid excessive chilling. Sprue runner ratio differ considerably from those of light metal and we can have some sprue-runner ratio for some metals see table

Table 6.2 Selected Sprue – Runner- Gate area ratio

Metal	Ratio
Steel	1:2:1.5
Steel	1:3:3
Steel	1:2:2

Fin-gate	1:1:1
Grey cast iron	1:4:4
Aluminum	1:2:2
	1:2:4
Aluminum pressure	1:3:3
Brass	1:1:1- 1:1:3

Runners and Gates

Should be design to obtain the following characteristics

1. Absence of sharp corners or changes of sections that may lead to gas entrapment
2. Proper relationship between CSA of several gates between gates and runners and between the runners and sprue
3. Proper location of the gates to ensure adequate feeding of low velocity metal into the mould cavity. To be completely satisfactory, the runner beyond each gate should also be reduced in cross section to balance the flow in all sections and thereby equalize further the velocity and pressure and such a design we have shown previously. In these case the runner is proportioned so that reasonably constant velocity and pressure are maintained further more the design is stream lined to avoid sudden changes in direction that may create turbulence therefore to satisfy Bernoulli's theorem. It is necessary the gates farthest from the sprue be of smallest cross section so that the volume of metal through these gate is the same as those through the sprue if so proportioning if not done there is tendency for the pressure to be a maximum at the farthest gate and therefore for the flow to be

The conversion of a liquid metal from pouring temperature to a solid casting at ambient temperature is generally accompanied by an appreciable volume contraction. This contraction occurs in three stages:

- i. Liquid state contraction
- ii. Phase change contraction
- iii. Solid state contraction

In design of feeding methods for sound casting production it is the phase change contraction which is of principal concern, although the effect of superheat on liquid state contraction should not be discounted. The magnitude of solidification contraction for selected metals is shown in Table 6.3

Table 6.3 Solidification Shrinkage

Metal	% Volume Contraction
Iron	3.5
Nickel	4.5

Copper	4.2
Aluminium	6.5
Magnesium	4.1
Zinc	4.7
Lead	3.5
Tin	2.3

The consequences of contraction are that the casting will be smaller than the mould cavity from which it was produced and the casting will contain shrinkage the form of which will depend on the mode of solidification of the metal or alloy. In earlier chapters we have discussed freezing range which explained short freezing range alloys, long freezing range alloys and their solidification pattern.

Consideration of Pattern

When the melt is such that it expands the pattern should be made smaller. If it contracts the pattern should be made larger. Grey cast iron either expands or contracts.

Review Questions for Chapter six

1. Using the heat transfer approach, state the formula for heat transfer per unit area and the thickness of uniform skin.
2. State Chvorinov's rule and express it in equation form
3. Which condition must be fulfilled before the metal in the feeder will solidify last?
4. List the design considerations for sound casting and explain them
5. List and explain the purpose and objectives of a gating system.
6. List casting defects which can be attributed to incorrect gating system practice
7. Draw and label the schematic representation of a gating system
8. What are the requirements of an ideal gating system?
9. What are the important points to consider in the design of pouring system of castings?
10. What is gate? List and explain commonly used gate designs.
11. Explain aspiration effect with the help of schematic illustrations.
12. What is gating ratio?
13. Write on the importance of directional solidification and how it can be achieved through gating design
14. State continuity and Bernoulli's theorems.
15. With the aid of a schematic diagram of a gating system explain Bernoulli's theorem.

16. What is the pouring time for a steel casting of 50 kg weight if the sectional thickness is great than 0.4 m and the value of k for steel is 1.2?
17. List the variables involved in feeding metal during the entire solidification period.
18. Explain Caine's method
19. List and explain four criteria to be satisfied if the requirement of feeding are to be met.
20. How does a foundryman control freezing in heavy sections and junctions?
21. What is choke area and what is the formula for calculating choke area?
22. List the three stage contraction of liquid metal from pouring temperature.
23. List and explain the characteristics that runners and gates should be designed to have.
24. Liquid metal is flowing through a gating system of 30 mm diameter under a guage pressure of 50 kPa, and with a mean velocity of 2.0 m/s. Neglecting friction, determine the total head, if the pouring basin is 1m above the datum or parting line.
25. A circular gating system of 25 mm diameter carries liquid metal of specific gravity 7.8 at the rate of 120 litres/s and and under a pressure of 2 kPa. Calculate the total energy in metres at a point which is 1.3 m above the datum or parting line.
26. Liquid metal of specific gravity 7.5 is flowing through a mould channel of 30 mm diameter at the rate of 50 litres/s. Find the type of flow, if viscosity for the liquid metal is 1 poise. 1 poise = 0.1 N-s/m²

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CHAPTER SEVEN

METAL AND ALLOY MELTING AND TREATMENT IN THE FOUNDRY

Introduction

The metallurgical integrity of a casting is a function of casting design and the methods used to gate and feed the casting. However, metallurgical integrity is also a function of the metal quality. The metal melting stage exerts a fundamental influence on the quality of the metal. The chemical composition of an alloy is specified to a close tolerance and the first objective of melting is the attainment of the specified alloy composition. Adjustments to the composition may be necessary and can include refinement, to reduce specific element levels, and/ or additions to increase levels. Adjustments of this nature require the availability of analytical facilities to provide rapid data on the chemical analysis of the melt.

Whilst they are molten, certain alloys are susceptible to gas absorption and/or the loss of volatile or reactive elements. Special treatments, such as degassing or vacuum melting and casting, may be required to overcome such problems. Careful control of the metal temperature is essential as these problems are exacerbated by higher temperatures. Furthermore, high metal temperatures will accentuate shrinkage problems and increase the likelihood of metal mould reactions. It is, of course, necessary to superheat the metal to provide sufficient fluidity for casting.

The opportunity also exists at the metal melting stage to treat the metal in order to modify the structure and, consequently, the mechanical properties of the casting. These treatments are usually carried out at the point of dispensation of the metal from the furnace and include deoxidation, grain refinement, modification and inoculation. It is the purpose of this chapter to outline the procedures for metal melting, and treatment with reference to selected alloy systems.

Melting Practice

Aim of melting is to achieve close control of metal composition with low melting losses and the avoidance of gas Contamination and nonmetallic inclusions. The choice of practice is governed by composition and quality requirements of the alloy and partly by the nature of the material forming the charge. Two broad types of practices can be distinguished viz:

1. The condition where by the charge is of virtually identical composition to that required of the liquid metal. Here rapid melting is practiced with minor corrections for avoidable losses
2. The practice where the final composition of the melt must be developed by controlled refining using slag-metal reactions (i.e chemical control is practiced). The nature of alloy is the main factor influencing the type of practice used.

Charge

The furnace charge may consist of pre-alloyed pig virgin metals and alloys scraps from outside sources or from internal fettling and machine shops and any mixture of this charge. The task of melting depends on the state of division as well as the composition of the charge large pieces e.g pigs and heavy scraps are least susceptible to melting losses and contamination, finely divided materials e.g swarfs or turnings are much less satisfactory and are feed directly into the liquid bath, but this introduce dangers of gas contamination.

Melting Conditions

Apart from effects inherent in the type of melting, melting conditions can be varied in respect of time –temperature sequence, the use of fluxes, and the atmosphere in contact with the charge. The furnace atmosphere can contain water vapour, carbondioxide, carbonmonoxide, and sulphurdioxide as a product of fuel combustion as well as the normal atmosphere gases. The most common reaction is between the melt constituents and oxygen in the atmosphere, refractory lining or in certain cases deliberately introduced by injection or as constituents of slag and fluxes.

The common basis of wide range of melting practice is the control of solute content, refinement is often sought by increasing the oxygen content to eliminate hydrogen, carbon, and metallic impurities after which similar relationship are employed in the reverse direction to remove oxygen. Vacuum melting, inert gas melting offers clean neutral conditions for melting, of charge with minimum chemical change.

Melting Losses cannot be Avoided

This have an influence on the economics. The losses are from oxidation or volatilization and also the entrapment of the liquid metal in the dross or slag removed from the surface. Another problem is that of spillage. Non-metallic inclusion included with the charge are another source of loss. The highest sources of loss are associated with contaminated scraps which contain a large proportion of swarfs and fines.

ADDITIVES TO MOLTEN METAL

Treatment of the molten alloy for further purification or to influence the metallographic structure of the casting. The treatment include reagent added to the furnace bath or ladle by plunging, injection, and similar techniques. Oxygen and hydrogen may create brittleness problem, it must be removed.

The reasons for treating molten melt are that the furnace atmosphere is sometimes mildly oxidizing it has to be deoxidized some of the gases can react with solute like carbon, sulphur, to precipitate a compound gas during freezing (Rundman, 2000).

Molten metal processing often involves a procedure where additives are introduced to the molten metal at some stage in the sequence of operations shown schematically in Fig. 7.1 below:

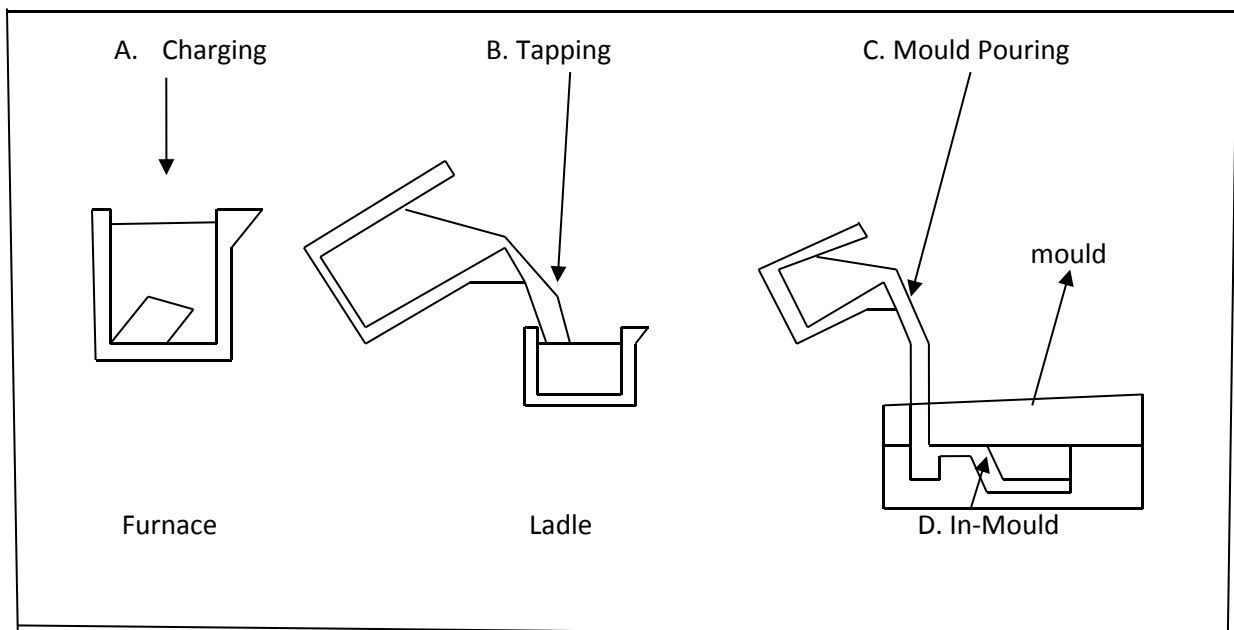


Figure 7.1 Schematic Illustration of Molten Metal Processing (Rundman, 2000)

Points of addition in the sequence include during charging, tapping, mould pouring, and in the mould. The reasons for additions are many and varied, a number of these being listed below:

- A. Alloying additions for control of chemical composition-** these can be made in the furnace charge (A above) or at some point after the metal is molten. Amounts from 0 to several % are typically added. The choice of at what stage the alloy is added depends primarily upon the ease with which the alloy melts or goes into solution.
- B. Additions for the purpose of providing nucleation sites for a phase or phases-** these are usually made at some point after charging. Amounts are usually small, and may be as small as 0.02% to be effective. A classic example of this type of addition is the inoculation process in gray and ductile cast irons. This process, where a ferrosilicon alloy is added for the

purpose of nucleating graphite, varies from plant to plant and from casting to casting. Most plants inoculate at the tapping stage (B above) when the metal flows into the ladle, but may add “insurance” inoculants when the mold is poured (C above) or they may actually put a small amount of inoculants into the gating system (The so-called in-mould stage D above). In this process it has been shown that the later the addition point the more effective is the inoculants. It is also true that the later the addition the more expensive the process; it costs nothing extra to deliver a paper bag filled with inoculants at point B, but may be quite expensive to deliver a controlled amount at points C and D. This class will experience the relative complexity of inoculation in the gating experiment on gray cast iron, in which we will attempt to deliver a controlled amount using Hickman-William’s commercial unit (The Post Inoculant Feeder PIF). The fact that lateness is important for effective inoculation implies that time in the metal is detrimental to the formation of nuclei. The inoculants is said to “fade” with time. Most processing requirements, for example, specify that the casting be poured no later than 10 minutes after inoculation if inoculation occurs at point B. if the time is exceeded then the molten metal is usually “pigged” to avoid pouring castings of uncertain quality. The detail effects of inoculant additions of processing in gray cast irons will be covered later on in these notes.

- C. **Additions for the purpose of changing the shape of the phases that form during solidification-** these can be made at all of the above points in processing, depending upon the material and the goal of processing. Amounts again are quite small, usually on the order of 0.01 to 0.05wt.%. Good examples of this processing are I., the addition of sodium (Na) or strontium (Sr) to aluminum–silicon alloys to force a change in shape of the eutectic silicon from plate–shape to rod–shape and II., the addition of magnesium (Mg) to a cast iron liquid to accomplish a shape change from plate-like to spheroidal. The addition of sodium to aluminum–silicon alloys is termed “modification” and the addition of Mg to cast iron is termed “treatment”. Both of these additions result in significant enough microstructural change that mechanical properties are impacted greatly. This is especially true for cast iron where the ductility changes from essentially zero for the flake-shaped eutectic graphite (gray Iron) to values in the range 0 to 20% elongation for the spheroidal shaped graphitic iron (ductile Iron). The details of processing ductile cast iron will be discussed at a later place in this book.
- D. **Additions for the purpose of refining grain size during solidification or for limiting grain growth in the solid state after solidification is complete.** These additions are usually made in the charge or on tapping the furnace into the ladle, and again the amounts added are often quite small, in the range of 0.01 to 0.04%. An example cited here would be that of adding titanium to aluminum alloy semi-continuous castings, where the titanium is often wire-fed into the tundish feeding the large vertically descending ingots. The mechanism by which the refinement occurs is thought to be as a result of the formation of titanium oxides which then hinder grain boundary movement during subsequent annealing operations.
- E. **Additions for the purpose of removing gaseous impurities in a melt.** These additions may be made either by purging a melt with a gas or by adding compounds which will react chemically with the impurity, forming an oxide or some solid compound which then goes into the slag and is removed. The most common example of the former is the degassing of aluminum alloys (removing hydrogen) by purging with argon containing SF_6 . Of course, since this operation requires a significant amount of time to carry to completion, it is necessarily

completed in the melting or holding furnaces. An example of the latter is the degassing operation (removing oxygen) in copper alloys where a compound containing phosphorous (often CuP_3) is added and the phosphorous reacts with the oxygen and the resulting compound goes into the slag. A similar deoxidizing step is used in the production of steel, where elements like silicon, aluminum, or magnesium are used to form oxides which then can be removed in the slag.

All of these additives with the exception of A above result in microstructural change to a degree which is out of proportion to the amount of the additive used. It is useful to point out that the additives are invariably fairly active elements chemically elements for example that oxidize readily in comparison to the other elements present. These are important “control rods” which the materials engineer had at his /her disposal to ensure that a quality product is produced consistently from one day to the next. Even though the quality of the additive is very small the presence of these active elements within the melt at the critical time of solidification is sufficient to affect and direct either the nucleation event and/ or the growth events in the solidification process. For example it is thought that inoculation in cast iron results by the formation and growth of nuclei within the melt, nuclei which provide crystallographically convenient sites for nucleation of the graphite. In the case of modification of Al-Si alloys and treatment of cast irons the presence of the active elements at the growing phase interfaces is likely responsible for altering the crystallographic manner in which growth occurs.

Deoxidants Used

The addition of deoxidants both to iron and nickel can be deduced from the Ellingham diagram. The elements lower down the diagram from stable oxides will combine with available oxygen at the expense of elements above.

Treatments for controlling metallographic structure often with grain refinement as the objective usually are important example in the addition of elements to cast iron to determine the form and distribution of the graphite phase. If you have grey iron you have to inoculate with silicon at the time of pouring and this is used to control the austenite/eutectic/grain size and graphite flake distribution. Spheroidal graphite structure – inoculate with magnesium or cerium

For the Al-Si system – small sodium is added for the modification of the eutectic structure. Porous plunger is used in plunging things in the vessel. It stirs the molten metal and injects nitrogen to degas the metal. Table 7.1 shows the various treatment methods given to molten metal, the Table shows the various treatment methods, main field of application and typical reagents used for melt treatment.

Table 7.1: Melt Treatment of Metals and Alloys

TREATMENT	MAINFIELD OF APPLICATION	TYPICAL REAGENTS USED
Degassing	Aluminum base	Nitrogen, chlorine

	Magnesium base	Chlorine
	Copper base	Nitrogen
	Nickel base	Oxygen
Deoxidation	Steel	Mn, Si, Al, Ca, at low pressure
	Copper base	P, Si, Li
	Nickel base	Mg, Si.
Desulphurisation	Steel	Soda –ash
	Cast iron	Soda-ash, calcium carbide
Grain and constituents refinement	Aluminum base	Titanium, B, Niobium, Zr
	Magnesium base	Carbon, Zirconium
	Steel	Aluminum, titanium
Refinement and eutectic modification	Cast iron (modification)	Si, C
	Cast iron (S.G. structure)	Mg, Ce
	Al- Silicon alloy	Na

Source: Rundman, 2000

Melt Quality Control

Melt quality can be assured in the following ways:

1. The molten metal is sampled or tested for composition
2. Judging from the gas evolution during freezing this is done with experience
3. Fracture appearance of the metal, impact test is used; this gives indirect evidence of contamination,
4. Chemical analysis can also be made using spectrography or x-ray fluorescence.
5. Composition control is improved and melting cost minimized by coordination of melting and casting to ensure that metals once melted can be discharged from the furnace without delay.
6. Quality control can also be improved if all the melting and casting are done under the same conditions.

Gases in Metals

The potential for gas contamination of the metal is very high at the melting stage. Reaction and solution rates usually increase with an increase in temperature and the solubility of gases is generally greater at higher temperatures. Whilst accepting that these problems are to some extent inherent at the melting stage, every precaution should be taken to minimize gas absorption at this stage.

Melting Precautions

The charge materials used in melting preparation can be a source of gas contamination. These materials may already contain dissolved gases from a previous melting stage or surface contamination in the form of oxides, corrosion products, paint, lubricants, or water. Careful selection of material, proper storage and preheating, can therefore reduce the problem of gas contamination. Additions to the melt in the form of refining or fluxing agents and alloys may also be potential sources of gas contamination and must be treated with similar care. Refractories used for furnace construction, crucibles, ladles, launders, and coating furnace tools, must be sufficiently preheated to remove both free and combined moisture. The furnace atmosphere will always be a source of contamination when metals are melted in air. However, the problem will be greatest when fuel-fired furnaces are used and the products of combustion, including water vapour, can contaminate the melt.

Degassing Procedures

Although precautions at the melting stage may minimize the problem, it is difficult to produce a melt which is free of gas contamination under normal foundry air melting conditions. Degassing procedures are conducted to remove those gases which are soluble in the liquid metal. Two problems can arise through the presence of such gases. Firstly, their solubility in the liquid metal is high but generally decreases with a decrease in temperature and is dramatically lower in the solid metal. Consequently, if the gas is not removed, its precipitation upon solidification will result in the formation of gas holes. Hydrogen is a prime example of a gas which behaves in this manner and is a potential problem in several alloy systems.

Oxygen does not usually precipitates in this manner as it is more likely to form stable metal oxides. However, when it exists in the soluble form it may react to form a compound gas. In steel it may react with carbon to produce carbon monoxide and in copper-base alloys it may react with hydrogen to produce steam.

A number of approaches are used in practice to degas melts and include those described in the following sections.

Gas Flushing or Scavenging

When a melt is held under equilibrium conditions with its atmosphere, the amount of gas dissolved within the melt will be a function of the partial pressure of that gas. Simply stated the greater the concentration of the gas in the atmosphere above the melt, the higher the contamination of the melt by the gas, if the atmosphere above the melt were to be replaced by one which had a low concentration of the contaminant gas, then the gas would diffuse from the melt to the atmosphere until an equilibrium condition was established. This provides a mechanism for degassing and its efficiency can be dramatically improved by bubbling the atmosphere through the melt.

Oxidation/ Deoxidation Practice

In a number of alloy systems the presence of oxygen in a melt reduces the melt's capacity for absorbing hydrogen. This feature can be deliberately exploited by melting under oxidizing conditions to prevent hydrogen dissolution. However, as the oxides may be harmful to the properties of the alloy, an effective method of oxidation must be practiced prior to casting.

Deoxidation

Although deoxidation is often considered to be a melt treatment in its own right, it is in effect a degassing treatment. However, whereas the gas flushing methods seek to remove the contaminant in gaseous form, deoxidation relies on the tendency of oxygen to form stable oxides which are then removed to the slag.

Vacuum Melting and Casting

The problems of melt contamination and composition control can be largely overcome by melting and casting under vacuum conditions. Elimination of an air atmosphere during melting prevents oxidation and gas absorption. In addition, gases already in solution may be removed because the reduced pressure above the melt aids in their nucleation and their diffusion is promoted by the low partial pressure of the gas above the melt. Vacuum induction melting and casting is considered to be an essential requirement for processing certain heat resisting alloys. The practice is not without certain drawbacks. For example, prolonged exposure to vacuum may result in the loss of certain volatile elements, and melts are more likely to be contaminated by reaction with the furnace refractories. Nevertheless, the advantages outweigh the disadvantages.

The capital cost of vacuum melting and casting equipment is very high. However, the advantages of vacuum degassing can be obtained without the need for an expensive, fully integrated melting and casting unit. Air melted material can be subjected to a vacuum degassing treatment prior to casting. Industrially established processes include: static bath treatment, induction degassing, fractional degassing, and stream droplet degassing.

Melt Treatments

According to Clegg (1991) and Heine *et al.*, (1967), the practices of degassing and deoxidation are treatments which improve the cleanliness and quality of the melt. However, there are a number of treatments which can be practiced that will modify the metallurgical structure of the castings and consequently their mechanical properties. To understand how these treatments work it is necessary to consider the mechanisms of nucleation and growth of solid from liquid metals, which has been treated in details in chapter 2. In commercial alloys nucleation occurs heterogeneously, this implies that there are sufficient impurities present within a melt to provide sites upon which solid can form. Clearly, the more sites at which solid can nucleate the more grains will be produced and the smaller they will be. This provides a potential mechanism for changing the structure of a casting. The deliberate addition of suitable nuclei to a melt will increase the number of solidification sites and

thereby decrease the size of the grains, this is the principle of grain refinement. This principle of grain refinement clearly agrees with Higgins (1985) and Shrager (1967) which they capture in their respective books.

In this section, selected alloy systems will be considered and details of the melt treatments practiced will be provided as a means of demonstrating how melt quality or metallurgical integrity can be improved.

Non-Ferrous Alloys

Nonferrous castings are characterized by low melting temperatures and that may be one of the reasons why most of the castings are produced using Al, Zn, Mg, and others including their alloys through die casting techniques. Die casting products using nonferrous metals include some of the following: crankcases, engine covers, transmission cases, clutch housing, cylinder blocks, brackets, carburetor bodies, float chambers and bodies, oil pump bodies, door handles, electric tool covers and handles, cigarette lighter cases, camera bodies, etc.

During melting of nonferrous metals for casting certain treatments are given to the melt during and after melting. These treatments include: deoxidation and degassing, inoculation, fluxing, modification and others. In the melting of mg alloys SF_6 gas is used to prevent oxidation and the burning of Mg. other substances which can be used include; ketone chloride gas, SO_2 , and $\text{MgO} + \text{M}_2\text{SO}_4$ and others are used as flux. Ethenehexachloride is normally used as inoculant for Mg alloy, chloride is however dangerous to humans. Carbon can also be introduced as inoculant. Magnesium castings have improved grain refinement on inoculation or superheat before the pouring. As crystal grain becomes fine, strength and elongation is equal to aluminium alloy casting. Other melt treatments include; degassing, deoxidation and the addition of additives.

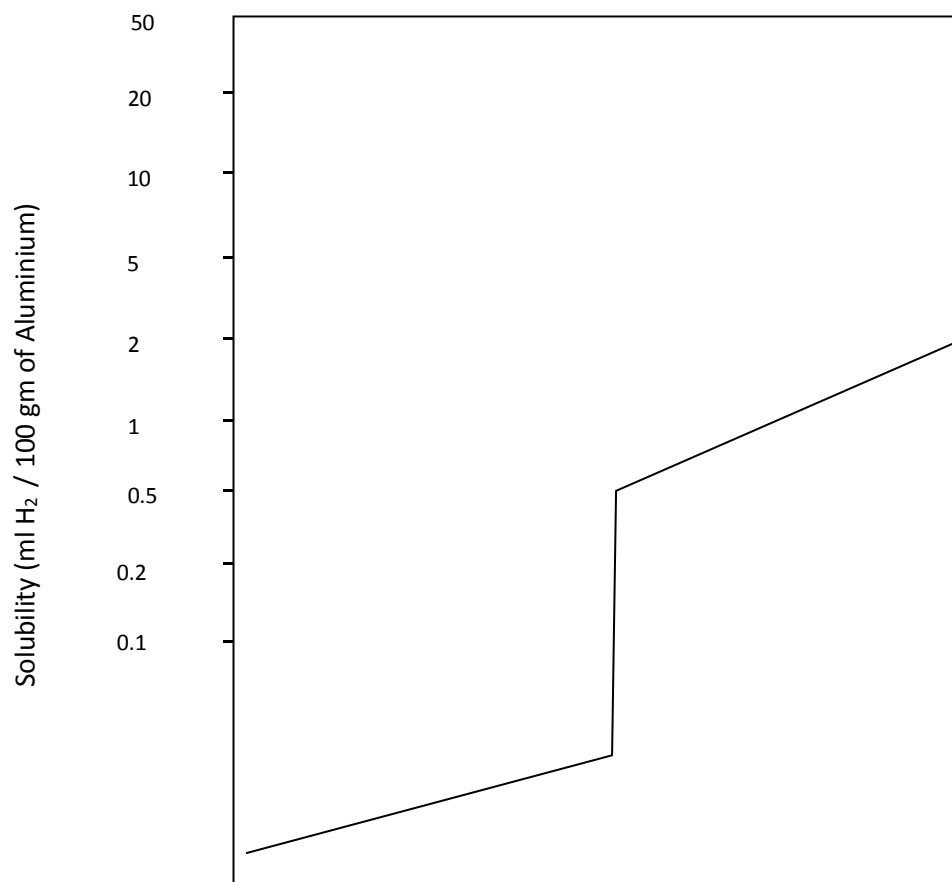
Aluminium-Base Alloys

According to Brown (1994) there is a large and confusing range of casting alloys in use worldwide, defined by the national specifications of the major industrial countries. Unfortunately, there is little correspondence between the standard alloys used in different countries. A European Standard for aluminium casting alloys is finalized. The various Standards include alloys for general engineering purposes and alloys for aerospace applications. This section will deal mainly with general engineering castings but the principles will apply equally to the aerospace alloys. Table 7.2 lists the BS1490 1988 "LM Alloys" and their approximate equivalents in other National and International Standards. Table 7.3 shows the chemical composition of the LM Alloys and Table 7.4 gives the specified minimum mechanical properties. Unfortunately here in Nigeria we do not have local standards for aluminum. The Aluminum Smelter Company, Ikot Abasi in Akwa Ibom State that would have assisted in this direction is moribund. Aluminium alloys can be cast by several processes these include: sand casting: chilled casting i.e. gravity die (permanent mould casting) or low pressure die casting in a metal die using sand cores, pressure diecasting: investment casting or plaster moulding precision casting techniques may also be used for aerospace castings. The casting alloys are designed to be cast by one or other of these techniques, although some alloys are suitable for more than one casting method.

These alloys are highly susceptible to oxidation and hydrogen absorption when in the molten state. This leads to a degradation of the mechanical properties of the alloys as a result of oxide inclusions and/ or gas porosity. In each case the problem is exacerbated by high temperatures, which emphasizes the requirement for careful control of melt temperature. Aluminium oxide in the form of films or particles impairs the fluidity of the metal and reduces the flow of feed metal. The inclusions also provide nucleation sites for the formation of both gas and shrinkage porosity. Cover fluxes provide a barrier to the reaction between the melt and the atmosphere and can absorb any oxides present at the surface of the melt. Suspended oxides and other non-metallic inclusions can be removed by using chemically active fluxes which de-wet the particles and remove them physically to the surface of the melt for removal by skimming. Porous foam ceramic filters are being used increasingly to remove suspended non-metallic inclusions from aluminium alloys and provide a demonstrable improvement in mechanical properties. However, their use should not be seen as a substitute for careful melting practice.

Hydrogen is the only gas that has appreciable solubility in aluminium alloys and its solubility versus temperature relationship is shown schematically in Fig. 7.2. Every effort should be made to minimize the presence of hydrogen in the melt by exercising the precaution referred to in the section on gases in metals. However, to reduce it to an acceptable level, a degassing treatment will be necessary. Gas fluxing techniques using chemically pure nitrogen, argon, chlorine or freon are effective, as is the use of compounds, such as hexachlororethane, which dissociate in the melt to generate a fluxing gas.

A fine grain structure improves mechanical properties, response to heat treatment, pressure tightness, hot tear resistance, and feeding characteristics. Certain aluminium alloys can be grain refined by the addition of alloys of titanium, or of titanium and boron, in aluminium. The formation of titanium aluminide, titanium boride and titanium carbide (carbon may be present as an impurity) provides the nuclei for effective grain refinement. However, it is possible that such nuclei may also promote porosity through the nucleation of shrinkage and gas porosity.



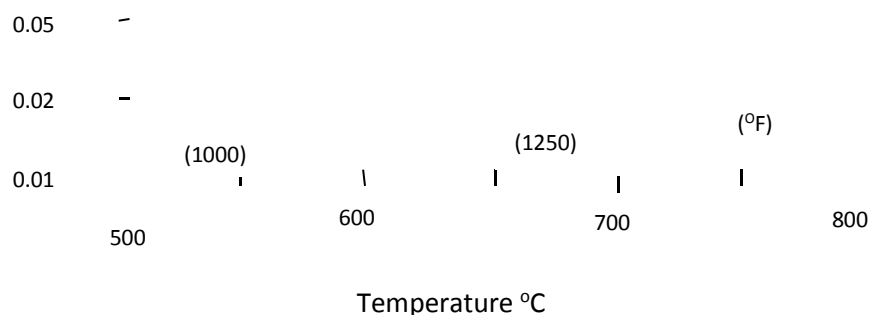


Fig.7.2 The Solubility of Hydrogen in Aluminium as a Function of Temperature

Hypoeutectic aluminium-silicon alloys consist, in the solid state of primary α (aluminium with a small amount of silicon dissolved in it) in a matrix of $\alpha + \beta$ (β is silicon with a small amount of aluminium dissolved in it). The eutectic β will be large in size and coarse in shape when the alloy is slow-cooled and this will impair strength and ductility. Faster rates of cooling, as encountered in die casting, refine the size and shape of the β phase and this improves strength and ductility. A similar effect can be obtained by a chemical addition of an element known as a modifier. Sodium is the preferred modifying agent and may be added in elemental form (vacuum packed) or as a salt in the cover flux. Very low sodium concentrations provide effective modification, although its effect fades with time and is lost on remelting.

Certain aluminium alloys, particularly those containing about 4% of copper, are amenable to heat treatment. Although clearly not a melt treatment, such treatments provide a valuable method of optimizing the properties of cast alloys. In the case of such aluminium-copper alloys the heat treatment procedure involves solution treatment followed by age or precipitation hardening.

Large foundries usually melt aluminium alloy ingot and foundry returns in a bulk melting furnace then transfer the metal to smaller holding furnaces near to the casting area. Degassing and metal treatment are usually carried out in the transfer ladle. The bulk melting furnaces can be coreless electric induction furnaces or more commonly gas-fired reverberatory or shaft furnaces. The tilting crucible furnace, which may be electric or gas is also popular. Holding furnaces may be electric or gas.

Table 7.2 BS 1490 Alloys and Approximate Equivalents

UK	ISO	EN provisional	France	Germany	Italy UNI	USA AA/ASTM	USA SAE	Japan	End uses
LM0 LM2 LM4	Al-993 Al-Si10Cu2Fe Al-Si5Cu3	- 46100 43200	A5 A-S9U3- Y4 A-S5U3	- - G- AlSi6Cu4(225)	3950 5076 3052	150 384 319	- 383 326	- ADC 12 AC 2A	Electrical, food, chemical plant, pressure diecasting, sand, gravity diecasting manifolds, gear boxes etc.
LM5	Al-Mg5Si1	31300	AG6	G-AlMg5	3058	514	320	AC 7A	Sand, gravity, corrosion resistant, for marine use
LM6 LM9	Al-Mg6 Al-Si12 Al-Si12Fe Al-Si10Mg	44100 43100	AS13 A-S10G	(244) G-AlSi12 (230) G-AlSi10Mg	4514 3049	A413 A360	309	AC 3A AC 4A	Food plant, chemical plant, sand, gravity, thin sections, manifolds etc. Low pressure etc. motor housings, cover plates etc. high

									strength when heat treated
LM12	Al-Cu10Si2Mg	-	A-U10G	(233) -	3041	222	34	-	Gravity, sand cast, machines well, hydraulic equipment
LM13	Al-Si12Cu	48000	A-S12UN	-	3050	336	321	AC 8A	Sand, chill used for pistons
LM16	Al-Si12CuFe Al-Si5Cu1Mg	45300	A-S4UG	-	3600	355	322	AC 4D	Sand chill cylinder heads valve bodies good pressure tightness
LM20	Al-Si12Cu	47000	A-S12-Y4	G-ALSi6Cu4 (225)	5079	A413	305	-	Pressure diecasting, corrosion resistant, marine castings, water pumps, meter cases. Sand gravity similar to LM4, crankcases, gear boxes, etc.
LM21	Al-Si12CuFe Al-Si6Cu4	45000	A-S5U2	G-ALSi6Cu4 (225)	736974	308	326	AC 2A	
LM22	Al-Si5Cu3	45400	A-S5U	G-ALSi6Cu4 (225)	3052	319	326	AC 2A	Chill casting, solution treated, good shock resistance, automotive heavy duty parts.
LM24	Al-Si8Cu3Fe	46500	A-S9U3A-Y4	G-ALSi8Cu3 (226)	5075 3601	A380	306	AC 4B ADC 10	Pressure diecasting, engineering diecastings
LM25	Al-Si7Mg	42000	A-S7G	G-ALSi7Mg	3599	A356	323	AC 4C	Sand, chill, general purpose high strength alloy with machinability, wheels cylinder blocks, heads
LM26	Al-Si9Cu3Mg	-	A-S7U3G	-	3050	332	332	AC 2B	Sand, chill versatile alloy, good castability, general engineering parts
LM27	Al-Si7Cu2Mn0.5	46600	-	-	7369	-	-	-	
LM28	Al-Si19CuMgNi	-	-	-	6251	-	-	-	Chill, high performance
LM29	Al-Si23CuMgNi	-	-	-	6251	-	-	-	pistons
LM30	Al-Si17Cu4Mg	-	-	-	-	390	-	-	Chill high performance
LM31	Al-Si7Cu4Mg Al-Zn5Mg	71000	A-Z5G	-	3602	712	310	-	pressure pistons, diecast, unlined cylinder blocks. Sand, large castings, good shock resistance, good strength at elevated temperature

Table 7.3 Chemical composition (weight per cent) of BS 1490:1988 alloys

Alloy	Cu	Mg	Si	Fe	Mn	Ni	Zn	Pb	Sn	Ti	Additional elements	Others	
												Each	Total
LM0	0.03	0.03	0.03	0.40	0.03	0.03	0.07	0.03	0.03	-	Al 99.5 min	-	-
LM2	0.7-2.5	0.30	9.0-11.5	1.0	0.5	0.5	2.0	0.3	0.2	0.2	-	-	0.50
LM4	2.0-4.0	0.20	4.0-60	0.8	0.2-0.6	0.3	0.5	0.1	0.1	0.2	-	0.05	0.15
LM5	0.1	3.0-6.0	0.3	0.6	0.3-0.7	0.1	0.1	0.05	0.05	0.2	-	0.05	0.15
LM6	0.1	0.10	10.0-13.0	0.6	0.5	0.1	0.1	0.1	0.05	0.2	-	0.05	0.15
LM9	0.20	0.2-0.6	10.0-13.0	0.6	0.3-	0.1	0.1	0.1	0.05	0.2	-	0.05	0.15

					0.7							
LM12	9.0-11.0	0.2-0.4	2.5	1.0	0.6	0.5	0.8	0.1	0.1	0.2	-	0.05 0.15
LM13	0.7-1.5	0.8-1.5	10.0-13.0	1.0	0.5	1.5	0.5	0.1	0.1	0.2	-	0.05 0.15
LM16	1.0-1.5	0.4-0.6	4.5-5.5	0.6	0.5	0.25	0.1	0.1	0.05	0.2'	-	0.05 0.15
LM20	0.4	0.2	10.0-13.0	1.0	0.5	0.1	0.2	0.1	0.1	0.2	-	0.05 0.20
LM21	3.0-5.0	0.1-0.3	5.0-7.0	1.0	0.2 0.6	0.3	2.0	0.2	0.1	0.2	-	0.05 0.15
LM22	2.8-3.8	0.05	4.0-6.0	0.6	0.2- 0.6	0.15	0.15	0.1	0.05	0.2	-	0.05 0.15
LM24	3.0-4.0	0.30	7.5-9.5	1.3	0.5	0.5	3.0	0.3	0.2	0.2	-	- 0.50
LM25	0.20	0.20-0.6	6.5-7.5	0.5	0.3	0.1	0.1	0.1	0.05	0.2'	-	0.05 0.15
LM26	2.0-4.0	0.5-1.5	8.5-10.5	1.2	0.5	1.0	1.0	0.2	0.1	0.2	-	0.05 0.15
LM27	1.5-2.5	0.35	6.0-8.0	0.8	0.2- 0.6	0.3	1.0	0.2	0.1	0.2	-	0.05 0.15
LM28 ²	1.3-1.8	0.8-1.5	17-20	0.7	0.6	0.8- 1.5	0.2	0.1	0.1	0.2	Cr0.6 Co0.5	0.10 0.30
LM29 ²	0.8-1.3	0.8-1.3	22-25	0.7	0.6	0.8- 1.3	0.2	0.1	0.1	0.2	Cr0.6Co0.5	0.10 0.30
LM30	4.0-5.0	0.4-0.7	16-18	1.1	0.3	0.1	0.2	0.1	0.1	0.2	-	0.10 0.30
LM31 ³	0.1	0.5-0.75	0.25	0.5	0.1	0.1	4.8- 5.7	0.05	0.05	0.25 ¹	Cr0.4-0.6	0.05 0.15

Source: BS, 1988

Notes: Single figures in the table are maxima

In cases where alloys are required in the modified condition, the level of any modifying element is not limited by the specified maximum value for "other element"

1. 0.05% minimum if Ti alone is used for grain refining
2. LM28 and LM29 castings are also subject to metallographic structure requirements.
3. LM31 castings in the M condition have to be naturally aged for 3 weeks before use or determination of mechanical properties.
4. For details refer to BS1490 1988

Table 7.4 Typical mechanical properties

Sand cast					Chill/ permanent mould cast					
Alloy condition	0.2% proof stress (N/mm ²)	Tensile stress (N/mm ²)	Elong (%)	Brinell hardness	0.2% proof stress (N/mm ²)	Tensile stress (N/mm ²)	Elong (%)	Brinell hardness	Strength at elevated temperatures	Alloy condition
LM0-M	30	80	30	25	30	80	40	25	-	LM0-M
LM2-M	-	-	-	-	90	180	2	80	G	LM2-M
LM4-M	100	150	2	70	100	200	3	80	G	LM4-M
LM4-TF	250	280	1	105	250	310	3	110	G	LM4-TF
LM5-M	90	170	5	65	90	230	10	65	F	LM5-M
LM6-M	70	170	8	55	80	200	13	60	P	LM6-M
LM9-M	-	-	-	-	-	200	3	-	G	LM9-M
LM9-11	150	180	2	70	150	280	2.5	80	G	LM9-TE
LM9-TF	220	250	-	100	280	310	1	110	G	LM9-IF
LM12-M	-	-	-	-	150	180	-	95	G	LM12-M
LM13-1L	-	-	-	110	-	220	1	105	E	LM13-TE
LM13-TF	200	200	-	125	280	290	1	125	E	LM13-TF
LM13TF7	140	150	1	77	200	210	1	75	E	LM13-TF7
LM16-TB	130	210	3	80	140	250	6	85	G	LM16-TB
LM16-TF	240	280	1	100	270	310	2	110	G	LM16-TF
LM20-M	-	-	-	-	80	220	7	60	P	LM20-M
LM21-M	130	180	1	85	130	200	2	90	G	LM21-M
LM22-TB	-	-	-	-	120	260	9	75	G	LM22-TB
LM24-M	-	-	-	-	110	200	2	85	G	LM24-M
LM25-M	90	140	2.5	60	90	180	5	60	F	LM25-M
LM25-TE	130	170	1.5	70	150	220	2	80	F	LM25-TE
LM25-TB7	100	170	3	65	100	230	8	65	F	LM25-TB7
LM25-TF	220	250	1	105	240	310	3	105	G	LM25-TF
LM26-TE	-	-	-	105	180	230	1	105	E	LM26-TE
LM27-M	90	150	2	75	100	180	3	80	G	LM27-M

LM28-TE	-	-	-	110	170	190	0.5	120	G	LM28-TE
LM28-TF	120	130	0.5	120	170	200	0.5	120	G	LM28-TF
LM29-TE	120	130	0.5	120	170	210	0.3	120	G	LM29-TE
LM29-TF	120	130	0.5	120	170	210	0.3	120	G	LM29-TF
LM30-M	-	-	-	-	150	150	-	110	G	LM30-M
LM30-TS	-	-	-	-	160	160	-	110	G	LM30-TS
LM31-M	170	215	4	70	170	240	5	70	G	LM31-M
LM31-TE	170	215	4	70	170	240	5	70	G	LM31-TE

Notes

1 suffix letters indicate the condition of the casting: M= as-cast; TE= Precipitation treated; TB7= Solution treated and stabilized; TF = Solution treated and precipitation treated; TF7= Fully heat treated and stabilised; TS = Stress relieved

2. Strength at elevated temperatures: E = excellent; G = good; F = fair; P = poor. Diecasting alloys are restricted to moderately elevated temperatures.

3. The typical properties shown in this table are those of separately cast test bars and may not be obtained in all parts of the casting. For details refer to BS 1490:1988

Copper-Base Alloys

A wide range of copper alloys is produced by casting and includes; brasses, aluminium, manganese, nickel, phosphor, silicon, and tin bronzes; copper-nickel alloys; copper-chromium alloys; beryllium-copper alloys; etc. The melt treatment procedure will depend on alloy composition, but most copper alloys are susceptible to hydrogen absorption. For many of these alloys the approach adopted for minimizing hydrogen contamination is that of oxidation /deoxidation. The metal is melted under oxidizing conditions and subsequently deoxidized before pouring.

In general these alloys are not grain refined, although certain alloys will respond favourably to the practice. Similarly, certain alloys will respond to heat treatment. The beryllium-copper and chromium-copper alloys respond to solution treating and ageing, and the aluminium bronzes (with >10% aluminium) will respond to a quench and temper treatment.

Magnesium –Base Alloys

These alloys are highly susceptible to oxidation during melting so that special precautions must be taken to prevent this, including the careful selection of refractories. Melting can be conducted under flux covers, but cleaner melts are produced when a protective gas atmosphere is used. The presence of carbon dioxide and sulphur hexafluoride is effective in reducing the extent of oxidation. The magnesium aluminium alloys can be simultaneously degassed and grain refined by plunging hexachlorethane tablets into the melt. The presence of zirconium provides effective grain refinement for the magnesium-zirconium alloys.

The surface of the molten metal must be protected during pouring, either by the protective gases described or by dusting with sulphur and boric acid. These alloys are highly susceptible to metal-mould reactions when the mould contains water. In such reactions the water dissociates to produce hydrogen, which dissolves in the metal, and a metal oxide. It is necessary to include inhibitors such as boric acid, potassium fluoborate or ammonium fluosilicate in the sand formulation to overcome

this problem. Certain alloys are amenable to heat treatment by solution treatment and age hardening.

Titanium –Base Alloys

These alloys represent a specialized and small area of casting production, but one which is growing. The molten alloys have an especially high affinity for oxygen, nitrogen and hydrogen. Melting is conducted under vacuum and special arrangements are required to ensure that titanium does not react with the oxygen in refractory materials. The principal method of melting titanium alloys is the vacuum consumable electrode method. In this method, a consumable titanium alloy electrode is lowered into a water-cooled copper crucible. A titanium-alloy skull or lining solidifies against the crucible so that no direct contact occurs between the molten alloy and the crucible. When sufficient alloy has melted it is quickly poured into the mould. As controlled superheating presents problems in this situation, melt treatments are not practiced. Post casting treatments include hot isostatic pressing, to eliminate porosity, and heat treatment procedures based on solution treatment and ageing have been developed.

Zinc –Base Alloys

These alloys, which are mainly processed by pressure die casting, are relatively straightforward to melt and cast. A high proportion of remelt material can be tolerated and provided that undue agitation of the melt is avoided and the temperature is controlled, oxidation and the loss of aluminium or magnesium will be minimized. Zinc alloy melts are not normally degassed, deoxidized, grain refined, or modified in any way. Certain alloys age and shrink with time so that castings may be subjected to a low temperature stabilization heat treatment to accelerate the ageing and prevent its occurrence during service life.

Superalloys

The superalloys are defined as those developed for elevated temperature service, usually based on group VIIIA elements, where relatively severe mechanical stressing is encountered and where high surface stability is frequently required. This definition includes iron, cobalt, and nickel-based alloys. As the former group is covered by high alloy steels, only the cobalt and nickel –based alloys are considered in this section.

Cobalt-Base Alloys

These alloys demonstrate relatively low melting points, good fluidity, freedom from dissolved gas defects, and low alloy losses due to oxidation. The majority of the alloys are melted in air since they are devoid of such highly reactive elements as aluminium, tantalum, titanium, or zirconium. However, inert gas (argon) covers are recommended to minimize oxidation, and vacuum melting is essential if the aforementioned reactive agents are present. Silicon and manganese can be added to certain alloys to improve alloy fluidity and act as deoxidants. Heat treatment has little effect on mechanical properties.

Nickel-Base Alloys

These alloys are far more complex in their formulation than are the cobalt –base alloys. They are used in the most demanding application and contain reactive elements to improve their mechanical properties and surface characteristics. Vacuum melting and casting is essential. Whilst, no other melt treatment is required, a grain refining effect can be induced, in castings requiring an equiaxed structure, by incorporating a refining agent in the investment casting mould slurry formulation. The nickel-base alloys are amenable to heat treatment by solution treatment and precipitation hardening.

Ferrous Alloys

This group contains the cast iron and steels, the former are considered first as they are somewhat easier to process.

Cast irons are widely produced as castings. The different types of cast irons produced depend on chemical composition, alloying elements addition and cooling rates. Typical cast irons include:

Grey Cast Iron

Cast iron is a generic term for a whole family of irons of which grey cast iron is the progenitor. These alloys, in which the principal alloying elements are carbon and silicon, can be melted by cupola or induction melting. Under normal circumstances they are not susceptible to oxidation or gas absorption. However, hydrogen porosity may arise in the presence of trace aluminium, and high nitrogen levels, generally associated with urea binders in the sand, will also produce gas defects. The characteristics of grey cast iron are a function of the amount and form of the carbon, which is normally present as graphite flakes. Thin sections are prone to solidify to white cast iron, because of the faster cooling rate which promotes the formation of iron carbide rather than graphite. To promote the formation of graphite, the iron may be inoculated at the ladle filling stage by the addition of certain silicon-containing alloys. Grey cast iron does not respond to heat treatment, although stress relief annealing can be practiced.

Ferritic Grey Cast Iron: can be found mainly in heavy sections of castings due to very low cooling rate

Pearlitic Grey Cast Iron: constitutes the major portion of engineering castings. They are usually obtained by inoculating ordinary grey iron melts with calcium silicate or nickel plus ferrosilicon, thus forming dispersed graphite flakes instead of graphite clusters of ordinary grey cast iron

Nodular Cast Iron or Spheroidal Graphite Cast Iron

Spheroidal graphite (SG) or nodular cast iron are the terms used to denote that the graphite appears in the form of spheroids or nodules rather than flakes. The absence of crack propagating flakes enables a high strength iron processing ductility to be produced. The production of SG iron requires careful attention to melt composition and processing. To achieve the best combination of strength, ductility and toughness, raw materials must be chosen that are low in those trace elements which promote a pearlite matrix. The spheroidal form of graphite is usually achieved by adding magnesium to the melt. As this element is highly reactive at the processing temperatures involved and combines readily with oxygen and sulphur, oxidation must be minimized and the metal desulphurised. Several methods of treating melts with magnesium are practiced. The effect of magnesium fades with time

and the presence of the element in the iron creates a dross forming tendency which is exacerbated by poor gating practice. The pearlitic grades of SG iron are amenable to hardening and tempering heat treatment practice. According to Ithom *et al.*, (2014) nodular cast iron is obtained by inoculating ordinary grey cast iron with magnesium or cerium. Nodular cast iron has its graphite in nodular form instead of flakes as in ordinary grey cast iron. Mg and Ce produced the nodular graphites. Nodular cast irons have good ductility, strength and toughness close to steel and that informs its use in recent times in place of steel in several applications. The chemical composition effect on the structure of resulting cast iron castings is expressed by carbon equivalent value (CEV).

The formula is: $CEV = \% C + 1/3 (\%P + \%Si)$

7.1

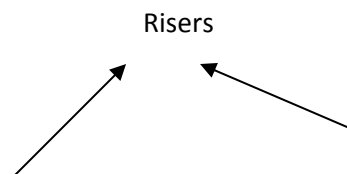
To obtain grey iron castings with very low minimum allowable thickness, CEV needs to be greater than 3.3.

Malleable Cast Iron

These irons were the original 'ductile iron' and their popularity has declined as that of SG irons has increased. The composition of these irons is deliberately chosen so that they will solidify white cast iron. A special heat treatment procedure is required to convert the carbide to graphite, which forms as aggregates in either a ferritic or pearlitic matrix. The pearlitic grades are amenable to hardening and tempering heat treatment practice.

Malleable Castings

Malleable castings are made to the desired shape by pouring molten metal in sand mould which on solidification gives white cast iron castings. If these castings are used as they are, they will have poor strength, poor ductility and poor machinability and hence will be less important from commercial point of view. In order to utilize the white cast iron castings, it is given an annealing treatment for a long time. It has been found that if white cast iron is annealed continuously at a temperature of 950 to 1000°C, carbon precipitates in the massive form. Graphite originally present in the form of flakes is a source of weakness and causes brittleness but when converted in a very finely divided form, it is not so harmful and makes the iron malleable.



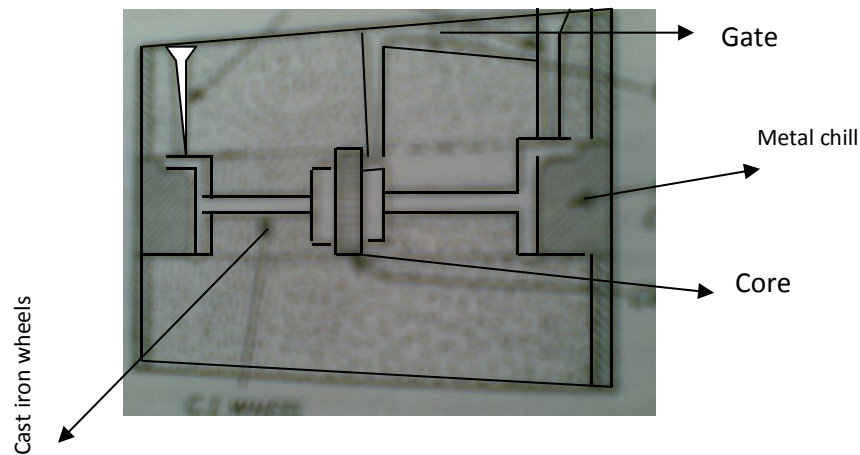


Fig. 7.3 Chilled Casting (Jain, 2009)

Several types of furnaces are used such as rotary furnace, cupola, air furnace and electric arc furnace. But the most commonly used furnace is an air furnace as it provides accurate control of carbon and other elements in the metal. The charge consists of 40% pig iron, 50% scrap and the rest material is iron and steel scrap. The temperature of molten metal before it is poured into the mould is 1500°C. See Fig. 7.4 for microstructure of grey cast iron and malleable cast iron.

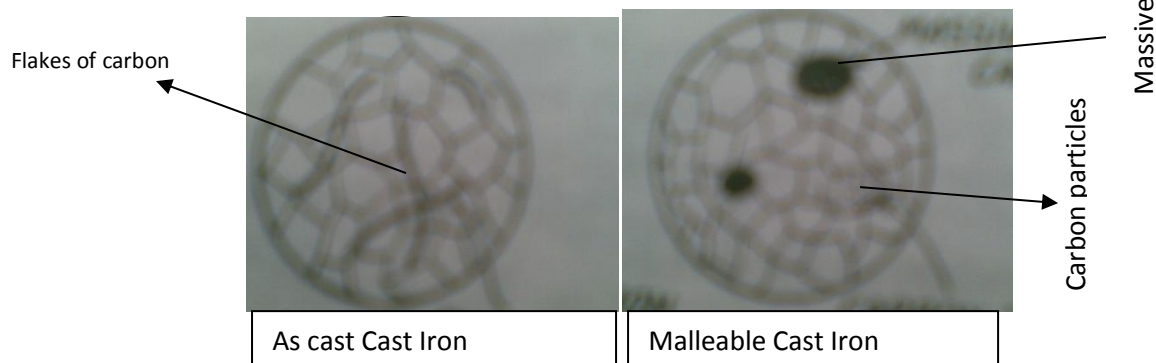


Fig.7.4 Microstructure of As-cast Cast Iron and Malleable Cast Iron (Jain, 2009)

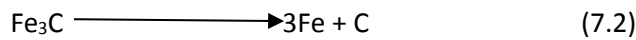
The moulds used for obtaining cast iron castings are made of green sand mould of high refractory material. Since the white cast iron cools rapidly and casting needs greater allowance for contraction, the mould should be such as to provide free contraction of the metal. The castings are cleared-off and also gates and risers are cut out. They are then packed in cast iron boxes containing sand and powdered slag. Packing helps in reducing the tendency of warping of the casting during annealing treatment. Depending upon the purposes for which the castings are to be used, they are classified in two ways:

- a) Black heart malleable castings.
- b) White heart malleable castings.

Black Heart Malleable Castings.

The castings are taken out of the mould and put into a drum having a neutral media, consisting of sand and powdered slag. The drum is closed and is kept in the air furnace and heated slowly. The

temperature is raised to 922°C in two days' time, kept at this temperature of nearly 50 to 80 hours and then the drum is allowed to cool in the furnace till it reaches the room temperature. The whole cycle takes about one week. During this treatment, combined carbon separates out and all the carbon does not change into graphite state but in another form of free carbon called tempered carbon.



This makes the casting less brittle or in other words malleable. The fracture portion of such a casting is dark grey or black in appearance. Black-heart malleable castings are specially used in the automobile industry.

White Heart Malleable Castings.

The castings are packed in a drum of oxidizing media, which is generally powdered iron ore or powdered scale (film of Fe_3O_4 on surface). The closed drum is kept in the furnace and heated to 900°C and kept at this temperature for nearly 60 to 80 hours and allowed to cool slowly in the furnace itself. The castings so obtained are supposed to be malleable like white heart cast iron.

The typical composition used for malleable casting is given below:

- Carbon 2.0 to 2.5%, silica 1% (max.), manganese 0.5 to 0.8%.
- Phosphorus and sulphur (as low as possible).

The percentage of carbon and silicon should be so selected that it promotes the development of free carbon when the castings are annealed. If thin section castings are to be obtained, then amount of silicon should be high and for large castings it should be low.

Mechanical Properties of Malleable Castings

- a) Tensile strength of the order of 2500 to 3000 kg/cm²
- b) Elongation value of 12%
- c) Hardness of 170 to 230 BHN
- d) Good machinability

Such castings are used for many industrial purposes such as agricultural implements, automobile parts, boilers, tanks, engines, conveyors and elevators, electrical and industrial power equipment, household appliances, pipe-fittings, plumbing supplies and especially for those parts which are subjected to impact and vibration.

Steels

The number of materials available under the heading of steels is very large and they are generally classified under three headings:

Plain carbon steels

Low alloy steels (total alloy content < 8%)

High alloy steels (total alloy content > 8%)

The latter group contains the heat, wear and corrosion resistant alloys

Plain Carbon Steels

Steels may be melted by induction or electric arc furnaces. If induction melting is chosen, there is a need to maintain close control over the composition of the charge materials as there is no opportunity for refinement. Electric arc melting, on the other hand, is ideal for refining and the term steelmaking is often applied when it is used. The approach adopted is based on the controlled oxidation of such elements as carbon, silicon and manganese. Steels are susceptible to defects and/or the impairment of properties caused by the failure to control the levels of oxygen, nitrogen and hydrogen. The latter two may be reduced to acceptable levels by the controlled oxidation of carbon. However, the residual oxygen must be removed by deoxidation if carbon monoxide gas hole formation in the castings is to be prevented. Silicon and manganese are mild deoxidisers, but aluminium is more effective and is commonly used as a ladle addition. Heat treatment by hardening and tempering is possible for steels containing > 0.4% carbon.

Ingot Casting

The starting metal for any deformation work is a regular type of casting termed ingot (Ihom, *et al.*, 2014). They can be rectangular, circular in cross section they may vary in size sometimes for about 10kg for nonferrous metal to over 100 tons for large steel forging ingots. Usually the moulds used for this casting are usually made of metal. They are permanent moulds. The mould is normally tapered to facilitate removal. They are normally termed big end up or big end down depending on the direction of the taper. Fig.7.5 below shows big end up and big end down types of moulds for casting ingots.

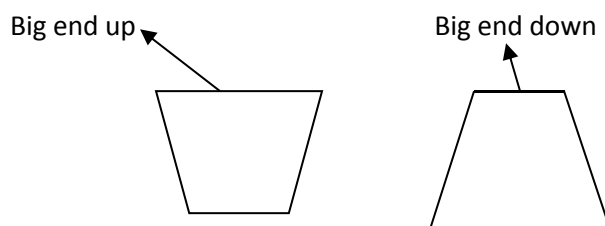
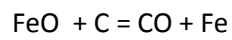


Fig.7.5 Types of moulds for casting ingots

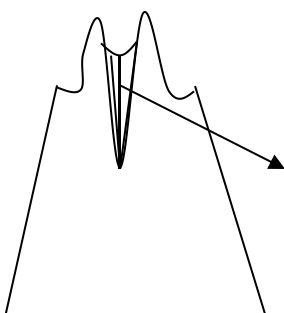
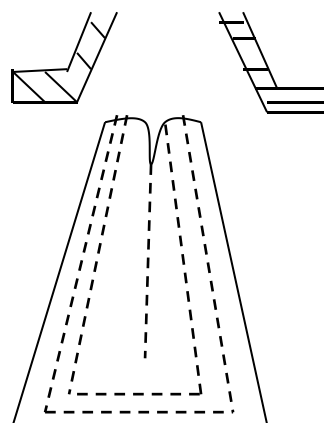
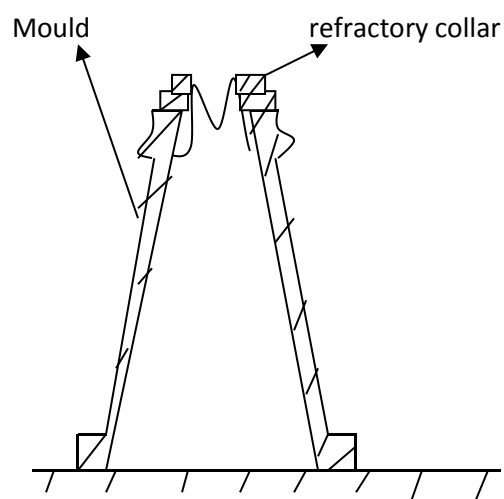
At the end of the steel refining stage the liquid steel is in highly oxidized state additions are usually added to the bath to deoxidize steel before pouring or teeming the steel. Fully deoxidized steel is termed killed steel, and most killed steels are poured into the mould of the big-end up variety. In order to minimize the pipe formation as a result of shrinkage the moulds are usually provided with a refractory collar or hot top to act as a reservoir to feed the shrinkage. Liquid metal poured into a large mould can splash considerably and the splashes will freeze instantly on the upper mould wall. Ingot casting is illustrated in Fig. 7.6 showing mould with refractory collar. The splashes, on the surface will then oxidize rapidly and not weld satisfactorily to the main body of the ingot when the mould is filled with liquid metal and this will give rise to surface defects in subsequent rolled or forged product. In order to avoid this some steel ingots are bottom poured. Some grades of low carbon or mild steel are not deoxidized before teeming. These are termed rimming steels and are

normally cast into moulds of the big-end down. When solidification first begins at the mould carbon-monoxide is evolved



(7.3)

The stream of the gas bubbles tend to carry the gas with it and the outer layers of the ingot solidify as almost pure clean iron with the impurities concentrate at the central portion of the ingot



Major segregation

Fig.7.6 Ingot Casting Illustrated Showing Mould with Refractory Collar.

Some of the gas bubbles are trapped between growing crystals of iron, giving a widely distributed porosity and this porosity compensate for the solidification shrinkage of the metal, if the internal surfaces of the gas pores are clean. They will readily weld together under rolling pressure giving sound products. Rim steel is very suitable for the production of mild steel sheets because the pure iron rim gives a ductile skin of good surface quality and this makes the steel ideal for deep and pressing operations. Large ingots cast in permanent moulds possess coarse grain structure across the ingot. There will be variation in crystal structure and if the ingot is sectioned there will be 3 main zones, the chilled, equiaxed, and columnar structures.

Casting of Steels

The basic principles of moulding and casting are similar for all cast metals, but there are considerations that are applied for each metal in each case depending on its physical and metallurgical characteristics and its castability. Some of the considerations under steel casting include the following:

1. Since steel melts at a higher temperature than Iron, higher pouring temperatures are involve and necessitating sands of greater refractoriness, usually high silica sand bonded with refractory clay are used for the casting.
2. In order to eliminate solidification shrinkage in the metal all castings must be fed in the heaviest section. This factor is not important in iron because the value of solidification shrinkage is very low
3. Since molten steel has a tendency to dissolve carbon; no carboneous material should be used on the mould faces.
4. In order to reduce cost new facing sand having refractoriness is usually used on the faces and backing up sand is used on the other part of the mould.
5. To produce sound casting the metal must be thoroughly deoxidized before it is poured into the mould. The unkilld metal spits and boils in the ladle due to dissolve oxygen and will produce defects such as gas holes, gas porosity and sponginess. Alloyed steels are invariably killed, whereas low carbon steel may be killed or unkilld.

Steels may be killed in one or several ways

1. By adding small amount of grain size control elements or deoxidisers such as aluminum, manganese, silicon to the molten metal.
2. By allowing the metal to remain in the crucible for a long time so that silicon of the crucible will combine with the oxygen to form slag on the surface of the metal
3. Another way is by normalizing treatment
4. Another way is by directional solidification and this also helps to ensure sound casting, by this method the metal starts solidifying from the point further from the riser, and solidification proceeds progressively towards the riser the riser been the last to solidify.

Generally speaking steel casting is characterized by the following factors:

- i. **High Melting Point:** the pouring temperature of steel ranges between 1550°C to 1700°C. Steel is therefore melted in low frequency induction furnace, high frequency induction furnace or electric melting furnaces
- ii. **Ladle Addition:** deoxidation of steel has to be carried out before pouring. This is done using Al (1kg per 100kg of steel) or calcium-silicon-manganese ferroalloy.
- iii. **Casting characteristics:** highly refractory sand such as zircon sand or high silica sand is required to make mould because of the very high pouring temperature of steel. The shrinkage of molten steel during solidification is high. Thus, generous risers have to be provided in the gating system.

Low Alloy Steel

The principal objective of alloying is to improve the hardenability of the steel, as this governs the depths to which hardening occurs in a section during quenching. Melting practice for this group of alloys is similar to that for the plain carbon steels.

High Alloy Steels

Whilst the basic approach to melt processing is essentially similar to the previous groups, some of these alloys can benefit from special treatments. Melt cleanliness can be improved by an Argon Oxygen Decarburisation (AOD) treatment. In this refining treatment oxygen, argon and nitrogen are injected into the molten steel and produce a melt with reduced inclusions and gas content. Steels refined in this way exhibit significantly improved ductility and toughness, and use of the process has been extended to plain carbon and low alloy steels.

Niobium and titanium can be added to certain alloys and have the effect of stabilizing the carbides. However, they must be added after deoxidation, otherwise their effect will be lost as the elements readily oxidise.

Special Techniques

The special techniques of directional solidification and single crystal production have been developed for nickel-base alloy turbine blade production. This technology is featured in the latest military and civil aircraft engine designs. The technique of hot isostatic pressing was mentioned briefly in relation to titanium castings and is used for enhancing the performance of superalloy castings. These techniques are described in the following section:

Directional Solidification

Turbine blades with an equiaxed grain structure tend to fail by creep fracture and thermal fatigue, with failure associated with those grain boundaries that are transverse to the applied stress. It was reasoned, therefore, that by eliminating such boundaries by producing a columnar grain structure parallel to the stress axis, grain boundary fracture could be eliminated and casting performance improved. This is the principle of the directional solidification process, which is an extension of the principle of directional solidification described in the previous chapter.

Casting production.

A schematic diagram of the equipment for producing directionally solidified castings is shown in Fig. 7.7. A ceramic shell mould is attached to a water cooled chill. The assembly is surrounded by a furnace unit and the whole device is contained within a chamber which can be evacuated. When the assembly is at the required temperature molten alloy is poured into the mould. Solidification at the chill surface and is encouraged to progress directionally by slowly withdrawing the mould from the furnace to ensure that the desired grain structure is produced. Two conditions must be simultaneously satisfied. Firstly, the heat must be withdrawn from the casting in a unidirectional manner, and secondly, a positive temperature gradient must be maintained ahead of the solidifying interface in order to prevent extraneous nucleation.

Apart from the grain structure, the process also promotes casting soundness.

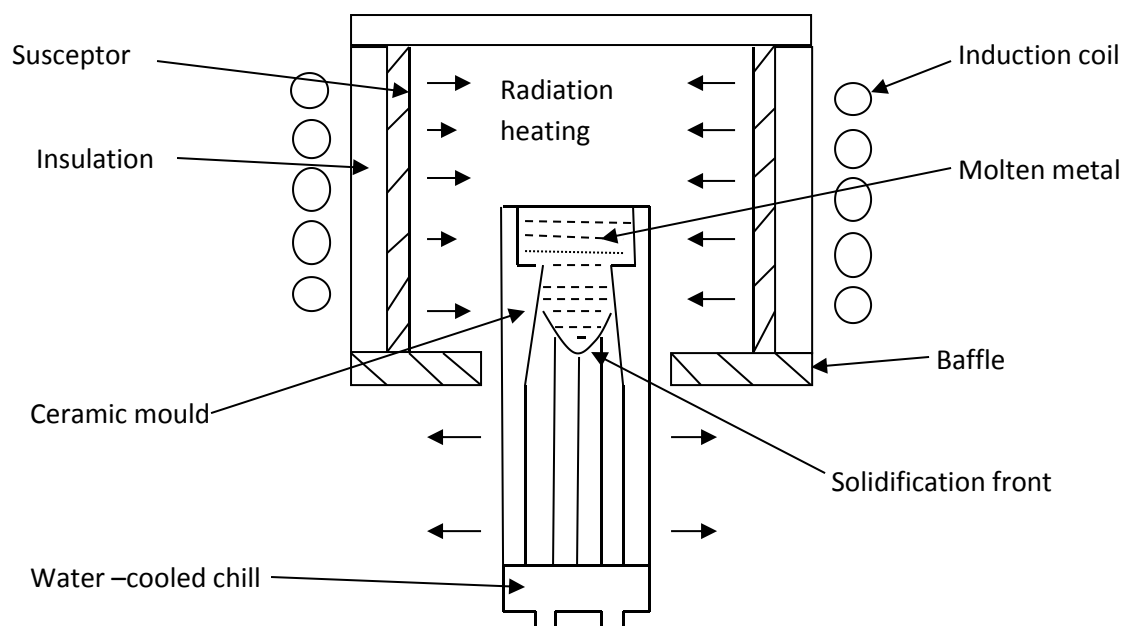


Fig.7.7 A schematic representation of the equipment for producing directionally solidified castings

Single Crystal Production

Single crystals have no grain boundaries and therefore do not require the presence of those elements added specifically to strengthen grain boundaries. As these elements lower the melting point of the alloy, their removal increases the alloy's melting point, and consequently increases the temperature at which it can be used in service. The equipment and techniques used for directional solidification can be applied to single crystal production. However, a modification in technique is required to ensure that only one crystal grows in the blade. This is achieved either by the use of a seed crystal or, more commonly, by the use of a special constrictor adjacent to the chill plane. The objective of the special constrictor is to permit only one grain to enter the airfoil portion of the mould. Whilst various design of constrictor have been proposed, the helix appears to be preferred, see Fig. 7.8. Only one crystal survives growth through the constrictor to emerge into the blade form.

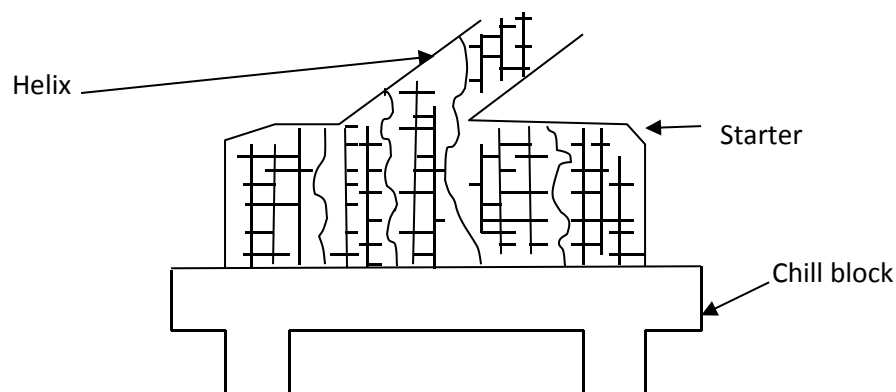


Fig.7.8 The use of a helical constrictor to encourage single crystal growth

Mould Material Requirement. In conventional investment casting the mould material is in contact with the liquid metal for a very short period of time. However, in the directional solidification process there is a prolonged period of contact between the mould material and the metal. Clearly this procedure places much greater demands on the chemical and mechanical integrity of moulds and cores than does conventional casting. It may be necessary to introduce alumina into the shell building procedure to improve the mould's high temperature properties. The combination of alumina and a silica binder may result in the formation of mullite when the shell is fired and cast, thus improving refractoriness.

Hot Isostatic Pressing (HIPing)

Hot isostatic pressing, or HIPing, is a process used to produce near net shape parts from metal, ceramic and cement powders; to diffusion bond similar and dissimilar materials including metals to ceramics; to improve the properties of parts formed by conventional powder compaction process; and to heal microporosity in castings, thus improving their mechanical properties and extending their service life.

In the process, parts are subjected to high pressures and temperatures in a pressure vessel, see Fig. 7.9. An inert gas, usually argon, is the pressurizing medium. For the processing of castings, argon is applied at pressures between 103 and 206 MPa (15,000 and 30,000 lbf/in²). Process temperatures

vary from 480 °C (896°F) for aluminium alloy castings to 1315°C (2400°F) for single crystal nickel-base superalloys.

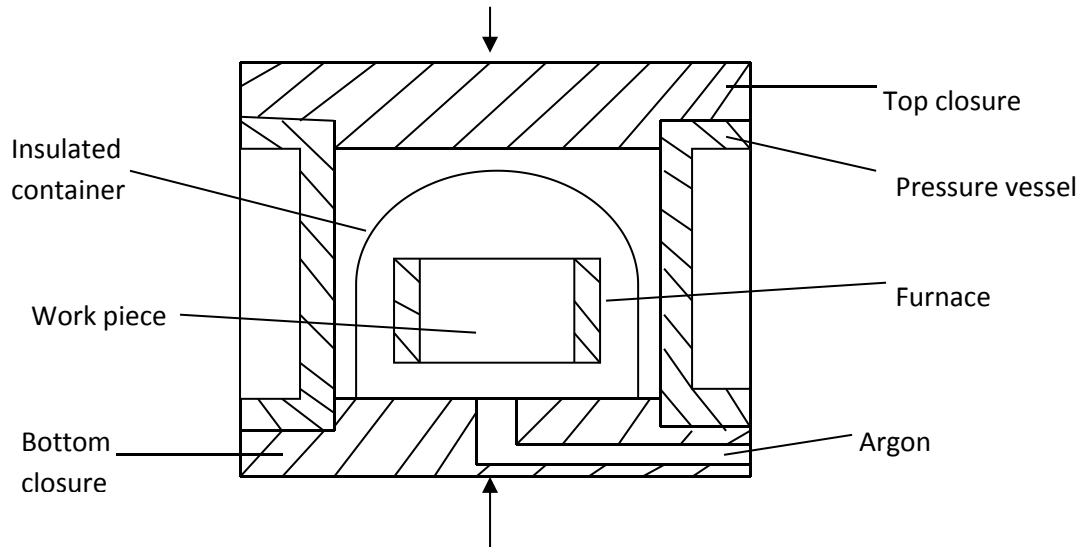


Fig. 7.9 Schematic diagram of the hot isostatic pressing process

When castings are processed, the simultaneous application of heat and pressure virtually eliminates voids and microshrinkage through a combination of plastic deformation, creep and diffusion. Since pressures are applied isostatically (uniform in all directions), parts with intricate shapes, including those with thick and thin sections, can be processed without distortion and with uniform properties throughout. Dimensions are not normally affected since the voids are usually small.

The process cannot seal surface connecting defects and high purity argon is essential. Contaminants such as nitrogen, oxygen, methane, carbon dioxide, and hydrogen, even in trace amounts, may cause undesirable surface reactions. Modern equipment permit cycle times of between two and six hours, with cooling rates sufficiently rapid to allow the solution heat treatment of many alloys at the end of a cycle. With the increase in productivity, costs have reduced and the process is being used more routinely.

Review Questions on Chapter Seven

1. Explain in your own words the importance of sound melting practice to metallurgical integrity of a casting.
2. List and explain in what ways can charge affect melt quality.
3. How can melt conditions be varied?
4. List and explain additives that can be added to metal melts
5. Write short notes on deoxidation and oxidation of molten metal

6. Tabulate melt treatment of metals and alloys indicating main field of application and typical reagents used.
7. How is melt quality control achieved in the foundry?
8. What are the commonly used melting precautions for quality melt?
9. List and explain some degassing procedures.
10. Explain vacuum melting and casting.
11. Explain melt treatment applicable to nonferrous metals, use some selected nonferrous metals.
12. Explain melt treatment applicable to ferrous alloys, use some selected ferrous metals.
13. Explain the following terms killed and unkilld, and state the ways that steels can be killed.
14. What is directional solidification? Explain.
15. Explain how single crystal can be produced.
16. What is hot isostatic pressing (HIPing)?

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CHAPTER EIGHT

CASTING PROCESSES AND TECHNIQUES

INTRODUCTION

Metal castings form integral components of devices that perform useful functions for human beings, an idea shown schematically below in Fig.8.1:

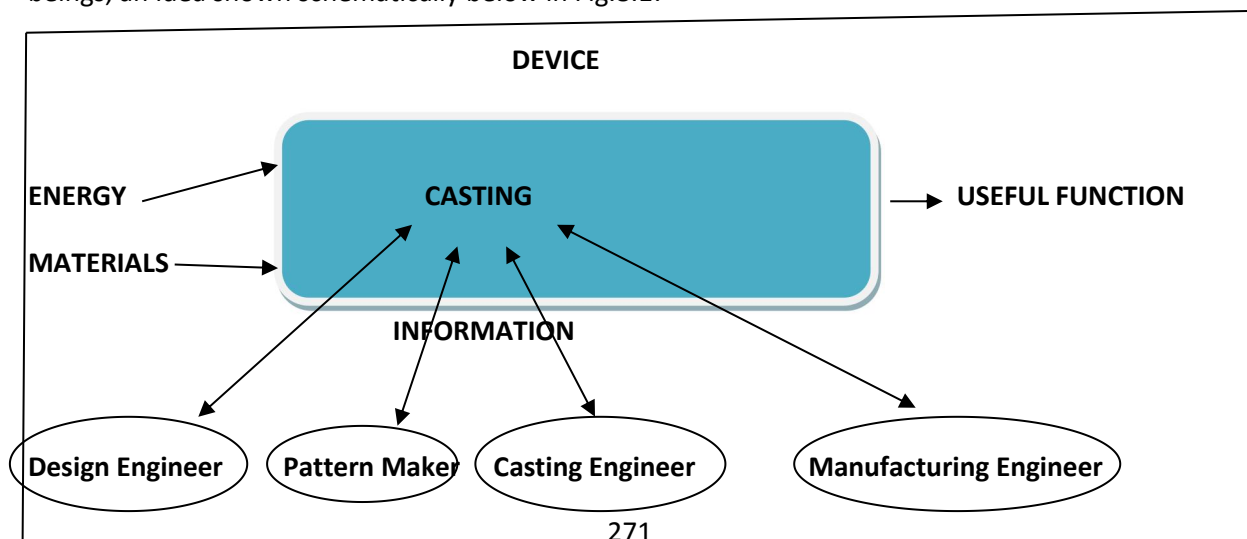


Fig.8.1 Metal casting form integral component of devices Source: Rundman, (2000)

The cast component has a shape, size, chemical composition and metallurgical microstructure which is determined by engineering decisions arrived at by:

- A. Design Engineers (Mechanical Engineers)
- B. Pattern Makers (skilled craftsman, CAD)
- C. Casting Engineers (Metallurgical Engineers)
- D. Manufacturing Engineers (Mechanical, Metallurgical Engineers)

The engineering professionals that carry out this process work together, sharing information so that the casting will perform as intended in a timely and cost effective manner. It should be noted that the casting may only be small part of the useful device (usually in more sophisticated devices like an automobile where there may be hundreds of components), or it may be the entire device (simple device like a frying pan).

Metal casting has an historic pedigree as the manufacturing process first used by man to produce intricate metal artifacts and art objects. It played a major role in the industrial revolution and remains the basis of current manufacturing equipment and manufactured goods. The process plays an important part in aerospace component production and, as such, remains at the leading edge of technology development. Despite the competition from plastics and ceramics, metals still remain the dominant materials in the production of capital equipment and manufactured goods. Metal casting will continue to play a major role, as a manufacturing process of considerable versatility, for the foreseeable future.

In common with other manufacturing processes, metal casting has not remained static and there have been significant developments in both the metallurgy of cast alloys and in casting processes. This chapter looks at the developments in processing, and various casting techniques some of which are modern. To fully understand the developments in metal casting this requires a definition and description of metal casting.

Metal Casting

In the metal casting process a metal, or more commonly an alloy, is heated until it is molten, whereupon it is poured into a mould or die that contains a cavity which represents the shape of the component or casting to be produced (Clegg, 1991). In the case of a mould the cavity is produced by a pattern which is a replica of the component required, whereas in the case of a die the cavity replicating the shape of the component is produced by machining. Moulds are invariably expendable, being destroyed when the casting is removed. Dies, on the other hand, are permanent and may be used to produce a succession of castings. Patterns may also be permanent or expendable. A permanent pattern is reusable, whereas an expendable pattern is consumed during the process of mould or casting production.

There are different casting processes, (Khanna, 2008, and Jain, 2009) an attempt will be made to list and explain most of the casting processes and techniques in common practice, these include:

- a. Sand casting
- b. Shell moulding
- c. Gravity die (permanent mould) casting
- d. Die casting
- e. Plaster mould casting
- f. Investment or lost wax casting
- g. Centrifugal casting
- h. Semi-permanent mould casting
- i. Slush casting
- j. Pressed casting
- k. Squeeze casting
- l. Centrifuged or pressure casting
- m. Vacuum process
- n. Frozen –mercury moulding (mercast process)
- o. Antioch casting
- p. Carbon dioxide process for mould hardening
- q. Continuous casting
- r. Reciprocating mould process
- s. Asarco process
- t. Chill casting
- u. Malleable casting
- v. Lost foam EPC
- w. Thixocasting
- x. Rheocasting
- y. Cosworth
- z. V process
- aa. Ingot –not cast to shape.

Sand Casting

There are so many sand casting processes some of which include:

Green sand moulding process

Dry sand moulding process

CO₂ / Silicate process

Shell moulding process

Cold set processes

Vacuum- sealed moulding process

Evaporative pattern casting process

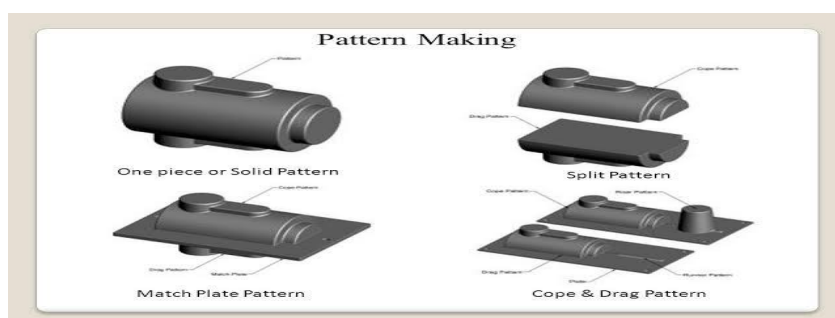
A Casting is made by pouring molten metal into a mould formed by pressing moulding sand around a pattern of the shape of the article to be cast. The pattern used for sand casting may be

of wood, metal, or any other material that can be shaped readily. Casting procedure is essentially the same with all metals used for sand casting, but with some modifications required by the nature of the metal. Steel is poured at such high temperatures that a mixture of silica and fire clay must be used instead of the moulding sand used in making castings of aluminium, brass, cast iron, and magnesium. Steel castings require prompt annealing after cooling. Because at high temperatures it has a tendency to absorb gases, particularly hydrogen, the pouring temperature of aluminium is kept as low as consistent with proper fluidity. Because aluminum has relatively high shrinkage, cores must be softer than those suitable for cast iron, for example, to avoid cracking of the casting as a result of resistance offered by hard cores. Multiple gating ordinarily is used for aluminium casting in order that the mould shall fill with metal as promptly as possible. The strong tendency of magnesium to oxidize makes it necessary to melt it under a flux containing such materials as fluorides, sulfur, and boric acid, and to mix inhibiting agents in the moulding sand (Shrager 1961).

Patterns for Casting

A pattern is defined as a model of a casting, constructed in such a way that it can be used for forming an impression (mould) in moulding sand (Jain, 2009). The first step in making a casting is to prepare a model, known as a pattern, which differs in a number of respects from the resulting casting. These differences, known as pattern allowances, compensate for metal shrinkage, provide sufficient metal for machining the surfaces and facilitate moulding.

Most patterns are made of wood because of its cheapness, ease of availability, lightness, ease of obtaining smooth surface and preserving surface by applying coating of shellac, ability to be worked on easily; ease of joining, ease of fabricating to numerous shapes. However wood is easily affected by moisture, its shape changes by change in moisture, it wears out quickly by sand abrasion, it may warp during improper storing, it can not stand rough usage. Wood used for pattern making should be properly dried and it should be straight grained and free from knots and free from excessive sap wood. Wood patterns made of white pine, cherry, or mahogany are used if the number of castings to be made is not large. Where durability and strength are required, patterns are made from metal- usually aluminium alloy, brass, or magnesium alloy. For mass production, steel or cast iron pattern may be preferred. A wooden master pattern is first made from which the metal pattern is cast. The pattern is made oversize to allow for the normal shrinkage of metal during cooling. Since each material has a different shrinkage rate, the pattern maker uses a special scale for making his measurements. Some patterns are made of plaster, plastic compound, wax etc (see Fig. 8.2).



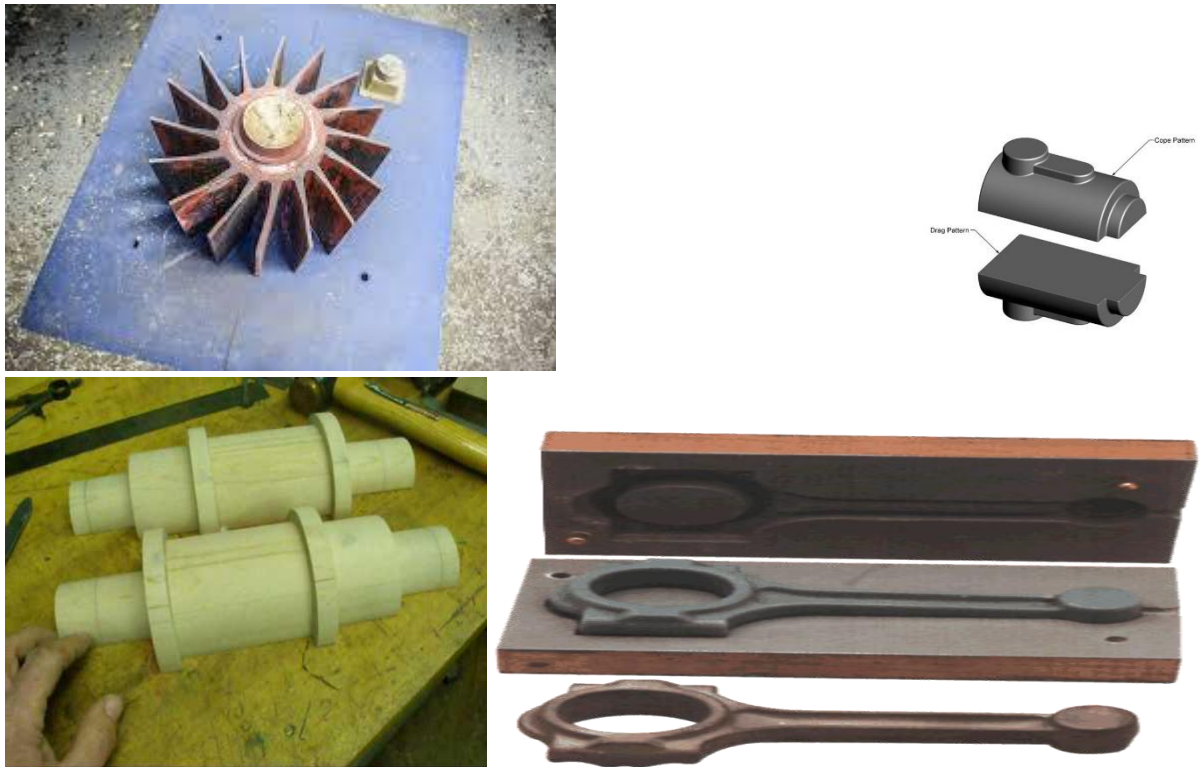


Fig. 8.2. Different patterns used for components casting

Type of Patterns

The type of particular pattern selected for a particular casting will depend upon: (a) the shape and size of casting (b) number of castings required, (c) method of moulding employed, and (d) anticipated difficulty of the moulding operation.

When the casting is of simple and regular shape, the corresponding pattern must be identical and in single-piece. If the casting is of intricate shape involving changes in section, the pattern may be made in a number of pieces.

- (i) **Single-piece or Solid Pattern.** This type of pattern is made without joints, partings, or any loose pieces. A solid pattern is made in one piece, and is so constructed that it can be moulded with a single joint. Use of a solid pattern requires more hand work in moulding, with the result that cost of production of castings is increased. Such a pattern is usually 'flat-back' type (Refer to Fig. 8.3), which may have a few or no irregularities and no core print.

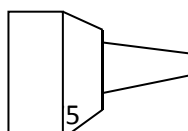


Fig. 8.3. Solid Pattern.

- (ii) **Split Patterns.** A split pattern is made in two pieces joined at the parting line along which the two sections of a mould separate (Refer to Fig.8.4). Sometimes a pattern is constructed in three or more parts for complicated castings. Such a pattern is called 'multi-piece pattern' (Refer to Fig.8.5).

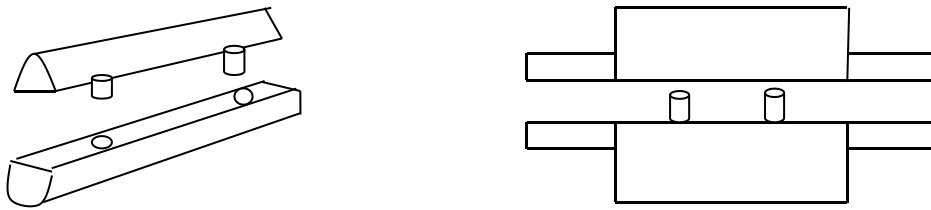


Fig. 8.4 Split Pattern

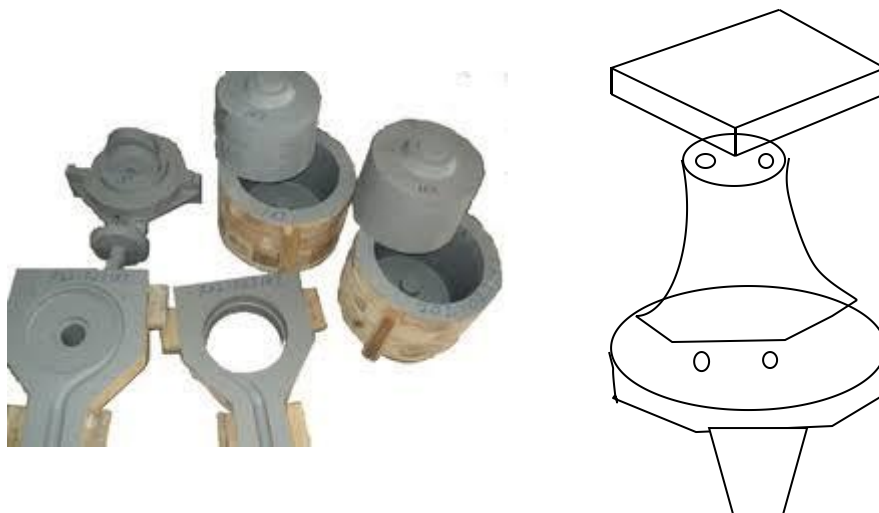


Fig. 8.5 Multi-piece Pattern (source: Jain, 2009)

- (iii) **Loose Piece Pattern.** It is a pattern with loose pieces which are necessary to facilitate withdrawal of the pattern from the mould. It is used to produce undercuts. Loose pieces are removed separately through the cavity formed on main pattern, after the pattern has been removed. These loose pieces may have to be turned or moved before taking them out. These also need to be fastened loosely to the main pattern by wooden dowel pins (Refer Fig.8.6)

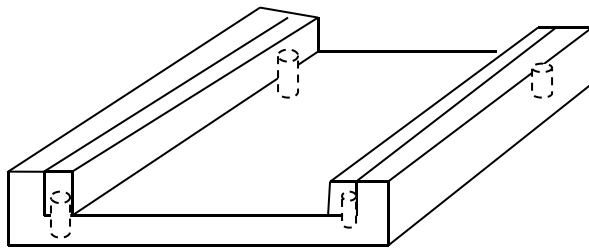


Fig. 8.6 Loose-piece Pattern (source: Jain, 2009)

- (iv) **A Gated Pattern.** A gated pattern is actually a group of patterns, usually but not necessarily identical, so connected that all patterns of the group are moulded at once. If such a gated pattern is mounted on a metal plate or on a wooden board, it is known as a match plate pattern (Refer to Fig. 8.7)

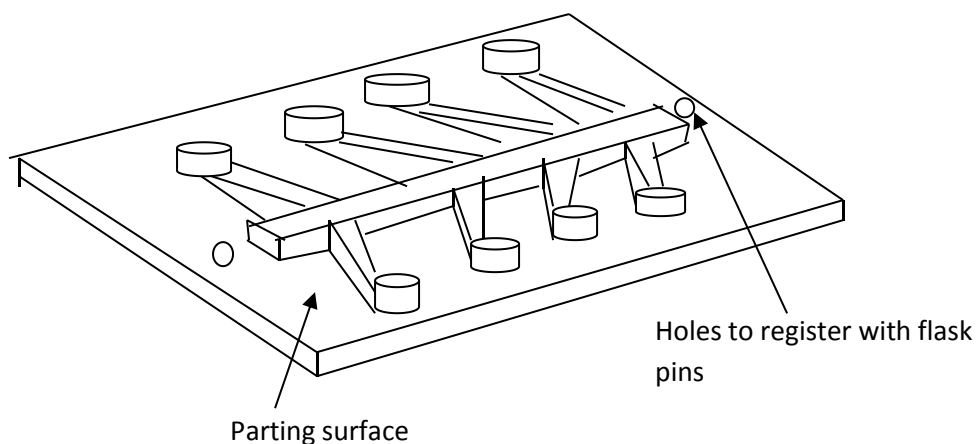


Fig. 8.7 A Gated Pattern or Match plate Pattern (source: Shrager, 1961)

- (v) **Follow Board Patterns.** The patterns having thin sections, (refer Fig.8.8), tend to get distorted or collapse during ramming. Sagging of thin pattern due to ramming can be easily overcome by constructing a supporting block (follow board) which may fit inside the pattern to serve as a support during ramming.

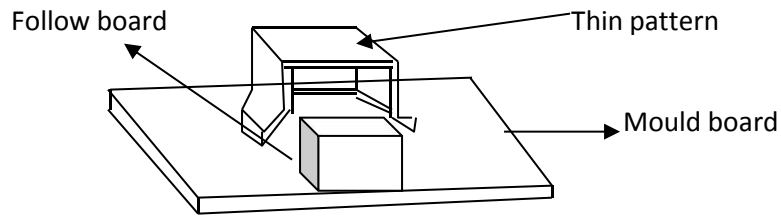


Fig 8.8 Follow-board Pattern (source: Jain, 2009)

- (vi) **Sweep Patterns.** Many patterns of symmetrical and regular shape, usually of large size, may be constructed by the use of sweep pattern (which has the shape corresponding to the shape of the desired casting) which sweeps the desired shape into the sand mould thus eliminating the need for costly three dimensional patterns. The sweep pattern is arranged to rotate about a central axis on a needle (refer to Fig 8.9).

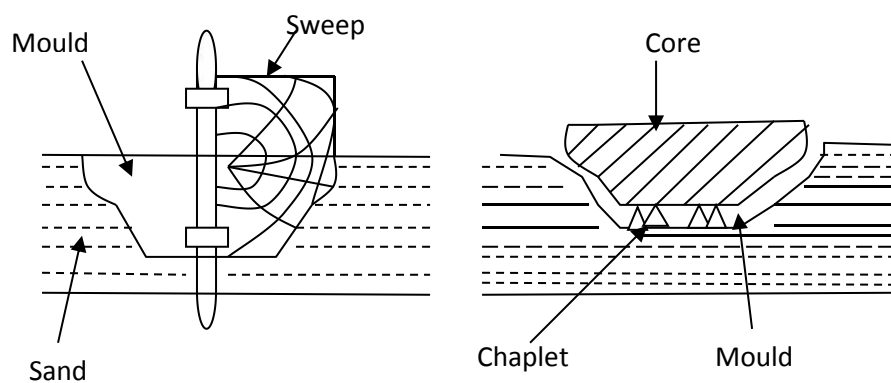


Fig. 8.9 Sweep Patterns (Jain, 2009)

- (vii) **Segmental Pattern or Part Pattern.** Segmental patterns are sections of a pattern arranged in such a manner as to form a complete mould by placing the segmental

patterns in the mould suitably. These are generally used for circular work, like rings, wheels, rims, gears, etc (refer to Fig.8.10)

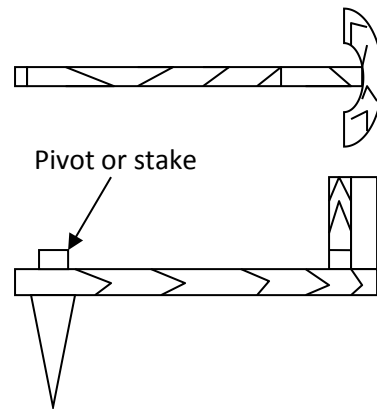


Fig. 8.10 Segmental Pattern (Jain, 2009)

- (viii) **Skeleton Pattern.** For very large castings solid patterns would require a tremendous amount of timber, which may not be economical particularly if the castings required are less. In such cases the pattern is made of wooden frame and rib construction (skeleton) so that it will form a partially exterior or interior outline of the casting and provide the general contour and size of the desired casting. The ribbed construction with a large number of square or rectangular openings between the ribs is filled and rammed with clay sand or loam. A 'strike-off board' known as a 'strickle board' is used to remove the excess sand out of the spaces around the ribs so as to make the exterior surface even with the outside of the skeleton. Usually skeleton pattern is built in two parts; one for the cope and another for the drag (refer Fig. 8.11).

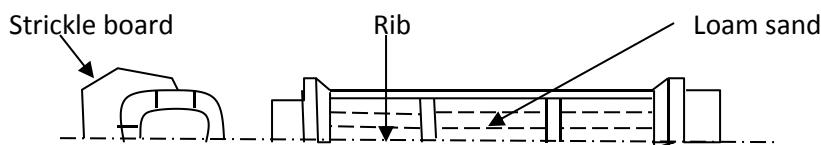


Fig. 8.11 Skeleton Pattern (Jain, 2009)

- (ix) **Shell Pattern.** Shell pattern is usually mounted on a plate and parted along the centre line, the two halves being accurately doweled together. Usually, these short bends are moulded and cast in pairs. This type of pattern is largely used for drainage fittings and pipe work (refer Fig. 8.12)

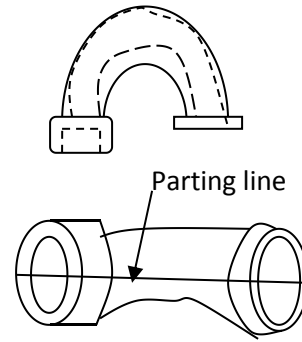


Fig. 8.12 Shell Pattern

- (x) **Built-up Pattern.** Built-up patterns are composed of two or more pieces. For special pulleys, patterns are built-up of segments of wooden strips. The segments are made by cutting strips of wood to the curvature required. The thickness desired is built-up by gluing them in layers. Flanges are also made similarly. Such patterns are used to make intricate shapes because it is easier to build-up the shape by gluing or joining number of segmental pieces together (refer to Fig.8.13)

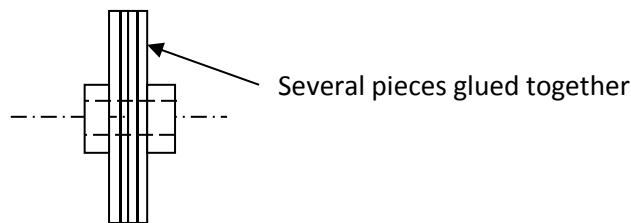


Fig. 8.13 Built-up Pattern

- (xi) **Boxed-up Pattern.** It is a box-like pattern in which planks or strips of wood are joined together either by glue, nails, or screws. This method economizes wood for large patterns and makes them lighter in weight.
- (xii) **Lagged –up Pattern.** Cylindrical patterns e.g., barrels, pipes or columns are built up with lag or stave construction to ensure proper shape. Longitudinal strips of wood, called 'lags' or 'staves', are beveled on each side and glued to the wooden end pieces called 'heads' as shown in Fig. 8.14.

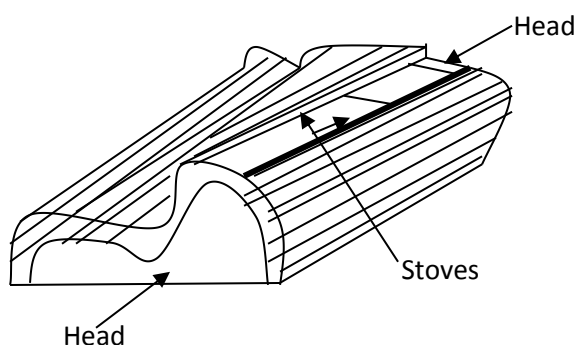


Fig. 8.14 Lagged-up Pattern (Jain, 2009)

- (xiii) **Odd –shaped Pattern.** An odd-side cope or false cope is used when the shape of the casting does not produce a convenient flat split in the pattern, such as in a cranked lever. The pattern is solid and an odd-side (or false cope) is used to assist in providing of a contoured split between cope and drag as shown in Fig.8.15. the odd side is often made of plaster of paris.

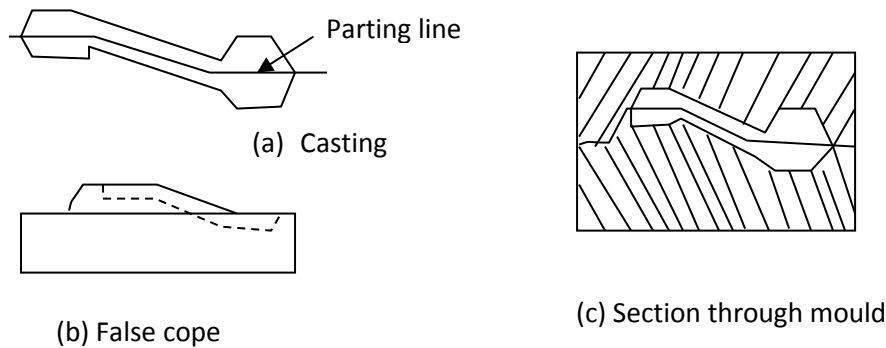


Fig. 8.15 Odd-shaped Pattern (Jain, 2009)

Pattern Allowances

Pattern allowances in order to produce a casting of proper size and shape depend partly on product design, mould design, shrinkage and contraction characteristics of the metal being cast, etc. actually it is very difficult to predict precisely mathematically any rule, and a process of trial and error is best to achieve adjustment of pattern dimensions to obtain desired results.

- (i) **Shrinkage Allowance.** When any metal cools, it naturally shrinks in size. The total contraction of a casting comprises of three elements viz., the contraction of liquid from pouring temperature to freezing temperature, contraction on account of change from liquid to solid and lasting contraction of solid casting from freezing temperature to surroundings. While first two contractions are taken care of in the design of castings, last effect is taken care of in the design of castings, last effect is taken care of by designing pattern of bigger size.

If the actual object itself is used for the pattern, the resulting casting would be slightly smaller than desired. To compensate for this possibility, a shrink rule is used in laying out of measurements for the pattern. A shrink rule for cast iron is 10mm per metre (the average shrinkage for cast iron) longer than the standard rule. Table 8.1 show typical shrinkage allowances for important casting materials in mm/metre.

Table 8.1 Typical Shrinkage Allowances for Important Casting Materials

S/NO	Material	Shrinkage Allowance mm/metre
1	Grey cast iron	7- 10.5

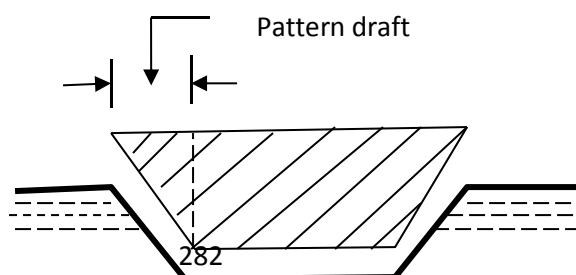
2	White Cast iron	21
3	Malleable iron	15
4	Steel	20
5	Brass	14
6	Aluminium	18
7	Aluminium alloys	13- 16
8	Bronze	10.5 – 21
9	Magnesium	18

Source: Jain, 2009,

In actual practice shrinkage allowance varies with the casting design, thickness and other dimensions of casting, type of metal, pouring temperature, and resistance of the mould to normal contraction of the casting caused by projecting lugs, cores, design and intricacy of casting, moulding material used and its hardness, method of moulding etc. when metal patterns are to be cast from the original patterns, double shrinkage must be allowed.

- (ii) **Draft Allowance.** When a pattern is drawn from the mould the tendency to tear away the edges of the mould in contact with the pattern is greatly decreased if the surfaces of the pattern are given a slight taper in a direction parallel to which it is being withdrawn, (refer to Fig.8.14). this tapering of the sides of the pattern, known as draft, is done to provide a slight clearance for the pattern as it is lifted up. The amount of draft required depends upon the shape and size of the casting (length of vertical side of pattern), moulding method, the method of production, intricacy of pattern, and whether moulded by hand or machine. Machine moulding requires minimum draft.

The amount of draft on exterior surfaces is about 10 -20mm per metre. On interior holes which are fairly small, the draft should be around 30mm per metre. In green-sand moulding, interior surfaces usually require more draft than exterior surfaces. Some pattern shops use a taper of from 2 to 4 degrees.



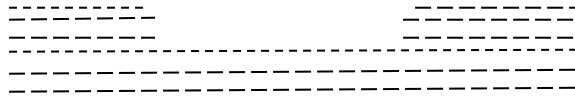


Fig 8.14 Draft Allowance (source: Jain, 2009)

- (iii) **Finishing Allowance.** When a draftsman draws up the details of a part to be made, each surface to be machined is indicated by a finish mark. The mark indicates that additional metal must be provided at this point so that there will be some metal to machine. The amount that is to be added depends upon the size, shape of casting, but in general, the allowance for small castings and average sized castings is 3mm for ferrous castings and 1.5 mm for nonferrous castings. Wherever possible, surfaces to be machined should be cast in the drag side of the mould. However, where finished surfaces are cast in the cope, an extra allowance should be made. Finishing or machining allowance depends on method of machining used (turning, boring, grinding, etc.), characteristics of metal (ferrous, nonferrous, soft, easily machinable), method of casting used (e.g. centrifugal casting requires more allowance on the inner side), size and shape of the casting (e.g. more allowance is required at top surface which collects impurities, long castings have tendency to warp), degree of finish required.
- (iv) **Distortion or Camber Allowance.** This allowance applies only to those castings of irregular shapes such as U-shape or those having large flat areas, which are distorted in the process of cooling as a result of metal shrinkage. For instance, casting of U-shape will be distorted with the legs divergent, instead of parallel. To compensate this, the pattern is made such that the legs converge, but on cooling the casting legs straighten. Such an allowance depends on the judgment and experience of the pattern maker, who understands the shrinkage characteristics of the metal.
- (v) **Rapping or Shaking Allowance.** When a pattern is rapped in the mould before it is withdrawn, the cavity in the mould is slightly increased. In an averaged sized casting this increase in size can be ignored. In large castings or in one that must fit without machining, however, shake allowance must be considered by making the pattern slightly smaller.

Pattern Construction Details

- (i) **Fillets.** A fillet is a concave connecting surface for the rounding out of a corner at two intersecting planes. In all castings sharp corners should be avoided. Rounded corners and fillets assist material in moulding, since there is less tendency for the sand to breakout when the pattern is withdrawn. The metal flows into the mould more easily, and there is less danger of sand washing into the mould. The appearance of casting is improved and it is generally stronger, having fewer internal or shrinkage strains.

A casting in a mould cools on the outside first. As the cooling progresses to centre, the grains of metal arrange themselves normal to surface in a dendritic structure. In patterns that have sharp corners there is a tendency for the metal at the corners to open up because of shrinkage strains. Fillets are made of wood, leather, or wax.

- (ii) Section Thickness. So far as service and design factors permit, all sections should be as uniform as possible. When light section must be adjacent to heavy sections the transition should be as gradual as possible since abrupt changes in thickness always result in strains, which are likely to cause cracks.
- (iii) Sanding and Shellacing the patterns. For getting good finishing, patterns are made smooth with abrasive paper. After sanding, shellac is applied to obtain hard and smooth surface coating on pattern. It is important to note that the degree of finish that can be obtained on the casting depends largely on the smoothness of pattern.

Materials used for Patterns

Wood: Although patterns are made from a variety of woods, white pine is a favourite choice because it is straight grained, light and easy to work, and has little tendency to warp. When a more durable wood is necessary for fragile patterns or hard use, mahogany is preferred. Other woods suitable for pattern making are cherry, beech, poplar, bass wood and maple, the last being especially desirable for work on the lathe. Before using a wood for pattern making, it must be dried and seasoned. Kiln drying, which requires only a short time, reduces the moisture to a minimum, drives off volatile matter, and is mostly employed. Since wood is susceptible to moisture, it tends to warp and wears out quickly due to sand abrasion, metal patterns are preferred where durability is the consideration.

Metal: many of the patterns used in production work are made of metal because of its ability to withstand hard use. Further more metal patterns do not change their shape when subjected to moist conditions and require a minimum of maintenance work to keep them in operating condition.

Aluminum is the best of all the metals because it is easy to work, light in weight, resistant to corrosion, easy to cast. Cast iron is cheap, easy to file and fit, strong, gives a good smooth mould surface with sharp edges and is resistant to abrasive action of sand. But it is heavy, easily broken and has hard edges difficult to be machined. Brass is strong, tough, does not rust, takes better surface finish than cast iron, withstands sand abrasion better. Brass patterns are, however, heavier and costly.

Polystyrene: This is known as a consumable pattern because the heat of the molten metal vapors the pattern so that it leaves the mould in the form of gas. The plastic is light, easily sculptured with a sharp knife, and the pattern can be made of several parts cemented together. Special care is required in ramming the mould as this material is fragile. It is best suited for cases where it is difficult or impossible to draw the pattern.

Machines used in Pattern Making

Modern pattern – shop practice requires the use of basic wood-working machinery. Some of the machines commonly used are described below.

- (1) Circular Saw. It is the most widely used, very accurate and versatile machine. It is used for ripping, cross cutting, mitering, beveling, and grooving lumber. It consists of a flat surface or table upon which the work rests while being cut; a circular cutting blade; a cut-off guide; and a ripping fence. See inserted plates. Tilting mechanisms on circular saws, either by tilting of table or by tilting saw arbor, provide for angular cuts. These mechanisms are of two basic designs. Both types of tilting arrangements are capable of tilting to a 45° angle.
- (2) Band Saw. This machine is ideally suited for making curved or irregular cuts in wood. It is designed to cut wood by means of an endless metal saw band that travels over the rims of two or more rotating wheels. For curves of small radii, it is necessary to employ narrow saw blades which will not bind when the work is being turned. Angular cuts are obtained by tilting the saw table.
- (3) Jig or Scroll Saw. It is used for making intricate irregular cuts on small work. It can be used conveniently for internal cuts by threading the blade through a hole bored into the work.
- (4) Jointer. The jointer planes the wood by the action of revolving cutter head. The board is hand fed against the revolving cutter head, which planes fine chips from the wood. An adjustable fence guides the board at a pre-determined angle to the surface of the table. This fence may be adjusted to a right angle with the table or may be inclined for bevel and angular cuts.
- (5) Wood –turning Lathe. Patterns for cylindrical castings are usually made by the pattern maker on the wood-turning lathe. The wood stock in a wood-turning lathe rotates and is shaped by the cutting action of turning tool held against the rotating work. Long and slender work is generally used for disc-shaped pieces.
- (6) Abrasive - disc Machine or Disc Sander. It is used for shaping or finishing flat surfaces on small pieces of wood and sanding the draft on small patterns. It consists of an electric motor with a metal disc mounted on its shaft, on which an abrasive disc is cemented. An adjustable work table is located below the centre of the face of the disc for supporting the work.
- (7) Abrasive-belt Machine. It makes use of an endless abrasive belt which travels over two drums. Cloth-back abrasive belts are available in several grits for sanding or polishing wood or metal. This machine is especially useful in shaping patterns or parts of patterns that would normally require the use of hand tools. The work is supported by an adjustable work-table that may be tilted at a predetermined angle.
- (8) Drill Press. In addition to drilling and boring holes, this machine is used for mortising, shaping, and routing with the special attachments available.
- (9) Wood Shaper or Wood Moulder. In this machine, a cutter head carrying a cutter rotates about a vertical axis. It has a horizontal table similar to a jointer. Wooden piece is fed by hand along the table against the cutter and guided by an adjustable fence. A number of shapes can be imparted to the surface of the wood according to the profile of teeth on the cutter.
- (10) Mortiser. It is used to facilitate the cutting of mortise and tenon. Chisel mortising machine consist of a revolving spindle carrying an auger bit at the bottom end. Auger bit rotates at a higher speed inside a square hollow chisel having four sides of equal width. A hollow chisel is forced into the wood, the auger bit bores the hole which is cut square by the sharp end of

the chisel. Thus auger bit and chisel work together performing boring of a square hole. By shifting the work on the table, the mortise of the desired length with square ends and square bottom is produced (Jain, 2009).

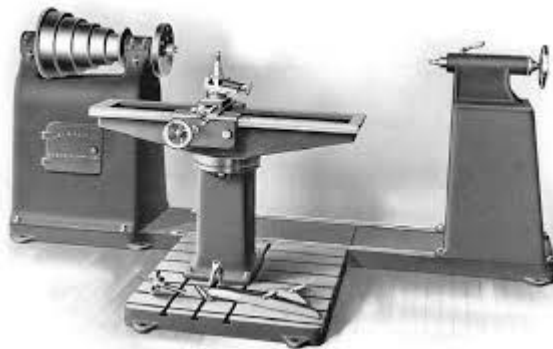
- (11) In modern pattern making shops a vital equipment is the 3-D printer, the computer and other accessories. The advent of the 3D printer has reduced the time required in producing a pattern.



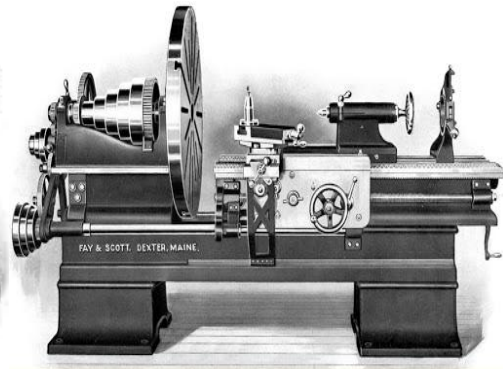
Simple hand tools for pattern making



Planner for pattern making



Simple wood lathe machine



Pattern making lathe machine



3D Printer

Fig. 8.17 Plates of some pattern making machines

Moulds and Cores

The sand form containing the cavity into which molten metal is poured is the mould (Shrager, 1961). A mould is made of moulding sand pressed around the pattern in a metal or

wooden container known as a flask. A flask is made in at least two parts, and often in three or more. The lower portion is known as the drag, and the upper portion as the cope. If a middle section is used, it is called a cheek. A flask is provided with lugs and pins on at least

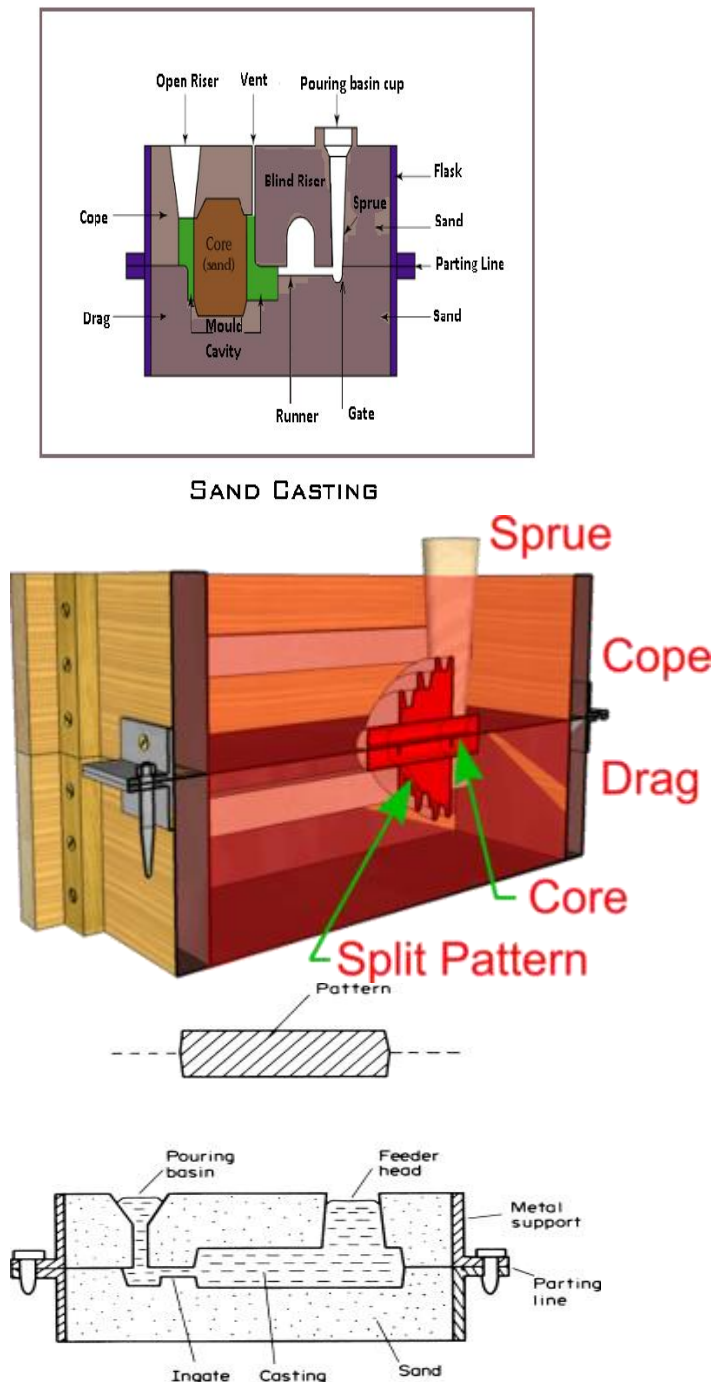


Fig.8.18. Different Mould Assemblies showing various parts.

two opposite sides to assure accurate alignment when the mould is closed. Moulding sand must be sufficiently refractory to withstand the temperature of the molten metal without fusing, sufficiently cohesive to retain its form until the molten metal has solidified,

sufficiently permeable to permit escape of gases and steam generated during pouring of the metal, and of uniform grain size (see Fig.8.18).

Green Sand Mould. Because they are the least expensive to make, and because they can be used immediately, green sand moulds are used for a majority of castings. Green sand is moulding sand in its natural state containing clay, and tempered by mixing with a suitable amount of water. Because of their softness, green sand moulds allow freedom of contraction of castings during solidification and cooling.

Dry Sand Moulds. Large castings of intricate design usually are made in dry sand moulds. The sand is mixed with a bonding agent such as dextrin, clay, pitch, or rosin, and the mould is baked before using, to dry out the water and to harden the bonding agent. Dry sand moulds are stronger than those of green sand, and have less tendency to collapse during normal contraction of the casting. Baking the mould reduces the possibility of the face being washed away as the metal is poured over it, and precludes the possibility of distortion resulting from steam.

Skin –Dried Moulds. For extremely large castings or for castings that must be made with maximum accuracy, skin-dried moulds are used. Such a mould is made of green sand with a facing of sand containing a bonding material, and the skin is dried by rapid application of concentrated heat. Heating is done with a kerosene torch, by brief heating in a hot oven, or by spraying with flammable material and igniting. A skin-dried mould must be used immediately after drying before softening of the dry skin by absorption of moisture from the green sand can occur. A skin-dried mould combines the advantages of a firm face and a relatively collapsible body.

Loam Moulds. Large symmetrical castings such as large gears, for example, often are moulded in loam moulds made of bricks, with surfaces of loamy sand applied wet, and dried before use. Some forms can be moulded by use of rotary sweeps instead of patterns.

Chill Moulds. In pouring a casting in which a thick section joins a thin section, distortion may occur as a result of the slower rate of cooling of the thick section; to compensate for the difference in normal cooling rates the thicker section may be chilled. Rapid chilling also helps to prevent formation of shrinkage cavities, and chilling sometimes is required to produce a hardened area on the surface of a casting. A metallic chill inserted in the mould conducts heat more rapidly from the molten metal at that spot, with the result that solidification and cooling take place more rapidly there than at other parts of the casting.

Cores. If a casting is of such design that an opening extends partly or completely through it, a core must be placed in the mould before casting. Cores also are used to assemble moulds of such complicated structure that they would be difficult or impossible to make by use of patterns of the usual type. A core is made of sand combined with a binder such as linseed oil, pitch, dextrin, molasses, or a cereal; sometimes wires are used to strengthen a core. Before use, the core is baked in an oven to give the strength required to enable it to retain its shape until the casting has solidified. A core must be sufficiently permeable to permit steam and gases generated during pouring to escape readily, and it should crush when the casting shrinks during cooling.

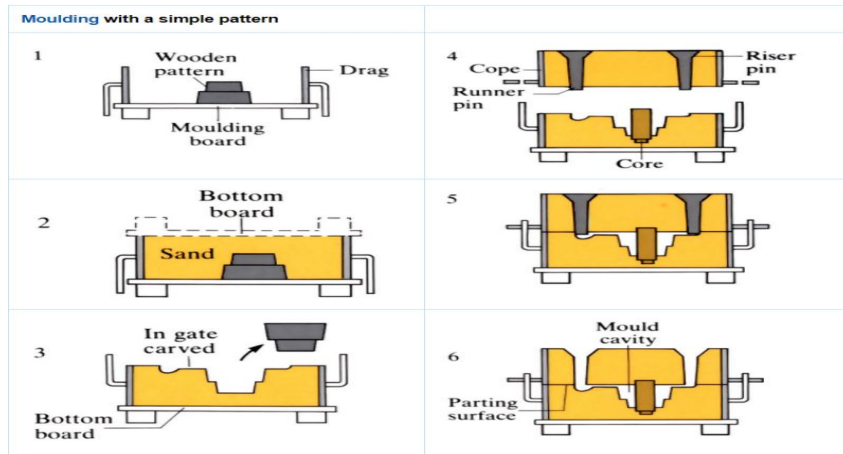
In small foundries, cores are made by ramming sand by hand into core boxes containing cavities of required sizes and shapes. Additional provision for escape of gases sometimes is provided by piercing vents in cores. Cores in large numbers are made by

extrusion or by a core-blowing machine that makes them automatically by ramming sand into core boxes.

Moulding

In bench moulding, the drag section of the flask is inverted on a flat moulding board, and the lower section of the pattern is placed within it, large side down. A small amount of sand is riddled (sifted) over the pattern and is followed by enough sand to fill the drag. The sand is peen-rammed around the outer edges of flask and pattern, taking care to avoid ramming heavily over the pattern. Additional sand is added to fill the drag again, and is built-rammed to uniform hardness sufficient to form a firm mould, but not so hard as to destroy permeability. Excess sand is scraped off level with the edges of the drag, a bottom board is clamped to the drag, the drag is rolled over, and the moulding board is removed, exposing the top surface of the lower half of the pattern. The surface is smoothed off and parting dust is sprinkled over it to prevent the two halves of the mould from sticking together; parting dust then is blown from the surface of pattern with a bellows. Fig.8.20 shows some patterns used in producing auto-parts.

The cope is fitted to the drag and the upper half of a pattern is fitted accurately to the lower half. A sprue pin is set on the sand in the drag, extending above the top edges of the cope, and the cope is filled with sand and rammed. The sprue pin then is removed and a funnel-shaped pouring basin is cut at the top of the sand in the cope around the hole left by removal of the sprue pin, to receive the molten metal. A similar opening made elsewhere in the cope section of the mould to serve as a riser through which air and gases escape and into which the molten metal rises after the mould is full. Openings for sprue and riser may be cut with a sprue cutter instead of making them by use of a sprue pin. The cope section then is removed from the drag and inverted on a board, and the sand around the edges of both sections of the pattern is swabbed (dampened) in order that the sand may hold firmly when they are withdrawn. Both sections of the pattern are drawn from the mould after rapping to loosen them, and all loose sand is blown from the cavities. Channels called gates then are cut in the sand of the cope section, to connect the sprue and riser to the mould cavity. If a core is used, it is set in core prints provided in the mould for its support, and the entire surface of the mould is dusted with powdered graphite. Finally the cope section is placed again in position above the drag section, the flask is clamped together, and the metal is poured into the mould. Figure 8.19 show a mould read for pouring.



(a) Illustration of moulding with a simple pattern



(b) Moulds ready for pouring

Fig. 8.19 Mould Preparation and Moulds Ready for Pouring

After the casting has cooled, the mould is broken up and the casting is removed. Gates, sprue, and the fins which appear at the parting lines or at junctions of cores with the mould are cut off, and the casting is cleaned by wire-brushing, sand-blasting, pickling, or tumbling. In large modern foundries nearly all of these operations are performed by machines. Their use accelerates production and reduces the amount of skilled labour required.



Fig.8.20 Some patterns used in producing auto-parts

Machine Moulding

Moulding by hand is a slow and laborious process and also does not yield good results as it does not impart uniform hardness to the rammed mould. In machine moulding, the production becomes faster, labour is minimized and less skill is required. The castings of good quality are produced as the moulds of greater uniformity can be produced by machine moulding. For mass production, the moulding machines can justify their initial cost and at the same time the quality of work will also be nice. However, the use of moulding machine is limited due to size and complexity of the job.

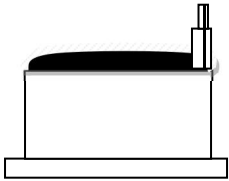
A moulding machine could be defined as a device consisting of several inter-related parts whose function is to transmit and modify various forces and motion so as to aid in the making of a sand mould. The various basic operations to be performed for moulding are given below:

- i. Ramming of moulding sand by jolting, squeezing or slinging.
- ii. Rolling or rocking moulds or cores over through 180° (inverting)
- iii. Rapping of pattern or core box by vibrating it.
- iv. Drawing of pattern or core box by raising or lowering the pattern or core box.

Out of these operations the moulding machine performs the function of ramming of moulding sand around the pattern in one or more of the following ways depending upon the type and design of machine: (a) Jolting (b) Squeezing (c) Slinging (d) Blowing

A moulding machine is generally named by the function it performs. A comparative study of different machines is made in Table 8.2 below:

Table 8.2 A Comparative Study of Different Moulding Machines

Method of ramming	Characteristics
 Hand ramming	1. Non-uniform hardness 2. Slow and laborious process 3. Equipment cost is low

Sand is loosely filled in the box and rammed by hand rammer.	
Ramming by Jolting Action Box filled with loose sand is raised and allowed to fall by gravity, thus producing impact and jolting action. The sand due to inertia packs with variable density around the pattern.	1. Uneven density of sand around the pattern 2. It is preferable for horizontal surfaces. 3. Operation is noisy. 4. Moulding flask should be of sufficient strength, because it has to be lifted and dropped repeatedly.
Ramming by Squeezing Action Loose sand filled in box is compressed with the application of compressed air through a piston table arrangement which squeezes the sand against a rigid board.	1. It is used for relatively small work. 2. The results are not as good as in jolting. 3. Plain squeezing is limited only to shallow work. 4. For most of cases, it is preferable to use combined squeezing and jolting
Sand Slinger Moulding sand is thrown in the box by an impeller which causes the packing of sand through inertia.	1. Very uniform ramming 2. Process is very quick 3. Initial cost of equipment is high.

Types of Moulding Machines

According to Beeley, (1982) four basic and widely employed types of machine exemplifying some of the main features include; jolt-squeeze pin lift moulding machine suitable for automatic or manual operation; jolt-squeeze turnover moulding machine suitable for automatic or manual operation; plain jolt rollover moulding machine with pattern draw; sand slinger and ramming head (see Figs.8.21 and 8.22.

Jolt Machine

This machine is equipped with adjustable flask lifting pins to permit the use of flasks of various sizes within the capacity of the machine. The flask is placed on the machine table and during operation the machine table raises the flask at short distance and then the flask is allowed to fall freely under gravity. This sudden fall causes the sand to be packed evenly around the pattern. The density of the

sand is greatest around the pattern and at the parting line. Further away from the pattern, the density keeps on decreasing. Since the moulding sand is firmly packed around the pattern, the mould is very strong and there is very less possibility of swells, scabs or runouts. After the moulding is complete the lifting pins on the machine engage the flask and raise it from the match plate. Thus it is obvious that jolt machines can take care of only one part of a flask at a time and are, therefore, suited specially to large work.

Apart from the sand ramming, every moulding machine has to perform several other functions also. After ramming one part of the complete mould, the first part is rolled over so that other part may also be made and the pattern from the first part removed. Pattern is usually rapped in the sand and can be removed with the help of air or electrically operated vibrator attached to the pattern plate or may be removed by hand.

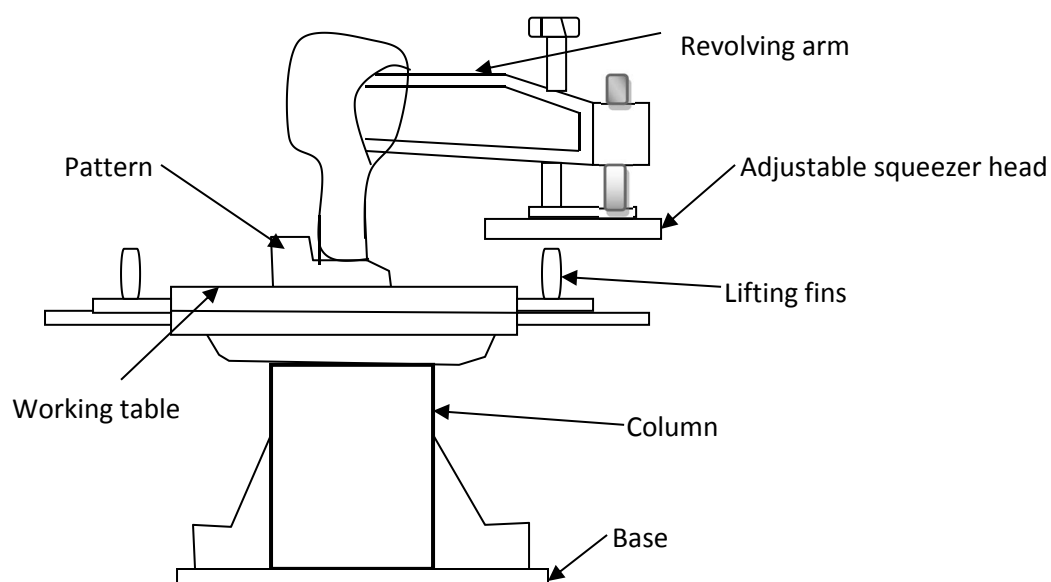
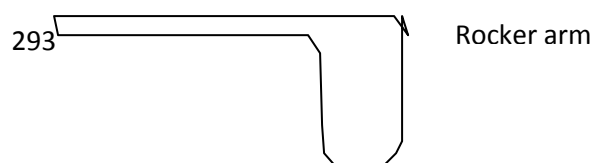
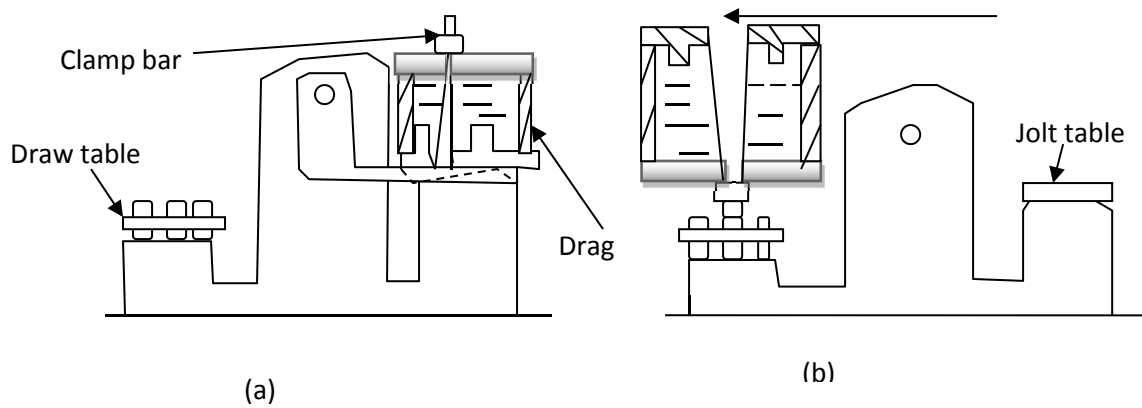


Fig. 8.21 Plain squeezing moulding machine





(a) Mould box filled by jolting. Bottom board clamped with box

(b) Mould rolled over by 180°. Draw table rises up and the mould is unclamped. Vibrator raps the pattern, as draw table comes down slowly, separating the mould from the pattern.

Fig.8.22 Jolt roll-over pattern-draw moulding machine used for making drag moulds.

Jolting is generally done in combination with other operations on the same machine, such as in the Jolt-squeeze machine, Jolt-pin lift machine, Jolt-roll-over-draw machine etc.

Squeezing Machine

In this machine sand is compressed through the application of compressed air or other suitable force transmitted through a piston table arrangement which squeezes the sand against a platen. The ramming is best at the sand platen interface from where pressure is applied and not near the pattern, whereas in jolt machine the ramming is best around pattern. Therefore, combination of jolting and squeezing gives best results and both the operations can be carried out in a single machine called Jolt-squeeze moulding machine (Fig.8.23). In pure squeezing, both the parts of the mould could be formed at the same time if the depth is not too great. It is generally limited to rather shallow work.

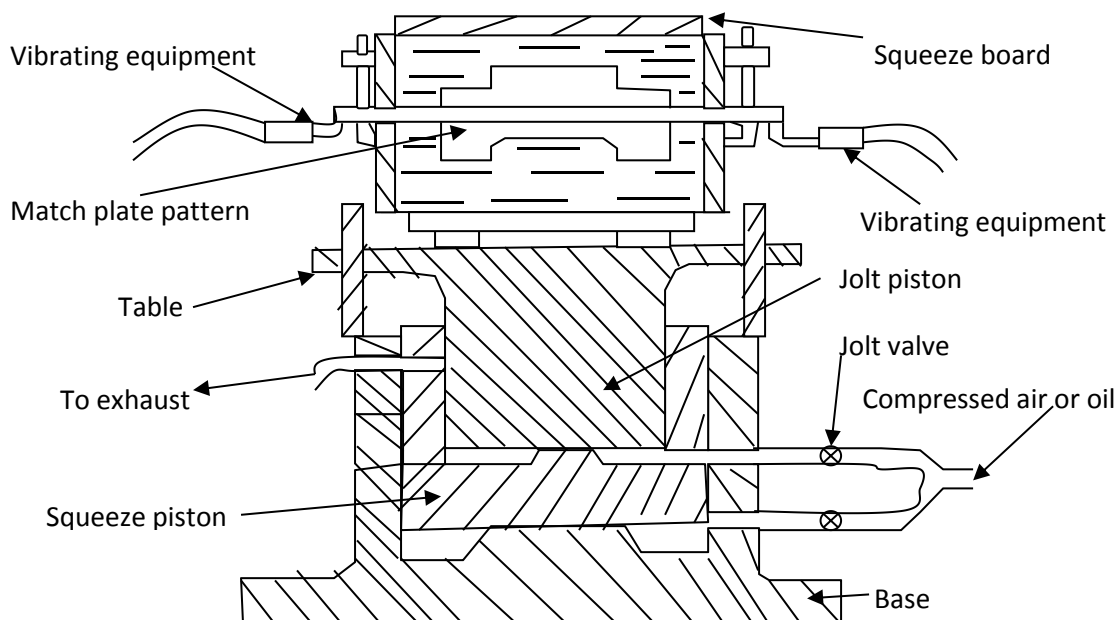


Fig. 8.23. Schematic diagram of jolt-squeeze moulding machine. In jolting operation, when exhaust port is cleared by the piston, it falls suddenly. For squeezing, the squeezing head is brought above the squeeze board and then squeeze piston lifted up by opening the squeeze valve.

Sand Slinging Machine

In this machine the moulding sand is thrown by impeller device which causes packing of the sand into the flask through inertia. In this method the sand density is most uniform at all the levels and it is, therefore, best suited method for any type of mould. The density can be controlled by changing the speed of the impeller which normally varies between 1200 and 1800 RPM. However, it is best adapted to work ranging from medium to very large size. The machine is generally available in various capacities with sand moving at a speed of about 3000 m/min. the moulding sand should be mixed with suitable binders etc., so that it can flow into place readily and afterwards binder should become hard. Various other moulding machines are explained in (Figs. 8.21 to 8.24), the schematic sketches of which are self-explanatory.

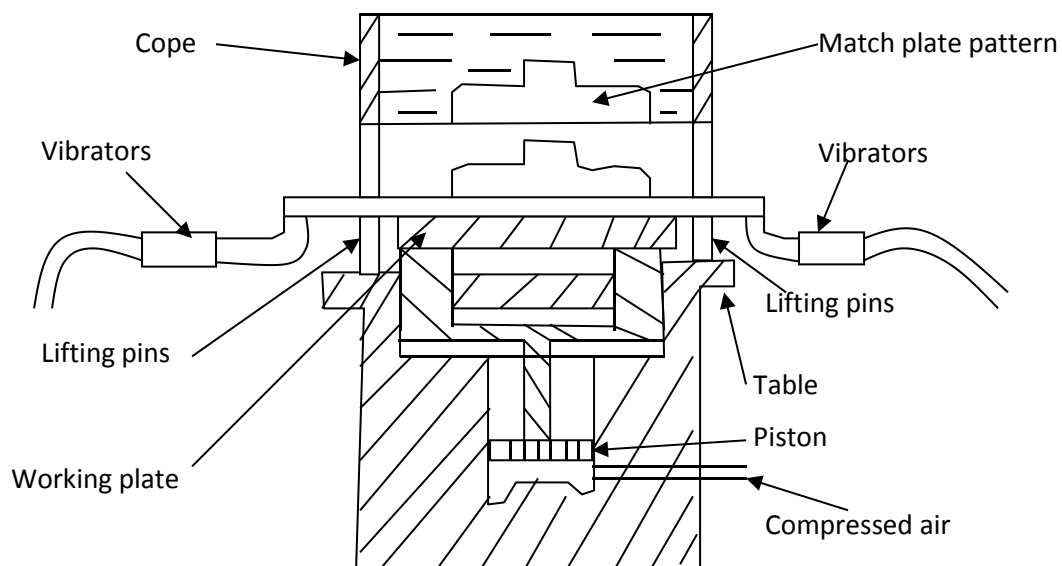


Fig.8.24. Schematic diagram of Jolt –squeeze pattern–draw moulding machine used for making cope moulds. Showing the drawing of the pattern with cope in lifted position.

Advantages and Limitations of Moulding Machines

Advantages

1. Prove to be economical by reducing the slow hand operation and fatigue on workers
2. These are best suited in mass production work
3. Semi-skilled persons can be employed whereas in hand moulding skilled artisans are required
4. The production rate is high, quality of moulds is better and hence castings with less defects are produced.

Limitations

1. These can't be used for bigger and complex jobs
2. For different types of moulds, the machines can't justify their cost and hence are suitable only in mass production work.
3. These lack flexibility for more specialized mould-making procedure.

Automation

According to Beeley (1982) although moulding machines are commonly operated under manual control, automatic controls are provided on many modern machines, with preset timing of the various phases of the production sequence. Such machines are suitable for inclusion in fully automatic integrated systems, in which the successive phases of moulding may be followed in varying degrees by automatic coring, closing and handling through the casting and knockout stages. Systems can be based on either the rotary or the in-line principle, in which several pattern plates are indexed through the system so that separate elements of the moulding operations can be performed at successive stations, in this case as follows:

1. Pattern preparation
2. Sand feed,
3. Ramming,
4. Pattern draw,

Additional stations can be provided for duplex sand feed, for the positioning of chills, or to enable further pattern plates to be simultaneously worked. Pattern changes can be readily accommodated where varied production is required.

Shell Moulding

It is a recent invention in casting techniques for mass production and smooth finish (Jain, 2009). It was originated in Germany during Second World War. For some time, it was called by the name of corning process (after the name of J. Corning who invented it), C-process, and finally shell process or shell moulding. It consists of making a mould that has two or more thin shells or shell like parts which are moderately hard and smooth, with a texture similar to that of a neatly made sand core, consisting of thermo-setting resin bonded sands. The shells are 0.3 to 0.6 mm thick, and can be easily handled and stored. Shell moulds are made up of a mixture of dried silica sand and phenolic

resin, formed into thin, half mould shells, which are held with clamps or adhesives and metal is poured either in a vertical or horizontal position. They are supported in racks or mass of bulky permeable material such as sand, steel shot or gravel (see Fig.8.25).

Pattern for Shell Moulding. The patterns for making the shell mould are made of metal as they are heated to 540°C during the cycle. The patterns should have provision of ejector-pins for removal of shell from the surface of pattern.

Materials for Making Shell. The sand used is fine dry silica sand, preferably round-grained, free from organic impurities and with not more than 1% clay. In addition to it, some additives have also been proposed, which are plumbago, iron oxide, sulphur and various minerals. Zircon sand is another raw material used for manufacture of shell. Although zircon sand is costly but gives a stronger shell than silica sand for the same percentage of resin binder. Zircon sand produces better surface finish because of its small round grains, and a dense mould of high thermal conductivity which rapidly and evenly cools the casting. The binders used are thermosetting synthetic resin (3 to 10% by weight), phenol formaldehyde and urea formaldehyde.

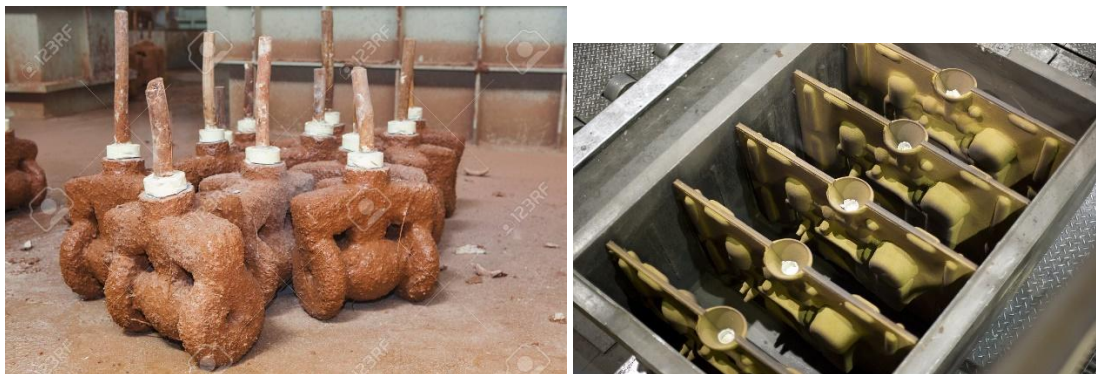


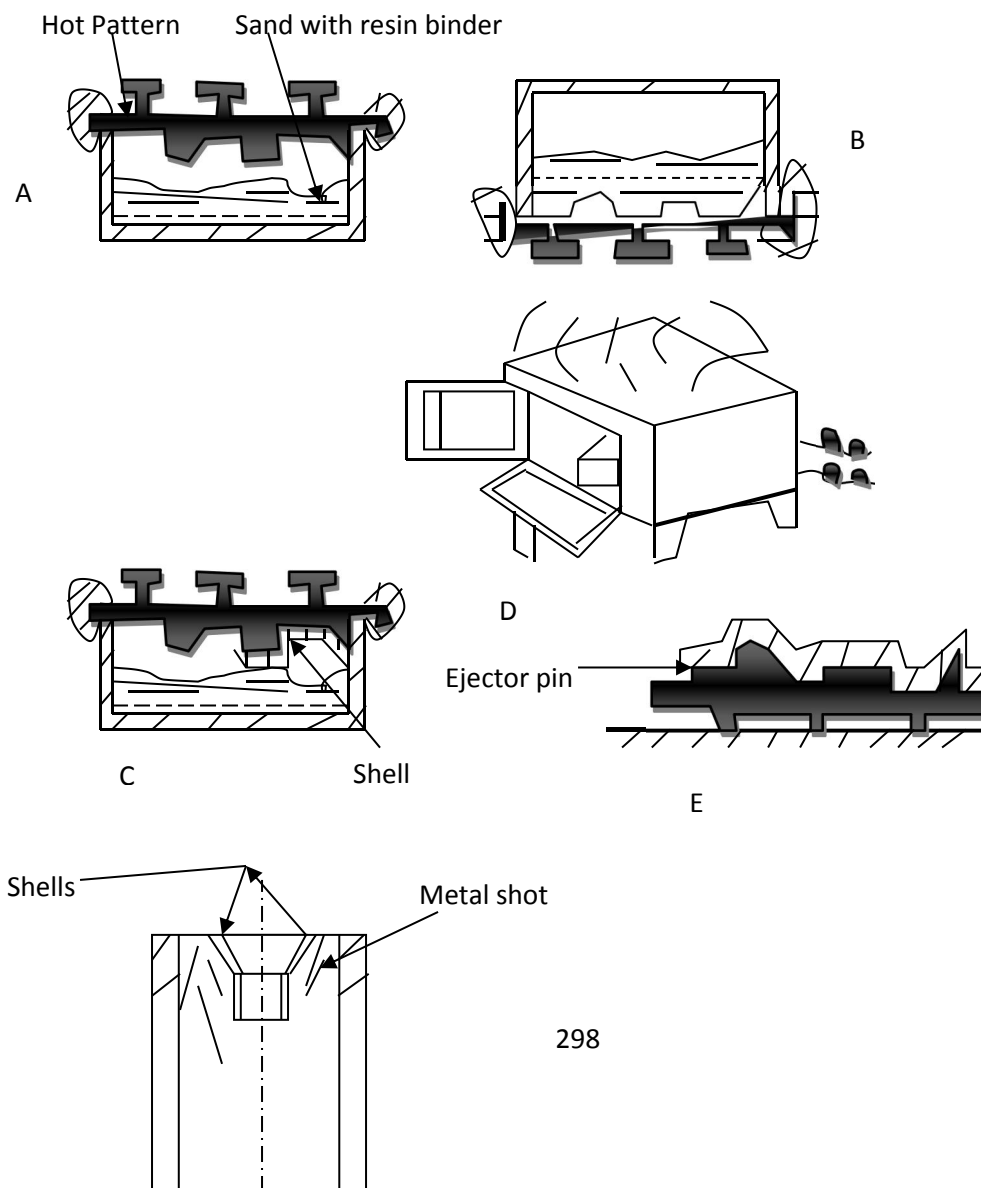
Fig.8.25 Shell moulds ready for pouring

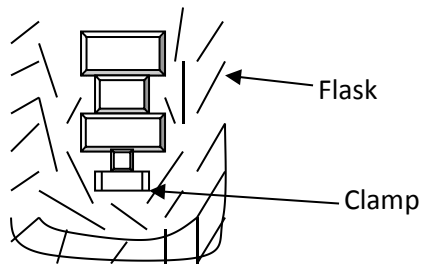
The proportions in which they are mixed are as follows:

Dry silica sand	100 parts by weight
Powdered phenol-formaldehyde resin binder	2 to 8 parts by weight
Wetting agent	0 to $\frac{1}{4}$ parts by weight

Process: Thermo-setting plastics, dry powder and sand are mixed intimately in a muller. Metal pattern is sprayed with a separating silicon grease, heated to 205 to 230°C and covered quickly with the resin bonded sand. After 30 seconds, a hard layer of sand (3 to 4.5 mm thick) is formed over the pattern. Pattern and shell are then heat-treated in an oven at 315°C for 60 seconds, and then the shell is ready to strip from the pattern. A complete mould is made in two or more pieces and similarly core is made by the same technique. The shells are clamped securely and usually embedded

in gravel, coarse sand or metal shot. Then the mould is ready for use. The various steps involved in making a shell mould are as illustrated in Fig. 8.26





F

Fig.8.26 Steps in Shell Moulding Process.

Following are the steps in shell moulding (refer Fig. 8.26)

- A. Hot pattern is clamped to the dump box containing a mixture of sand and thermo-setting plastic resin.
- B. Pattern and box are inverted and kept in this position for some time. Hot pattern melts resin in contact with it.
- C. Box and pattern are again inverted and brought to original position. A thin shell of resin-bonded sand sticks to pattern and the rest falls.
- D. Pattern with shell is placed in oven and heated to cure resin bond.
- E. Shell is stripped from the pattern with the help of ejector pins.
- F. Two shells are assembled, clamped and properly backed with sand in a suitable box. This forms a shell mould ready to receive the metal.

Merits and Demerits

Merits.

- (1) Shell moulding is very suitable for casting thin sections of high definitions, for example, petrol engine cylinder.
- (2) Surface finish obtained by this process is excellent and much superior to that possible with green sand moulding. Finer details can be reproduced.
- (3) The dimensional accuracy obtained is the order of 0.002 to 0.003 mm per mm and in large castings, it may be reduced to as low as 0.001 mm in the line of the shell.
- (4) Machining and cleaning cost is negligible.
- (5) It occupies less floor space and material handling equipment, thus greater production from a given floor space.
- (6) The total sand used is only 5 to 10% that of green sand mould. This reduces sand handling difficulties.
- (7) As the resin does not absorb moisture, it offers more flexible scheduling.
- (8) Capital layout for shell moulding is considerably low for mass production as compared to other foundry techniques.
- (9) Process being semi-mechanised, cycle time involved in producing a shell-mould is considerably less compared to sand-mould.
- (10) Less skilled labour is required.
- (11) The moulds can be stored until required.

(12) The thin shell does not have as great a chilling effect as a sand mould and the gases easily escape through the walls, therefore, a better quality of casting is assured.

Demerits.

- (1) Initial cost of patterns and sand is high and hence unsuitable for small production.
- (2) Specialized equipment are to be used.
- (3) Resin binder is an expensive material and little of sand can be economically reclaimed.
- (4) This process is limited to small sizes.
- (5) Minimum thickness of the section that can be cast is 4 mm.
- (6) Certain casting shapes are unsuitable when proper partings and gatings are not available.
- (7) This process is more suited to the production of castings in large quantities so that the initial tooling cost can be offset.
- (8) Due to use of fine and dry silica sand, adequate dust extraction equipment is required to be installed.

Permanent Mould Processes

Permanent mould processes include the following:

Die Casting Processes

- Gravity die casting
- Pressure die casting
- Low-pressure die casting

Squeeze Casting

Counter Gravity Casting

Centrifugal Casting

Continuous Casting

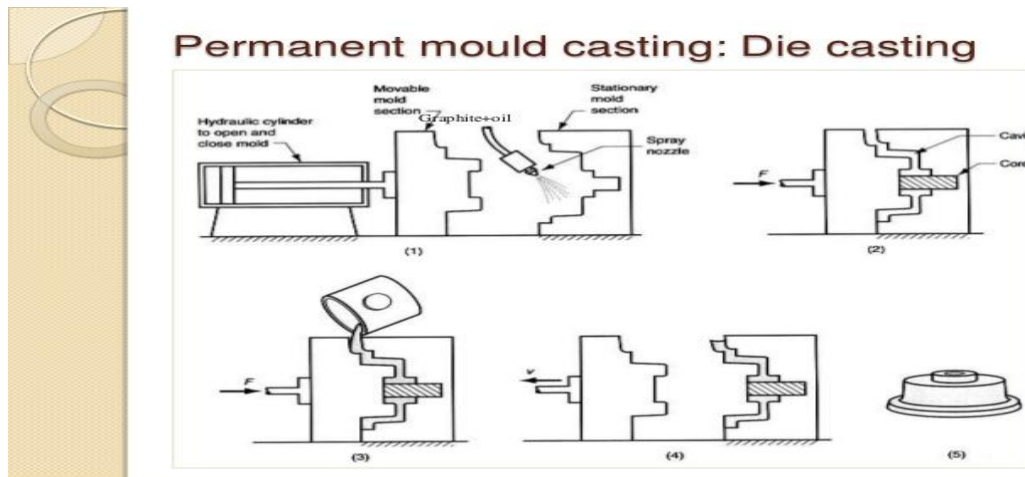


Fig.8.27 Permanent mould casting Illustrated

The die casting processes employ a permanent, reusable mould or die, generally made of metal, and this feature distinguishes them the refractory aggregate moulding processes considered so far (see Fig. 8.27). Through their use of permanent metal dies these processes are characterized by relatively high tooling costs combined with low production costs. The processes are suited to the mass production of castings, predominantly in the non-ferrous alloys. This restriction is imposed by the reduction in die life which results when high temperature alloys are processed in metal dies. In terms of volume of output, aluminium alloys are the most important and are suited to each of the four processes considered. Zinc alloys are produced by pressure die casting and the process is also used in the production of magnesium-and copper-base alloys. Ferrous materials can be die cast, grey cast iron is processed successfully by gravity die casting, and steel components have been produced by pressure die casting and squeeze casting. Melting temperature and die life considerations apart, not all alloys are suitable for die casting. To be suitable for die casting an alloy must not be susceptible to cracking due to the constraint imposed by the die during solidification and contraction of the casting.

Capital costs, in terms of equipment and dies, can be very high for these processes and this is the principal reason for the requirement for large order quantities. These costs are generally at their highest for pressure die casting and squeeze casting and lowest for gravity die casting (Clegg, 1991).

Gravity Die Casting

The gravity die casting or permanent mould casting process is quite simple in concept. A permanent, usually metal, mould replaces the expendable, refractory aggregate mould of sand and similar processes. Molten metal is poured into the permanent mould or die where it remains until it has solidified. The mould or die, which is usually made in two halves, is then opened and the casting is removed. The process is particularly suitable for the medium to high volume production of castings (predominantly non-ferrous) with fairly uniform wall thickness and simple shape. Whilst there are similarities between the sand casting and gravity die casting processes, the latter permits the production of more uniform castings with closer dimensional tolerances, superior surface finish and improved mechanical properties. Simple cores, made of metal, or complex cores, made of sand or plaster, can be used with the process to improve the degree of casting complexity attainable. Figure 8.28 show the schematic diagram of a gravity die casting die. Improvements in the gravity die casting process have been directed toward the mechanization of the process to minimize operator involvement and simultaneously improve die life, product consistency, quality, and productivity.

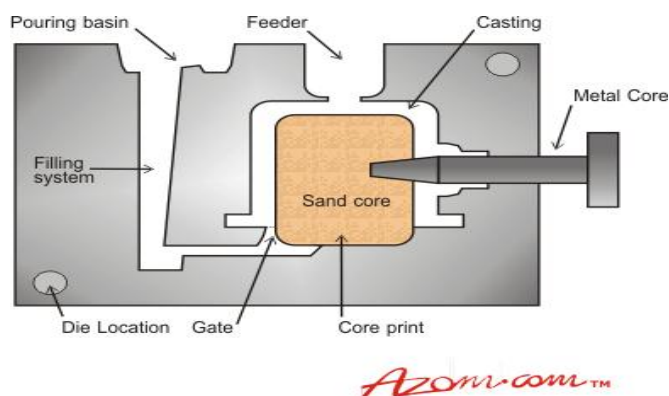


Fig.8.28 Diagram of a Gravity Die Casting (Azom.com, 2020)

The advantages of the process may be summarized as follows:

- Castings can be produced to a higher level of consistency than can sand castings.
- Gravity die castings generally have a better metallurgical structure and higher mechanical properties than sand castings.
- The surface finish of gravity die castings is generally better than that for sand castings.
- Castings produced by the process may require less machining than sand castings.
- The porosity level of gravity die castings is generally lower than that of sand castings.

The disadvantages of the process include:

- Higher tooling costs requiring larger order quantities.
- Not all alloys are suitable for casting by the process.
- The process is not as flexible as sand casting in terms of design complexity, size and weight range.

Pressure Die Casting

The pressure die casting process has its origins in typecasting machines, which had reached a high level of automation and mechanical efficiency by the mid-1800s (Clegg, 1991). By the end of the 19th century variants of the typecasting machines were being used to produce components for cash registers and gramophones, and by the beginning of the current century die cast bearings were being produced for automotive applications. Although the technology of the process continued to evolve during the early part of the 20th century, it was not until the 1920's that the forerunners to the modern hot chamber and cold chamber machines were developed. These processes have been refined to the extent that tiny zinc alloy castings can be produced in a one second cycle on fully automated hot chamber machines. The cold chamber process is used predominantly for the production of aluminium alloy components, which include complex castings weighing in the region of 15kg (30lb), for the automotive industry. For such components the cycle time would be about two minutes.

Process outline

Hot Chamber Process

A schematic diagram of a hot chamber pressure die casting machine is shown in Fig. 8.29. The metal for casting is maintained at an appropriate temperature in a holding furnace adjacent to, if not part of, the machine. The injection mechanism is located within the holding furnace and a substantial part of it is therefore in constant contact with the molten metal. Pressure is transmitted to the metal by the injection piston, which forces it through the gooseneck and into the die. On the return stroke metal is drawn into the gooseneck for the next shot. In this process there is minimum contact between air and the metal to be injected, thus minimizing the tendency for turbulent entrainment of air in the metal during injection. However, there is prolonged contact between the metal and parts of the injection system, which effectively restricts this process to zinc-base alloys. The diagram below is a variant of the gooseneck hot chamber pressure die casting machine.

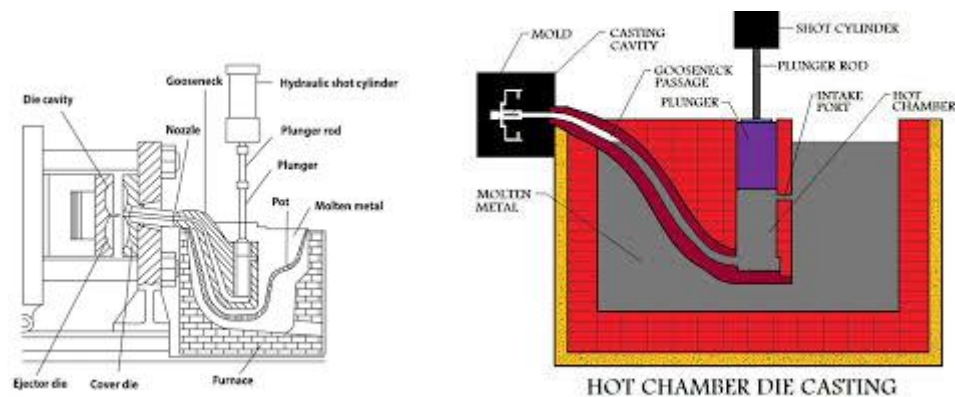


Fig. 8.29 Schematic Diagrams of a Hot Chamber Pressure Die Casting Machine (Azom.com, 2020)

Cold Chamber Process

The essential feature of this process is the independent holding and injection units. In the cold chamber process metal is transferred by ladle, manually or automatically, to the shot sleeve. Actuation of the injection piston forces the metal into the die. This is a single-shot operation. This procedure minimizes the contact time between the hot metal and the injector components, thus extending their operating life. However, the turbulence associated with high speed injection is likely to entrain air in the metal, which can cause gas porosity in the castings. The cold chamber process is used for the production of aluminium and copper-base alloys and has been extended to the production of steel castings. Fig. 8.30 shows a die for the production of castings by the cold chamber process.

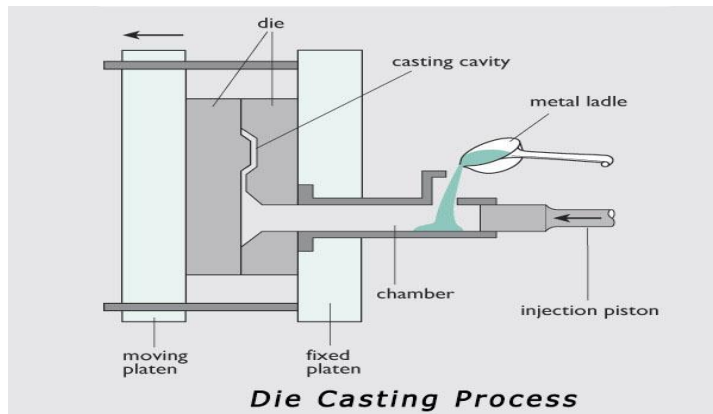


Fig.8.30 Schematic Diagram of a Cold Chamber Pressure Die Casting Machine

The advantages of the pressure die casting processes may be summarized as follows:

- The ability to produce castings with close dimensional control.
- The ability to produce castings with a good surface finish
- The ability to produce castings with thin walls, and therefore of reduced weight.
- The ability to produce castings at a high rate of production.

Against these advantages the following disadvantages should be weighed:

- High capital plant costs.
- High tooling costs.
- Restrictions on the range of alloys which can be cast.
- Restrictions on the maximum size of casting that can be cast.

Process Developments

The Acurad Process

To improve the soundness of hypereutectic aluminium-silicon alloy cylinder block castings for the Vega engine, General Motors developed the Acurad process. The development of this process was necessitated by the problem of turbulence resulting into gas entrapment and lack of metallurgical integrity associated with pressure die castings. The name Acurad

derived from the objectives of the programme, which were to produce castings accurately, rapidly and to an improved standard of density. The main features of the process are:

- controlled cooling of the of the die
- large ingate
- lower metal injection velocity or rate
- use of a secondary plunger

Die filling is achieved at a comparatively slow rate and low injection pressure through a comparatively large gate, and these factors combine to minimize turbulence and the associated gas entrapment. The unique feature of the process is employed once the cavity has been filled. The process employs two concentric plungers which advance together during the die filling stage. As the casting begins to solidify it does so primarily at the interface with the die. Once this casting skin has formed it restricts the movement of the external plunger. However, the internal or secondary plunger remains free to exert pressure on the remaining liquid, thus providing a degree of pressure assisted feeding. The larger gate employed ensures that the gate does not freeze before the secondary pressure is applied. The principle of the process is shown in Fig.8.31.

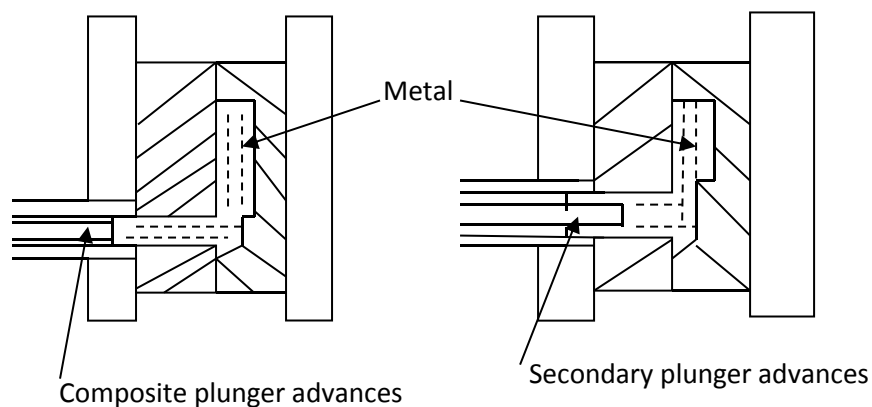


Fig.8.31 Schematic Diagram Showing the Principle of the Acurad Process

It is claimed that the process produced castings with a density some 3 to 5% higher than conventional die castings. The advantages resulting from the use of the Acurad process include castings with improved pressure tight integrity that are amenable to welding, heat treatment and coating without blistering.

The advantages claimed for the process over conventional pressure die casting include:

- gas porosity is virtually absent
- castings can be heat treated
- castings can be used at elevated temperature
- castings can be used in welded assemblies
- thinner and lighter castings can be produced, since there is no gas to displace from the die
- mechanical properties such as tensile strength and ductility are improved
- improvements in fatigue properties are obtained.

Castings produced by the process in aluminium alloys include: car wheels, motor cycle wheels, brake master cylinders, suspension arms, air-conditioner, compressor components, hydraulic power steering cases, bicycle hubs and crankcases, heat exchangers, and agricultural equipment.

Vacuum Die Casting.

As its name implies, the vacuum die casting process attempts to minimize gas porosity by reducing the amount of air in the die cavity before metal injection commences. No special seals, gaskets or heads are required and die design, construction and operation is in most respect unchanged. However, precautions must be taken to ensure that the molten metal is not drawn into the vacuum system. One method relies on a chill vent which is a water-cooled, corrugated, thin sectioned vent that quickly freezes any metal that enters it, thus preventing it from reaching the vacuum pump. Other methods, such as the Hodler Optivac system and the Ube Gas Free system, use cut-off valves activated by the metal pressure to prevent the metal entering the vacuum pump.

The Vacural process

In this process vacuum suction is used to draw the metal from the holding furnace into the shot sleeve. It is, therefore, quite different in its concept to the vacuum die casting process described in the preceding section. The method of metal transfer is claimed to reduce the presence of inclusions in the castings. The application of a vacuum during casting enables lower injection pressures and therefore smaller machines to be used.

Secondary Pressurization

The problem of shrinkage, especially that in remote sections such as bosses, may be overcome by secondary pressurization, which has a similar objective, but different method of application to that employed in the Acurad process. In secondary pressurization, also known as the pressure pin or additional pressure exertion process, pins-not unlike ejector pins- are actuated so that they penetrate the casting surface. By exerting local pressure they

provide pressure assisted feeding and an improvement in soundness. These pins usually driven into areas on the casting which are drilled out afterwards.

The Vertical Pressure Die Casting Process

The concept of vertical die casting is not new, as such a machine was developed during the 1920's. However, the machine developed by Toyota and Ube, to complement their squeeze casting machine development, has features designed to overcome the problems associated with conventional pressure die casting. Its objectives are to prevent the inclusion of aluminium oxide in the metal, to avoid turbulent inclusion of air and to provide pressure assisted feeding. The principle of the machine is shown schematically in Fig 8.32.

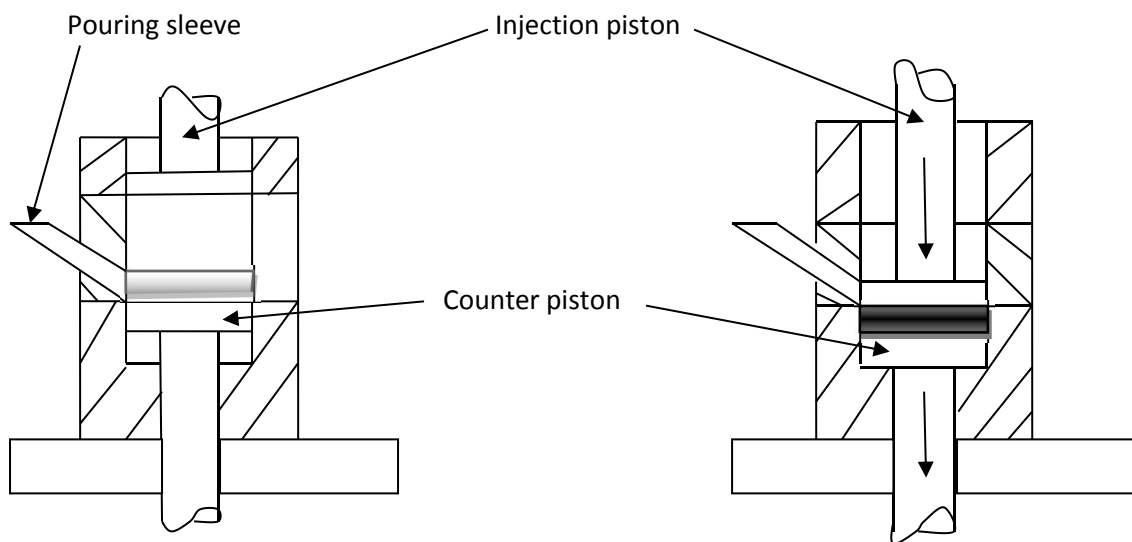
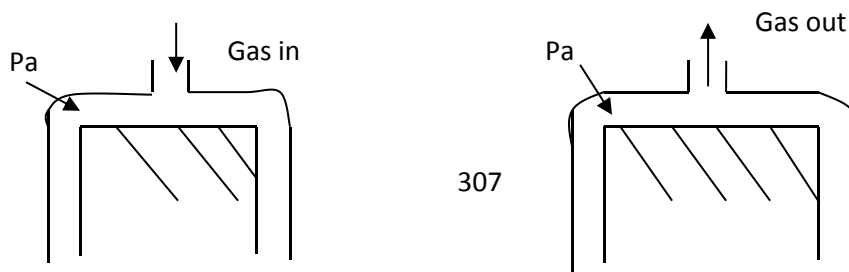


Fig. 8.32 Schematic Diagram of a Vertical Pressure Die Casting Machine (Clegg, 1991)

The Counter-Pressure Casting Process

Although this process has features which are similar to low pressure die casting and the counter gravity casting processes, it has one feature which is unique, and that is that at the beginning of the operating cycle the whole system is pressurized. The die is contained within an upper pressure chamber which sits upon a lower pressure chamber that contains the molten metal. The two are connected by a fill tube which penetrates below the surface of the metal, see Fig.8.33



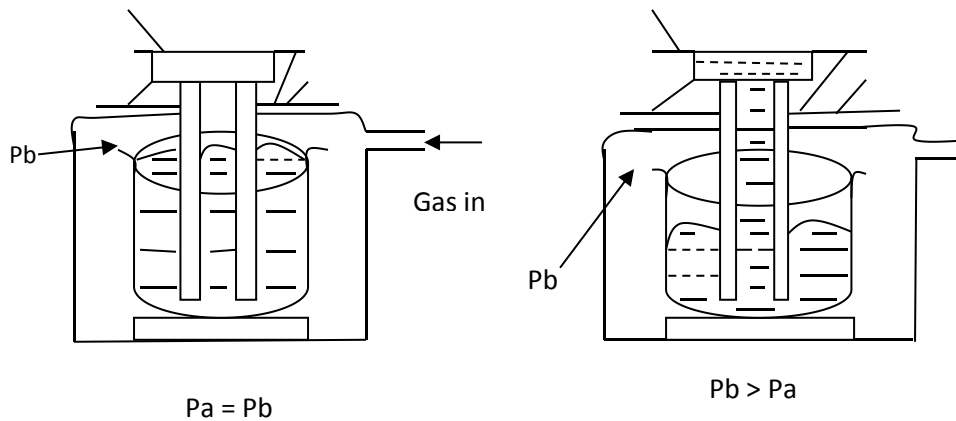


Fig. 8.33 Schematic Diagram of the Counter-Pressure Casting Process (Clegg, 1991)

Rheocasting

The Fulmer Research Institute claims that not only can air entrapment in pressure die castings be reduced but shrinkage porosity may be reduced, yield and die life increased, and die design simplified if the rheocasting concept is adopted. By vigorously agitating an alloy as it cools through the region between its liquidus and solidus, a slurry is produced in which the dendrites have been broken down to form globular solid particles. The semi-solid alloy may be processed by pressure die casting, or a related process, to produce a shaped casting or, alternatively, processed through a continuous casting unit which is the Fulmer approach. Material produced by the Fulmer route can therefore be used as bar feedstock, cut to a predetermined weight and re-heated, to provide an individual charge for the pressure die casting operation. Injection of the apparently solid charge through the ingate provides the shearing action, filling is achieved without the turbulence associated with the injection of superheated liquid, and the associated lower temperature improves die life. As the injected alloy is partially solid there is reduced solidification shrinkage to accommodate and less latent heat of fusion to dissipate. Whilst it is not claimed that shrinkage porosity is entirely eliminated, the absence of entrained air permits heat treatment of the castings to realize high mechanical properties. Fulmer claim that components produced by this route have performed satisfactorily in domestic equipment, cars and other vehicles.

Thixocasting

In this process the alloy is heated only into the two phase region until it contains about 50% solid and liquid. At this point the charge can still be handled as a solid, the liquid-solid mixture holding together by surface tension forces. This volume can then be placed into a die and then subjected to forces which result in the solid-liquid mixture flowing in response to those forces. It is said to be thixotropic (like catsup). Advantages include low energy costs for melting, minimization of shrinkage problems, distortion is kept to a minimum because of reduced temperature gradients, etc.

Ferrous Die Casting

Considerable effort and resources have been expended to develop a ferrous die casting process. The GKN Ferrodi process is a cold chamber pressure die casting process based on a conventional machine adapted for ferrous production to incorporate special features in the metal contact areas much as the dies, injection system and metal melting.

Considerable technical problems had to be overcome, particularly those associated with the need to construct economical dies to withstand extremely severe thermal shock, thermal fatigue and erosion by liquid alloys at temperatures up to 1600°C (2910°F). A Molybdenum-based alloy known as TZM exhibits high resistance to thermal fatigue or heat checking. This is largely attributed to its high thermal conductivity and thermal diffusivity which, combined with a low coefficient of thermal expansion, minimize thermal gradients and hence thermal stresses. It is only inserted in those regions of the die contacted by hot metal because of its high cost. A die life of 10,000 shots, which is three times the economic minimum die life, is attainable.

Castings in the weight range 0.6 to 3kg (1.3 to 6.6lb) and in various materials including stainless steel, have been produced. Good dimensional accuracy is attainable and although castings may contain some dispersed micro-shrinkage, the improved microstructure results in mechanical properties at least equivalent to conventional casting.

Low Pressure Die Casting

The low pressure die casting process represents an attempt to obtain the benefits of die casting without some of the disadvantages. Although the gravity die casting process employs relatively low-cost tooling and can be accomplished without major capital plant expenditure, it cannot be claimed that it is a method for producing castings requiring minimum machining, with minimum section and optimum metallurgical integrity at high yield. The pressure die casting process is undeniably without competition where the production of large numbers of thin section castings having good surface detail and finish are required, and has the advantage that machining may be eliminated or at least reduced. However, metallurgical integrity is not a feature of pressure die castings and, melt quality apart, they may exhibit shrinkage porosity and gas porosity, the latter as a result of cavity air and/ or die coating degradation products entrained in the injected metal stream. The presence of gas porosity not only reduces mechanical properties of heat treatable alloy from being realized, because the gas expands during heating and causes blistering of the casting surface.

A feature of the process is the low pressure displacement of liquid alloy through a refractory stalk connecting the holding furnace unit to the base of the closed die, see Fig.8.34. Quiescent filling, under controlled pressure from the bottom of the die cavity, eliminates entrained air and the sustained pressure during solidification improves soundness. Castings may be heat treated and the integrity attained is demonstrated by the use of the process for automobile wheels and cylinder head castings.

The advantages claimed for the process include the following:

- lower capital cost (compared with pressure die casting)
- improved process control (compared with gravity die casting)

- improved metallurgical integrity through reduced shrinkage porosity and nonmetallic inclusions
- good surface definition in castings
- consistent dimensional accuracy
- disposable cores may be used with the process
- high yield attainable
- suitable for the production of thin –wall castings.

Against these advantages there are a number of disadvantages, relative to the pressure die casting process:

- production rate is slow
- surface finish is not as good
- thin section capability is not as good

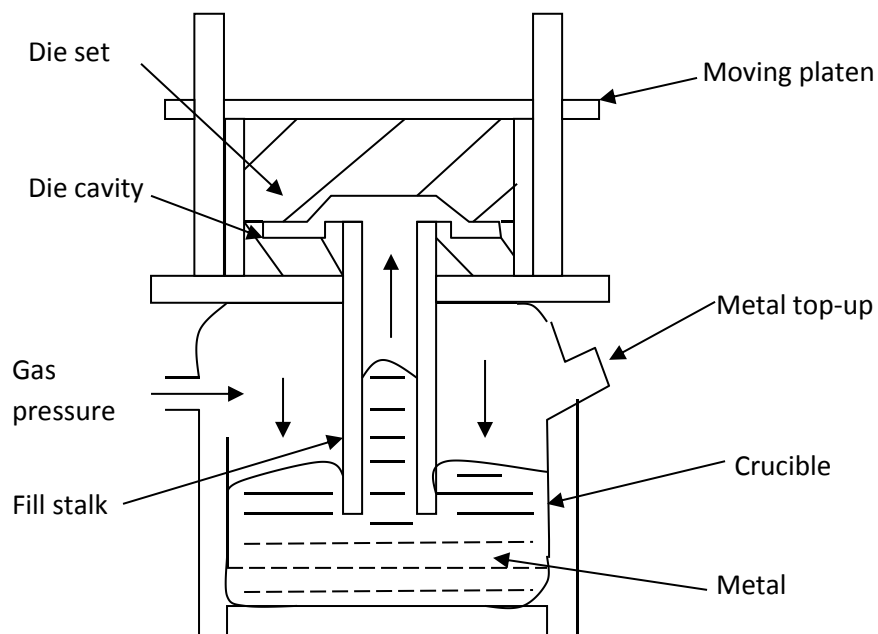
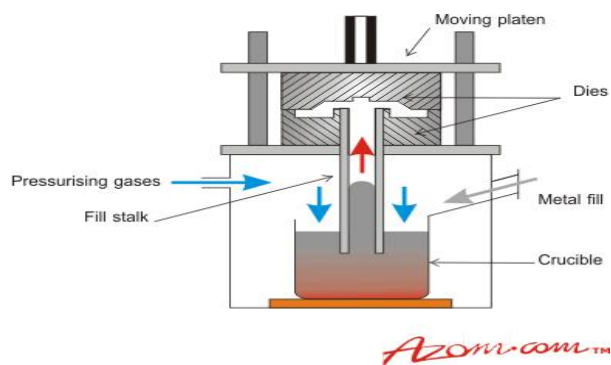
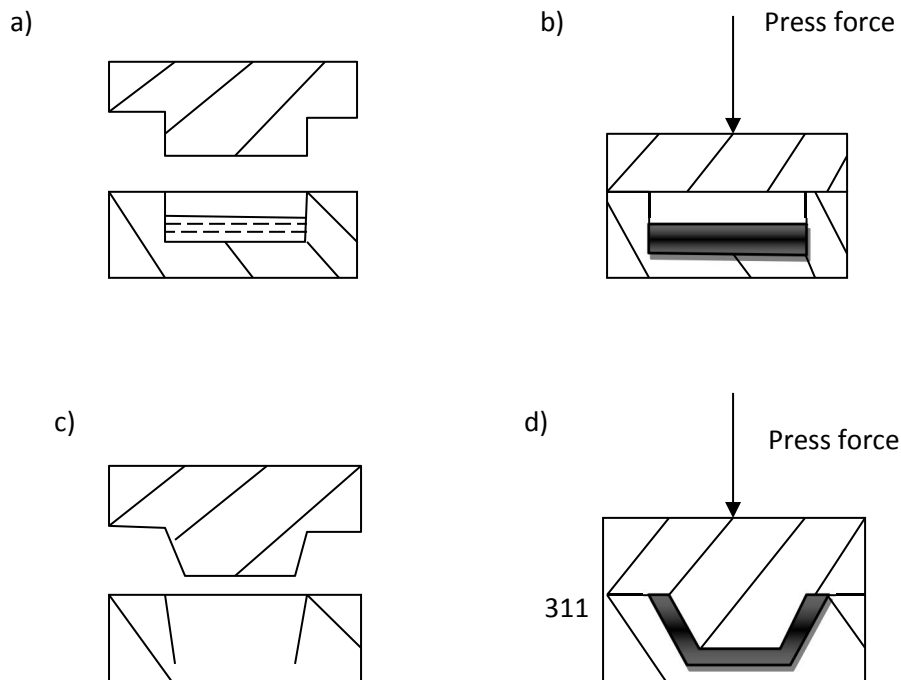


Fig.8.34 Schematic Diagram of the Low Pressure Die Casting Process (Clegg, 1991)

Although the concept of low pressure die casting was developed in the early part of the century. It was not to any extent for the production of aluminium alloy castings until World War II. It was not until the mid- 1950's that the process was adopted for the production of automotive castings.

Squeeze Casting

Squeeze casting is a single step process for converting liquid metal into a fully shaped component of precise dimension, excellent surface finish and metallurgical integrity equivalent to that obtained in forgings. By combining precise metal metering, quiescent die filling and high applied pressure during solidification, air entrapment, oxidation, hydrogen gas nucleation and shrinkage are eliminated. The combination of liquid metal and a vertical movement press suggests a hybrid combination of casting and forging, which has led to the terms liquid metal forging and squeeze forming being used. Other names by which the process is called include: extrusion casting, liquid pressing and pressure crystallization. In the simplest form of operation, liquid metal is metered into the bottom half die mounted on the lower platen of the press, see Fig. 8.35 a and b), and the upper, or moving, platen holding the upper die half, or punch, is actuated



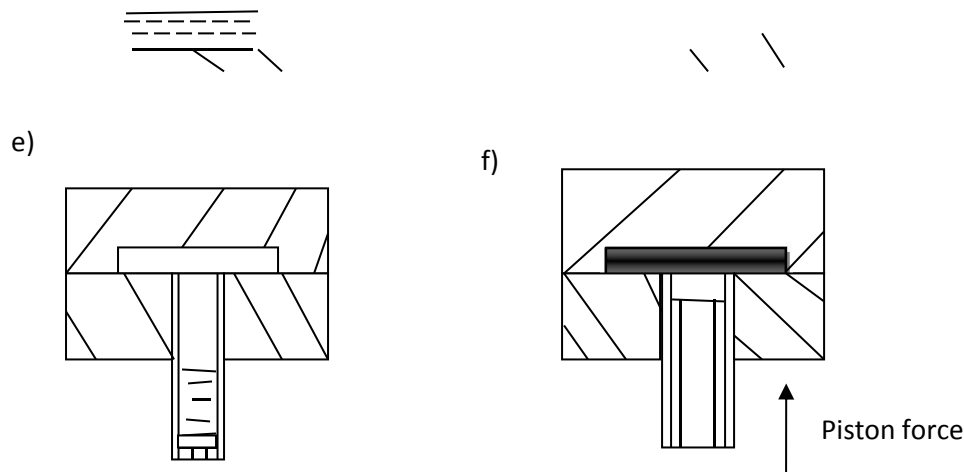


Fig. 8.35 Schematic Diagram of the Squeeze Casting Process Variations: a) and b) direct pressure application; c) and d) extrusion variant; e) and f) indirect pressure application.

Closing of the die halves is accompanied by transmission of the press force through the punch on to the liquid metal. Not only does the sustained pressure during solidification eliminate shrinkage, it also ensures intimate contact between the metal and die, which accelerates solidification, improves the metallurgical structure and promotes precision. Close control of such variables as: metal temperature, die temperature, pressure, pressure delay time, and pressure application time is essential for consistent operation.

Two variations of the squeeze casting theme are shown schematically in Figs.8.35 c) and d) and e) and f). In the extrusion variant, the liquid metal is extruded backwards around the contoured punch, enabling a more complicated casting shape to be obtained. The indirect pressure variant is essentially a vertically die casting arrangement which features a controlled slow fill followed by high applied pressure.

Advantages claimed for Squeeze Casting include the following:

- ability to produce parts with complex profile and thin sections beyond the capability of conventional casting and forging techniques
- substantial improvement in material yield because of the elimination of gating and feeding systems
- significant reduction in pressure requirements, in comparison with conventional forging, while at the same time increasing the degree of complexity that can be obtained in the parts
- ability to use both cast and wrought compositions
- improvements in product quality in regard to surface finish, dimensional accuracy and mechanical properties
- castings may be heat treated
- complete elimination of shrinkage and/ or gas porosity
- potential for using cheaper, recycled material without the loss of properties that would occur with other processes.

- The potential for increased productivity in comparison with gravity die casting or low pressure die casting
- Suitable for the production of cast composite materials.

Disadvantages

- High capital cost, comparable to pressure die casting but lower than forging
- Relatively low die life, in comparison with the true die casting processes
- Shape complexity limitation, in comparison with the true die casting processes
- An accurate metal metering system is required.

Cast Metal Matrix Composites

The squeeze casting process has featured prominently in the development of cast metal matrix composite, i.e. metal matrix composite (MMC), material. Its principal advantage in this application is the production of a defect-free matrix, which is vertical to the attainment of improved mechanical properties. In composite production by squeeze casting two approaches may be used. In the first, the composite alloy is produced by stirring the reinforcement into the liquid alloy. The resultant material can then be shaped by the pressure applied by squeeze casting. In this approach the reinforcement is distributed throughout the casting. If a more discriminating incorporation of reinforcement is required, for example to produce the required properties in a specific area of the casting, then a preform can be inserted in the die with application of pressure during casting ensuring infiltration of the preform by the metal. MMC materials provide improved properties which include: improved strength, better retention of strength at elevated temperatures, improved modulus (stiffness), potential for component weight reduction through improved strength to weight ratio, improved wear resistance, and reduced coefficient of thermal expansion.

Indirect Squeeze Casting

The original Ube vertical Squeeze casting machine was developed jointly with the Toyota Motor Corporation and was first used for the production of the production of cast automobile wheels in 1976. The features which distinguish this machine from the direct pressure machine are the patented tilting-docking mechanism of the shot unit and the controlled slow-filling of the die by bottom injection followed by sustained pressure. The non-turbulent transfer of metal and very low gate velocity, compared with pressure die casting, eliminates the problem of trapped air in thicker section castings. To enable thin section castings to be produced a higher gate force is necessary. To overcome the air entrapment problem that would accompany this higher velocity, a vacuum system is employed. Shrinkage porosity is eliminated by the maintenance of pressure between 50 and 90 MPa (3 and 6 tonf/in²) on the casting during solidification. The original vertical shot, vertical clamping design is used for the production of pistons, disc drives, connecting rods, compressor housings, and other parts. The more recently developed horizontally clamping, vertical shot machine is used in the production of thin section components such as master brake cylinders, brake calipers, manifolds, fuel rails, valve bodies, gear lever forks, and other components.

The Vacustract Process

Researchers at SCRATA developed an improved shell support system with the added advantage of fume and flame suppression. In this process the shells are immersed in a bed of fluidized granular material. During pouring, and for a period thereafter, extraction is applied in such a way that air passes from the atmosphere through to the base of the bed, where it is removed, see Fig.8.36. This approach has three principal advantages:

- (i) The pressure differential created increases the resistance of the bed to shear forces, thereby enhancing the support that the bed provides, which considerably reduces the risk of mould failure
- (ii) The extraction draws emissions from the mould through the bed, rather than allowing them to escape to atmosphere, thus controlling the immediate environment and suppressing the formation of flame.
- (iii) The continuous flow of air reduces the amount of heat transferred to the bed material from the castings, thus reducing the need for subsequent cooling.

This approach is applicable to moulds produced by other processes and is fundamental to the successful application of the Replicast CS Process.

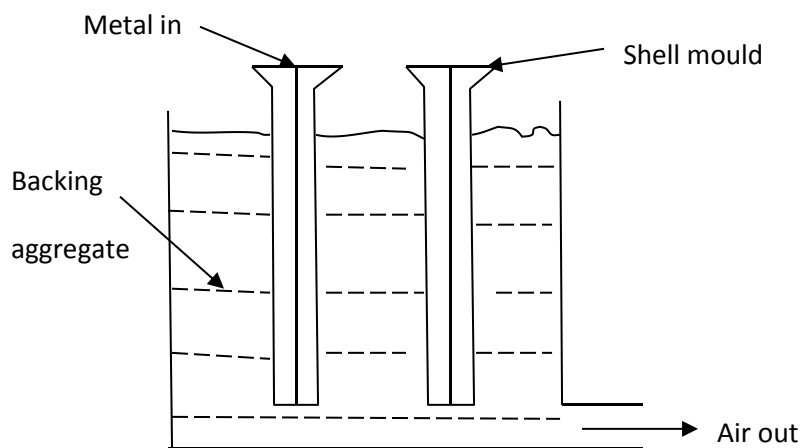
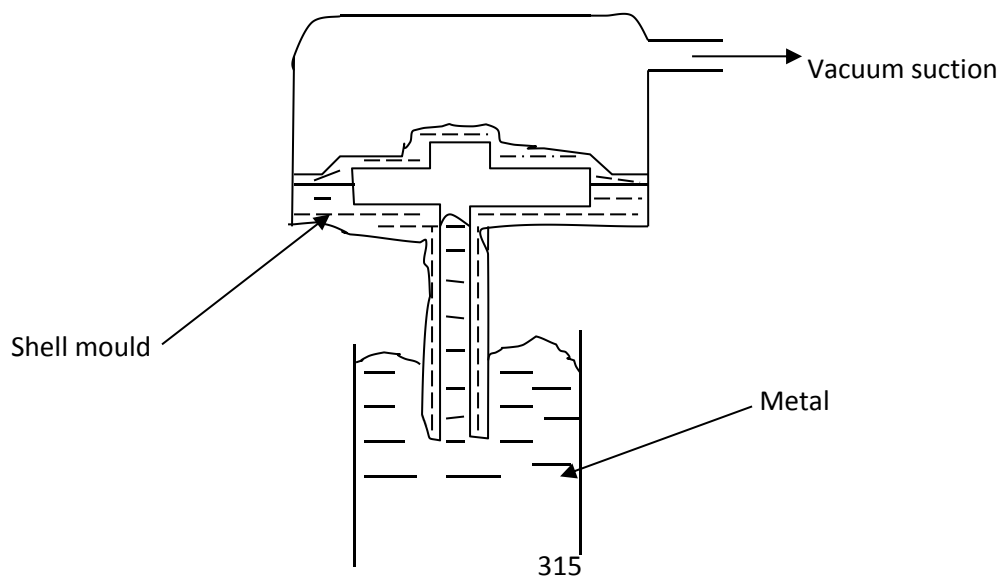


Fig. 8.36 Schematic Diagram of the Vacustract Process (Clegg, 1991)

The CLAS Process

Shell moulds are normally poured under gravity and, as they are permeable, are subject to the problems of turbulent filling, aspiration, and the associated problems of gas absorption and inclusions. The CLAS Process applies the concept of counter gravity casting to the production of a shell mould. In this process the castings are gated through the base of the mould directly into the cavity or a blind feeder. Mould filling is achieved by attaching the top of the mould to a vacuum chamber and submerging the mould base into a bath of molten metal, see Fig.8.37. The metal is drawn into the mould by the vacuum suction, which also removes the fumes generated by the mould. Improved casting yield and metallurgical integrity are claimed and the castings are produced at a cost lower than that for conventional shell moulded castings. No evidence has been found of melt contamination from the shells and the problem of gas defects in certain steels has been overcome by a patented technique which incorporates gas collection voids in the mould.



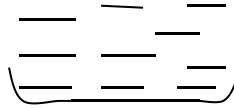


Fig. 8.37 Schematic Diagram of the CLAS Process (Clegg, 1991)

The Colshell Process

As its name suggests, this process is a combination of the cold set process and shell mould. Contoured moulds are produced from a sand mixture which hardens in contact with the pattern without the application of heat. To achieve an acceptable rate of output, a fast reacting cold set system must be used. The process was developed by BCIRA in partnership with Spenklin Polygram Ltd. and the totally enclosed structure of the machine ensures its suitability for the Isocure and SO₂ systems.

In this method of mould production the sand mixture falls from a hopper into a shallow frame which has a flexible diaphragm base. The frame containing the sand is pressed vertically upwards against the pattern and pressure and vibration are used to consolidate the mould material. Whilst in this position the mould material is hardened by the passage of the reactive gas to produce a contoured shell mould. The mould would typically be 1.5 x thicker than a hot shell mould, but its production requires less binder and energy.

Wood and resin pattern are suitable for the process and an output of 90 mould halves/hour can be achieved in the production of moulds with a size of 610 x 405 mm (24 x16 in). it is claimed that the process provides a sand saving of 65% over conventional cold set sand moulds. The moulds can be produced for casting in the vertical or horizontal plane.

The Zeus Process

Although the cosworth process radically improved the precision attainable in sand castings, the use of zircon as a mould material limited the minimum section of casting that could be attained. The Zeus process reverts to the use of silica sand in the production of thin section, precision sand castings. For such castings, produced in aluminium alloys, the heat input to the sand is insufficient to raise the sand's temperature to α to β quartz inversion temperature. Consequently, for such thin section castings, precision is retained. Casting sections in the range of 2 to 2.5 mm (0.08 to 0.10 in) are claimed to be routinely possible for this casting process.

The Evaporative Pattern Casting (EPC) Process

The Evaporative Pattern Casting (EPC) Process, also known as the expanded polystyrene moulding process, the evaporative foam process, the lost foam process, or by such trade names as Full Mould, Policast, Replicast and Styrecast, has been known to the foundry industry since 1958. The application of dry, unbounded sand to the process is credited to Smith, whose US Patent was granted in 1964. Since the expiration of this patent significant development work has taken place, mostly associated with the automotive

industry. During the latter part of the 1980's considerable interest has been generated in the use of the process for the mass production of castings.

In the USA a survey once predicted that the output of aluminium alloy castings by the process will increase to over 152,250 tonnes (150,000 tons) by the year 1993 and that for iron castings to 121,800 tonnes (120,000 tons). By the year 2000 these tonnages are expected to double and increase beyond 2000. Although other materials are suitable, expanded polystyrene is used predominantly as the pattern material. Fig. 8.38 shows the diagram of EPC Process.

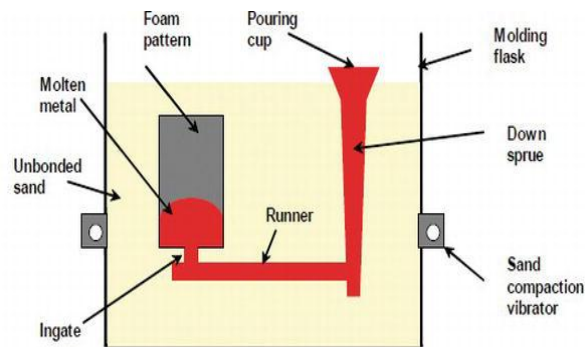


Fig.8.38 Schematic illustration of Evaporative Pattern Casting (EPC) Process

The Vacuum-Sealed Moulding Process

The Vacuum- Sealed Moulding process, or V-process as it is commonly known, was developed in Japan in 1971 and introduced to Japanese foundrymen at their spring meeting in 1972. By mid-1973 30 licenses for the process had been granted to Japanese foundries and by 1984 the number of licences granted had increased to 130. In western Europe 37 licenses had been granted and in 1985 it was estimated that these licenses were producing 2100 tonnes (2058 tons) of castings/month compared with 9100 tonnes/ month (8920 tons), representing about 2% of the total national castings output, in Japan. Although it cannot be described as a major foundry process, only four UK foundries were using the process in 1988, there are still developments being undertaken which could lead to its wider use (Clegg, 1991).

Process outline

In the process the pattern assembly is mounted on hollow pattern box which is connected to a vacuum pump. Vents in the pattern/board assembly enable air to be drawn through the assembly by the pump. A thin plastic sheet is heated in a position directly above the pattern until it softens, whereupon it is vacuum-formed to the contour of the pattern assembly by vacuum suction applied to the pattern box. At this stage a refractory mould coat may be sprayed over the plastic sheet and dried before the specially constructed moulding box is located onto the pattern box assembly. The

moulding box is filled with dry, unbounded sand which is vibrated to optimize packing and bulk density. A second plastic sheet is used to seal the top of the moulding box. Vacuum suction is applied to the sand through the specially constructed moulding box to hold the sand in a rigid and compact state. At this point the vacuum suction is released from the pattern box to enable the mould to be separated from the pattern. Vacuum suction is maintained in the mould. Two half moulds produced in this manner are located together, after coring if required, and are transferred to the pouring station. Vacuum suction is maintained in the mould at all times. After pouring, and when the casting has solidified, the vacuum is released. Following a period of cooling the sand and casting are removed from the box; the sand is recycled for future use and the casting is processed through the fettling shop.

The CO₂ /Silicate Process

The concept of the cold set process, in which a mould or core hardens in contact with the pattern or corebox at ambient temperature to produce an accurate replica, originated with the introduction of the CO₂ / Silicate process to the foundry industry in the 1950's. According to Gotheridge the art of mixing sand with a liquid sodium silicate based binder, compacting it into a shape and then passing carbondioxide gas through it, thereby causing it to harden, was first described in a British patent granted to Hargreaves and Paulson in 1889. Dry sand, silica, or an alternative, is mixed with a viscous sodium silicate binder. This mixture is transferred into the moulding box and compacted by vibration and /or tamping. Carbon dioxide is introduced to the compacted sand by one of a number of methods, whereupon the sodium silicate gels to produce a rigid mould which can then be stripped from the pattern. The moulds are usually coated with a refractory wash, to improve casting surface finish, before assembly prior to pouring. The binder used in the CO₂ / Silicate process is a ternary, liquid mixture of silica (SiO₂), Sodium oxide (Na₂O) and water (H₂O). The ternary mixture is produced by steam autoclaving a crushed glass, prepared by heating a mixture of crushed or granular silica with soda ash (Na₂CO₃). Foundry grades of sodium silicate are specified by their silica:sodium oxide ratio and by their specific gravity. The ratios in most common use range from 2:1 (low ratio) to 3:1 (high ratio) and the specific gravity is a function of the silicate to water ratio of the mixture.

The Cosworth Process

The Cosworth process is a high-precision, low-pressure sand casting process which was developed for the production of premium-quality aluminium alloy castings for the automotive industry. Unable to obtain castings that could consistently meet their exacting standards of quality, Cosworth established a research and development programme to study the fundamental problems in moulding, melting, casting and heat treatment of aluminium alloy castings. The starting point for the production of an accurate casting is accurate pattern and core box equipment. Resin pattern equipment is suitable and permits any parts which are susceptible to wear to be fitted as replaceable inserts which can be recast from a master. To overcome the problem of unpredictable expansion associated with silica sand, zircon sand was chosen. To enhance the surface finish of the castings, careful choice was exercised over sand grading and quality and the

chemical binder system. The choice of a cold set process eliminated the problems associated with clay-boned sands. It also eliminated the inaccuracies associated with hot processes, as there is no distortion caused by thermal expansion of either core or core box. The gas-hardening SO_2 process was chosen. The total binder content required is low and this reduces the danger of blowholes caused by the decomposition of the binder when subjected to heat from the metal. The moulds and cores are produced by automatic core shooters and the cores are manually placed in the drag moulds. Mould closure is automatic with location effected by a pin and bush system accurate to within $\pm 0.05\text{mm}$ ($\pm 0.002\text{in}$). The closed mould is transferred to a pick and place unit which positions it on the casting station above a sealed holding furnace.

Slush Casting

This method is a special application of permanent mould casting in which hollow castings are produced without the use of cores. Molten metal is poured into the metallic mould and allowed to solidify up to the required thickness. The mould is then turned over so that the remaining liquid metal falls out and castings of desired thickness can be obtained. Normally small thickness castings of lead, zinc and low melting alloys are obtained by slush casting method.

Pressed Casting

It is another method of producing hollow castings from permanent moulds, but differs from gravity die casting and slush casting in operation. In this case a definite amount of molten metal is poured into the mould and then close fitting cores are pushed in the cavities so that the molten metal can be forced into the mould cavities. When the metal sets into the cavities, the core is removed and hence we get a thin walled hollow casting. Pressed die castings are limited to ornamental articles. This method was developed by Carthias of France and hence it is also popular by the name of Carthias casting.

Centrifugal Casting

In this process the molten metal is poured in a mould and allowed to solidify, while the mould is revolving, i.e. the metal solidifies under the pressure of centrifugal force. The centrifugal forces cause the metal to take up the impression of the mould cavity. The pressure is selective, that is, the greater force is exerted on the denser components. This is of considerable benefit in eliminating non-metallics and gases during casting. This process is best suited for mass production. Cylindrical parts and pipes are most adaptable to this process. In centrifugal casting, the molten metal is subjected to centrifugal force due to which it flows in mould cavities easily and results in the production of high density castings. See Fig.8.39.

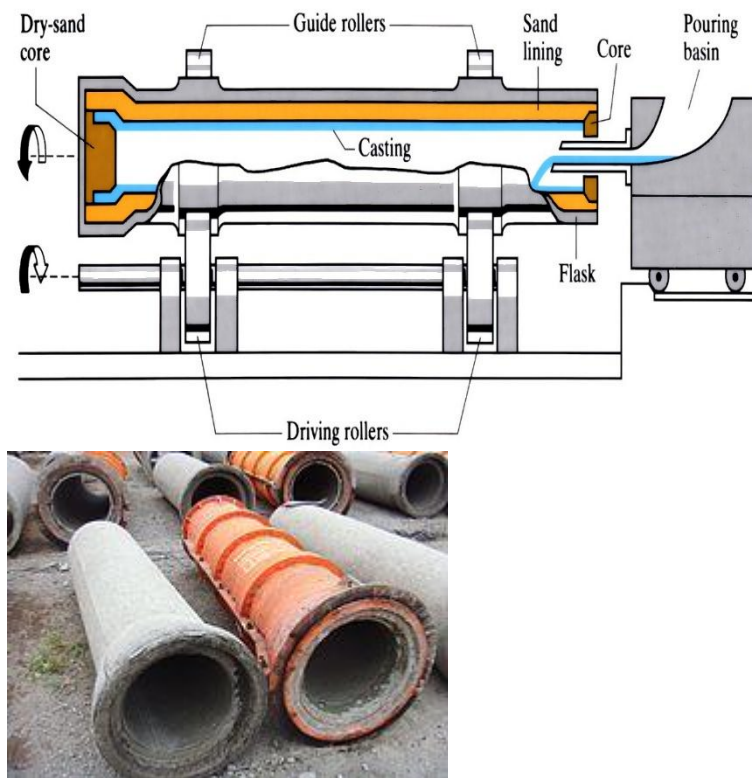


Fig.8.39 Centrifugal casting machine and products

There are three recognized centrifugal casting processes: true centrifugal casting, semi-centrifugal casting and centrifuged or pressure casting.

True Centrifugal Casting

In this process, the casting are made in a hollow, cylindrical mould rotated about an axis common to both casting and mould ; the axis may be horizontal, vertical or inclined. Usually the mould is rotated in horizontal plane. See Figure 8.39. The most commonly cast parts by this process are cast iron pipes, liners, bushes and cylinder barrels etc. the mould used for this process may be either of permanent type or a sand lined mould.

Semi-centrifugal Casting

This is also known as profiled centrifugal casting. It is nearly similar to true centrifugal casting with the only difference that a central core is used to form the inner surface. The particular shape of the casting is produced by the mould and core shapes and not by centrifugal force. However centrifugal force aid in proper feeding of mould cavities like rim sections and eliminates the possibility of porosity in the castings.

Centrifuged or Pressure Casting

This process is used for non-symmetrical castings having intricate details and also for precision castings. The centrifugal force provides high fluid pressure to force the molten

metal into mould cavity. A number of similar components can be cast simultaneously. The mould cavities are positioned about its own axis and also about the axis of a central down sprue. The metal is introduced at the centre and fed into the moulds through radial in-gates. Centrifuging is possible only in vertical direction.

Moulds for centrifugal casting include;

1 **Temporary or sand moulds**- these are prepared by conventional moulding techniques in the special moulding boxes.

2 **Permanent or Metal Moulds**- these are generally made of commercial grades of carbon steel, or alloy steel.

3 **Graphite Moulds**- these are made by machining the commercially available stock of compressed graphite or used electrodes in furnaces etc. These can be used several times before replacing. The graphite is very economical and has sufficient strength and is easily machinable. Any reader wanting to know more about centrifugal casting can lookup in any of the references included at the end of the chapter.

Investment or Lost-wax Casting

This process is called the lost-wax process or precision casting. This process uses wax pattern which is subsequently melted from the mould, leaving a cavity having all the details of the original pattern. Castings obtained by this process have very close tolerances or the order of ± 0.005 mm. Generally this process is used for producing light and intricate parts. This process does not need a parting line or any form of split mould. The process of investment casting consists of two stages. First of all a master pattern is made of steel or brass and it is replica of the part to be cast. Around it, a split mould is formed from gelatin or an alloy of low melting point. This alloy is poured over the master pattern. After solidification master mould is obtained. This master mould is used for making the wax or lost –pattern. The following are the materials used for preparing master mould.

1. Plaster of Paris or gypsum products for non-ferrous castings.
2. Ethyl Silicate, sodium silicate and phosphoric acid for steel castings.
3. Sometime fine-grain silica sand is also used for preparing master mould.

The master mould is then filled with either liquid wax or thermoplastic polystyrene resin which when solidified forms a wax-pattern. This wax pattern is used for making the final casting. Then the process of investment of the pattern is followed which consists of casting the wax-pattern with slurry consisting of silica sand or graphite mixed with water. Coarse sand is sprinkled over the wet slurry to form the quartz shell. This wax-pattern is used for making the final mould in the same fashion as the conventional moulding process. This mould is then dried in air for 2 to 3 hours and then baked in an oven so that the wax may melt out. When the temperature reaches 100 to 120°C, the wax melts out and is collected through a hole in the bottom plate.

To improve the resistivity, the mould is further heated up to 1000°C called the sintering of the mould and finally cooled to 100°C for obtaining the castings. The castings can be obtained by gravity, pressure, vacuum or centrifugal operation. After the metal is cooled, the plaster is broken away and gates and feeders are cut out. The castings so obtained are finally cleaned by sand blasting, grinding or other finishing processes. The

castings so obtained have good surface finish and are exact reproduction of master pattern. This process is used for making jewellery parts, dental castings, castings of satellite tools (which are difficult to be produced either by forging or machining), turbine blades, parts of motor cars and sewing machines, type writers, calculating machines and various other intricate parts. See Fig.8.40

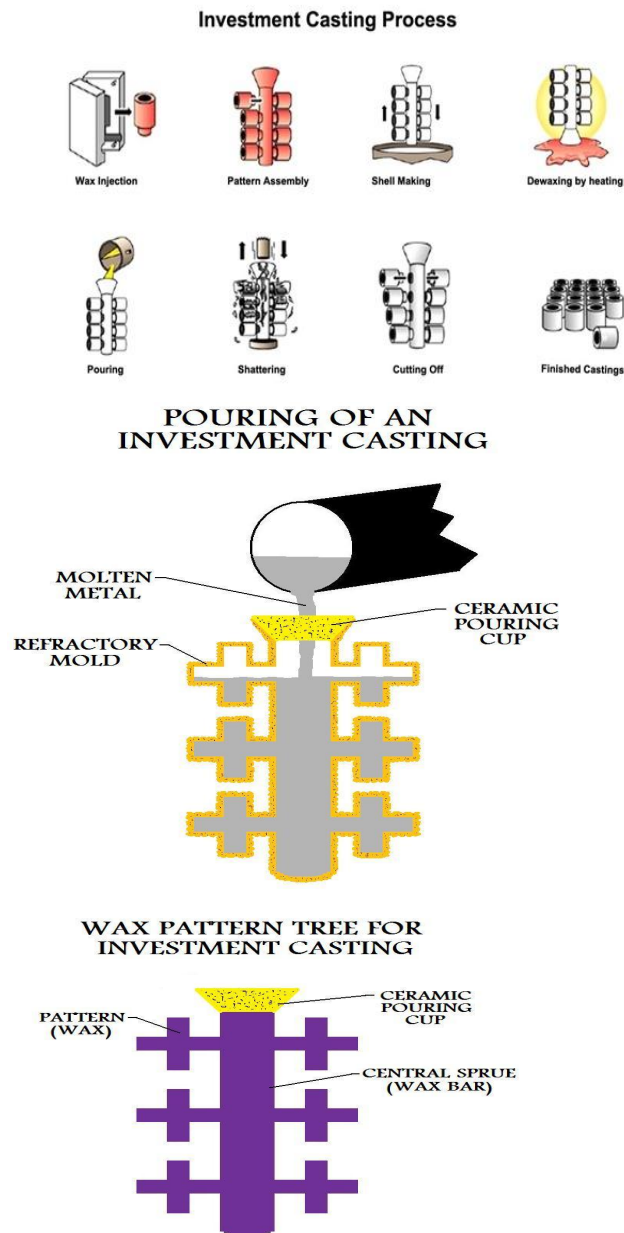


Fig.8.40 Investment or lost wax casting process

Vacuum Process

In this process the mould is made from reclaimable dry sand and is vacuum sealed in a plastic film. Due to application of vacuum the surface finish is excellent, and vacuum holds the mould rigid during the pouring and solidification of casting.

A vacuum chamber is fitted beneath a pattern plate. Thus when a pattern is mounted over the pattern plate, the vacuum chamber can be connected to the pattern. After placing the pattern, a heated plastic film is placed over the pattern and drawn down on to it by the vacuum. A moulding box is placed over the pattern and vibrated. After forming the feeder and risers, the top of the mould is sealed with a second plastic sheet and a vacuum is applied to the box to compact the dry sand. The mould is then ready for pouring after withdrawing pattern plate. The other half of the mould is produced in a similar manner. The two halves are assembled and filled with molten metal. During pouring, a vacuum is applied to both upper and lower boxers.

Frozen –Mercury Moulding (Mericast Process)

In this process frozen mercury is used for the production of precision castings. In this case, the metal mould is prepared to the necessary shape with gates and sprue-holes. It is then placed in cold bath and filled with acetone (which acts as a lubricant). Mercury is poured into it and freezing of mercury takes place at -200°C after about 10 minutes of pouring. The patterns are then removed and are given dippings in a cold ceramic slurry bath, until a shell of about 3mm is built up. Mercury is then melted and removed at room temperature. The shell is dried and heated at high temperature to form a hard permeable shape. The shell is then placed in a flask, surrounded by sand, preheated and filled with metal. After solidification of metal, the castings can be removed. Both the ferrous and non-ferrous metals can be cast by this process, but its application is limited for commercial use due to high cost of casting process.

Plaster Mould Casting

For casting silver, gold, aluminium, magnesium, copper, and alloys of those metals (particularly brass and bronze), plaster of paris or gypsum ($\text{CaSO}_4 \cdot n\text{H}_2\text{O}$) is extensively used. Gypsum is particularly used for investment casting or for cope and drag moulding. For preparing the mould a slurry is used which consist of 100 parts of metal casting plaster and 160 parts of water. It is important to note that plaster is to be added to water and not water added to plaster of Paris. They are then stirred slowly to creamy consistency. This slurry is poured over a carefully made match plate type pattern, usually of metal. The mould is vibrated slightly to ensure plaster's filling all small cavities. The initial setting takes place at room temperature after few minutes of pouring of slurry and then the pattern can be removed. Sometimes, the initial setting time is decreased by heating or by adding a small quantity of terra-alba. Copes and drags are made simultaneously on separate lines and dried in ovens at $200\text{--}425^{\circ}\text{C}$, until all free and combined moisture is removed. Normally 20 hours is the time for drying purposes. In order to prevent the cracking of moulds, 20 to 30% talc is added to the plaster, while mixing. In addition other compounds such as terra-alba or magnesium oxide are added to reduce the initial setting time. Sometimes lime or cement is also added to control the

expansion of plaster during caking. Mould sections obtained by this process are very fragile and require care in assembling.

Antioch Casting

This process is a further application of plaster casting. It was first developed by Monis Beam for making special engineering parts of complex shape requiring minute details and thin sections (Jain, 2009). For preparing the mould a creamy slurry is obtained by adding water to a dry mixture of gypsum, sand, asbestos, talc and sodium silicate. This slurry is piped by hose into metal core- boxes or cope and drag flask fitted to special match plates. After the initial setting which is somewhat faster than plaster moulding, the patterns are drawn and then the mould is assembled in a green condition. After keeping them at room temperature for nearly 6 hours, they are autoclaved in steam at about 0.7kg/cm^2 pressure, cured in air and finally dried in an oven at temperature of 230°C for 10 hours. This autoclaving develops a special permeable structure in the mould, but greatly reduced dry strength. Drying in oven removes the free and combined water and hence good permeability is obtained.

Continuous Casting

Continuous casting has proved itself to be a most economical way of casting wherever feasible and several methods have been devised and successfully used. In this process the molten metal is continuously poured into a mould around which there are facilities for rapidly chilling the metal to the point of solidification. The solidified metal is then continuously removed from the mould at the calculated rate. The following processes have been successfully used for continuous casting of metals.

Reciprocating Mould Process

In this process molten metal is poured into a holding furnace there is a needle valve arrangement by which quantity of flow can be changed. Metal from this needle valve flows to a mould (generally slab shape) and is distributed all along the mould surface by a submerged horizontal cross piece. The level of the metal in the mould is kept constant at all times. The mould is surrounded all around by cooling water. The water cooled mould is reciprocated up and down. The down-stroke is synchronized with the discharge rate of slab. As the mould moves up after its down limit, it is again filled with molten metal and again in down stroke, cooling starts and this process continues. As messy metal comes out of mould, it is directly cooled by water sprayed on it. The rolls at the bottom keep on pulling the slab to match with the cooling rate. Below the rolls is a saw which keeps on cutting the slab to the required lengths. Slabs produced by this process are further processed by cold rolling into sheets and strips. Fig. 8.41 shows a reciprocating mould process.

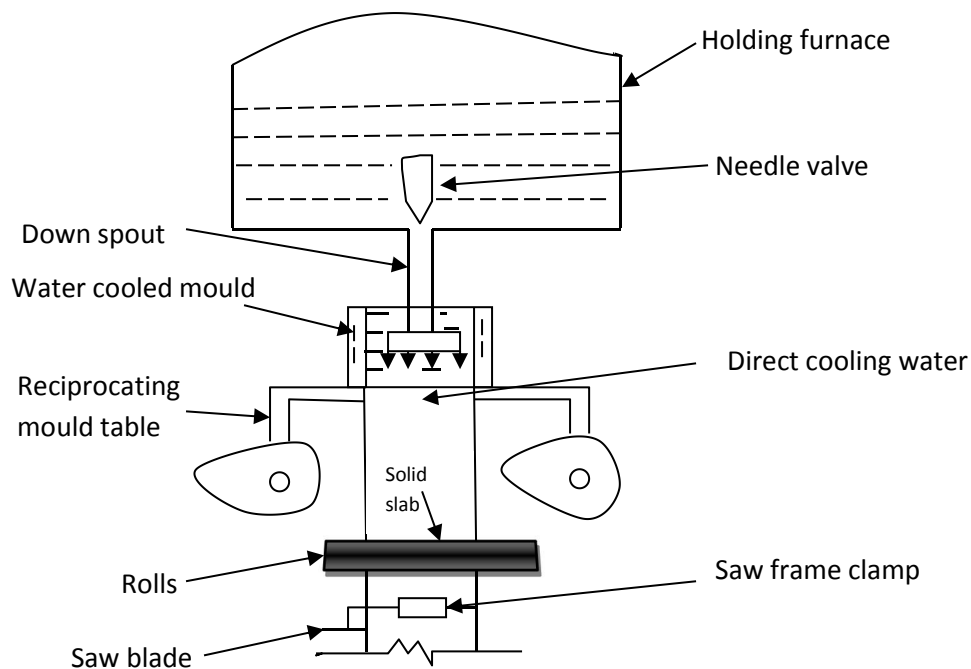


Fig .8.41 Reciprocating Mould Process

Asarco Process

It is a modification of the reciprocating process. In this process, the forming die is an integral part of the furnace and thus there is no problem of controlling the flow of metal. The metal is fed by gravity into the mould from the furnace as it is continuously solidified and withdrawn by the rolls below. The die is water cooled and self-lubricating and thus has excellent resistance to thermal shocks. The upper end of the die is molten metal and thus serves the function of riser and acts as path for dissipation of evolved gases. At the time of starting, a similar rod is put into the die till its upper end melts and forms continuity with molten metal, and it is then withdrawn by rolls and the process becomes continuous. By this process, rounds, tubes, squares and special shapes can be conveniently produced and it is particularly suited to alloys like phosphorised copper and standard bronzes.

Chill Casting

It is used, where hard outer surfaces and wear resistant castings are required. This process is nearly similar to sand casting. Moulds are made of sand or cast iron and for the purpose of chilling the cast iron, steel blocks are used as shown in Fig.8.42. The figure shows an example of composite mould of sand and metallic chills for casting a cast iron wheel. The examples of chill castings are wheel tread, railway brake shoe,

tram-car wheels, crusher jaw, chilled rolls used in rolling mills and sideways of machine tools.

Malleable Castings

Malleable castings are made to the desired shape by pouring molten metal in sand mould which on solidification gives white cast iron castings. If these castings are used as they are, they will have poor strength, poor ductility and poor machinability and hence will be less important from commercial point of view. In order to utilize the white cast iron castings, it is given an annealing treatment for a long time. It has been found that if white cast iron is annealed continuously at a temperature of 950 to 1000°C, carbon precipitates in the massive form. Graphite originally present in the form of flakes is a source of weakness and causes brittleness, but when converted in a very finely divided form, it is not so harmful and makes the iron malleable.

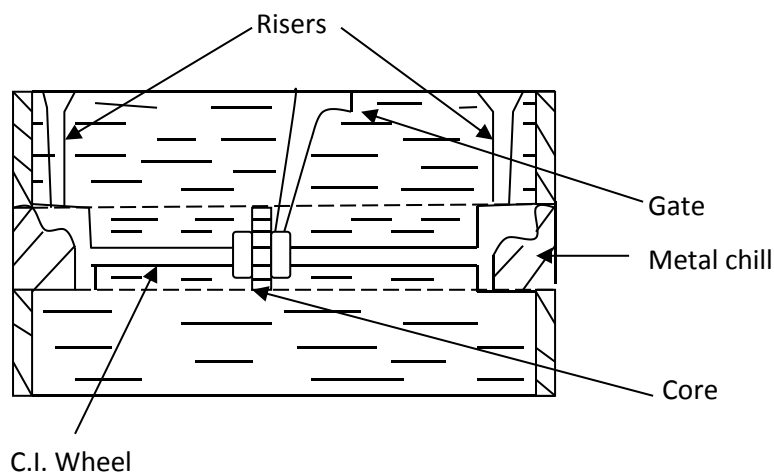


Fig.8.42. Chilled Casting (Jain, 2009)

Several types of furnaces are used such as rotary furnace, cupola, air furnace and electric arc furnace. But the most commonly used furnace is an air furnace as it provides accurate control of carbon and other elements in the metal. The charge consists of 40% pig iron, 50% scrap and the rest malleable iron and steel scrap. The temperature of molten metal before it is poured into the mould is 1600°C. See Figure 8.4 3 for microstructure of grey cast iron and malleable cast iron.

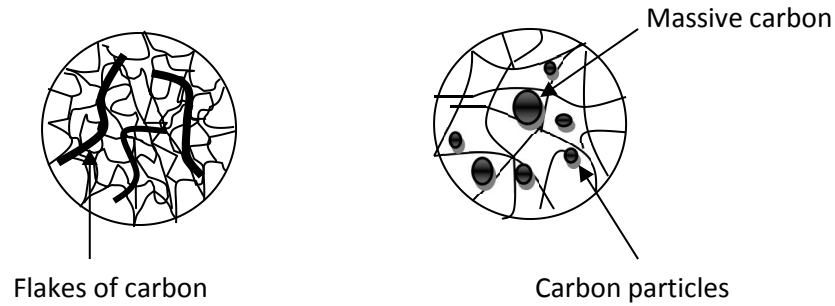


Fig 8.43 Microstructure of as-cast cast iron and malleable cast iron (Jain, 2009)

The moulds used for obtaining cast iron castings are made of green sand mould of high refractory material. Since the white cast iron cools rapidly and casting needs greater allowance for contraction, the mould should be such as to provide free contraction of the metal. The castings are cleared-off and also gates and risers are cut out. They are then packed in cast iron boxes containing sand and powdered slag. Packing helps in reducing the tendency of warping of the casting during annealing treatment. Depending upon the purposes for which the castings are to be used, they are classified in two ways:

- c) Black heart malleable castings.
- d) White heart malleable castings.

Black Heart Malleable Castings.

The castings are taken out of the mould and put into a drum having a neutral media, consisting of sand and powdered slag. The drum is closed and is kept in the air furnace and heated slowly. The temperature is raised to 922°C in two days' time, kept at this temperature of nearly 50 to 80 hours and then the drum is allowed to cool in the furnace till it reaches the room temperature. The whole cycle takes about one week. During this treatment, combined carbon separates out and all the carbon does not change into graphite state but in another form of free carbon called tempered carbon.



This makes the casting less brittle or in other words malleable. The fracture portion of such a casting is dark grey or black in appearance. Black –heart malleable castings are specially used in the automobile industry.

White Heart Malleable Castings.

The castings are packed in a drum of oxidizing media, which is generally powdered iron ore or powdered scale (film of Fe_3O_4 on surface). The closed drum is kept in the furnace and heated to 900°C and kept at this temperature for nearly 60 to 80 hours and allowed to cool slowly in the furnace itself. The castings so obtained are supposed to be malleable like white heart cast iron.

The typical composition used for malleable casting is given below:

- Carbon 2.0 to 2.5%, silica 1% (max.), manganese 0.5 to 0.8%.
- Phosphorus and sulphur (as low as possible).

The percentage of carbon and silicon should be so selected that it promotes the development of free carbon when the castings are annealed. If thin section castings are to be obtained, then amount of silicon should be high and for large castings it should be low.

Mechanical Properties of Malleable Castings

- e) Tensile strength of the order of 2500 to 3000kg/cm²
- f) Elongation value of 12%
- g) Hardness of 170 to 230 BHN
- h) Good machinability

Such castings are used for many industrial purposes such as agricultural implements, automobile parts, boilers, tanks, engines, conveyors and elevators, electrical and industrial power equipment, household appliances, pipe-fittings, plumbing supplies and especially for those parts which are subjected to impact and vibration.

REVIEW QUESTIONS FOR CHAPTER EIGHT

1. List the engineering professionals that collaborate to produce a casting
2. Explain the process of metal casting
3. List some metal casting processes that you know
4. List some sand casting processes that you know
5. Explain sand casting process
6. Define a pattern and explain how patterns are made
7. List the types of pattern that you know
8. Write an essay on pattern allowance
9. What are the construction details to be noted when constructing patterns?
10. What are the materials used for pattern making?
11. List the machines used for pattern making
12. Draw an assembled mould with core and label it
13. List and explain the different types of moulds that you know
14. Explain sand moulding process
15. Write briefly on machine moulding
16. Tabulate a comparative study of different moulding machine
17. List and explain some types of moulding machines
18. List the advantages and disadvantages of moulding machines
19. Write briefly on automation of moulding machines
20. Explain shell moulding process and the materials for making shell
21. Elaborately write on permanent mould processes
22. What are the advantages and disadvantages of pressure diecasting machine
23. Explain the Acurad process

24. Write short note on the following: Rheocasting, thixocasting, ferrous die casting, low pressure die casting, squeeze casting, cast metal-matrix composite, vacustract process and the CLAS Process
25. Explain the following casting techniques: the colshell process, the Zeus process, the evaporative pattern casting process, vacuum-sealed moulding process, the CO₂/Silicate process, the Cosworth process, slush casting, pressed casting, centrifugal casting, investment or lost wax casting, vacuum process, plaster mould casting, Antioch casting, continuous casting, chill casting and malleable casting.

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CHAPTER NINE

FERROUS AND NON-FERROUS METAL CASTING

Ingot Casting

The starting metal for any deformation work is a regular type of casting termed ingot. They can be rectangular, circular in cross section they may vary in size sometime for about 10kg for nonferrous metal to over a 100tons for large steel forging ingots. Details on ingot casting is found in chapter 7.

Considerations

Casting of Steels

The basic principles of moulding and casting are similar for all cast metals, but there are considerations that are applied for each metal in each case depending on its physical and metallurgical characteristics and its castability. Some of the considerations under steel casting include the following:

1. Since steel melts at a higher temperature than Iron, higher pouring temperatures are involved and necessitating sands of greater refractoriness, usually high silica sand bonded with refractory clay are used for the casting.
2. In order to eliminate solidification shrinkage in the metal all castings must be feed in the heaviest section. This factor is not important in iron because the value of solidification shrinkage is very low
3. Since molten steel has a tendency to dissolve carbon no carboneous material can be used on the mould faces.
4. In order to reduce cost new facing sand having refractoriness is usually used on the faces and backing up sand is used on the other part of the mould.
5. To produce sound casting the metal must be thoroughly deoxidized before it is poured into the mould. The unkilld metal spits and boils in the ladle due to dissolve oxygen and will produce defects such as gas holes, gas porosity and sponginess. Alloyed steels are invariably killed, where as low carbon steel may be killed or unkilld.

Steels may be killed in one or several ways

6. By adding small amount of grain size control elements or deoxidisers such as aluminum, manganese, silicon to the molten metal.
7. By allowing the metal to remain in the crucible for a long time so that silicon of the crucible will combine with the oxygen to form slag on the surface of the metal

8. Another way is by normalizing treatment

9. Another way is by directional solidification and this also helps to ensure sound casting by this method the metal starts solidifying from the point furthest from the riser and solidification proceeds progressively towards the riser the riser being the last to solidify.

Introduction: Types of Cast Iron

The first iron castings to be made were cast directly from the blast furnace. Liquid iron from a blast furnace contains around 4% C and up to 2% Si, together with other chemical elements derived from the ore and other constituents of the furnace charge. The presence of so much dissolved carbon, etc. lowers the melt point of the iron from 1536°C (pure iron) to a eutectic temperature of about 1150°C so that blast furnace iron is fully liquid and highly fluid at temperatures around 1200°C. When the iron solidifies, most of the carbon is thrown out of solution in the form either of graphite or of iron carbide, Fe_3C , depending on the composition of the iron, the rate of cooling from liquid to solid and the presence of nucleants.

If the carbon is precipitated as flake graphite, the casting is called “grey iron”, because the fractured surface has a dull grey appearance due to the presence of about 12% by volume of graphite. If the carbon precipitates as carbide, the casting is said to be “white iron” because the fracture has a shiny white appearance. In the early days of cast iron technology, white iron was of little value, being extremely brittle and so hard that it was unmachinable. Grey iron, on the other hand, was soft and readily machined and although it had little ductility, it was less brittle than white iron.

The great merits of grey iron as a casting alloy, which still remain true today, are its low cost, its high fluidity at modest temperatures and the fact that it freezes with little volume change, since the volume expansion of the carbon precipitating as graphite compensates for the shrinkage of the liquid iron. This means that complex shapes can be cast without shrinkage defects. These factors, together with its free-machining properties, account for the continuing popularity of grey cast iron, which dominates world tonnages of casting production.

Greater understanding of the effect of chemical composition and of nucleation of suitable forms of graphite through inoculation of liquid iron has vastly improved the reliability of grey iron as an engineering material. Even so, the inherent lack of ductility due to the presence of so much graphite precipitated in flake form limits the applications to which grey iron can be put.

A malleable or ductile form of cast iron was first made by casting “white iron” and then by a long heat treatment process converting the iron carbide to graphite. Under the right conditions the graphite developed in discrete, roughly spherical aggregates, so that the casting became ductile with elongation of 10%, or more. Malleable cast iron became a widely used casting: being particularly suitable for automotive transmission components and many other applications.

Relationship between Composition, Strength and Structure of Grey Cast Iron

The properties of grey irons depend on the size, amount and distribution of the graphite flakes and on the structure of the metal matrix. These, in turn depend on the chemical composition of the iron, in particular its carbon and silicon content and also on processing variables such as method of melting, inoculation practice and the cooling rate of the casting.

The three constituents of cast iron which most affect strength and hardness, they are; total carbon, silicon and phosphorus. An index known as the carbon equivalent value combines the effects of these elements.

$$\text{Carbon equivalent (CE)} = \text{TC}\% + \frac{\text{Si}\% + \text{P}\%}{3}. \quad (9.2)$$

Cast iron with carbon equivalent values of less than 4.3% are called hypoeutectic irons, those having carbon equivalent values higher than 4.3% are hypereutectic irons. Since the structure (and hence the strength) of flake is a function of composition, a knowledge of the CE of an iron can give an approximate indication

of the strength to be expected in any sound section. This is conveniently expressed in graphical form in Fig. 9.3.

From Fig. 9.3 it is possible to construct a series of curves showing the reduction of strength with increasing section thickness. It is important to realise that each of these curves represents an average figure and a band of uncertainty exists on either side. Nevertheless, these figures represent those likely to be achieved on test bars cast in green sand moulds.

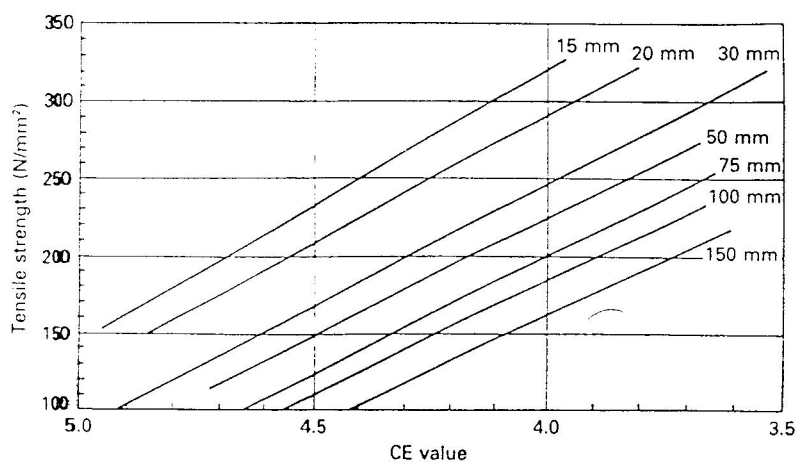


Figure 9.3: Relation between tensile strength and carbon equivalent value for various bar diameters for uninoculated iron. (Data supplied by BCIRA.)

The Production of Grey Irons

In order to produce castings having the required properties, the following factors must be controlled:

- i. The charge to be melted.
- ii. The method of melting.
- iii. Treatment of the liquid metal before casting.

When deciding on a chemical composition for any casting, the effects of the main constituents have to be considered. These can be summarized briefly as follows:

Carbon: The effect of carbon must be considered together with that of silicon and phosphorus and the concept of carbon equivalent value has already been discussed. CE has a major effect on the strength and hardness of the casting (Fig.9.3). CE also affects the casting properties of the iron. Irons having CE below about 3.6% become difficult to cast sound, because liquid shrinkage occurs and feeding is necessary to achieve complete soundness.

Silicon: Next in importance to carbon, with regard to the properties of iron, is silicon. Silicon is a graphitising element: high silicon irons, over about 1.6% Si, tend to be graphitic, while low silicon irons are mottled or white. Silicon contents of grey iron are generally around 2.0%. Table 9.1 shows the areas of applications of some grades of grey cast iron.

Table 9.1: Properties and applications of grey cast iron

Class of Casting	Grade of Grey Iron Used (Tensile Strength N/mm ²)
Air-cooled cylinders	200—250
Agricultural machinery	200—250
Bearing caps	200
Bearing housings	200
Boilers (central heating)	180—200
Brake cylinders	200
Brake discs	200
Brake drums	200
Clutch housings	200

Clutch plates	200
Cooking utensils	180—200
Counterweights	100—150
Cylinder blocks	200—250
Cylinder heads	200—250
Diesel	250
Electric motor stator cases	200
Drain covers, gulleys, etc.	150
Flywheels	200
Gear boxes	200—250
Ingot moulds	100—150
Lathe beds	200
Machine tool bases	200
Manifolds	200—250
Paper mill drier rolls	150—200
Piano frames	150—200
Rain water pipes, gutters	150
Refrigerator compressors	250
Tractor axles	150-200
gear boxes	200
Valves, low pressure (gas)	150—200
Water	200
Hydraulic	250
Water pumps	200

Manganese: Manganese is necessary to neutralise the effect of sulphur in iron. Without sufficient Mn, iron sulphide forms during solidification and deposits

around grain boundaries where it renders the metal hot-short and likely to produce cracked castings. If sufficient Mn is present, MnS forms as the molten metal cools and floats out of the metal into the slag layer. The formula $Mn\% = 1.7 \times S\%$ represents the amount of Mn needed to neutralize the sulphur, although the sulphur should not be allowed to exceed about 0.12%. In addition to combining with sulphur, Mn is a pearlite stabilizer and it increases the hardness of the iron. However it is not primarily used for strengthening because it can affect nucleation adversely. Mn levels in most irons are typically 0.5 – 0.8%.

Sulphur: Sulphur is generally harmful in grey iron, and should be kept to below 0.12%. Even if the sulphur is adequately neutralised with Mn, if the high S slag is trapped in the casting, it can cause blow hole defects beneath the casting skin.

Phosphorus: P has limited solubility in austenite and so segregates during solidification forming phosphides in the last areas to solidify. While P increases the fluidity of all cast irons, it makes the production of sound castings more difficult and the shock resistance of the iron is reduced. For most engineering castings, phosphorus should be kept below 0.12%, but up to 1.0% may be allowed to improve the running of thin section castings where high strength is not required.

Melting Cast Irons

Iron is usually melted in a cupola or in an electric induction furnace. Gas-fired or oil-fired rotary furnaces can also be used, but their use is less common.

Cupola Melting

The cupola is the most widely used primary melting unit for iron production because of its simplicity, reliability and ease of operation. While the cupola is an efficient primary melting unit, it does not adapt easily to varying demands, nor is it

an efficient furnace for superheating iron. For this reason it is often used in conjunction with an electric duplexing furnace

Cupola Operation

The cupola is charged with:

1. Coke, the fuel to melt the iron.
2. Limestone, to flux the ash in the coke, etc.
3. Metallics, foundry scrap, pig iron, steel and ferroalloys.
4. Other additions to improve the operation.

The cupola is blown with air to combust the coke and the air flow controls the melting rate and metal temperature. The air is frequently used cold (the cold-blast cupola) or it may be heated to improve thermal efficiency (the hot-blast cupola). In a small number of cupolas, the air blast is enriched with oxygen and gas is sometimes injected to supplement the fuel. The data in this section applies primarily to conventional cold-blast cupolas, which are the most commonly used type.

The output of a cupola depends primarily on the diameter of the shaft of the furnace and on the metal/coke ratio used in the charge.

A useful measure of the efficiency of operation of a cupola is the specific coke consumption (SSC) which is:

$$\frac{\text{Annual tonnage of coke} \times 1000}{\text{Annual tonnage of metallics charged}} = \text{SSC (kg/tonne)} \quad (9.3)$$

This takes into account both charge coke and bed coke. When the cupola is operated for long enough campaigns, the amount of coke used to form the bed initially can be ignored. However, as the melting period decreases, the role of the cupola bed becomes more important.

Coke

The performance of the cupola is highly dependent on the quality of the coke used.

Typical foundry coke has the following properties:

Moisture	-	5% max
Ash	-	10% max
Volatiles	-	1%
Sulphur	-	1%
Mean size	-	100mm
Undersize	-	<5% below 50mm

The coke size directly affects coke consumption per tonne of iron melted and also the melting rate. Optimum cupola performance is achieved with coke in the size range 75—150mm. If smaller coke is used, metal temperature is reduced and a higher blast pressure is needed to deliver the required amount of air to the cupola. Increasing the size of coke above about 100mm has no beneficial effect, probably because large pieces of coke tend to be fissured and break easily during charging and inside the cupola.

Furnace Lining

Silica, is mined as quartzite and should have the following approximate composition:

SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Alkali
98.9%	0.6%	0.2%	0.1%	0.04%	0.02%max

20%	-	>1mm
20%	-	0.5-1.0mm
30%	-	0.1-0.5mm
30%	-	<0.1mm

Boric oxide is usually used as the bonding agent, being mixed by the refractory supplier. Around 0.7–0.8% B₂O₃ is used. During the fritting cycle, as the temperature at the hot face increases, the boric oxide dissolves the silica fines, producing a borosilicate glass which fills the interstices between the silica grains and cements them together.

The usual practice with medium frequency furnaces is to coat the copper coil of the furnace with a layer of “mudding” about 6mm thick, of a medium to high alumina cement. This remains in place when the hot face is knocked out. Between this and the hot face is a layer of ceramic fibre insulation. The working face is formed by compacting the silica refractory behind a steel former concentrically placed within the coil. Formers are normally constructed from mild steel sheet according to the furnace manufacturer’s design, using vibratory ramming tools or manual compaction. Inhalation of silica dust presents a hazard and respirators should be used during installation or wrecking of the lining.

The lining is fritted by slow inductive heating of a metallic charge placed inside the steel former. The heating rate depends on the size of the furnace and the manufacturer’s recommendations should be followed. In general, a low heating rate of 50–100°C/h should be used until the temperature reaches 700°C, after which the rate can be increased to 100–200°C/h (the faster rate being possible with furnaces of size 10 tonnes or less). The temperature should be raised to 30–50°C above the normal operating temperature of the furnace, and held for about one hour to complete the fritting operation.

The lining life is very dependent on the particular practice used in the foundry and the type of iron being melted. For example, the high carbon and low silicon contents of most ductile base irons, together with the higher temperatures involved tend to result in lower lining lives than furnaces used for grey or malleable irons. A 5-tonne furnace melting grey iron should be capable of melting 600–800 tonnes of iron from one lining, but less than half this amount if a ductile base iron is being melted.

If a range of irons is melted, requiring higher temperature than normal, or producing more aggressive slags, it may be necessary to use an alumina lining. These can be used up to 1750°C and have greater corrosion resistance, but the cost is much higher. The installed lining cost is around 2.5 x greater than a silica lining, although the life may be 3x longer.

Shop Floor Control of Metal Composition

The carbon and silicon content of unalloyed cast irons can be quickly determined on the shop floor by thermal analysis. A sample of molten iron is poured into a small, expendable test mould about 25mm diameter and 65mm deep made from resin-bonded sand and coated with tellurium to ensure that the sample freezes white. The test mould also contains a thermocouple connected to a temperature recorder. As the sample solidifies, the temperature recorder plots a cooling curve which displays the “liquidus arrest” when the sample first starts to freeze, then the “eutectic arrest” when freezing is complete. The liquidus arrest measures the Carbon Equivalent Liquidus value (CELV) given by:

$$\text{CEL} = \%C + \frac{\%Si}{4} + \frac{\%P}{2} \quad (9.4)$$

Note that CEL is not the same as CEV, $\%C + (\%Si + \%P)/3$.

The eutectic arrest temperature, on an unalloyed iron of low P%, is a measure of the silicon content of the iron. Thus from the two arrest temperatures, the carbon and the silicon content can be calculated. Simple calculators are available to enable the C% and Si% to be read, or digital meters are available which display the C% and Si% directly. The carbon content can be determined with an accuracy of $\pm 0.05\%$; the silicon measurement has an accuracy of about $\pm 0.15\%$. To achieve good results:

The sample must be poured at a high enough temperature to give a well-defined liquidus arrest. This means that the sampling spoon must be pre-heated.

The iron should not be inoculated before testing.

The sample must solidify white.

Special expendable sample moulds are available for the purpose.

Inoculation of Grey Cast Iron

In order to achieve the desired mechanical properties in iron castings, the liquid iron must have the correct composition and it must also contain suitable nuclei to induce the correct graphite structure to form on solidification. The liquid iron must have a suitable “graphitization potential”, determined mainly by its carbon equivalent value, and in particular by the silicon content. It is normal practice to adjust the graphitisation potential by controlling the silicon content. However the effect of other elements must also be considered.

Ladle Lining

KALTEK segments and base boards are fitted inside the permanent lining, joints being filled with KALSEAL refractory cement. The gap between the KALTEK liner and the permanent lining is filled with coarse, dry silica sand or BAKFIL product. Multiple filling is possible as long as the ladle lining is not allowed to cool down between fillings.

Casting Defects Due to Poor Ladle Maintenance

Slag and dross inclusions: these arise from slag carried over from the melting furnaces, from slag deposits left in the ladles after pouring and from fusion of the ladle lining material. They can be reduced by:

- i. Removal of adhering slag before use.

- ii. With tea-pot ladles, removing molten slag by back-tilting, to avoid contamination of the spout.
- iii. Use of good quality ganister and other lining materials.

Hydrogen Pinholing: Is caused by molten metal being poured from improperly dried ladles or damp furnace launders. Hydrogen from the moisture is dissolved in the liquid metal and released during solidification. The problem is increased by trace amounts of aluminium in the metal. The defect is avoided by correct ladle drying and pre-heating.

Adding Alloy Additions in the Ladle

Silicon and molybdenum additions can be made to cast iron by adding LADELLOY fluxed additives.

SILICON LADELLOY 33 additive is a fluxed ladle addition allowing the silicon content of the iron to be increased quickly and accurately. The amount of silicon to be added is determined by a wedge/chill test. SILICON LADELLOY 33 additive contains about 62% Si with a flux to ensure optimum pickup. The required quantity of additive is slowly poured into the metal stream as it passes down the launder to the ladle. The use of ladle additions simplifies melting operations since a standard charge can be adjusted at the ladle to cover a wide variety of requirements.

MOLYBDENUM LADELLOY 33 additive contains about 66% Mo and a small amount of flux to ensure optimum pick-up of the element. The required number of units should be placed in the bottom of the ladle and metal tapped onto them. The phosphorus content of the iron must be less than 0.2% to avoid the formation of molybdenum phosphide.

Ductile Iron

Ductile iron, also known as spheroidal graphite (s.g) iron or nodular iron, is made by treating liquid iron of suitable composition with magnesium before casting. This

promotes the precipitation of graphite in the form of discrete nodules instead of interconnected flakes. The nodular iron so formed has high ductility, allowing castings to be used in critical applications such as automotive transmission components.

Production of Ductile Iron

While a number of elements, such as cerium, calcium and lithium, are known to develop nodular graphite structures in cast iron, magnesium treatment is always used in practice. The base iron is typically:

TC	Si	Mn	S	P
3.7	2.5	0.3	0.01	0.01

having high CEV and very low sulphur. Sufficient magnesium is added to the liquid iron to give a residual magnesium content of about 0.04% the iron is inoculated and cast. The graphite then precipitates in the form of spheroids. It is not easy to add magnesium to liquid iron: magnesium boils at a low temperature (109°C), so there is a violent reaction due to the high vapour pressure of Mg at the treatment temperature causing violent agitation of the liquid iron and considerable loss of Mg in vapour form. This gives rise to the familiar brilliant “magnesium flare” during treatment accompanied by clouds of white magnesium oxide fume. During Mg treatment, oxides and sulphides are formed in the iron, resulting in dross formation on the metal surface. This dross must be removed as completely as possible before casting. It is important to remember that the residual magnesium in the liquid iron oxidises continuously at the metal surface, causing loss of magnesium which may affect the structure of the graphite spheroids. Moreover, the dross formed may result in harmful inclusions in the castings.

Several different methods of adding magnesium have been developed, with the aim of giving predictable, high yields. Magnesium reacts with sulphur present in

the liquid iron until the residual sulphur is about 0.01%. Until the sulphur is reduced to near this figure, the magnesium has little effect on the graphite formation. In the formation of MgS, 0.1% S requires 0.075% Mg. A measure of the true Mg recovery of the treatment process can be expressed as:

$$\begin{aligned} &\text{Mg recovery \%} \\ &= \frac{0.75 \times (S\% \text{ in base metal} - S\% \text{ residual}) + \text{residual Mg\%}}{\text{Mg\% added}} \end{aligned} \quad (9.5)$$

Mg recovery is lower at high treatment temperatures and is dependent on the particular treatment process used. Magnesium may be added as pure Mg, or as an alloy, usually Mg – ferrosilicon or nickel – magnesium. Other materials include MAG-COKE, Mg-impregnated coke, or NODULANT briquettes, formed from granular mixtures of iron and magnesium.

Treatment Materials

Ni – Mg alloy	-	5-15%Mg
Mg-Fe-Si alloy	-	3-20%
Mg-impregnated coke	-	40%
Mg-Fe briquettes	-	5-15%

MgFeSi alloys frequently also contain 0.3—1.0% cerium accompanied by other rare earth elements. 0.5-1.0% Ca is also a common addition to the treatment alloy.

Treatment Methods include (Fig.9.4)

Sandwich Ladle: The treatment alloy is contained in a recess in the bottom of a rather tall ladle and covered with steel scrap. The method is only suitable for use with alloys containing less than 10% Mg.

Tundish Cover: This is a development of the treatment ladle in which a specially designed cover for the ladle improves Mg recovery and almost eliminates glare and fume.

Plunger: The alloy is plunged into the ladle using a refractory plunger bell usually combined with a ladle cover and fume extraction.

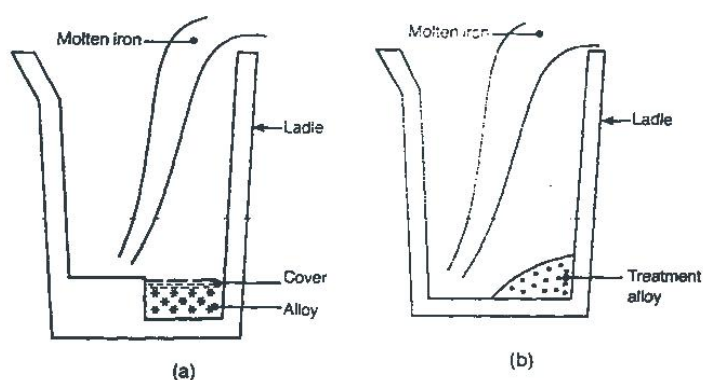
Porous Plug: A porous-plug ladle is used to desulphurise the metal with calcium carbide and the treatment alloy is added later while still agitating the metal with the porous plug.

Converter: A special converter ladle is used, containing Mg metal in a pocket. The ladle is filled with liquid iron, sealed and rotated so that the Mg metal is submerged under the iron.

Treatment in the Mould (In-Mold): MgFeSi alloy is placed in a chamber moulded into the running system; the iron is continuously treated as it flows over the alloy.

All the methods have advantages and disadvantages; simple treatment methods can only be used with the more costly low-Mg alloys, generally containing high silicon levels which can be a restriction. In order to use high Mg alloys and pure Mg, expensive special purpose equipment is needed so the method tends to be used only by large foundries.

A survey on ductile iron practice in nearly 80 US foundries in 1988 (AFS Trans., 97. 1989. p. 79) showed the biggest change in the last 10 years.



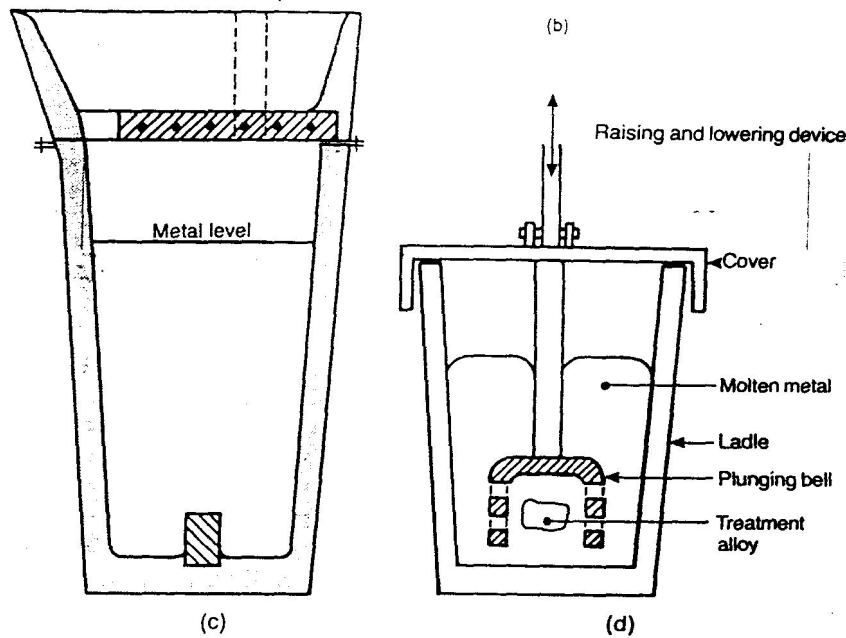


Figure 9.4: Treatment methods for making ductile iron. (a) Sandwich treatment. (b) Pour-over treatment. (c) Tundish cover ladle. (d) Plunging treatment.

Hardened and Tempered Structures

Austenitise at 900 – 920°C then oil quench. Tempering is usually carried out at 600 – 650°C.

Austempered Ductile Iron

Austempering is an isothermal heat treatment for producing bainitic structures. It improves strength and wear resistance while retaining relatively good impact strength and ductility. Austenitising is carried out at around 900°C, holding for 1 hour plus 1 hour for each 25mm of the thickest section of the casting. Slow initial heating of the castings are then quenched to the required isothermal heat treatment temperature, usually between 235 and 450°C. This is done in a salt bath or fluidized sand bed. The castings are held at temperature for 1-2 hours to complete the transformation of austenite to bainite. The lower temperatures give high hardness, strength and wear resistance, while the higher heat treatment temperatures result in

higher ductility and toughness. After the isothermal treatment, the castings are cooled to ambient temperature.

Unalloyed ductile irons may be austempered in sections up to about 8mm. Thicker section castings require the addition of Mo or Ni to increase the hardenability.

Table 9.2 Typical changes in properties due to austempering of an unalloyed iron are:

	<i>As-cast</i>	<i>Austempered 1h at 300°C</i>	<i>Austempered 1h at 375°C</i>
Tensile strength kN/mm ²)	475	1465	1105
Elongation (%)	19	450	9
Hardness HB	160	1465	320

Austempered ductile iron finds applications as a replacement for forged steel components.

Stress Relief

Heat at 50—100° C/h to 600°C (taking care not to exceed 610°C), soak for one hour plus an hour for every 25 mm of section thickness in the thickest section. Cool at 50—100°C/h to 200°C or less. Ensure that the castings are adequately supported in the furnace so that they are not subjected to stress.

Casting Ductile Iron

Ductile iron differs from grey iron in its casting characteristics in two important respects. Unlike grey iron, ductile iron is a dross forming alloy. The residual magnesium which is needed to ensure nodular graphite formation rapidly oxidizes whenever the liquid metal is exposed to air: in the ladle, during metal transfer and in the mould. A magnesium silicate dross is formed which may give rise to defects at or just below the casting surface, usually on the upper surfaces of the

castings. For this reason, it is common practice to filter ductile iron castings through ceramic filters.

The other major difference compared with grey iron is the need to feed ductile iron castings to ensure freedom from shrinkage defects. Ductile irons always have a high carbon equivalent so the volume of graphite precipitated during solidification should result in completely sound sections. However, the expansion resulting from the graphite precipitation results in large pressures being exerted on the mould walls, much higher than those found with grey iron (figures of 1000–1500kPa or 145–2171 lbf/in² have been measured compared with 170 - 200kPa or 24–291lbf/in² in grey iron). Only the strongest moulds such as sodium silicate bonded moulds or well-vibrated lost foam moulds will resist such pressures so the use of feeders is common when ductile iron castings are made.

Malleable Cast Iron

Malleable irons are cast white, that is, their as-cast structure consists of metastable carbide in a pearlitic matrix. The castings must then be annealed to convert the brittle carbide structure and develop a structure of roughly spherical graphite aggregates in a matrix which can be either ferritic or pearlitic, depending on composition and heat treatment.

There are two types of malleable iron, blackheart and white-heart. Malleable iron has a long history, white-heart iron having been developed in 1722 by the French metallurgist, Réaumur while blackheart iron was developed in the LISA in 1820. Malleable iron was widely used for automotive and agricultural components, pipe fittings, valves, etc. but since the development of spheroidal graphite ductile iron, its use has declined, due to the high cost of the annealing treatment which requires expensive furnace equipment. Malleable iron is still widely used for small pipe fittings, electrical fittings and builders' hardware, particularly for thin section castings and castings which are subsequently galvanized.

White Heart Malleable

In the white heart process, the white, as-cast iron is decarburized during annealing leaving a structure of iron carbide in a metallic matrix. When fractured, the appearance is whitish, giving rise to the name white heart. Decarburization is only possible in thin sections; in heavier sections, some conversion of carbide to graphite nodules occurs so that the annealed casting has a white rim with a core having different structure and mechanical properties. This limits the applications to which it can be put. White heart can be melted in a cupola and is a low cost material which still finds applications in small, thin section castings.

The Composition of White Heart Malleable

Table 9.3 Typical compositions are;

	Before annealing	After annealing
Total carbon	3.0—3.7%	0.5—2.0%
Silicon	0.4—0.8	0.4—0.7
Manganese	0.1—0.4	0.1—0.4
Sulphur	0.3 max	0.3 max
Phosphorus	0.1 max	0.1 max

Annealing is a combined decarburisation and graphitisation process performed in an oxidising atmosphere. Originally it was done by packing castings into iron ore mixtures, but now it is carried out in continuous, atmosphere-controlled furnaces at about 1070°C. Small castings may be fully decarburized and are referred to as weldable malleable irons.

Blackheart Malleable Iron

The iron is typically melted in a cupola and duplexed into an electric furnace where temperature and composition are adjusted. The cupola metal has the composition:

C	Si	Mn	S	P
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2.5 – 2.6	1.1	0.2 – 0.3	0.2	0.1
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The final composition in the electric furnace is:

C	Si	Mn	S	P	Cr
2.4 – 2.6	1.3 – 1.45	0.4 – 0.55	0.2 max	0.1 max	0.05 max

Castings are poured at around 1450°C. Sometimes small additions (around 0.01%) of bismuth are added in the ladle to ensure fly white as cast structures. White iron contract on solidification so, to ensure freedom from shrinkage, the castings must be fed. As-cast malleable iron is extremely brittle, allowing feeders and running systems to be broken easily from the castings. Castings which have abrupt changes of section develop internal stresses on cooling which may be enough to cause cracking of the castings after shake-out. Slow cooling in the mould may be needed to avoid this happening.

The castings are annealed to develop the required graphite clusters. A typical cycle is about 48 hours long (Fig. 9.5) and may be carried out in batch-type or continuous furnaces in a controlled atmosphere to avoid oxidation of the castings. The rate of cooling in the final section of the heat treatment determines the matrix structure of the castings which can be ferritic or pearlitic according to the physical properties required.

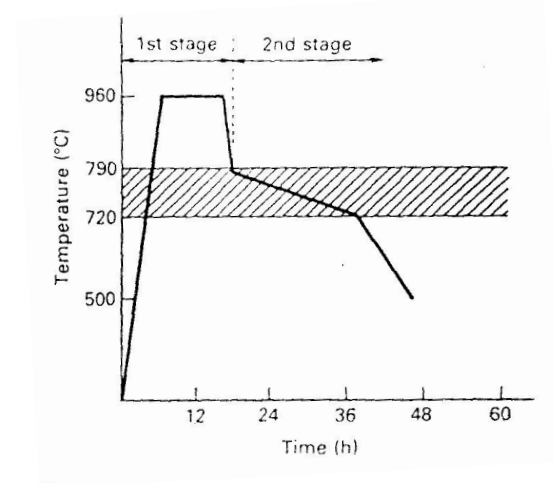


Figure 9.5: *Typical heat treatment cycle for a short Cycle blackheart malleable iron. (From Elliott, R. (1988) Cast Iron Technology, Butterworth Hejnenmann reproduced by permission of the publisher.)*

Compacted Graphite Irons

Compacted graphite irons are a range of cast irons having mechanical properties intermediate between those of grey and ductile irons. Under the microscope the graphite appears as short, thick flakes with rounded ends, readily distinguished from true flake graphite.

Compacted graphite iron has good founding characteristics, due to its high fluidity and low solidification shrinkage. The tensile, yield and fatigue strengths of CG iron are 1.5 - 2 times that of grey iron, approaching ductile iron. Thermal conductivity is comparable to grey iron and machinability is intermediate between grey and ductile irons of similar matrix structures. This combination of properties makes CG iron suitable for upgrading of castings traditionally produced of grey iron.

Production of Compacted Graphite Iron

There are several methods by which compacted graphite may be produced:

Cerium additions

Magnesium additions

Nitrogen additions

Magnesium plus titanium additions

In recent years most interest has been shown in the joint addition of a nodularising and a de-nodularising agent, usually magnesium and titanium often with a small cerium addition as well. Special treatment alloys such as CG alloy have been developed by BCIRA for the production of compacted graphite iron:

	Mg	Ti	Ce	Ca	Al	Si	Fe
Low Ca CG alloy	4.5—5.5	8.0—10.0	0.3—0.4	1.0 max	1.5 max	50—54	balance
High Ca CG alloy	4.0—5.0	8.5—10.5	0.2—0.35	4.0—5.5	1.0—1.3	48—52	balance

It is desirable to start with a low sulphur iron, below 0.035%, though the high Ca alloy is claimed to allow for treatment with a wide sulphur range. The base iron for treatment is best melted in an induction furnace and should have composition in the range:

CE	C	Si	Mn	S	P
3.7-4.5	3.1-3.9	1.7-2.9	0.1-0.6	0.035max	0.06max

The usual method of using CG alloy is by a sandwich technique with addition rates between 0.6 and 1.6% depending on the foundry conditions. The treatment temperature should be above 135°C to avoid the formation of a fully nodular structure. Inoculation of the treated iron is necessary and additions of 0.2 – 0.5% ferrosilicon are common. The matrix structure may be made ferritic or pearlitic as

with ductile iron. Titanium – containing alloys can, however, cause problems due to build-up of Ti in foundry returns.

Foundry Properties

The fluidity is governed by Carbon Equivalent and temperature and is similar for grey or ductile irons of the same CE. Because CG irons are stronger than grey irons, a higher CE can be used to obtain the same strength. This allows greater fluidity and easier running of thin sections. CG iron is stress-forming, just as ductile iron, and filtration of castings is desirable. CG irons are more prone to chill than grey irons, but less likely to chill than ductile iron. Good inoculation is necessary. Fading occurs, but to a smaller extent than in ductile iron, but excessive delays between treatment inoculations and casting should be avoided. There is some disagreement about the level of feeding required for CG iron. There is less tendency for mould wall movement than with ductile iron; nevertheless some Feeding appears to be desirable.

Applications of Compacted Graphite Irons

One of the first uses for CG Iron was the production of ingot moulds since the life of the mould is increased by 40–60% over grey iron moulds. There has been great interest in its use for automotive castings such as diesel cylinder blocks and heads, exhaust manifolds, brake drums, brake discs, flywheels, etc. Unfortunately, lack of consistency of properties has held back the wide-scale application of CG iron, and it has not achieved the market that at one time seemed possible.

Steel Castings

Steel is the most versatile of the structural engineering materials, so that more grades of steel are available for casting than any other alloy type. The casting of steel presents a number of special problems due mainly to the high casting temperature and the shrinkage that occurs on freezing. Steel castings are often used in critical situations where optimum mechanical properties are essential so that freedom from

casting defects is particularly important. The advantages of cast steel over other cast metals are;

High modulus - minimizing deflection under heavy static loading.

Shock and impact resistance – to cope with severe dynamic loading

Heat-treatable – to give the required toughness hardness and strength.

Weldable – so that castings can be joined to wrought steel products

High temperature strength - special alloys are available.

The main applications of steel castings, roughly in order of tonnage used, are;

Valves, pumps and compressors.

Construction and earth moving equipment.

Crushing, grinding, quarrying and dredging.

Oil and gas rigs.

Mining equipment.

Motor vehicles.

Defence equipment.

Railways.

Shipbuilding.

Iron and steel works.

Nuclear power plant.

General engineering equipment.

Electrical plant.

Agricultural equipment.

While the overall tonnage of steel castings has been on a downward trend for a number of years, the overall value has increased due to a growing trend towards increased quality standards, reflecting the high standards needed for nuclear plant, gas and oil rigs, etc.

It is convenient to classify steels into groups:

Carbon steels.

Low and medium alloy steels.

High alloy steels.

Carbon Steels

These are steels in which carbon is the main alloying element, other elements such as manganese and silicon being present for the purposes of deoxidation. The effectiveness of heat treatment in increasing the strength of the steel depends on carbon content and carbon steels may be further subdivided into;

Low-carbon steel	<0.20% C
Medium-carbon steel	0.20-0.50% C
High-carbon steel	>0.50% C

Applications of carbon steel castings include;

Ships' structural castings

Railway rolling stock.

Automotive castings.

Hot metal ladles.

Rolling mill equipment.

Rolls and rollers.

Machines and tools.

Mine and quarry equipment.

Oil and petroleum equipment.

Carbon steels are most frequently used in the annealed, normalized or annealed and normalized conditions, though other heat treatments may be used to develop special properties, for example, for magnetic permeability.

Low and Medium-Alloy Steels

Castings in this class normally contain amounts of manganese or silicon greater than is needed for deoxidation (e.g. $> 1\%$ Mn) or to which other elements have been specially added. Alloy steels will contain Ni, Cr or Mo as main alloying constituents and smaller amounts of V, Cu and possibly B. These elements are added primarily to alter hardenability so that the required properties can be obtained in different section thicknesses.

Pearlitic manganese steels (1.5% Mn) are used where strengths are little higher than attainable in plain carbon steels together with good toughness are required. Applications are excavating buckets, travelling wheels, gears, tractor track links and pneumatic tool parts.

Frequently used alloy steels are $1\frac{1}{2}\%$ Mn – Mo, $1\frac{1}{4}\%$ Cr – Mo, 0.75% Ni – Cr – Mo, $1\frac{1}{2}\%$ Ni – Cr – Mo and 3% Cr – Mo. Such higher strength steels find use for gears, shaft pinions, impellers, rolls, rollers, crusher heads, mill liners, crankshafts, cement processing machinery, fittings and components in the oil industry.

Steel casting with a hard skin and a very tough core may be obtained by local hardening (flame or induction hardening or carburizing or nitriding).

Austenitic Manganese Steel

This widely used steel contains from 10-14% Mn and 1.0-1.4% C (typically 12% Mn, 1.25% C). The as-cast structure contains carbides and other transformation products which produce brittleness. The castings are therefore austenitised at 1000°C or above and quenched in water, producing a fully austenitic structure that is quite tough. On account of their unique ability to resist pounding and severe abrasive wear, Mn-steel castings are used for railway track work, dredging, excavating, pulverizing and crushing equipment for mines and quarries, cement mills, etc.

High Alloy Steels

These may be subdivided into three main groups:

Fe — Cr

Fe—Cr—Ni

Fe—Ni—Cr

The iron—chromium steels contain little or no nickel and 10—30% Cr. The Cr content influences their resistance to scaling, the 13% Cr steels having reasonable oxidation resistance up to 650°C while 28% Cr steel can be used up to around 1100°C. The 13% Cr steels are used for pumps and steam turbine equipment. 20—30% Cr steels are used in the chemical industry for pump parts and also for furnace parts, grates, kiln parts, etc.

The iron – chromium – nickel alloys include the well-known 18/8 stainless steels to which additions of Nb or Ti may be used to stabilise the austenite on heating. Mo may also be added and Ni raised to 10% to allow steel to be used at higher temperatures (up to 1100°C) and improve the corrosion resistance. High corrosion resistance and toughness require the lowest carbon possible and special melting techniques allow figures as low as 0.03% C to be achieved, although achieving such low carbon contents at the surface of the casting is not easy since most moulding materials can cause surface recarburisation due to the breakdown of carbon-containing binders. These corrosion resistant steels are widely used for marine fittings, pump parts, valve bodies, impellers, etc.

Alloys for heat resisting applications contain 25% Cr and 12% Ni for use up to 1050°C and 25% Cr—20% Ni for use up to 1100°C. They are used for exhaust manifolds, burner nozzles, furnace spares, stack flues, etc.

The iron – nickel – chromium alloys are used for heat resisting applications. Widely used alloys include one containing 17% Cr, 25% Ni and one having 37% Ni, 15% Cr. The castings are used for furnace parts, salt and cyanide pots, annealing trays, etc.

Melting and Treatment of Steel for Casting

Electric arc furnaces or induction furnaces are used to melt steel or making castings. Arc furnaces have some limitations since there is always some pickup of carbon from the graphite electrodes, so that very low carbon stainless steels ($<0.03\%$ C) cannot be made. Arc furnaces are capable of using low cost scrap charges, since refining takes place in the furnace. Refining is not possible in the induction furnace, so a carefully selected charge must be used, but any type of steel may be melted.

Arc Furnace Melting

The charge is usually cold steel scrap. Furnace linings may be acid or basic. Acid linings consist of silica ganister rammed into place. Acid melting practice does not remove sulphur or phosphorus so that the charge material has to be low in these impurities. Basic linings of dolomite are more commonly used since sulphur and phosphorus can be removed and also steels high in chromium and manganese can be refined.

Melting in a basic arc furnace is a two-stage process. The first oxidising slag is made up by adding limestone. When the charge is melted, a boil is induced by adding iron ore or gaseous oxygen to the melt. The slag is then removed, taking the phosphorus from the charge with it. The steel is then deoxidised and a second slag formed by adding limestone. This slag removes sulphur and is taken off before pouring the steel into the ladle. The steel is finally deoxidised with aluminium.

Induction Furnace Melting

The coreless, medium frequency (around 1000 Hz) induction furnace is the most flexible melting unit. Small scrap can be melted when cold and the furnace can be used for successive melts of widely differing composition, the bath is in contact with the atmosphere. While nitrogen alone can contribute to porosity, its normal level is far below the limit of solid solubility. In 0.10% C plain carbon steel castings, when nitrogen is at the 0.013% level, there is a distinct tendency towards porosity. Nitrogen together with hydrogen can sometimes be the cause of porosity in high-

alloy steels, particularly those containing large amounts of chromium, when high nitrogen ferrochromium has been used.

Nitrogen pinholes occur in castings made in moulds using nitrogen containing resins such as UF-furans, and it is important to use low nitrogen binders, particularly when reclaimed sand is used.

Carbon Monoxide

The more thorough the deoxidation of the steel, the less the pinholing tendency and proper deoxidation with aluminium is the most effective control. There must be an excess of deoxidant to compensate for the higher oxygen content that develops in the surface layer of a casting as it comes in contact with the mould wall. It is possible for silicon and aluminium to be removed locally which may result in pinhole porosity.

Hot Tearing

Hot tearing is a common foundry problem caused by the contraction of the steel on freezing being hindered by the mould or cores. Chemical composition of the steel affects hot tearing in a minor way, sulphur having the greatest effect. Lowering sulphur to below 0.02% can be beneficial in carbon and low-alloy steels, and a manganese content of 0.7 – 1.3% Mn ensures that any sulphur present precipitates as MnS rather than as the Fe – FeS eutectic which increases the tendency to hot tear. In high alloy steels, austenitic 18/8 steels do not tear as severely as plain carbon or 13% Cr steels. As in the case of carbon steels, sulphur has the greatest adverse effect and manganese improves tear resistance.

Since hot tearing is caused by mechanical restraint preventing metal shrinkage occurring, casting design changes, such as use of adequate fillets at junctions, can be of great help. The minimum binder should be used in cores and moulds for any casting susceptible to the problem.

The above description of the melting and treatment of steel for casting is far from complete. For further details see W. J. Jackson and M. W. Hubbard (1979) *Steelmaking for Steelfounders*, Steel Castings Research and Trade Association, Sheffield. Thanks are due to Castings Technology International, 7 East Bank Road, Sheffield for permission to use data from this book and from *Steel Castings Design Properties and Applications* referred to above.

Ladle Practice

There are three types of ladle used for steel casting:

Lip pour

Teapot

Bottom pour

Lip Pour Ladles

In this type of ladle the metal is discharged over the lip; flow is controlled by tilting the ladle using a geared hand-wheel. Since the metal flows from the top of the ladle, the metal surface should be slag-free or a skimmer must be used to prevent slag entering the mould. The advantages of lip pouring ladles are that there are no narrow passages in which the metal can freeze so they are ideal for handling small quantities of metal. They are easy to prepare and are immediately ready for use. The disadvantage is that slag can easily be entrained in the metal stream.

Teapot Ladles

A refractory dam before the ladle lip ensures that metal is drawn from the bottom of the ladle so that the stream is slag-free. Deoxidation products have more time to float away from the area where metal is being withdrawn so the steel is generally cleaner than from a lip pour ladle. The disadvantage is that the narrow

‘spout’ may permit the liquid steel to freeze if the heat is tapped cold or pouring is prolonged.

With both lip pour and teapot ladles, it is only necessary to invert the ladle to remove all slag and metal ‘before refilling or reheating.

Bottom Pour Ladles

The ladle is fitted with a pouring nozzle in its base, closed by a refractory stopper rod. The metal is drawn from the bottom and is therefore slag-free and non-metallics such as deoxidation products are able to float out of the melt. The metal stream flows vertically downwards from the ladle so that there is no movement of the stream during pouring. The velocity and rate of flow change during pouring as the ferrostatic head changes.

Unless a re-usable system is fitted, the nozzle and stopper rod assembly must be changed after each use, thereby increasing the turn-round time, costs and the number of ladles required to handle a given output of metal. The stopper rod may also distort or erode making it impossible to shut off the stream completely. It is not practical to handle less than 100kg of steel due to the chilling effect of the stopper rod assembly.

Ladle Linings

The ideal lining is highly refractory, non-reactive with metal or slag and of low thermal conductivity and heat capacity. Fireclay is the traditionally used material either in the form of pre-fired bricks or as a plastic ramming grade. Brick linings must be installed by skilled personnel to ensure tight joints. Monolithic refractories are easier to install and eliminate the weak spots associated with bricks.

Although fireclay is the lowest cost refractory, it is possible to raise the level of as-cast quality considerably by using better lining materials. High alumina monolithic linings are popular because of their better refractoriness and their longer life.

Whether bricks, rammed monolithic refractories or castables are used, there is a long preparation and drying time needed. The KALTEK ladle lining system has been developed to overcome the problem.

The “Kalktek” Ladle Lining System

The KALTEK range of products are insulating, refractory ladle linings for steel, iron and non-ferrous applications. The low thermal mass and insulating properties of KALTEK linings eliminates the need for preheat in virtually all ladle sizes and with most alloys. KALTEK one-piece ladle linings are used for lip pouring in ladle sizes from 40 – 400kg. Larger ladles are lined with KALTEK boards segments and bottom boards designed to suit individual ladles. KALTEK boards and linings are supplied in silica-based refractory and also alumino-silicate for severe applications.

The ladle to be lined with a preformed one-piece lining must be free from holes. The KALTEK one-piece lining is fitted inside the shell with a minimum of 15mm backfill of coarse, dry, silica sand. The top exposed ring between lining and shell should be capped with a suitable mixture such as silicate bonded core sand and adequately vented with wire.

Larger ladles to be lined with KALTEK boards must first be stripped and then furnished with a permanent base lining of alumina or firebrick to act as a safety lining. The KALTEK segments and base boards are then carefully fitted inside the permanent lining, the joints between them being filled with KALSEAL refractory cement. The gap between the refractory and backing brick safety lining should be filled with coarse, dry, silica sand.

Initially, the concept of the KALTEK cold ladle lining system for steel foundries was based on single use of the disposable lining, but in some cases, more than one life is possible. With KADLTEK linings, there is:

No preheat.

Faster ladle turnaround.

- Better temperature control.
- Better working environment.
- Lower inclusion levels.

Pouring Steel Castings

Moulds for steel castings can be of green sand or one of the chemically bounded sands. Running systems have to be capable of withstanding the heat and erosive action of the metal stream. For large steel castings the whole of the running system may be made in refractory sleeves. For smaller castings the runner system may be coated with mould paint to reduce erosion. Unpressurised gating systems having a ratio sprue-runner-gate of 1:2:2 are frequently used to give rapid filling with low metal velocity to avoid erosion around the in gates. The introduction of ceramic foam filters for steel (STELEX filters) has changed the methods by which steel castings may be poured.

All steels contract during solidification and feeder heads are essential to avoid the formation of shrinkage cavities. The design of feeders for steel castings is dealt with in earlier chapters.

Non-Destructive Testing of Steel Castings

Many steel castings are used in critical situations such as nuclear installations, oil rigs, and chemical plant. The castings must be subjected to rigorous non-destructive testing before acceptance by the customer. This takes the form of testing for surface discontinuities and internal defects. The methods used include;

<i>Surface Inspection</i>	<i>Internal Inspection</i>
Visual examination	Radiography
Magnetic particle	Ultrasonics
Liquid penetrant	Pressure and leak testing

Radiographic Inspection

This is probably the most extensively used inspection technique. The data is only useful if it can be evaluated by reference to a particular set of standards. The ASTM reference radiographs provide a widely accepted method of classification of defects into a particular type and relative severity.

ASTM E446 refers to steel castings up to 2 inches in thickness

E186 2 – 4.5 inches in thickness

E280 4.5 – 12 inches in thickness

A skilled radiographer is essential in order to obtain consistent interpretation since classification of the severity of defects is subjective.

Nonferrous Casting

Introduction

There is a large and confusing range of casting alloys in use worldwide defined by the national specifications of the major industrial countries. Unfortunately there is little correspondence between the standard alloys used in different countries. A European Standard for aluminum casting alloys is under preparation but at the time of writing, has not been finalized. The various standards include alloys for general engineering purposes and alloys for aerospace applications. This section will deal mainly with general engineering castings, but the principles will apply equally to the aerospace alloys. Chapter 7 has tables with designation for nonferrous alloys.

Aluminum alloys can be cast by several processes:

Sand Casting: Chill casting, i.e. gravity die (permanent mould casting) or low pressure die casting, in a metal die using sand cores.

Pressure Diecasting: Investment casting or plaster moulding precision casting techniques may also be used for aerospace castings.

The casting alloys are designed to be cast by one or other of these techniques, although some alloys are suitable for more than one casting method.

The Effect of Alloying Elements

Silicon:

Pure aluminium is not suitable for casting and is only used for electrical applications (where high conductivity is essential), and a few other special applications. Most casting alloys contain silicon as the major alloying element. Silicon forms a eutectic with aluminium at 11.7% Si. Silicon additions improve casting characteristics by improving fluidity, feeding and hot tear resistance. The silicon-rich phase is hard, so the hardness of the alloys is increased with Si content but ductility and machinability are reduced.

Light Alloy Castings

Typical silicon levels of popular casting alloys are;

Low silicon	-	4-6% Si.
Medium silicon	-	7.5-9.5% Si.
Eutectic alloys	-	10-13% Si.
Special hypereutectic alloys	-	>16% Si.

The eutectic alloys have the highest fluidity for a given casting temperature, but having a short freezing range they solidify with primary shrinkage. They are good for thin section castings.

Where higher strength is needed, the lower silicon alloys are used. The hypereutectic alloys are difficult to machine and are used for wear-resistant applications such as pistons.

Copper: Improves strength, hardness, machinability and thermal conductivity. Heat treatment is most effective with 4-6% Cu alloys. Copper decreases castability and hot tear resistance together with corrosion resistance.

Magnesium: Small additions of 0.25-0.5% Mg allow Al-Si alloys to be hardened by heat treatment, improving mechanical properties through the precipitation of Mg_2Si in a finely dispersed form. Their proof stress can be almost doubled. Mg is used at levels of around 1% in high silicon piston alloys. Higher levels still, around 3-6% Mg, are used in low silicon alloys to improve the anodizing characteristics and give a bright surface finish for decorative components.

Magnesium content is kept low in pressure diecasting alloys to avoid embrittlement. The presence of magnesium increases the oxidation losses of liquid aluminium.

Iron: Over 1.0% Fe is used in diecasting alloys to prevent die sticking. High Fe contents decrease castability, ductility, shock resistance and machinability and most alloys are limited to less than 0.8% Fe.

Manganese: Improves casting soundness at levels over 0.5% Mn controls the intermetallic form of iron in the alloy, leading to improved ductility and shrinkage characteristics.

Nickel: When combined with copper, enhances strength and hardness at elevated temperature.

Zinc: When combined with copper and magnesium, heat treatment and natural ageing characteristics are improved. The fluidity is increased but shrinkage problems may occur.

Lead : Improves machinability at levels over 0.1%.

Titanium: Refines the grain structure when combined with boron.

Phosphorus: Refines the primary Si phase in hypereutectic alloys. In hypoeutectic alloys, low levels of phosphorus coarsen the eutectic structure and reduce the effect of Na and Sr eutectic modifiers.

Strontium: Levels of 0.008 – 0.04% Sr modify the Al-Si eutectic structure.

Sodium: Used to modify the eutectic structure.

Casting Alloys: The alloys fall into three groups, suitable for:

- Sand casting

- Chill casting (gravity and low pressure)

- Pressure diecasting.

Sand Casting: More alloys can be satisfactorily sand cast than can be cast in metal moulds.

- LM4 (Al – Si5Cu).

- LM25 (Al-Si7Mg).

- LM27 (Al-Si7Cu2Mn0.5).

- LM6 (Al-Si12)

- LM20 (Al-Si12Cu).

In some respects the eutectic silicon alloy LM6 is outstandingly good, but the need for modification treatment and the tendency to form shrinkage pipes reduce its advantages.

LM25 (Al-Si7Mg, A356) is now the most popular UK sand casting alloy and has the advantage of being heat treatable.

Chill Casting

The gravity and low pressure diecasting processes can use most of the sand casting alloys, but in the UK LM4 (Al-Si5Cu₃, US 319) is the most commonly used alloy. LM6 (Al-Si12, US A413) is particularly suitable for permanent moulds, having the advantage that modification treatment is less critical and may be unnecessary for thin walled castings. LM4 (Al-Si5Cu) and LM6 (Al-Si12) are used for applications such as manifolds. Where higher strength is needed, such as for cylinder head, LM25 (Al-Si7Mg) is used.

Pressure Diecasting

The mechanical properties of diecastings are influenced more by the casting process than the basic properties of the alloys used, so the alloys are chosen for their casting characteristics. The commonly used diecasting alloys contain around 8-10% Si and 2-3% Cu with around 1% Fe.

LM24 (Al-Si8Cu3.5) and LM2 (Al-Si10Cu2) are the most commonly used in the UK. The very similar Al-Si9Cu3(Fe) is used in other European countries and A380 in the US.

The higher Si alloys LM6 (Al-Si12) and LM20 (Al-Si12Cu) (European Al-SiCuFe and US A413) are used when better corrosion resistance is needed.

The Melting, Treatment and Casting of Aluminium Alloys

Molten aluminium, when exposed to air, immediately oxidizes forming a skin of Al₂O₃. This oxide causes problems during melting and also during casting since an oxide film can form, even as the metal is filling the mould, which can give rise to entrained oxide in the casting reducing the physical properties of the casting and possibly causing leaking castings. Fluxes are used to protect the metal from oxidation during melting.

Oxide inclusions in aluminium alloys are mainly of Al₂O₃ which has a density only 5% less than that of liquid aluminium so flotation of oxide inclusions takes

place slowly. For inclusion – free castings; it is advisable to use metal filters to clean the metal as it enters the mould.

The micro-structure and therefore the mechanical properties, of Al – Si alloys can be modified and improved by appropriate metal treatment. “Modifiers” and/or grain refiners are usually added to the alloy before casting.

Molten aluminium readily picks up hydrogen from the atmosphere or from moisture containing refractories. The solubility of hydrogen in solid aluminum is very low, so that as the alloy freezes hydrogen gas is expelled, causing micro-or macro-porosity in the casting. To achieve high integrity castings aluminium alloy melts must be degassed before casting.

Aluminium alloys contract on freezing so that, if sound casting are required, castings must be correctly fed. To avoid the above problems, great care must be taken at all stages of melting, treatment and casting of aluminium alloys.

Melting Aluminium Alloys

Large foundries usually melt aluminium alloy ingot and foundry returns in a bulk melting furnace, then transfer the metal to smaller holding furnaces near to the casting area. Degassing and metal treatment are usually carried out in the transfer ladle. The bulk melting furnaces can be coreless electric induction furnaces or more commonly, gas-fired reverberatory or shaft furnaces. The tilting crucible furnace, which may be electric or gas, is also popular. Holding furnaces may be electric or gas.

Higher thermal efficiency can be achieved in a tower or shaft furnace (Fig. 9.6).

Energy consumption of 580–640 kWh/tonne (20 - 22 therms/tonne) can be achieved with melting loss of 1–1.5% when melting 50/50 ingot/foundry returns.

The tilting crucible furnace (which may be gas-fired or electric resistance heated remains popular for batches of aluminium up to 700 kg. Containment in the

crucible helps to achieve a high melt quality and low melt loss, and alloy changes are readily carried out.

The low density of aluminium retards the “float-out” of oxide inclusions, and it is desirable to allow the liquid alloy to stand in tranquil conditions for several minutes under a protective flux to allow the non-metallics to float out before transferring to the casting or transfer ladle.

If the coreless induction furnace is used, the stirring effect of the electric current would cause fluxes to be entrained in the melt, so it is usual to melt without flux cover, then to switch off the current before adding the flux. Sufficient time must be allowed for the oxides to float out before transferring the metal.

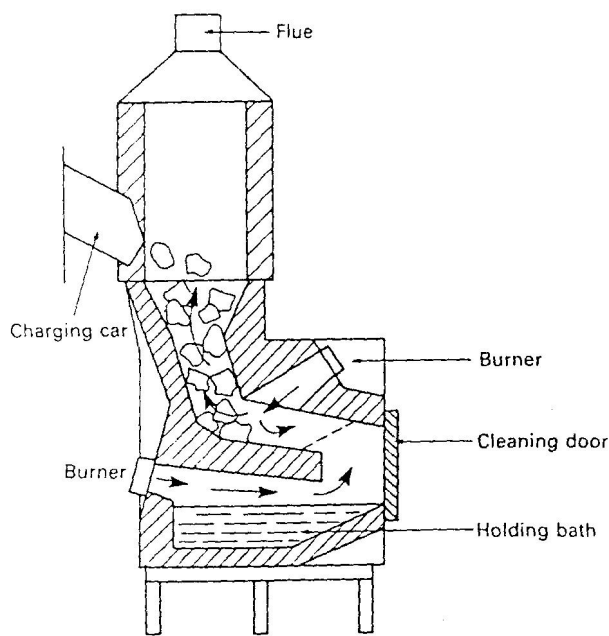


Figure 9.6: Tower or shaft furnace for melting aluminium. (From Aachwal, D. and Pennington, D. (1992) *Metal melting with natural gas, a review for ferrous and non-ferrous foundries*, *The Foundryman*, 85 51.)

Holding Furnaces

In pressure and gravity diecasting foundries, it is convenient to have a holding furnace adjacent to the diecasting machine in which metal is held at the correct temperature and from which it may be baled out to fill the die. They are frequently resistance heated crucible furnaces or radiant-roof bath furnaces (Fig. 9.7) in which high insulation allows low holding power to be achieved. Capacities are typically 250 or 500kg, although much larger holding furnaces are possible.

Crucible Furnaces

Smaller foundries frequently melt in the casting crucible itself, the crucible usually being heated in a "lift-out" furnace having electric resistance wire elements or silicon carbide rod-type elements. This type of melting is very flexible and is suitable for foundries which melt a range of different alloys. Degassing and metal treatment can be done in the crucible before it is removed for casting. Melt quality and temperature can be controlled well.

Ladles

Transfer ladles to convey metal from the bulk melter to the holding furnace may be electrically heated when very accurate temperature control is needed. More frequently, highly insulating ladle linings are used. In some foundries, molten metal is transferred by heated or highly insulated launders.

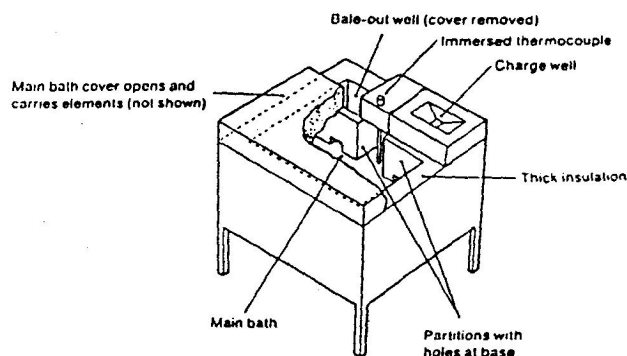


Figure 9.7: *Low energy bath furnace for holding aluminium. (From Atkins, R. and Crookes, W. (1992) Electric resistance -melting-and holding furnaces - type of elements, The Foundryman 85, 393).*

Fluxes

Chemical fluxes for aluminium have a number of functions:

- Covering fluxes which form a molten layer to protect the melt from oxidation and hydrogen pick-up drossing-off fluxes which agglomerate the oxides allowing easy removal from the surface of the melt.
- Cleaning fluxes which remove non-metallics from the melt by trapping the oxide particles as they float out.
- Fluxes which “modify” the alloy, by introducing sodium, improving its microstructure.
- Exothermic fluxes which ensure that aluminium liquid trapped in the dross layer is returned to the melt Fluxes for reclaiming swarf, skimmings and turnings, giving a high metal yield.
- Fluxes for the removal of oxide build-up from furnace; walls.

Some fluxes combine several of these functions. The Foseco range of COVERAL fluxes is designed to be used on a range of alloys in a variety of melting units. They are in powder form and supplied in bulk.

In general, the lower the melting point of the cover flux, the more efficient its use. Fluxes for aluminium contain chemicals such as chlorides and fluorides which may give rise to potentially harmful fumes on molten metal. Avoid inhalation of the fumes or dust. Used flux must be disposed of with care, referring to the Local Authority or a specialist disposal company for instructions.

Application of Coveral Fluxes

Covering and Protecting During Melting

Aluminium alloys containing up to 2% Mg are usually treated with dry Fluxes in crucible and induction melting and with liquid fluxes in reverberatory, shaft, rotary and large electric furnace melting. Sufficient COVERAL flux to form a cover (usually about 0.5—1% of the metal weight) is added, preferably in two stages, half early in the melting procedure and the remainder as soon as the charge is fully molten. The cover should be kept intact if possible until the melt is ready for degassing and grain refining.

Most fluxes contain sodium and it is possible for the metal to pick up as much as 0.001% Na from them. For most Al alloys the sodium has no effect or is beneficial, but alloys containing more than 2% Mg may become brittle with even trace amounts of sodium, so they are treated with one of the sodium-free fluxes. In the case of COVERAL 65 flux, approximately 0.5% of the product is put onto the solid charge and a further 2% sprinkled evenly over the surface when the alloy is fully molten. When the flux becomes pasty or liquid at about 750°C, the flux is worked well into the melt with a bell plunger for about 3 minutes. With the pre-fused COVERAL 33FF flux, the procedure is slightly different. 1% of the flux is placed in the bottom of the hot melting unit and the charge placed on top of it. When the metal is wholly melted, a further 3% of flux is spread evenly over the surface. When the flux becomes pasty (at about 700°C) it is worked well into the melt for about 3 minutes with a bell plunger.

Drossing-Off Before Pouring

The function of a drossing-off flux is to absorb oxides and non-metallic material, cleansing the metal and forming a good metal-free dross which can easily be removed.

In crucible furnaces, when drossing off is carried out, the crucible sides are scraped and the required quantity of the selected COVER flux (250 g is normally enough for the lift-out or bale-out furnace) is sprinkled onto the metal surface along with the existing flux cover and mixed into the surface of the melt until a red-glowing dross is obtained. This is exceptionally free of metal and can be removed with a perforated skimmer.

In reverberatory and shaft furnaces, the quantity of flux needed will depend on the cleanliness of the charge material and on the surface area of the metal. As a guide, it is recommended that an application of 1-2 kg/m² will suffice. The behaviour of the flux will indicate whether the dosage needs to be reduced or increased in future applications.

When the melt is ready for drossing-off, the flux is spread over the metal surface, allowed to stand for a few minutes until fused and then rabbled into the dross for several minutes with a skimmer. For best results the melt should preferably be above 700°C although fluxes will function well below 650°C. The furnace is then closed and the flame turned on for 10 minutes. This helps to activate the flux, heating the dross and giving good metal separation. The dross is then pulled to the door, allowed to drain and transferred to a dross bogie. If the dross in the bogie is raked, further metal will collect in the bottom.

Reclamation of Swarf, Skimmings and Turnings

A heel of metal is melted using heavy scrap or ingot and a quantity of COVER 48 or 52 flux is added to form a fluid cover. The amount of flux used depends on the degree of dirtiness and oxidation of the scrap and will vary between 1 and 5%. The swarf, turnings, etc. are fed through the flux cover a little at a time, adding more flux as required to keep the cover in a fluid condition. The temperature of the melt is kept relatively low during this procedure and, when charging is complete, the heat is raised to pouring temperature. At this stage the flux may be poured off from rotary

or reverberatory furnaces but there is a significant advantage to be obtained by passing more than one melt through the same flux.

Modifying Aluminium/Silicon Alloys

The metallurgical structure of alloys containing more than 9% Si is modified to increase ductility (some lower silicon alloys may also benefit from modification). This is done by the introduction of sodium using either NAME TAL or NAVAC sodium or COVERAL fluxes containing sodium salts (COVERAL 29A, 36A). The metal is melted down under COVERAL II flux and when the required temperature is reached, the melt is degassed and skimmed clean. The modifying flux is then sprinkled evenly over the metal surface and when pasty or fluid, is worked into the melt for about 3 minutes. After standing quietly for a further 5-10 minutes or until the pouring temperature is reached, the melt is drossed-off with COVERAL II flux and then skimmed.

COVERAL 29A flux is used at about 1.5% and a temperature of 790 - 800°C.

COVERAL 36A flux is used at about 30% and a temperature of 740 - 750°C.

Degassing Aluminium Melts

Hydrogen Gas Pick-Up

Hydrogen has a high solubility in liquid aluminium which increases with melt temperature, but the solubility in solid aluminium is very low, so that as the alloy freezes, hydrogen gas is expelled forming gas pores in the casting. The hydrogen in molten metal comes from a number of sources:

- i. Water vapour in the atmosphere.
- ii. Water vapour from burner fuels.
- iii. Damp refractories and crucible linings.
- iv. Damp fluxes.
- v. Oily or dirty scrap charges.

vi. Dirty or damp foundry tools.

To reduce hydrogen pick-up, refractories, crucibles, tools and oily scrap should be thoroughly pre-heated to remove water. Burner flames should be slightly oxidising to avoid excess hydrogen in the products of combustion. The melt temperature should be kept as low as possible since more hydrogen is dissolved at high temperature. Whatever precautions are taken, however, hydrogen will still be present.

The amount of porosity that can be tolerated in a casting is determined by the method of casting and the end use of the component. If the metal cools relatively slowly, as in a sand mould, the ejected gas can build up into small bubbles which are trapped in the pasty metal. These are then uncovered by any subsequent machining or polishing operation and show as a “pinhole” porosity defect in the finished surface. The mechanical strength and pressure tightness can also be seriously affected.

Where the rate of solidification is more rapid as in gravity and low pressure diecasting the emerging bubbles are usually small and well dispersed. They therefore affect mechanical properties less, and indeed often have a beneficial effect in offsetting possible localised shrinkage unsoundness that might otherwise cause the casting to be scrapped. For high integrity gravity and low pressure castings, it may still be necessary to apply a full degassing process.

It is not usual to degas metal for pressure diecastings, which usually contain gas porosity from air entrapped in the casting during metal injection and additional porosity from hydrogen may not be serious, particularly since the metal holding temperature for pressure diecasting is usually low, reducing the amount of gas pick-up.

Degassing Aluminium Alloys

The maximum concentration of dissolved hydrogen possible in aluminium alloys can be as high as 0.6 ml H₂/ 100g. By careful attention to melting practice this

can be reduced but even with the best practice, remelted foundry alloys may be expected to contain 0.2-0.3 ml H₂/100g Al.

The degassing process involves bubbling dry, inert gases through the melt to reduce the hydrogen level to around 0.1ml /100g. The liquid and solid solubilities of hydrogen are different in different alloy systems and a hydrogen level of 0.12ml/100g will make castings free from porosity in LM4 (Al-Si5Cu3Mn0.5) while the low silicon Al—Cu—Ni alloy BSL119 will be porosity-free at 0.32mL H₂/100g. If levels of hydrogen are taken too down, it is difficult to avoid some shrinkage porosity.

For many years, the use of chlorine gas, developed by plunging hexachloroethane in the form of DEGASER tablets, was the standard method of treatment. This can produce harmful fumes and the technique is being replaced in many foundries by degassing using a rotary impeller which disperses fine bubbles of dry nitrogen or argon through the melt.

Grain-Refinement of Aluminium Alloys

Grain-refining improves hot-tear resistance, reduces the harmful effects of gas porosity (giving pressure-tight castings) and redistributes shrinkage porosity in aluminium alloys. The grain size of a cast alloy is dependent on the number of nuclei present in the liquid metal as it begins to solidify and on the rate of undercooling. A faster cooling rate generally promotes a smaller grain size.

Additions of certain elements to aluminium alloy melts can provide nuclei for grain growth. Titanium, particularly in association with boron, has a powerful nucleating effect and is the most commonly used grain refiner. Titanium alone, added at the rate of 0.02 – 0.15%, as a master alloy can be used but the effect fades within 40 minutes. The addition of boron together with titanium produces finer grains and reduces fade. Titanium and boron additions may be added as a flux or as a master alloy.

Refinement of Hypereutectic Alloys

Al – Si alloys containing over 12% Si are used for their wear resistance and it is important for consistent casting properties that primary silicon is evenly dispersed throughout the casting. With long solidification ranges, growth and flotation of primary silicon particles may occur. Large silicon particles are detrimental to castability machinability and mechanical properties. Refinement of the structure is therefore desirable.

Hypereutectic alloys are refined with phosphorus additions of 0.003 – 0.015%. The aluminium phosphide formed provides nucleation sites for primary silicon ensuring a fine dispersal of silicon in the eutectic matrix. Phosphorus can be conveniently added in the form of NUCLEANT 10 or 120 tablets.

The melt should be brought to between 730 and 750°C and the power reduced. When the temperature of the metal is falling the correct amount of NUCLEANT tablets are plunged using a perforated bell plunger coated with FIRIT coating. This procedure may be carried out in one or more stages. When all turbulence has ceased, the metal is stirred thoroughly, drossed-off and poured. It is important to have as low a sodium content in the metal as possible, otherwise it will combine with the phosphorus. Sodium can be removed from the melt by degassing with hexachloroethane degassers. Therefore it is wise to degas the melt with DEGASER tablets before treatment with NUCLEANT 10 or 120 flux. Degassing with inert gases in a rotary degassing unit does not remove residual sodium.

NUCLEANT 120 flux contains copper, so the alloys treated should be tolerant of a small increase in copper content. The copper specifications for hypereutectic alloys are fairly wide so problems do not usually occur.

FOSPERL TiB 5/1 grain refiner is a master alloy containing titanium and boron in the ratio 5:1 which has the optimum effect. FOSPERL grain refiner is supplied in the form of “piglets” each weighing 200g which dissolve quickly and completely in the melt. They are added to the melt by plunging usually prior to degassing, though if degassing is carried out by means of a rotary degassing unit.

The FOSPERL grain refiner may be conveniently placed in the plunging cage of the unit allowing grain refinement and degassing to take place simultaneously. Solution is complete in about 3 minutes. Any increase in hydrogen content caused by the addition of FOSPERL piglets will be removed at once by the rotary degassing or by the subsequent degassing if the grain refiner was added by hand.

Normally one 200g piglet is used per 150 kg of metal. For treatment in a rotary degasser, normal degassing temperature is used. For hand addition by plunging, use a temperature 20 -30°C above the intended degassing temperature so that when grain refinement and degassing are completed, the bath temperature is at the level required for casting.

Modification of Aluminium Alloys

The composition of the alloy and the choice of casting process affects the microstructure of the aluminium alloy castings. The microstructure can also be changed by the addition of certain elements to aluminium - silicon alloys which improve castability, mechanical properties and machinability.

Sand cast and gravity diecast (permanent mould) alloys cool relatively slowly, resulting in a coarse lamellar eutectic plate structure which is detrimental to the strength of the castings. Changing the chemical composition to alter the microstructure is called "modification". The addition of sodium or strontium modifies the cast microstructures to give finely dispersed eutectic fibres and the coarse crystalline fracture of the alloy is refined to a fine, silky texture. These changes are accompanied by a considerable improvement in the mechanical properties of the alloy.

Pressure diecastings are rapidly cooled in the mould giving small grain size with a fine eutectic structure with small dendrites. Modification of pressure-diecast microstructures is also possible and the lamellar eutectic silicon will be changed to a fine fibre structure.

Modification increases hot tear resistance and alloy feeding characteristics, decreasing shrinkage porosity.

Eutectic Silicon Alloys, 12% Si

The alloys should be melted under a covering/drossing flux. Grain refinement benefits heavy section castings and the eutectic alloys benefit greatly from modification.

Crucible Melting (Using Degaser Tablets and Sodium Modification)

1. Melt under COVERAL II flux, about 250g per 50kg of metal (0.5%). Continue charging until the melt is complete, maintaining a complete flux cover. Do not exceed 750°C.
2. DEGASER 90 tablets (which grain refine as well as degas) should be plunged, using about 0.3% (150g for 50 kg metal), holding down until bubbling has ceased, usually 2 - 3 minutes. Additional grain refinement can be carried out by plunging NUCLEANT 2 tablets (125 g/50 kg melt) before the degassing treatment.
3. With the temperature between 720 and 740°C, modify the alloy by plunging a NAVAC unit (one NAVAC 25 unit for 50kg metal). When the reaction has subsided, raise and lower the plunger to stir the melt without breaking the surface.
4. Add more COVERAL II flux (250 g/50kg metal) and allow the melt to stand for 5 - 10 minutes. Rabble the flux into the surface of the melt until a red glowing dross is obtained, signifying that the exothermic reaction has freed the dross from metal. Skim cleanly and pour without delay.

Treatment of Hypereutectic Al—Si Alloys (Over 16% Si)

These are wear-resistant alloys used for pistons and unlined cylinder blocks. They may be sand, chill or pressure cast. Grain refinement is necessary to improve

castability and machinability. Hypereutectic alloys must be refined with phosphorus. Melting must be under a sodium-free flux, since sodium prevents the refining action of phosphorus. Degassing is necessary but modification with sodium or strontium is not used.

Melting Practice

1. Melt under COVERAL 65 sodium-free flux, adding 0.5% with the charge and a further 0.5% when molten.
2. Bring the melt to 780° and plunge NUCLEANT 120 (0.4%) tablets, dross off.
3. Degas with the rotary degasser (the use of DEGASE tablets is likely to deplete the phosphorus but if the rotary degasser is not available, then DEGASER 400 tablets can be used, but prolonged degassing should be avoided).
4. Skim the metal clean before use.

The casting temperature for these alloys is high, around 750 – 760°C.

Melting and treatment of aluminium—magnesium alloys (4–6% Mg)

These alloys oxidise rapidly during melting and also pick up hydrogen readily. Traces of sodium are harmful and sodium-free fluxes should be used. Grain refinement is necessary.

Crucible Melting

1. Heat the crucible and charge the solid metal dusted with a generous quantity of COVERAL 65 flux (250 g for 50 kg of metal) and melt rapidly.
2. At a temperature of around 600°C, when the metal is pasty, add a further quantity of COVERAL 65 flux (1kg for 50kg of metal).
3. Without exceeding 750 C, stir the fluid flux into the melt using a skimmer or plunger to contact the flux as much as possible with the metal.

4. Degas and grain refine with DEGASER 190 tablets (0.3%), or use DEGASER 400 tablets together with NUCLEANT 2 (0.25%).
5. Dross-off by sprinkling COVERAL 66 flux (250g per 50kg of metal) and leaving for 5 minutes.
6. Rabble into the surface to start the exotherm and skim off the powdery dross.
If the MDU is available, degas and grain refine using FOSPERL TiB 5/1 piglets or by plunging NUCLEANT 2 tablets before degassing.

Casting temperature is typically 700°C. A metal—mould reaction may occur in green sand moulds if an inhibitor such as boric acid was incorporated in the sand. With chemically bonded sand moulds and cores, a suitable coating such as MOLDCOTE 41 coating may be used instead of an inhibitor.

Magnesium Casting

Magnesium alloy castings are used for aerospace, automotive and electronic applications. Their main advantage is their light weight, typical magnesium alloys having a density of 1.8 g/ml compared with 2.70 g/ml for aluminium alloys. Aluminium is the principal alloying constituent of magnesium-based casting alloys with zinc and manganese also present in small amounts. Pressure diecasting is the most commonly used casting process and because of the low casting temperature (650-700°C), hot chamber diecasting machines can be used. Magnesium diecastings can be made with thinner walls than aluminium, allowing the overall weight of components to be substantially reduced and compensating for the higher alloy cost per kilogram. Gravity diecasting and sand casting are also used, particularly for more highly stressed castings. The use of high purity alloys with low levels of Fe, Ni and Cu improves corrosion resistance, allowing their use in automotive applications exposed to road salt.

The most commonly used casting alloys (using the ASTM designation, which is frequently used) are:

Alloy	Characteristics	Typical Uses
AZ91	The most common alloys for pressure and gravity die and sand casting	Housings, covers, brackets, chain saw parts, hand tools, computer parts, etc.
AZ81		
AM50	Both alloys combine strength,	Seat frames, instrument panels, brackets, wheels.
AM60	ductility, castability and cold workability	Automotive safety parts.
AM20	Used for pressure diecastings where high ductility and impact strength are required	

The Melting, Treatment and Casting of Magnesium Alloys

Molten magnesium alloys attack firebrick and refractory furnace linings resulting in harmful silicon contamination for this reason, steel crucibles, pressed or cast, are used. Iron is also slightly soluble in magnesium alloys but it has a much less harmful effect than silicon. Scrap should be cleaned and if possible shot blasted to remove adhering sand as a further precaution against silicon pick-up. To eliminate ladling, the molten alloy should, if possible, be poured direct from the melting pot.

Magnesium alloys must be melted under covering and cleansing fluxes, to avoid oxidation losses and to remove inclusions. Inhibitor powders should be used to cover exposed metal during holding and pouring, and added to moulding sand to prevent chemical reaction. Magnesium alloys benefit from grain refinement which is

carried out by inoculating with carbonaceous material, usually in the form of hexachloroethane.

REVIEW QUESTIONS FOR CHAPTER NINE

1. starting metal for any deformation work is a regular type of casting termed ingot.

Explain ingot casting

2. What are the considerations under steel casting?

3. In which ways can steel be killed?

4. List the types of cast iron that you know

5. What is the relationship between composition, strength, and structure of grey cast iron.

6. Write on the production of grey cast iron

7. Explain the role of some alloying elements in cast iron production

8. In which furnaces can cast iron be melted?

9. Write briefly on cupola furnace

10. What is the difference between CEV and CEL?

11. What is specific coke consumption (SSC)?

12. Write on inoculation of grey cast iron

13. Write on ladle lining

14. Write comprehensively on adding alloy additions in the ladle

15. How do you produce ductile cast iron?

16. What is magnesium recovery?

17. Write briefly on magnesium treatment of cast iron to produce ductile cast iron

18. How do you produce Austempered ductile iron?

19. Compare casting ductile iron with grey iron

20. Write on the following: malleable iron, white heart malleable and blackheart malleable iron.

21. Write on production of compacted graphite iron, list some applications of compacted graphite iron.
22. Write on steel casting and types of steel
23. Write on melting and treatment of steel for casting.
24. Write on pouring steel castings
25. Mention some nondestructive testing techniques for steel castings
26. List and explain some of the processes that can be used for casting aluminium alloys
27. List and explain the effects of some alloying elements in aluminium casting
28. Mention some aluminium alloys that can be cast using chill casting, pressure diecasting, and sand casting
29. Write on melting, treatment and casting of aluminium alloys.
30. What are the functions of fluxes used for aluminium production?
31. Write on the application of coverall fluxes.
32. Write on reclamation of swarf, skimmings, and turnings.
33. Write on modifying aluminium/silicon alloys
34. What are the sources of hydrogen in molten aluminium?
35. Write on degassing, and grain refinement of aluminium alloys
36. Explain how degaser tablet and sodium modification is handled in crucible melting
37. Write on melting and treatment of aluminium-magnesium alloys (4-6%Mg)
38. Write on magnesium casting process.

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CHAPTER TEN

DEFECTS IN CASTING

The General Origin of the Defects

The general origin of defects in castings are as follows:

1. Casting design
2. The technique of manufacture
3. Application of the technique

Defects are classified as follows:

1. Shaping faults arising in pouring
2. Inclusions and sand defects
3. Gas defects
4. Shrinkage defects due to volume contraction in the liquid and during solidification
5. Contraction defects occurring mainly or wholly after solidification
6. Dimensional errors
7. Compositional errors and segregation

1. Shaping Faults Arising in Pouring

- a) Cold Shot: this is a defect in which a discontinuity is formed due to imperfect fusion of two streams of metals in the mould cavity and this defect may appear as a crack or a seam with smooth edges.
- b) Misrun or shotrun : is a defect that occurs due to incomplete solidification and is due to the failure of metal to fill the entire mould cavity. The reasons for shotrun or misrun may be too thin sections and wall thickness improper gating systems, damaged patterns, slow and intermittent pouring poor fluidity of metal cause by low pouring temperature and improper alloy composition.

Elimination of the Problem

Special gating techniques, high super heat and these are the principal aids to the shape outline of the mould to be completely filled.

2. Inclusions and Sand Defects

(a) Inclusions

They can be divided into two main groups which are

- (i) Indigenous or indogeneous inclusions
- (ii) Exogeneous inclusions

Indigenous inclusions are those that are relatively small particles which remain suspended in the alloy at the time of pouring or which may be precipitated due to changes in solubility on cooling.

Exogeneous inclusions are those which result from entrapment of nonmetallic during pouring this may vary in size and type. They include dross, slags and flux residues formed and separated in the melting furnace but carried over with the metal stream other sources are from ladles and furnace lining a further group originate from the mould itself they include the moulding material, the sludge during closing and pouring.

Exogeneous inclusions tend to concentrate on the upper surfaces and adjacent to the ingates. An important method of reducing inclusions is allowing the molten metal to stand in the furnace or ladle for an interval before casting this reduces the total content though the elimination of the smallest inclusion is impossible. Very low inclusion in light alloys can be achieved by filtration through a porous bed or granular material before casting, some of the materials that have been used include Al_2O_3 , Chamotte, quartz, fluorspar, magnesite, they have been employed as constituents of the filter bed.

For exogeneous inclusion the use of fine sand, filler, hard ramming, mould paints, they can all prevent erosion. A useful method against surface fragility is the spraying of mould surfaces with water or dilute solution of molasses. In the design of the gating system, it should be such that the impingement of metal against mould and core surfaces must embody smooth curves rather than ϵ Massive ; and the abrupt changes in direction.

Sand Inclusion

Can originate from loose material in the mould cavity so careful closing is essential mould materials can also be eroded during pouring, leading to either massive inclusion.

- (i) Erosion scabs: these defects are associated with major inclusions. Erosion scab is a rough projection formed on the casting where sand has been

- washed from the mould wall although the scab itself can be removed by fettling its presence implies wide sprayed inclusion in the cast
- (ii) **Mould crush:** occurs when a mold is close over an unfitting core or badly finished joint surface when the boxes are assembled and clamped the pressure shears a section from the edge of mould cavity providing a large inclusion and a corresponding projection on the casting. The defect can be avoided by careful maintenance of pattern equipment to eliminate distortions and the need for manual parching.
 - (iii) **Expansion defects:** this results from partial or incomplete spalling of a section of mould phase and penetration of liquid metal behind the surface layer of sand. The defect is seen as irregular metal scab which can be removed to expose the under lined. Sand trapped within the casting. In some cases the expansion is insufficient to bring about spalling and metal penetrates but burging and shearing cracking of the mould face produce a surface fissure or line defects known as rat tail. In these case the casting surface shows either a step or shallow indentation along the path of the incipient mould failure often with a short metal fin representing the original crack. Expansion defect is associated with siliceous material with slow high expansion on heating to relatively low temperatures during pouring the upper surfaces of the mould are subject to intense radiation from the rising liquid metal so that the surface layer of sand can reach the transformation temperature before being submerged. The expansion of the mould face setup compressive stress causing the surface successively to burg, crack, pill, spall, allowing metal to penetrate behind the original surface alternatively the sand expanse and shears along a plane of an edge close to a zone of intense heating.

Remedy to Expansion Problem

Additions to counter expansion include wood flour, coal dust and other organic material, which soften or decompose to cushion the sand grains. Cereal binders such as starch dextrin exercise similar effect. Approximate additions of 0.5% been frequently made to clay bonded sand for the purpose. The incidence of expansion defects is found to be greatest in the case of uniformly graded sand while in a widely distributed sand the smaller grains will attain the transformation temperature at a earlier stage and the sand will undergo its major expansion over along interval of time. A radical solution to persistent scabbing can be solved by a change to other moulding materials e.g. nonsiliceous materials e.g. zircon sand.

Surface Roughness and Sand Adherence

The ideal mould will possess a smooth impervious surface capable of being faithfully reproduced in casting this situation is closely approached with alloys of low melting point but at high temperatures surface roughness and sound adhesion can be encounter with lost of appearance and increase dressing cost. In the worst cases the moulding material becomes impregnated with metals to form a solid mass this can be difficult to remove and if the condition occurs in a confined pocket the casting itself may be scrapped since metal flow depend on superheat a low temperature minimized surface

roughness and sand adherence. Surface quality is directly influenced by the mould material and finish. The predominant characteristics been the initial porosity penetration is thus directly related to permeability. Low porosity can be achieved with either low grain size, continuous grading or the use of powdered filler materials. However, mould coatings or facings enable surface porosity to be reduced without sacrificing the qualities required in the bulk material carboneous dressing containing volatile matter are also held to improve casting surfaces by creating a back pressure opposing penetration.

Gas Defects

Gases may be present in castings, in solution as chemical compounds or as included cavities the gas may result from entrapment of air during pouring from evolution on contact between liquid metal and mould material or may be precipitated during solidification as a result of either chemical reaction or of change in solubility with temperature. The defects take the form of internal blow holes, surface blows, air locks, surface or subcutaneous pin holes or intergranular cavities depending on the immediate cause. The causes of gas defects may be considered into two main groups: those caused by physical entrapment during pouring or those resulting from precipitation by the metal on cooling.

Entrapment Defect/ Retention of Mould Gases: Air may be trapped within a particular casting during excessive turbulence or aspiration in pouring is combined with a metal of little superheat. Bubble may then be unable to escape before partial freezing of the casting. Defects may also result from failure of the mould to exhaust air displaced by the liquid metal as when a confined mould pocket is filled at a faster rate than the venting system and mould permeability can be sustained. The cushioning effect of the entrapped air delays air long enough for solidification to prevent further flow into the recess. This produces an air lock defect in upward facing projections confined air in mould pockets and cores is also capable of expanding sufficiently to blow back through the metal and produce internal cavities in extreme cases metal can be ejected from the mould, penetration depends on effective venting of the mould cavity vent for mould pockets and cores need to be of the whistler type communicating directly with the outside atmosphere and must be large enough to sustain high rate of gas flow.

Precipitation Defect /Gases Evolved by the Metal

The second type of defect is cause by precipitation of gases from the metal on cooling. The gases may have been dissolved during melting, as a result of interaction between liquid metal and mould surface or result from reaction between liquid elements in solution the gas most frequently precipitated as a single element is hydrogen which is soluble in most casting alloys. Nitrogen can behave similarly in iron and steel, but is virtually insoluble in the principal nonferrous casting alloys for which it can be employed as a scavenging gas. Oxygen is not precipitated directly tending to form stable oxides with metals. Where appreciable solubility exist the element can play a major role in reaction porosity through the precipitation of compound gases mainly carbonmonoxide and H₂O (Steam) formed in combination with other solute. Other sources of mould gas are moisture and volatile organic compounds in moulding mixtures excessive moisture in green sand and under baked or damped cores are common causes of gas cavities especially when associated with low permeability and inadequate venting surface blows and pinholes can result from pellets of unlimited clay from oxidized metals, shut in reclaimed sand from improperly dried mould coating, from porous

chills and from condensation or rust on chills and chaplets. Precautions are principally to reduce gas forming substances present in the mould while ensuring adequate permeability and venting.

The Origin of Gases

The solubility of a gas in a liquid metal is a function of the external pressure in accordance with sieverts law which states that the solubility of a gas in a liquid metal at constant temperature is proportional to the square root of the external partial pressure. Molten metals will thus absorb gaseous element from atmosphere from which they are in contact with up to a level determined by the gas metal equilibrium. By the same principle gas is evolved from a solution in contact with a gas free atmosphere surface absorption or adsorption is an essential step in such a transfer the rate depends on the degree of mixing in the liquid and the presence or absence of stable surface films or oxides which reduce the number of sites for adsorption and so diminish the rate of transfer of other gases. Solubility increases with temperature. Gaseous elements can also be absorb by dissociation of compound gases on contact with metal e.g water vapour present in normal atmosphere and formed by fuel combustion and by evaporation from furnace additions and mould. Hydrogen absorption occurs more readily through this type of reaction than from an atmosphere of molecular hydrogen. Depending on the composition of melt the oxygen either dissolves in the alloy or combined with its reactive component to form a stable oxide phase the most significant factor in relation to precipitation defect is the relative solubility in the liquid and solid alloys. Very low solid solubility can lead to porosity even with low initial gas contact hence the case in hydrogen in aluminum and therefore the special susceptibility of this metal and its alloys to gas porosity.

Prevention of Gas Defects

The most effective method of gas defect prevention is low gas content in the metal when being poured this can be achieved in some cases by careful design of melting techniques in other cases the molten metal may be degas in a separate operation.

Melting Precautions: gas free charge, contaminated materials are separately processed to remove the gas the gas defects can be eliminated by careful design of melting techniques and in other cases you may need to degas.

Vacuum Melting: can prevent gases from being absorbed in the molten metal

Degasing: gas absorbed can be reduced by precautions in material selection and melting it is difficult to avoid the presence of some gas at melt out under routine foundry conditions, can be eliminated by various method of gas degassing one of the effective method uses flushing or scavenging e.g (aluminum alloys) gas which bubble through the melt provides a large gas metal interface e.g. gases used are argon, nitrogen, chlorine. Chlorine can be generated within the melt through the decomposition of unstable compounds such as hexachloroethane tablets of the compound are then plunged into the melt and controlled amount of chlorine are liberated scavenging gas is also performed by the oxygen injected for removal of carbon and other elements in steel making.

Contraction Defects

The cooling of cast metal from the solidus to run temperature is accompanied by considerable contraction unlike the liquid and solidification shrinkage which can be compensated by an influx of

liquid, solid contraction affects all linear dimensions of the casting and hence the need for standard pattern allowances in accordance with the expected contraction behavior of the alloy.

Hot Tears or Pulls: are internal or external ragged discontinuities or cracks on the casting surface caused by hindered contraction occurring immediately after the metal have solidified. They may be produced when the casting is poorly designed and abrupt sectional changes take place. No proper fillets and corner radii are provided and chills are inappropriately placed. Hot tears may be also be cause when the mould and core have poor collapsibility and when the ramming is too hard and the casting is therefore under severe strain during cooling incorrect pouring temperature, improper placements of gates and risers can also create hot tears. Methods to prevent hot tears may entail improving the casting design achieving directional solidification and even rate of cooling all over. Selecting the proper mould material to suit the cast metal and controlling the mould hardness in relation to other ingredients of sand.

Dimensional Errors

Dimensions of castings are subject to variation from minor changes in production conditions within the limits of normal working practice. Errors can occur from faults in equipment and practice, such as occur in pattern making, moulding, casting, and fettling. Most dimensional errors occur during moulding or in casting and the principal causes are misalignment of mould parts and errors mould distortion, anomalous distortion and contraction in cooling. Most gross dimensional errors except those originating from contraction anomalies can be eliminated with adequate equipment and workmanship.

Compositional Errors and Segregation

Most compositional errors arise from simple causes for example melting losses of reactive element or the use of incorrect furnace charges such errors can be avoided by careful melting practices, but segregation presents different problems.

Segregation : is a term used to describe compositional differences arising during solidification and persisting in some cases as a permanent feature of the cast structure in differential freezing , the solute concentration in the solid at any stage in the solute during freezing differs from that in the residual liquid since equilibrium and homogeneity requires a prolong time at temperature high enough for diffusion, differences arising in freezing persist in the solidified casting segregation may occur with respect to either alloying or impurity elements the final pattern been either as a compositional gradient in a single phase or as local concentration of a second phase the inherent segregation tendency in an alloy can be represented by the equilibrium distribution coefficient K , $K < 1$. For solute which lower the freezing point. $K > 1$ where the freezing point is raised. Major deviations from unity tends to produce high local concentration of certain impurities even though they may be present only in small amounts in the parent solution and may cause the precipitation of a second phase which may find no place in the equilibrium structure constitutional factors which produce strong segregational tendencies are long-freezing range gentle liquidus slope, and low solute solubility. The degree and pattern of solubility depends on solidification condition in casting including cooling rate, the mode of development of the grain structure, and motion of crystals and residual liquid under various forces. Segregation occurs in two types of distribution

It may be on microscale extending over dimensions of the order of a single grain or less (microsegregation) or they may be zonal segregation between one part of a casting and another this is macrosegregation. One of the ways of removing of segregation is by homogenisation

Defects due to Wall Movement

These defects affect the dimensions of the casting. The production of a mould with the object of reducing mould wall movement requires an assessment of the effects of common variables (bulk density, hardness, moisture, clay content, etc) in a green sand mould. Mould compaction, i.e., density of mould influences all the the mechanical properties of the moulding sand. While a mould with low rigidity produces an oversized casting, the hard mould results in casting of reduced size.

Mould movement is a general phenomenon applying to all clay-bonded natural and synthetic green sands and occurs with all types of cast iron, grey flake graphite, white and malleable irons. The mould wall movement can be reduced by controlling moulding sand composition, i.e. clay content, water, and mould additives (carbonaceous additives and wood flour).

REVIEW QUESTIONS FOR CHAPTER TEN

1. What are the general origin of defects in castings?
2. How are defects classified?
3. Explain some types of defects and their remedies
4. Write on gas defects in castings
5. Write on the prevention of gas defects
6. Write on defects due to wall movement and how they can be controlled.

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CHAPTER ELEVEN

FINISHING OPERATIONS OR FETTLING / CLEANING OF CASTINGS

Much of the remaining work in producing the finished casting is carried out in the fettling shop. Basic requirements are initial cleaning for removal of adhering sand and core residues, separation of feeder heads and runners, and final dressing to eliminate flash and excess metal. Integrated with these operations are heat treatment, rectification and inspection procedures, for which there is no rigid sequence. According to Jain (2009), castings require cleaning and trimming before passing them on for machining, or other operations. Fettling is not a precision operation like machining. Its purpose is to remove all unnecessary metal, and the production of a reasonably smooth finish. Generally, the higher the metal melting point, the greater the surface roughness of the castings. Thus the heavier castings in grey and malleable cast iron and cast steel call for the most work in fettling.

This chapter focuses on the characteristics of fettling equipment and methods, and it should be emphasized at the outset that the task is profoundly influenced by the techniques used in moulding and casting, for example the positioning of gates and feeder heads, and by the degree of surface smoothness and freedom from sand adhesion. Such qualities can contribute both to low costs and to good working conditions in the fettling shop.

Initial Cleaning

The main mass of moulding materials is normally removed at the knockout station, whether manually or mechanically, the separated material being returned to the system. This rough cleaning may need to be continued in the fettling shop, particularly for the heaviest castings or those with confined internal cavities: the residual sand is loosened with crowbars or pneumatic picks. Castings are then subjected to a general cleaning operation, most commonly shotblasting; alternative treatments include, hydraulic and chemical cleaning. These operations may in some cases be performed or repeated at a later stage, for example after head removal, fettling and heat treatment, to give the final finish. Method of sand removal is dependent on the size of the casting and the intricacy of the casting.

Shotblasting

Blast cleaning is accomplished by streams of dry abrasive particles energized either by compressed air or high speed centrifugal impeller to impinge on the work. Various designs of pneumatic system can be used, but the highest efficiency for heavy duty operations is achieved by the mechanically energized system. Shot velocities of the order of 16 000 ft/min ($\approx 80\text{m/s}$) are attained in commercial equipment. The nature of the abrasive is an important factor both in cost and surface finish. The least expensive material is chilled iron grit, but this is subject to loss by fragmentation: a greater rate of replenishment is therefore required than, for example, in the case of the more expensive steel shot. The economics of selection depend also upon the extent of direct loss of unchanged abrasive. The relative merits of various abrasives with respect to cleaning rate, attrition loss and impeller wear are shown in Table 11.1. Under pneumatic-type shot blasting machine, a stream of shot falls into a chamber through which compressed air at pressure of 1.5 to 2 kg/cm² for grey iron and non-ferrous castings, and upto 6 kg/cm² for cast steel is passed. The shoot and dislodged material then fall on perforated floor of the cleaning machine. Sand and shots are then separated by a screen and suction dust extraction system.

Table 11.1 Relative Performance of Abrasives

Abrasive	Cleaning rate	Relative addition rate	Wheel wear	Order of price
Cut wire pellets	1	1	1	1 (high)
Steel shot	1	1.5	1	2
Malleable iron grit	1.5	7.5	1	3
Chilled iron grit	2	15	10	4 (low)

Source: Beeley, 1982.

Since abrasive cleaning involves interchange of molecules between the abrasive particles and the abraded surface, non-metallic abrasives such as slag, alumina and silicon carbide need to be used in certain cases to avoid contamination with iron: they are also used to obtain a fine finish on soft alloys and very small components. Compressed air rather than mechanical equipment is used for these purposes. If design is more intricate, it takes longer to remove cores and wire reinforcements. Although a wide range of castings are made in green sand moulds, cores are more usually dried. Dried sand, if artificially bonded, does not break easily. On the other hand in such cases casting surfaces require little cleaning once the sand is removed. Cleaning by picks and bars alone becomes very laborious in case of intricate castings. Pneumatic picks are, therefore, used to some extent. But these are heavy and considerable dust is created by their exhaust. Water sprays in conjunction with pneumatic pick eliminate the dust problem.

Numerous designs of shotblast equipment are employed. Heavy castings are normally processed in a fixed chamber, the shot nozzle being either manipulated directly by the operator, clad in a protective suit, or remotely controlled from outside. A similar principle is embodied in the glove box cabinet units used at the opposite end of the scale for the blast cleaning of extremely small castings. Castings of a wide range of intermediate sizes, including machine moulded mass produced

components, are processed automatically in either of two basic types of plant. Castings can be supported on a turntable or suspended from a pendulum conveyor within a fixed chamber or cabinet, the shot stream being traversed to obtain complete coverage of the exposed surfaces. Alternatively the load can be tumbled in the shot stream through continuous rotation of the chamber itself about a horizontal axis.

Automatic shotblast plants are capable of high production rates, although abrasive wear of parts can involve high operating costs: in this respect it is particularly important to maintain full loading of the abrasive feed to the discharge point. Provision is required for dust extraction and for cleaning and recirculation of the abrasive: effective separation of sand and fines has been shown to be vital to the economic operation of shotblast plant: such separation also reduces the need for preliminary cleaning and decoring of the castings. A close approach to continuous operation can be achieved by skip loading and by dual turntable plants enabling loading and unloading to proceed outside the work chamber during blasting. Similar to blasting cleaning treatment is shot peening, employed to improve fatigue resistance by cold working the surface layers of the material. For this purpose angular grits are avoided in favour of round shot or prerounded cut wire, ensuring smooth indentations rather than pitting of the surface. Fig.11.1 shows two different shotblasting machines. According to Jain (2009) modern automatic units for smaller castings rotate or tumble the castings under the grit blast.



Fig.11.1 Two different makes of shotblasting machine (manufacturingmachines.com, 2020)

In the sand blasting the abrasive used is sand of fairly large grain size. In sand blasting, the sand (silica) being in granular form, is comparatively soft and it rapidly breaks into smaller size on impact with a hard metallic surface. Thus the life of the abrasive is less. Further the silica dust can lead to tubercular disease (Jain, 2009).

In shot blasting, round, or angular, chilled iron shots are used in place of sand resulting in better cleaning and longer life. The selection of round or angular shot depends on the finish desired and the material to be treated. The round shot is generally restricted to the shot blasting of non-ferrous

castings. Chopped steel wire and steel grit are claimed to be economical because of their long life. The abrasives may be propelled either by pneumatic means or airless (Jain, 2009).

Hydraulic Cleaning

In hydraulic cleaning systems the castings are exposed to high pressure water jets, which may also incorporate sand as an abrasive. Pressures up to 2350 lbf/in² ($\approx 1.6 \text{ MN/m}^2$) are used and highly effective sand removal is obtained. One of the principal advantages of this method is the total elimination of dust, whilst the separated moulding material can be conveniently classified for re-use. Arrangements for applying the jet are analogous to those used in shotblasting, the nozzle being handled directly by the operator or, especially where the highest pressures are used, subject to remote control from outside the workchamber. The wet cleaning principle is used more simply and without major plant installations by dispensing water to a decoring bar through an annular spray collar, a technique developed by B.C.I.R.A. For heavier equipment the gun operated mechanically from outside the chamber is used. The gun is mounted in a carriage which can be moved the entire length of the room vertically as may be required. The gun swivels in the carriage in a cone of more than 90°. All the motions are controlled by two levers outside the room actuated hydraulically and electrically. This process cleans the surfaces of the casting rapidly and thoroughly.

Chemical Cleaning

When compared with blast cleaning methods there has been little application of chemical cleaning in the foundry industry. Chemical cleaning utilizes baths of molten caustic soda into which additional reagents are introduced to react with and break down the surface oxide layer, thereby loosening adhering sand. In the electrolytic method the same object is achieved by applying current: oxide is reduced by nascent sodium liberated at the casting, which is made the cathode in the cell.

Other methods of cleaning include barrel tumbling and scratch brushing. In the former method, now of declining importance, light castings are rotated with metal pieces to achieve impact abrasion and burnishing of the surfaces: the method has been much applied to cast iron. Wire brushing is primarily used for non-ferrous production, where the normal clean strip often renders a full cleaning operation superfluous.

Runner and Feeder Head Removal

Numerous alternative methods are available for the removal of feeding and gating systems. These extend from simple knocking off or prizing away, possible only in some circumstances, through the standard methods of machine cutting by saw, abrasive wheel or parting tool to a highly versatile range of flame cutting processes. Each of these methods fulfils a useful function in the foundry, depending on the type of alloy and dimensions.

Knocking Off

This method can be applied to alloys in which the as-cast ductility is low, especially where the area of the junction with the casting is small. To facilitate fracture use is made of various types of restricted neck and knock-off core, both to reduce the metal section and to provide a notch effect; the initial notch may, alternatively, be produced by one of the slitting processes.

Sawing

Although sawing is potentially suitable for most types of cast material it is most widely applied to the softer non-ferrous alloys. Band-saws, hacksaws and circular saws can all be used, but the band saw is the most versatile machine in respect of cut dimensions and working conditions. Band-saws can be used over a wide range of speeds. The normal saw cutting principle operates at speeds from approximately 5000ft/min (≈ 25 m/s) down to 50 ft/min (≈ 0.25 m/s), the speed being reduced to diminish the heating effect as the length of cut increases. For aluminium and magnesium alloys the higher speeds are suitable.

Abrasive Wheel Slitting

Abrasive cut-off machines provide a rapid means of head removal for sizes within the capacity of the wheel diameters available, being particularly suitable for cast iron and steel, including the hardest alloys. On a full sized machine the wheel can be mounted in a fixed position, the casting being pushed along the workrest by hand, or the casting may be clamped to the table, the wheel mounting being swung into the contact position. Much use is also made of portable machines on which the disc is mounted on a right angled shaft. The wheel thickness used is commonly $1/8$ in (≈ 3 mm), in diameters up to 20 in (≈ 500 mm): rubber bonding, or laminated construction with fabric reinforcement, provides limited flexibility, but the casting needs to be held firmly to avoid wheel shatter. For each type of wheel there is an optimum peripheral speed, usually in the range 95 000-16 000 ft/min (≈ 48 - 81 m/s) and the machine should therefore incorporate provision for an increase in rotational speed to compensate for wheel wear.

Machining

In certain cases heads can be conveniently removed by machine parting, especially where the process can be combined with other machining operations. The method is particularly suitable for large heads and those where a continuous cut can be achieved, as in the case of axially positioned and annular heads; a narrow parting tool is employed and no further finishing need be carried out.

Flame Cutting

Flame cutting techniques are widely employed for the removal of heads from steel castings; cutting is most commonly based on the oxyacetylene system, although propane and other fuel gases can also be used. In cutting ferrous alloys the oxygen-gas reaction is important primarily as a means of preheating the metal to its ignition temperature, after which heat is derived mainly from combustion of the metal itself with excess oxygen supplied through the torch. This is accordingly provided with preheating jets and a main oxygen orifice. Cutting occurs by a combination of melting and oxidation to slag. Flame cutting is a flexible process in that a skilled operator can follow irregular contours, and heads of a wide range of sizes can be removed.

Dressing and Finishing

The last stage of fettling is involves dressing for the removal of excess metal and residual adhering sand. Material to be removed includes flash, pads and the stumps of feeder heads and ingates, which need to be dressed flush with the surface. The object is to ensure that the shape, surface finish and dimensions of the black casting conform to design requirements. The principal techniques

are chipping and grinding but hot fettling techniques with specially designed torches have also been developed. Apart from surface dressing it may also be necessary to gouge out surface defects prior to rectification.

Chipping: is carried out to prize away flash and adhering sand. Apart from limited use of hand hammers and chisels, the principal tool is the pneumatic chisel operating at the normal mains pressure in the range 80-100 lbf/in² ($\approx 550\text{-}690\text{ kN/m}^2$).

Grinding operations: are carried out on swing frame, pedestal or portable machines. The first of these is suitable for the removal of stumps of feeder heads and other heavy duty grinding on large castings. Fixed head pedestal or bench grinders, using wheels up to approximately 30 in ($\approx 750\text{ mm}$) diameter, are suitable for small castings capable of being individually handled. The most universal tool for general dressing is the portable grinder, using a wide variety of wheels for manual operations on castings of all sizes. Most portable machines are electrically powered: for heavy duty grinding high frequency motors (200 Hz or higher) are preferred. The commonest design uses an axially mounted wheel but angled shafts and flexible drives are also used. Many shapes of wheel are available, but most grinding is carried out using plain wheels, for example the 6x1x 5/8 in ($\approx 150\text{x } 25\text{x } 16\text{ mm}$) size. Small high speed pneumatic or electric machines are used for delicate shaping and polishing with mounted points and tungsten carbide burrs.

A further development in grinding is the use of abrasive belt machines: given sufficient power a very high rate of stock removal can be achieved. Other methods of surface abrasion include filing and wire brushing: these methods are frequently adopted for the softer non-ferrous metals, in which fettling problems are generally much less severe.

Hot fettling processes: As adopted for ferrous alloys these have the particular advantage of avoiding dust generation. In powder washing, iron powder is dispensed through a specially designed torch into an oxyacetylene flame, which is played across the casting surface to remove superfluous metal and adhering sand. The powder, reacting with excess oxygen, increases the temperature in the reaction zone, whilst the oxide product exerts a fluxing action on the sand to form a slag which runs off the surface. In the air-carbon arc process, an arc is applied to achieve local melting of excess metal, which is blown away from the surface by a stream of compressed air as in the previously mentioned cutting process. Both processes can be used as alternatives to grinding in heavy fettling operations. Yet another modern development in high temperature processes is the use of plasma torches, both for cutting and for metal removal.

Costs of feeder head removal and dressing to final shape depend heavily on the positioning of heads and ingates in relation to the features of the casting. The object should be to eliminate contour fettling wherever possible by placing heads and ingates on flat surfaces, permitting accurate, smooth cuts close to the surface: reliance on sculpture by the fettler is then avoided. Where a plane interface cannot be obtained, simply contoured contact surfaces should be sought and the task of dressing simplified by provision of templates to shape the final surface.

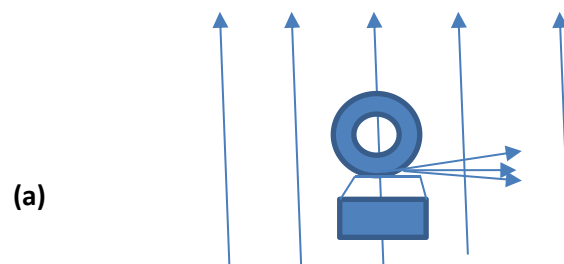
The Dust Hazard

The problem of dust generation exists throughout production, but is most serious where dry operations are performed, at the knockout and in the fettling shop. The main health hazard arises

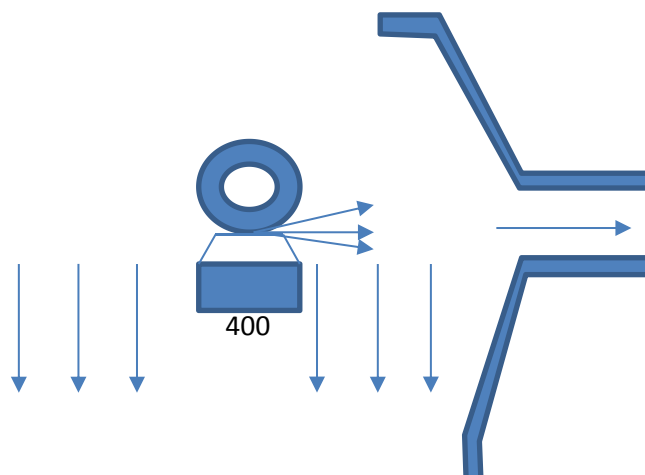
from silica particles in the size range below $2\text{ }\mu\text{m}$, which are active in inducing pneumoconiosis. Airborne foundry dust consists predominantly of particles below $2.5\text{ }\mu\text{m}$ with a median size of about $1\text{ }\mu\text{m}$: a particle of this size has a free falling velocity of only 18 mm/min and so stays airborne indefinitely in normal environments. One can read more on this from Ihom, *et al.*, (2008). Apart from the use of methods and materials which avoid production of harmful dust particles, suppression can be assisted by a number of alternative or complementary measures, namely:

- i. General ventilation of the workspace;
- ii. Local extraction in the immediate region of the work;
- iii. Local extraction at the point of dust creation.

These basic systems are schematically illustrated in Fig.11.2.



(b)



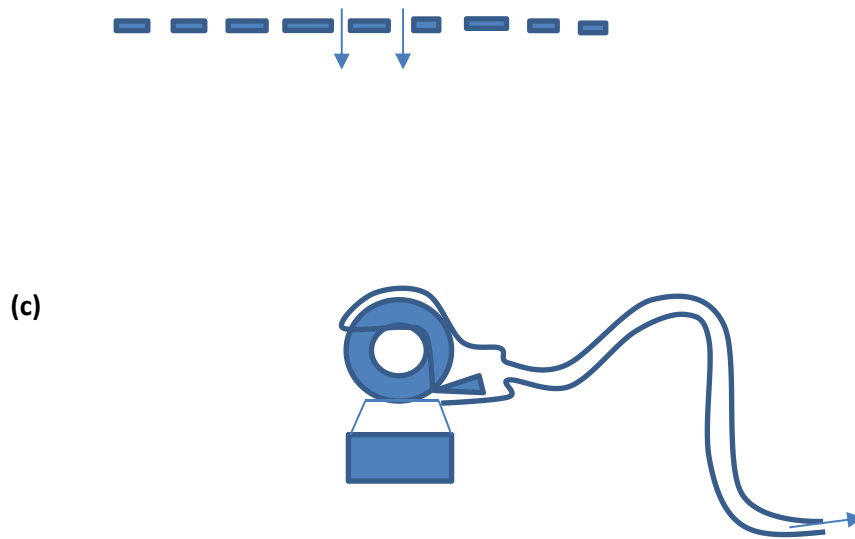


Fig.11.2 Systems of dust extraction: (a) general ventilation of workspace (b) local extraction adjacent to work, (c) local extraction at tool.

General ventilation is most commonly sought through an upward movement of air, brought about by high level extraction fans or a raised roof. Recent opinion, however, has moved towards downdraught ventilation with high level inlets, air flow being created by extraction close to the points of dust production: in this way local exhaust is used as an aid to general shop ventilation.

Local exhaust systems are based on two different concepts. Extraction may be localized to the work region, either by the use of hoods and booths, positioned in the paths of the main dust stream, or by downdraughts grids or exhausted fettling benches, designed to maintain a positive air current past the work and away from the operator (Fig.11.2b). This type of system is paralleled by the hood and downdraught systems employed at knockouts.

In the second type of local system extraction is more intensely localized at the machine or tool, using integral suction attachments providing closely confined high velocity air streams (Fig.10.2c). Such systems are available for each type of fettling equipment. For a pedestal or bench grinding machine the dust is extracted through a perforated work rest and wheel cowling. Whilst a swing frame grinder is exhausted through the wheel hood. A portable grinder is provided with an extraction shoe or guard exhausted through a flexible lead; pneumatic chisels are fitted with a concentric rubber suction sleeve. In all these high velocity, low volume systems the attachments must be carefully designed not only to trap the primary dust stream but to avoid escape of the secondary stream which closely follows the rotating wheel. Additional protection of the operators can be derived from face masks incorporating simple filters or more positive breathing aids. Two types of air fed mask are designed to diminish the difficulty encountered in drawing the entire air supply through the filter in a simple mask.

Considering fettling shop operations as a whole, production engineering has not attained the same advanced level as in mould production. The operations have a high manual content and batch rather than flow production systems predominate. Since automatic fettling is not established except in the

shotblasting of light castings, mechanization in fettling shops principally takes the form of systems for handling castings between stages and for serving the operator. Most of the foundries in Nigeria are also like that. Whilst reliance is still placed on crane or hoist lifting for transporting and manipulating heavy castings, the emphasis for small castings is upon batching in stillages which can be moved and stacked by forklift truck. The pendulum conveyor is also employed in fettling shops for light castings.

Further Operations

Several other measures can be involved in the concluding stages of casting manufacture. Heat treatment, the application of special surface treatments and coatings, and inspection are coordinated in various sequences with fettling shop operations; rough machining is also carried out in specified cases. These are discussed in subsequent chapters.

REVIEW QUESTIONS FOR CHAPTER ELEVEN

1. The higher the metal melting point, the greater the surface roughness of the castings. Explain.
2. Explain how initial cleaning of a casting is done
3. What is shotblasting?
4. What is the difference between shotblasting and sandblasting?
5. What is the difference between shotblasting and shotpeening?
6. Explain hydraulic cleaning
7. Explain chemical cleaning
8. Explain the various methods employed in runner and feeder head removal.
9. Write elaborately on grinding operations as a finishing operation on castings
10. Elaborate in details on hot fettling processes.
11. Write on dust hazard in the foundry and how it can be ameliorated.

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CHAPTER TWELVE

HEAT TREATMENT OF CASTINGS

Introduction

Heat treatment of castings is one of the post casting operations carried out on castings to ensure that castings meet up with design specifications (Aponbiviede, 2009). It is used to control the properties of metal castings. As for a variety of metal products such as are made from steels, aluminum alloys, copper alloys and the like. Industrially manufactured, they are used after performing a heat treatment to draw their most suitable characteristics. Particularly as for steel products, there are many kinds of steel materials, the respective knowledge of carbon steel, alloy steel, stainless steel, special steels, and the like are required, in order to understand the heat treatment technologies, fundamental technology and practical information required (Suzuki, 2008).

Typical heat treatment administered on castings includes the following:

- i. Homogenizing
- ii. Annealing
- iii. Subcritical annealing

- iv. Normalizing
- v. Hardening and tempering
- vi. Surface hardening
- vii. Age hardening/ precipitation hardening.

Homogenizing: this is carried out on metal castings in order to homogenize the microstructure of the casting; it removes micro-segregation and other concentration effects.

Annealing: normal annealing is often used. However, for special products, methods of annealing such as diffusion annealing, spheroidising annealing, isothermal annealing, low temperature and k stress annealing, stress relieving treatment and the like are performed.

Subcritical annealing: annealing is carried out below the critical temperature

Normalizing: is referred to as an operation of keeping the metal in the air quietly to cool after it has been heated to the temperature 30-50°C higher than A_3 or A_{cm} transformation points for the purpose of standardizing the material.

Hardening : is achieved by heating to austenite temperature and quenching.

Tempering: is the holding of a metal at a low temperature for sometime after quenching.

Surface hardening: is the hardening of the surface of metals. It is done using various techniques.

Age hardening: is normally carried out on castings made of age hardening alloys.

Heat treatment of Steel Castings

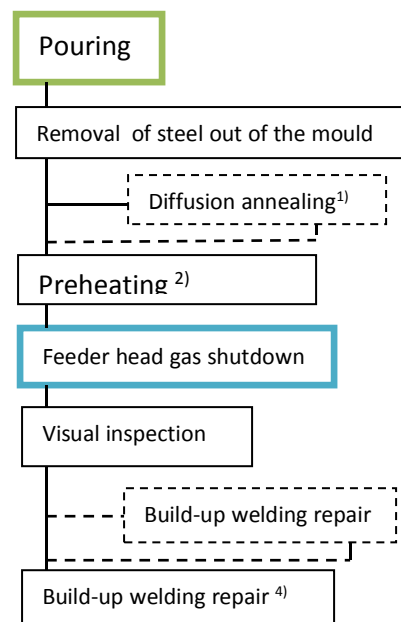
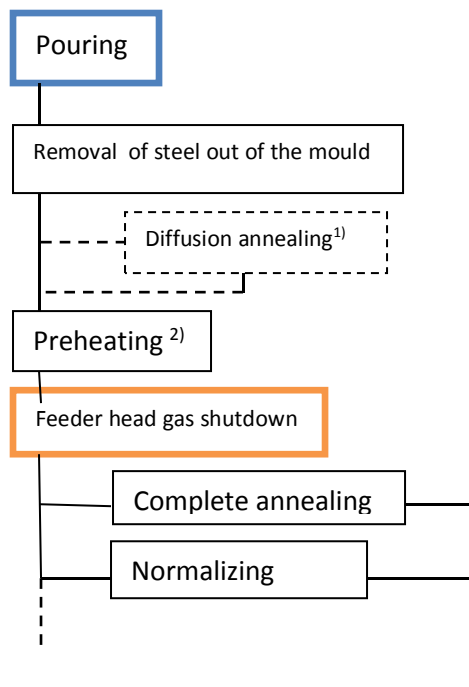
Material Classification and Heat Treatment Processes

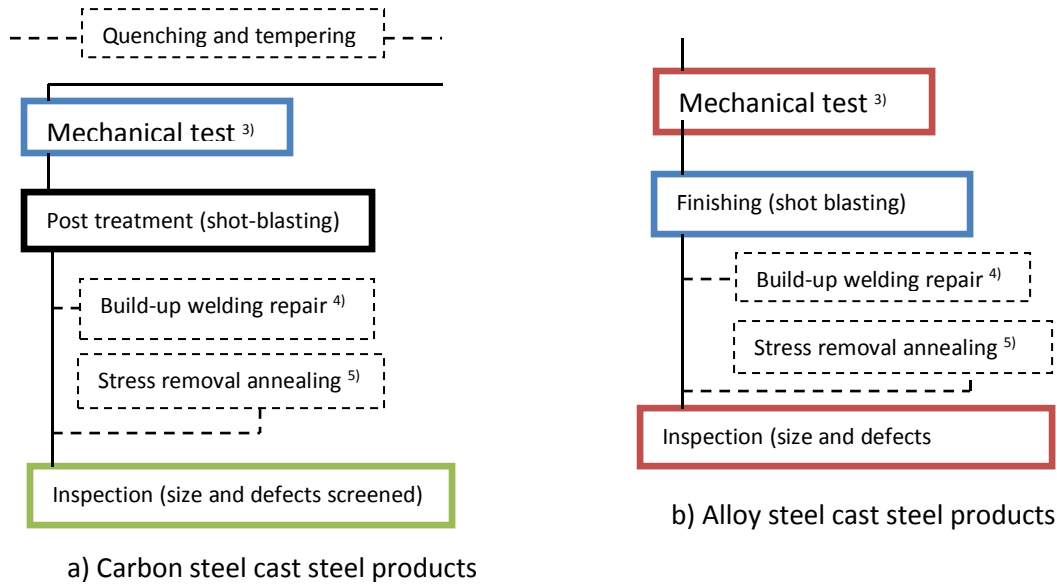
Cast steels include various kinds of steels. The kinds of heat treatment of steel castings are shown in Table12.1 and working processes of steel castings are shown in Fig.12.1.

Table 12.1 Kinds of Heat Treatments of Steel Castings

Classification (in accordance with JIS)	Kinds of heat treatment
Carbon steel castings	Annealing, normalizing, tempering,

	quenching, and tempering
Structural casting for welding	Same as above
High tensile strength structural carbon steel castings	Same as above
Low alloy structural steel castings	Same as above
Stainless steel castings	Quenching and tempering, heat treatment for solid solution, precipitation hardening heat treatment (also referred to as ageing)
Heat resistant steel castings	Annealing
High manganese steel castings	Water-toughening





- 1) In the case where a significant segregation exists, 2) prevention of cracking, 300-500°C, 3) judgement of heat treatment, test for mechanical property, 4) preheating is required for a large defect (150°C or more), 5) perform at lower temperature than tempering temperature.

Fig.12.1 Working Processes of Steel Castings

Annealing

For general heat treatment of steel castings, normal annealing is often used. However, for special products, methods of annealing such as diffusion annealing, spheroidizing annealing, isothermal annealing, low temperature and stress annealing, stress relieving treatment and the alike are performed.

i) Normal Annealing

Normal annealing is carried out on castings to soften the castings in order to facilitate the machining of the metal. It sufficiently removes the casting strain and gives them a predetermined mechanical property. The heating temperature is about 50°C above the transformation point, and then slowly cooled through critical zone to about 500°C at which it is reduced to flame color, and subsequently it may be air cooled rapidly to room temperature. Conventionally, customary annealing is performed in the furnace by slowly cooling to ordinary temperature. But even if it is taken out from the furnace at 500°C and air cooled or water cooled, there is little difference in terms of qualities. However, in the case of castings having complex shapes or having a large scale, there is fear that a very large heat stress will generate if they are not cooled slowly, even if it is

cooled from nearby 500°C. In summary the factor that determines the degree of softening when the annealing is performed, is how it is cooled through the temperature range until Ar' transformation point is completed. If Ar₁ transformation has been completed at a temperature about 500°C, even if it is air cooled, a soft structure is obtained. In this way the cooling time is shortened and the availability of the furnace can be made speedy by several hours, by rapidly cooling through the range from about 500°C or less making it economical.

ii) Diffusion Annealing

An annealing to diffuse the segregation generated during solidification in a steel casting, it also homogenizes the structure, this annealing is referred to as a diffusion annealing. The diffusion of carbon is comparatively easy, but phosphorous and sulphur impurities have a slow diffusion rate. Therefore the effect of diffusion annealing cannot be much as expected. This treatment is applied to the homogenization of a large scale carbon steel castings and special steel castings. The temperature of diffusion annealing is higher than the normal annealing temperature, and usually the range is from 1000 to 1200°C

iii) Spheroidizing Annealing

The annealing for spheroidizing carbide (lamellar pearlite and net carbide) in the steel casting is referred to as spheroidizing annealing. Usually, steel containing carbon more than medium carbon steel is subjected to this spheroidizing annealing. If the spheroidizing treatment is performed, the toughness of the steel becomes large, and the machining of steel becomes easier, and after the refining treatment the mechanical characteristics become excellent. Therefore it is always necessary to perform spheroidizing treatment to cast steel roll of high carbon steel or low alloy steels. Spheroidizing annealing includes the following methods:

- i. a method in which the steel is heated to slightly higher than Ac₁ point and slowly cooled
- ii a method in which it is annealed for long hours at a temperature of 20-30°C lower than Ac₁ point,

iii a method in which heating and cooling are repeated between the temperatures 20-30°C above the A_1 point and 20-30°C below the A_1 point. Moreover, for the steels containing carbon more than eutectoid steel, i) and ii) may be combined.

Apart from these mentioned above there are other annealing methods, such as stress removal treatment (also referred to as pre-annealing), which treats alloy steel castings having high hardenability, by heating to 500- 600°C in order to prevent cracking during cutting of feeder head or a low temperature annealing which heats to 500-600°C, the castings in which welding repair of partial small defect generated during machining of steels after the refining has been performed.

Normalizing

Normalizing in steel castings is referred to as an operation of keeping the steel in the air quietly to cool after the steel has been heated to the temperature 30-50°C higher than A_3 or A_{cm} transformation points for the purpose of standardizing the material. Since the cast structure was heated to complete austenite zone by this operation, the cast structure is improved to homogeneous to some extent, the crystal grain is refined and the mechanical properties are also enhanced. In castings whose thickness changes are significant, air cooling rate is slow in the thick section, resulting in lower tensile strength and hardness, and air cooling rate is comparatively high in the thin section, resulting in higher tensile strength and hardness, accordingly, we have to take care of the way of loading and air cooling so that the cooling rate of the charge put in the furnace is as uniform as possible. In the case of a large scaled casting having a complex shape and whose thickness variations are significant, the normalizing work should be performed carefully because there is the fear that large temperature difference may generate at the respective portions of the casting during air cooling, leading to uneven hardness or initiation of heat treatment strain. In such a case, annealing is safer than normalizing though the mechanical properties are slightly inferior.

Moreover, as for medium and small scale steel castings, the mechanical property of normalized steel is more excellent than the annealed. It can be said that normalizing is a superior heat treatment method also from the viewpoint of enhancing the operating efficiency of the furnace and economy of the fuel. As for an alloy steel casting having a strong tendency of self-hardening, pre-annealing is performed since there is a risk of cracking, and then it may be preferably normalized after the feeder head and cross gates

are cut. However, as for the other general cast steel, the pre-annealing is meaningless, or rather, the feeder head and cross gates are cut immediately after the as-cast, then the normalizing is performed. The appropriate normalizing temperature for general steel castings is in the range of 870 to 900°C.

Table 12.2 Normalizing Temperature of Carbon Steel for Machine Structural Use

Steel Kinds Symbol	Normalizing Temperature (°C)	Steel Kind Symbol	Normalizing Temperature (°C)
S10C	900-950	S35C	840-890
S15C	880-930	S40C	830-880
S20C	870-920	S45C	820-870
S25C	860-910	S50C	810-860
S30C	850-900	S55C	800-850

Quenching (Hardening)

In the case where sufficient hardening is needed, or in the case of casting of special steel requiring a superior strong toughness, an operation in which it is quenched in water or oil after it has been heated to a temperature of 30-50°C higher than A_3 or A_1 transformation point of the steel (In the case of the steel having carbon more than eutectoid point, the hardening is performed from a temperature higher than A_1 point after previous spheroidizing annealing) is referred to as a quenching. The most excellent mechanical nature is obtained by quenching and tempering, the good combination of tensile strength, hardness and strong toughness is obtained. Problems usually found in this quenching are the occurrence of quenching crack and warping. Since there are steel castings whose thickness variations are significant and whose shape is complex, it is necessary to take care of these when the quenching is performed. Quenching of steel castings is often applied particularly to local hardening for the location where the hardness and wear resistance are required, and to special steel casting of small size requiring a superior strong toughness.

The key point of the quench hardening operation is that the steel is cooled rapidly through the critical zone (temperature zone from the quenching temperature to the nose of S curve) and is slowly cooled through the risky zone (lower than 250°C, Ms-Mf

zone), that is, ‘‘rapid and slow’’ cooling as shown in Fig.12.2. The temperature range of martensite generation of normal cast steel and alloy cast steel is as indicated in Table 12.3. The hardening of steel castings mainly include normal quenching (high frequency induction hardening, flame quenching, time hardening) and solid solution treatment.

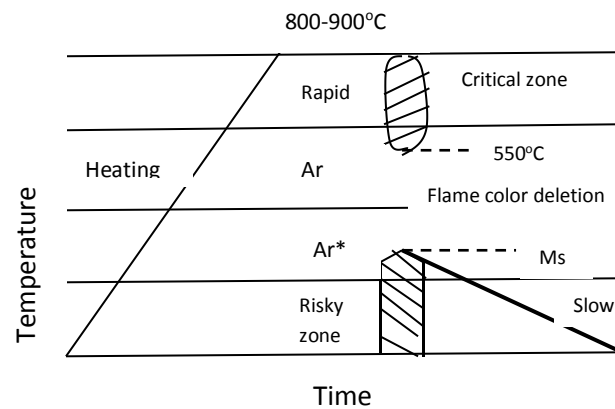


Fig.12.2 knack in Quenching

Table 12.3 Temperature Range of Martensite Generation of Ordinary Cast Steel and Alloy Cast Steel

Steel Kinds SAE No.	Martensite Generation Temperature (°C)	50% Martensite Generation (°C)	99% Martensite Generation (°C)
1030	343	293	232
1065	277	219	149
1090	219	157	82
1335	343	293	232

2340	304	293	207
3140	335	288	221
4130	380	243	288
4140	343	299	227
4340	288	249	188
4640	343	299	249
5140	343	299	232
6140	316	239	232
8630	366	332	277
9440	330	282	202

i. Normal Quenching

It is a general quenching operation performed by water quenching or by oil quenching. Since the hardening is easily accomplished in the case of special steel castings containing Ni, Cr, Mn, Mo or the like, oil hardening is usually performed. In general, oil Quenched products have smaller hardness than the water- quenched, however, since oil quenching only rarely generate quenching crack and strain, it is often used for hardening of steel castings. The cooling rate due to the kind of quenching media and the degree of agitation is referred to as severity of quench, conventionally; it is represented by the character H. Hs of major quenching media are indicated in Table 12.4.

Since water quenching or oil quenching of a large scale casting has a risk of cracking, air blast quenching or fog quenching is effective, since the deformation strain due to these quenching is slight and wide range of cooling rate is obtained by appropriately adjusting airflow pressure, quantity of airflow, amount of water, distance and the like, they are applied mainly to the quenching of a large sized gear base or cast steel roll made from Cr-Mo cast steel. Moreover, in order to locally give strength and wear resistance to the cast steel products used as mechanical parts, a flame hardening or a high frequency induction hardening is generally performed as shown in Figs. 12.4 and 12.5. As the characteristics of these methods, only surface layer portion is locally hardened, the material change is scarcely seen in the other portions, and since the hardening strain is slight, tempering is scarcely needed, and this is conveniently and easily applicable to a large steel casting. These are the major cast steel to which local

hardening method is applied; tooth portion of gear base, pin portion of caterpillar, the edge of shovel nail, bearing portion of crankshaft, road surface of roller wheel or the like can be listed, and the method is used in good popularity as a surface hardening method.

Table 12.4 Severity of Quenching H According to a Variety of Quenching Methods

Agitation degree	Air	Oil	Water	Salt water
Still	0.02	0.25-0.30	0.9-1.0	2.0
Light	-	0.30-0.35	1.0-1.1	2.0-2/2
Moderate	-	0.35-0.40	1.2-1.3	-
Well	-	0.40-0.50	1.4-1.5	-
Strong	-	0.50-0.80	1.6-2.0	-
Very strong	-	0.8-1.10	4.0	5.0

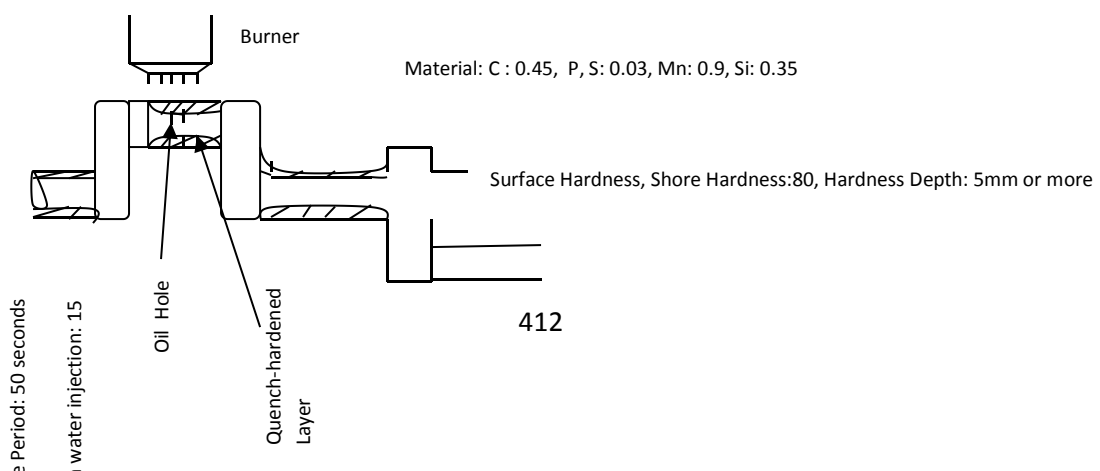


Fig. 12.4 flame hardening method of crankshaft

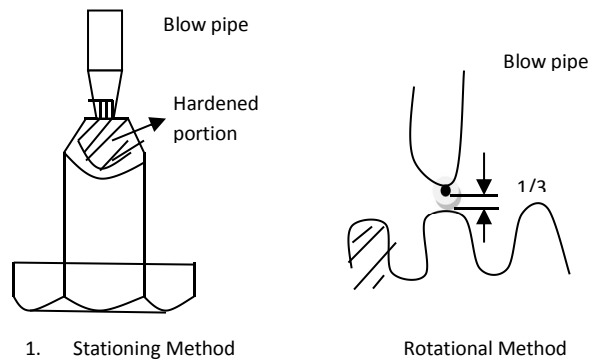


Fig. 12.5 Various Kinds of Local Hardening Methods

Solution Heat Treatment

Solution heat treatment used for austenite based stainless cast steel high manganese cast steel and heat resistance cast steel is a heat treatment in which, contrary to normal quenching where martensite transformation is caused by quenching from the temperature more than the transformation point to obtain the hardened matrix or the increased strength, the steel is heated to and maintained at a high temperature ranging from 950 to 1200°C to make carbide precipitate in the as-cast state and the other compounds completely solid soluble in the austenite, then quenched to make the structure uniform and stabilized. In general, all of the austenite base stainless steels and high manganese casting steels are subjected to this treatment, however, as for heat resistant cast steels, there are some steels in which according to their nature and the purpose of use, no special heat treatment may be performed, only annealing is carried out for improving the cast- structure and reducing of casting stress.

Moreover, as for precipitation hardening type stainless casting steels, after solution heat treatment at a temperature above 950°C, temper-ageing is carried out according to the material, the steel is hardened and can then be used. The solution heat treatment of high

manganese steel has been referred to as water-toughening (water annealing) from the past. A high manganese cast steel is hard and brittle due to the precipitation of carbide in the as-cast state, however, if it is heated to 1000-1100°C, the carbide is made completely solid soluble in the austenite. Then, if it is rapidly cooled in water, it becomes a uniform austenite structure without being hardened like carbon steel, and becomes a steel rich in toughness. In this way, it is referred to as water-toughening or water annealing from the fact that the toughness is increased by rapid cooling in water.

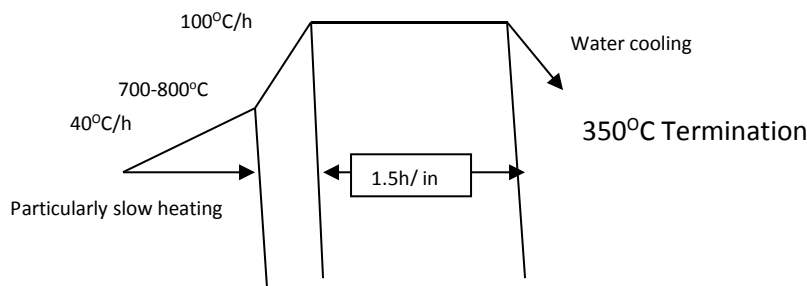


Fig.12.6 Temperature Curve of Water-toughening Cast Steel

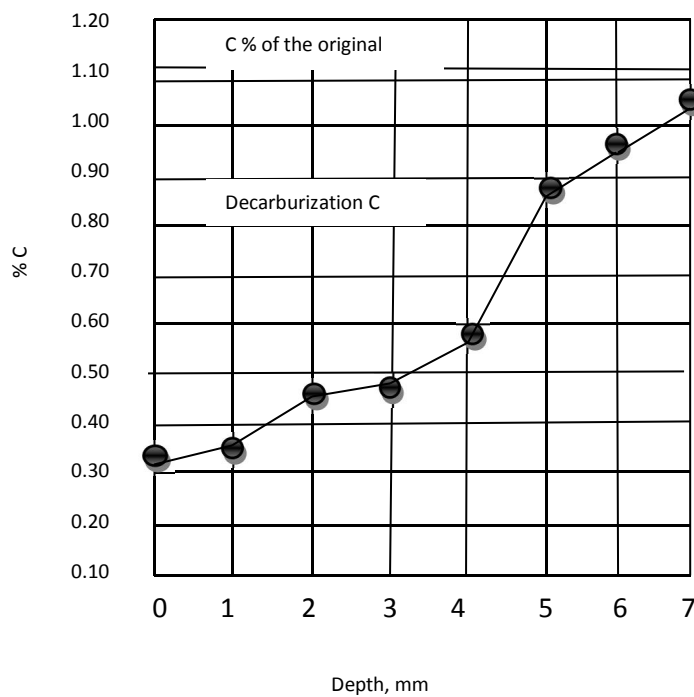


Fig. 12.7 Change of Surface %C Due to Heating at 1100°C

Since high manganese steel is extremely bad in thermal conductivity, which is about 1/3 of carbon steel at nearby ordinary temperature, and its thermal expansion coefficient is 50% larger than that of carbon steel, because of this thermal strain tends to occur. Therefore, for complex shaped castings and castings having a thick thickness, it is

necessary to heat them particularly slowly to about 700°C as shown in Fig. 12.6 from the view point of preventing cracking and straining during the heating. Since the water-toughening temperature of the high manganese steel is high, decarburization due to the surface oxidation tends to occur. Fig.12.6 shows the changes of surface %C when the steel is heated to the water-toughening temperature 1100°C for 2 hours. It is understood that the decarburization significantly occurs. Moreover, if the water-toughening temperature is too high or the retention time is too long, the crystal grain grows and the mechanical property is lowered. Therefore de-oxidation and overheating must be taken care of very seriously.

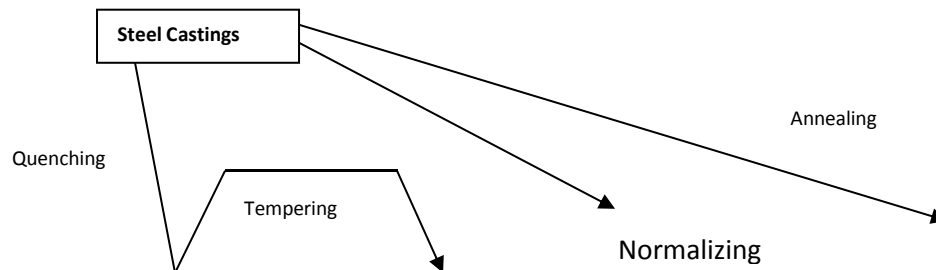
Surface Structure Change by Mould Reaction (Carburizing and Decarburizing)

In a cooling process after pouring, the surface structure of castings changes by reaction with the mould. In the case of the inorganic binder mould, the surface layer can easily change to ferrite structure by oxidation. In the case of the organic binder mould, the surface layer can easily become pearlite structure due to carburizing atmosphere.

The heat treatment of steel castings is basically the same as in forged steel.

It is an important point to note and to be careful for segregation and heat crack by the transformation and cooling that steels go through during heat treatment.

The surface structure of castings changes by reaction with the mould.



Heat Treatment of Cast Iron

General Characteristics and Classification of Cast Iron

It is considered that the structure of cast iron is like graphite being scattered in the matrix of steel. This scattered graphite causes a variety of characteristics to the nature of cast iron. That is to say, the nature can be significantly different depending upon the existing graphite amount, shape and size, and distribution state. In almost all cases, the purpose of use is realized by a single or the combination of the following characteristics:

- i. Designed parts having a complex shape/size can be easily manufactured
- ii. Machinability is superior
- iii. Wear resistance is superior
- iv. Capable of combining a suitable strength and ductility
- v. Corrosion resistance is good
- vi. Damping capacity is large
- vii. Heat conductivity is large

For cast iron; besides white cast iron, gray cast iron, spheroidal graphite cast iron (ductile cast iron) and malleable cast iron, in recent times, a variety of alloy cast irons and CV (Compacted vermicular) graphite cast iron have been widely used. See Figs. 12.8-12.11



Fig.12.8 Microstructure of White Cast Iron (x300)



Fig.12.9 Microstructure of Gray Cast Iron (x 400)

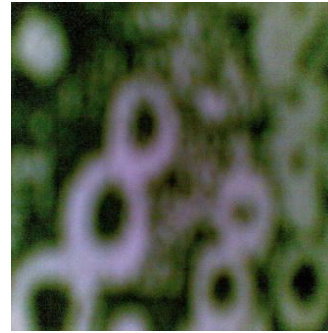
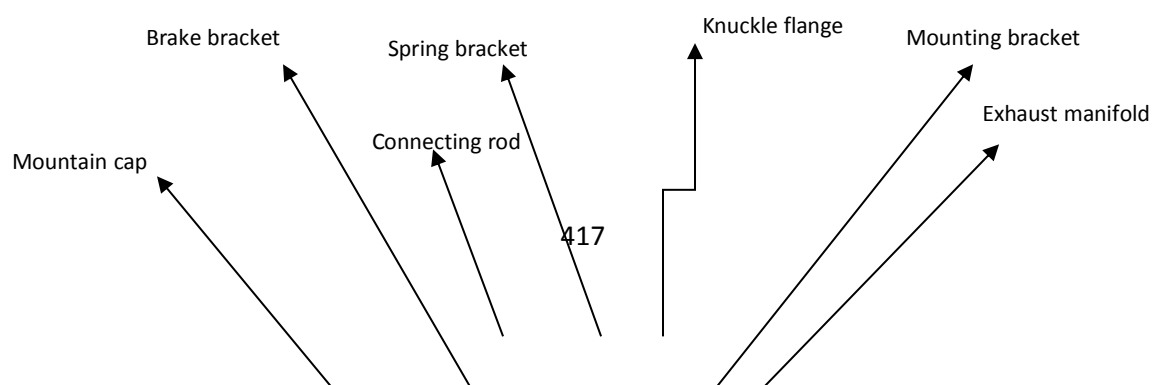


Fig.12.10 Microstructure of Spheroidal Graphite Cast Iron (x 80)



Fig.12.11 Microstructure of Malleable Cast Iron (x 100)



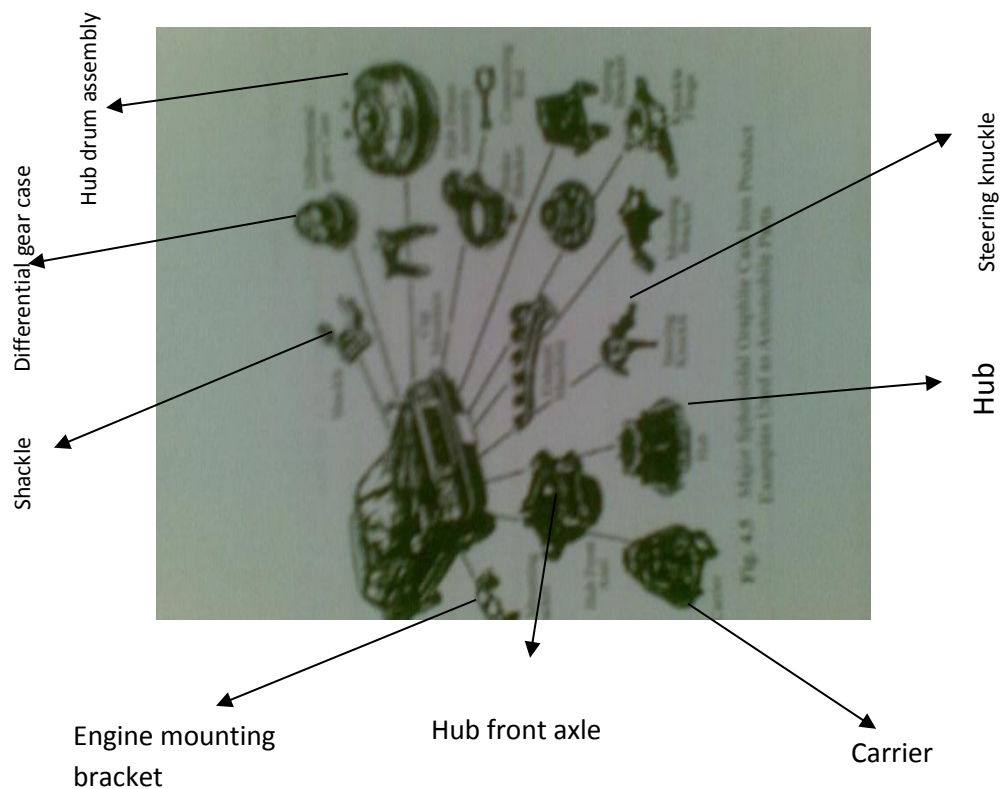


Fig. 12.12 Spheroidal Graphite Cast Iron Products used as Automobile Parts.

Ductile Cast Iron (Spheroidal Graphite Cast Iron)

Half a century has passed since the spheroidal graphite cast iron was invented. After the technologies for the utilization have been established, its production has been continuously increasing year after year, and at present, ductile cast iron is the major stream of cast iron, and also in the future, it will continue to develop. Spheroidal graphite cast iron, has the fundamental condition that first, the graphite shape must be spherical, and this cast iron is referred to as ‘SG (spherical graphite) cast iron’, or “nodular graphite Cast Iron”. It is also referred to as “Ductile Cast Iron” since it is rich in toughness, and this name is often used because of easy naming. This cast iron is far superior in mechanical properties compared to the conventional gray cast irons. Fig.12.12 shows spheroidal graphite cast iron products used in automobile parts.

Table 12.5 Mechanical Properties of Spheroidized Graphite Cast Iron

Types	Symbols	Tensile Strength N/mm ² (kgf/mm ²)	Proof Stress N/mm ² (kgf/mm ²)	Elongation (%)	Charpy Absorption Energy J (kgf.m)		(Reference) Hardness HB
0	FCD370	370 or more (38 or more)	230 or more (24 or more)	17 or more	Average of 3 pieces	Test value of one piece	179 or less
					13.0 or more (1.3 or more)	11.0 or more (1.1 or more)	
1	FCD400	400 or more (41 or more)	250 or more (26 or more)	12 or more	-		201 or less
2	FCD450	450 or more (46 or more)	280 or more (29 or more)	10 or more	-		143-217
3	FCD500	500 or more (51 or more)	320 or more (33 or more)	7 or more	-		170- 241
4	FCD600	600 or more (61 or more)	370 or more (38 or more)	3 or more	-		192- 269
5	FCD700	700 or more (71 or more)	420 or more (43 or more)	2 or more	-		229-302
6	FCD800	800 or more (82 or more)	480 or more (49 or more)	2 or more	-		248- 352

The Specification of this cast iron is standardized as JIS G 5502

As for types and symbols, these are divided into 7 stages in Table 12.5. The mechanical properties for these stages are indicated in JIS G 5502 and are described. Chemical compositions are fundamental for manufacturing a type of iron specified in JIS, there is no standardized definition, but the reference values, are shown in Table 12.6

Table 12.6 Chemical Composition of Spheroidal Graphite Cast Iron (Reference Table)

Compositions/ Type	C	Si	Mn	P	S
0	2.5 or more	2.5 or less	0.4 or less	0.08 or less	0.02 or less
1-6 type	2.5 or more	-	-	-	0.02 or less

Remarks: as for 0 type, Si can be increased by 0.08% per each reduction of P by 0.01%. however, in this case, it is desirable that Si is less than 2.75%.



1. Ferrite



2. Ferrite + Pearlite



3. Pearlite

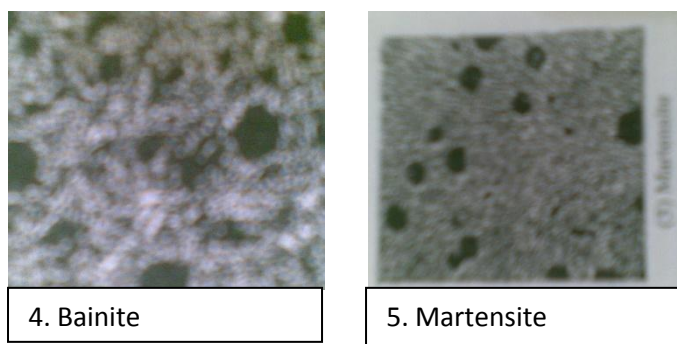


Fig.12.13 Microstructure of Matrix Spheroidal Graphite Cast Iron

The material property of spheroidal graphite cast iron mainly changes only by the microstructure of the matrix if the graphite shape is identical. And even if chemical compositions of the melt are the same, the matrix composition can be changed by the solidification condition / cooling condition of the cast, and microstructure of the matrix structure can also be changed by heat treatment. In Fig.12.13, microscopic photographs of 100 magnification for various microstructures of matrices of spheroidal graphite cast iron are shown

Heat Treatment Method and Microstructural Changes of Ductile Cast Irons

General Description

It is the principle that cast irons are equipped with the property of the object in the as-cast state. The reason is that, besides the cost reduction of the heat treatment, since the shape of the casting is generally complex, heat stress is easily generated due to the heating and cooling during the heat treatment, causing strain and cracking. However, in order to obtain the property of the object, the heat treatment is sometimes unavoidable from the viewpoint of manufacture. The first factor that influences the mechanical property of the cast iron is the shape, distribution and the amount of graphite, almost all of these are determined during the solidification process, and the subsequent heat treatment changes them little. The second factor next to this is the microstructure matrix.

Therefore, in many cases, the heat treatment is carried out for the purpose of improving the matrix structure.

The considerable ranges of property such as ferrite and pearlite ratio, hardness, mechanical properties of the cast iron can be achieved in the as-cast condition. However, for the products which require high uniformity, high mechanical properties, or for thin thickness products, and further, for the products whose shapes and sizes are different and which flowed in the same process, heat treatment is needed. Furthermore, there is a problem of residual stress generated during the casting, the heat treatment for reducing this is often carried out, and there is also a heat treatment for obtaining the surface hardness. In the case of gray cast iron, the mechanical properties are little enhanced by heat treatment except for the hardening because the graphite shape is in a flake state. Therefore, the heat treatment is carried out for the purpose of removing the stress.

In the case of ductile cast iron, since it has spheroidized graphite, mechanical properties comparative to steels are obtained by changing the matrix microstructure through heat treatment. In this case, although the heat treatment technology for steels can be applied, it should be considered that the amounts of C and Si are largely different from those of steels. The following are a representative heat treatment performed for ductile cast iron:

- i. Softening annealing (annealing)
- ii. Stress relieving annealing
- iii. Normalizing
- iv. Quenching and tempering
- v. Special heat treatment (austempering, surface hardening or the like)

In Table 12.7 the outline of the respective heat treatment are shown, and in Fig.12.14, the respective heat treatment patterns are shown. In any of the heat treatments, in order to obtain sufficient properties, we should take note of alloy composition, size, the most suitable atmosphere within the furnace for the shape, heating rate, holding time and cooling rate of the product. Hereinafter, the respective heat treatments will be explained with the ductile cast iron as in subject.

Table 12.7 Outline of Respective Heat Treatment

Types	Definition	Temperatures, period, example	time	Microstructure obtained
Annealing	Heating above A_1 point	840-960°C	1-3hr	Ferrite

	after retention, slow cooling. 1 st stage: cementite decomposition. 2 nd stage: becoming ferritic (pearlite decomposition) above	670-700°C 5hrs (or furnace cooling to 650°C)	
Normalizing	After heating A ₁ point, cooling above	840-870°C 1hr Subsequently air cooling	Acicular or pearlite
Quenching	After heating A ₁ point, quenching (oil quenching)	840-870°C 1hr Subsequently quenching	Acicular or martensite
Tempering	After heating to less than A ₁ point, slowly cooling	Lower (A ₁ -90°C) 1hr Subsequently slow cooling	Determined by combination of quenching and normalizing
Stress relieving	After heating above yield point of high temperature, slowly cooling above	540-650°C 1hr Subsequently furnace cooling to 370°C	Structure is not changed
Austempering	After heating above A ₁ point, rapid cooling to constant transformation temperature above M _s point, retained, subsequently cooling	850°C 1hr, subsequently rapid cooling to 300-400°C, after 1hr retained, slow cooling	Bainite

Note: A₁ point (eutectoid transformation temperature) is a transformation temperature of γ -Fe (austenite) and α -Fe (ferrite), and changes according to the amount of Si.

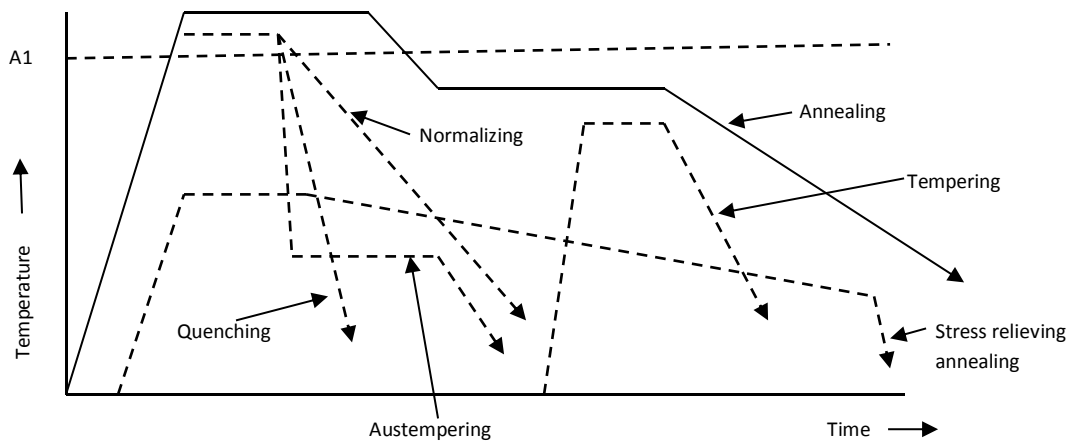


Fig.12.14 Respective Heat Treatment Patterns

Annealing

The objective of performing an annealing is to improve toughness (enhancement of ductility, enhancement of value) and to enhance the workability (lowering of hardness) by uniformly changing the matrix microstructure.

Softening Annealing

It is an operation in which after the cast iron is heated and held at a high temperature above A_1 for a suitable time, the softening is carried out by slowly cooling in the furnace. This treatment is carried out in two stages, the first stage is the decomposition of carbide (cementite), and the second stage is the decomposition of pearlite. In this case, note should be taken of the amount of graphitizing inhibition element such as Cr or the like and the amount of pearlite stabilizing element such as Cu, Mn, Sn, As, Pb, P or the like.

Heat Patterns

In Fig.12.15, one example of heat pattern in the case of ductile cast iron is shown. At the first stage treatment, the cementite is decomposed and homogenized by retaining in the range from 900 to 1030°C and subsequently, as the second stage, the pearlite is decomposed while it is slowly cooled through the temperature zone below the eutectoid transformation point, and the structure becomes ferritic. The microstructure is shown in Fig.12.16.

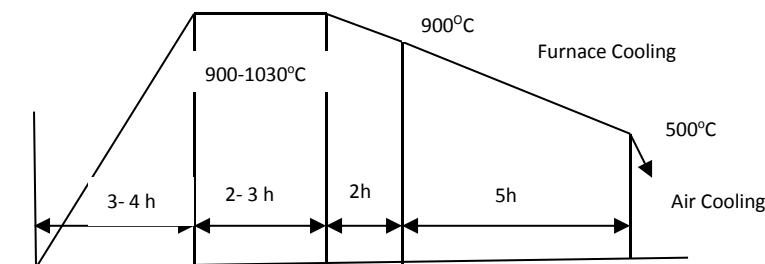


Fig.12.15 Annealing Cycle (using pot)

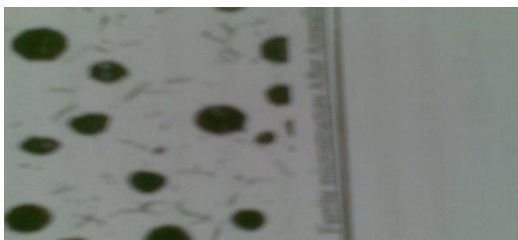


Fig.12.16 Ferrite microstructure after Annealing

ii. Stress Relieving Annealing

In the casting whose thickness is different within itself, the cooling rate also is different according to the thickness, in the as-cast state residual stress will be generated. This may result in the lowering of the strength, deformation and cracking during usage. A treatment for removing this residual stress is referred to as a stress relieving annealing. The stress removal annealing is necessary for the castings of machine tool and precision instruments.

Heat Pattern

As for the change due to the temperature of the yield point of spheroidal graphite cast iron, the lower yield point is significant for the temperature over 500°C . Therefore, the internal stress is reduced by heating the casting to this temperature range, and if it is slowly cooled so that the difference of temperature does not occur during the cooling, then residual stress can be removed. However, it is necessary to note that if the cooling rate is increased, in reverse, the internal stress may increase. If it is heated immediately below the eutectoid temperature, the decomposition of pearlite occurs and the hardness is lowered, it is preferable that it is in the range of 500 to 650°C . In Fig.12.17, one example of heat pattern is shown.

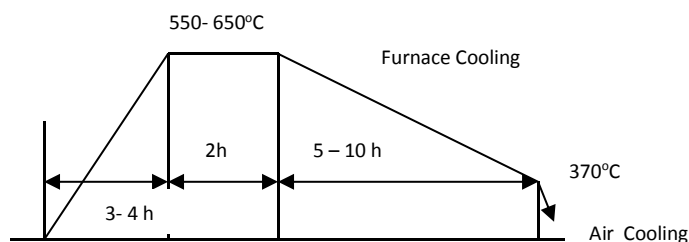


Fig.12.17 Stress Relieving Annealing Cycle

iii. Normalizing

Normalizing is referred to as an operation in which after the ductile cast iron has been heated to about $40-60^{\circ}\text{C}$ higher than A_1 point to make the matrix into a uniform austenite, it is cooled quietly in the air. The objective of performing a normalizing

operation is to make the matrix into finely homogenized pearlite and enhance the toughness. Moreover, in order to lower the hardness or reduce the residual stress by adjusting the matrix structure, subsequent tempering is carried out in some cases. The casting in which the mould-breaking is carried out earlier before cooling to lower temperature has similar structure as that of the normalized, while it is in the as-cast state. Although, the variation may be wide, the production process becomes easier if Ni, Mo, Cu, Mn, and the like are added.

Heat Patterns

One example of heat patterns is shown in Fig.12.18. In order to make the matrix structure a uniform and fine pearlite, after it is heated to around 900°C, air cooling is carried out. In some cases, the adjustment of the matrix structure may be carried out by subsequent tempering. But if the thickness is heavy, the cooling rate is lowered and ferrite is precipitated, it is prevented by alloying with Cu, Ni, Mo, and the like. This structure is shown in Fig.12.19

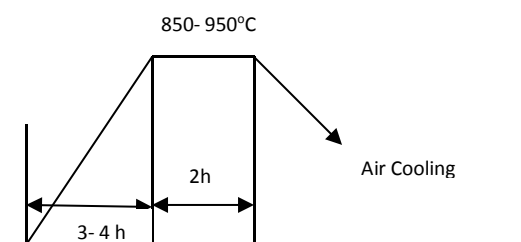


Fig.12.18 Normalising Cycle

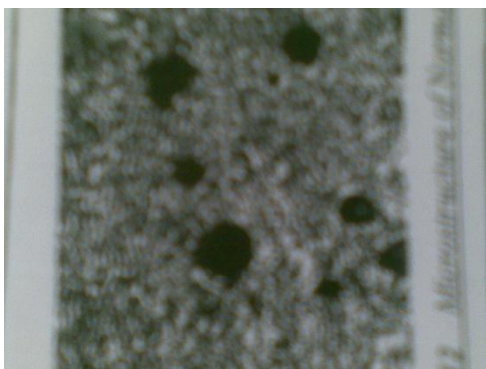


Fig.12.19 Microstructure of Normalising

Quenching and Tempering

Quenching is an operation in which uniform austenite structure obtained by heating to the temperature higher than the eutectoid transformation temperature is rapidly cooled by oil cooling or in the other suitable methods and thereby transforming the austenite into mainly a martensite based structure having an extremely high hardness, and this process increases the hardness of cast iron and enhances the wear resistance. After quenching, the hardness is very high, but it is not suitable for use because of the internal stress accompanying the cooling and the brittleness of martensite. Therefore the need to carry out tempering arises. Tempering is referred to as an operation in which the internal stress is removed by re-heating to a suitable temperature below the transformation point, and the structure is made into pearlite in a grain shape. As the temperature of tempering increases, the higher the temperature is, the larger toughness is obtained due to the removal of internal stress and the progression of spheroidising of carbide.

Heat Patterns

General quenching and tempering heat cycles of spheroidal graphite cast iron is shown in Figs. 12.20-12.21. Moreover, the structure, after quenching and tempering is shown in Fig.12.22.

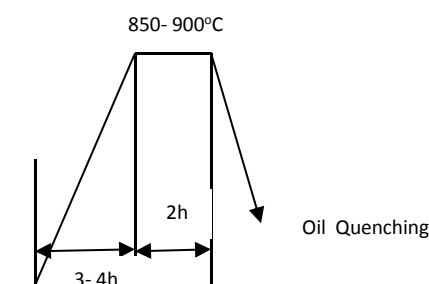


Fig.12.20 quenching cycle

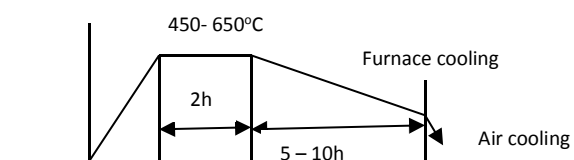


Fig.12.21 Tempering cycle.



Fig.12.22 Microstructure of Quenching and Tempering Cycle.

Others

i Austempering Treatment

When steel is heated to a temperature higher than A_1 point and quenched and isothermally held at a certain temperature zone above M_s point, the mixture structure of ferrite and fine cementite which is called bainite is generated. This treatment is referred to as austempering treatment. The ductile cast iron to which this technology has been applied is an austempered ductile cast iron (ADI). This bainite structure is a structure which is defined as an intermediate between pearlite and martensite and has the properties of strength and excellent toughness and ductility. However, still now the use is limited because of the bad workability due to its hardness, work-hardening due to the decomposition of retained austenite. Although the bainite structure can be manufactured by alloy addition (Ni, Mo, and the like) even for as cast state, however, the control is difficult, and usually, it is manufactured by heat treatment. However, since the mass effect is large, in the case of the product whose thickness is thick, alloy addition is performed even if the heat treatment is carried out.

Heat Pattern

A heat pattern when ADI (Austempered Ductile Cast Iron) is produced is shown in Fig.12.23. The iron is heated to a temperature above A_1 point (austenite zone), after austenitizing, it is quenched and isothermally retained, then subsequently cooled to room temperature. Depending upon the temperature of austempering treatment, the structure is changed, a tight acicular structure which is called lower bainite precipitates at 300°C and the retained austenite is slight, and if the temperature is raised to a higher temperature of $350\text{--}400^{\circ}\text{C}$, the structure becomes a slightly rough, featherly structure called upper bainite. The respective structures are shown in Fig.12.24 and 25. When the treatment temperature is higher, the hardness and tensile strength are reduced and the elongation is increased.

A comparative rapid cooling rate to the bainite zone, is required therefore the furnace for austempering treatment is usually a salt bath furnace which is also used for performing subsequent isothermal holding.

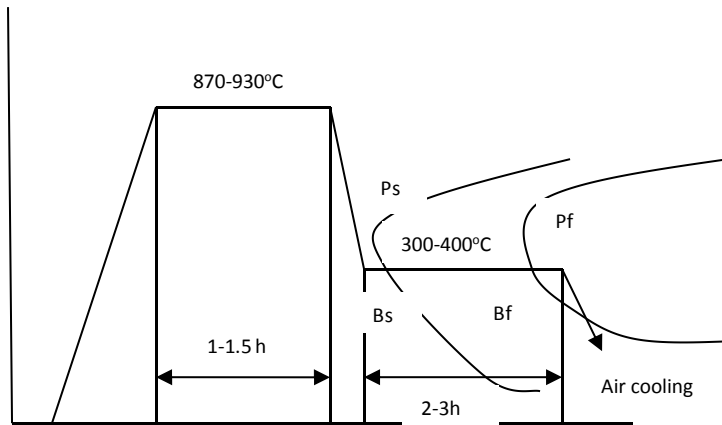


Fig.12.23 Austempering Treatment Cycle

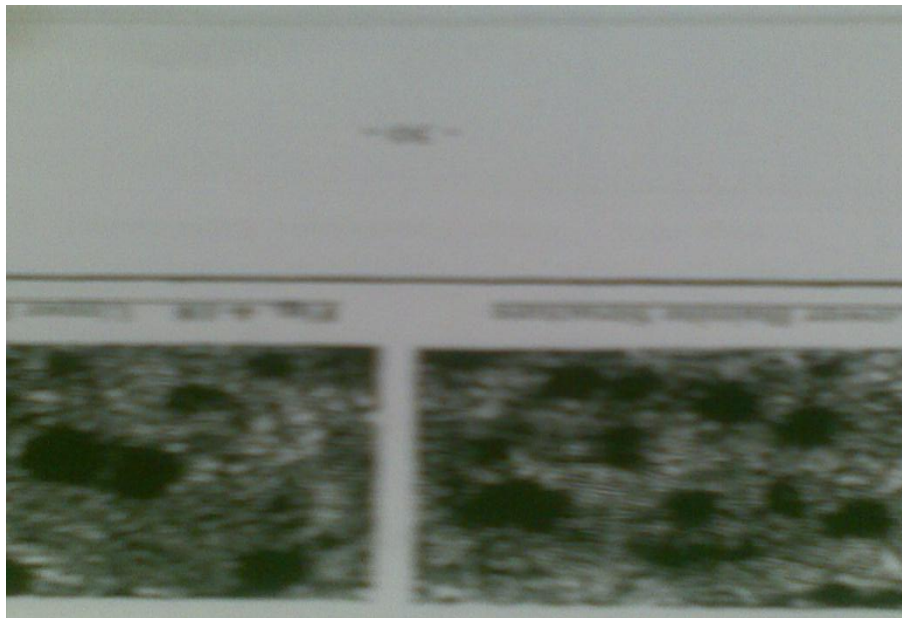


Fig.12.24 Lower Bainite Structure

Fig.12.25 Upper Bainite Structure

ii Surface Hardening

As a method of hardening the surface of castings, there are methods like flame hardening and high frequency induction hardening. As for ductile cast iron, surface hardening can be easily carried out to HRC 60 by flame hardening and high frequency induction hardening, the inside is not hardened by these methods and the toughness is maintained. In the case of pearlite structure, a sufficient hardening is obtained even if the time period for retaining at quenching temperature is very short. However, in the case of ferrite matrix, it requires some heating time period for diffusing C into the austenite matrix, in essence it is not suitable for surface hardening.

Summary of Heat Treatment of Cast Iron

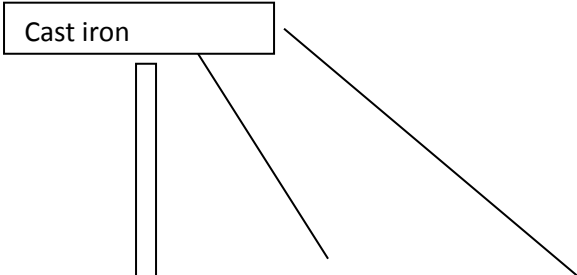
Cast iron is fundamentally used in the as-cast condition

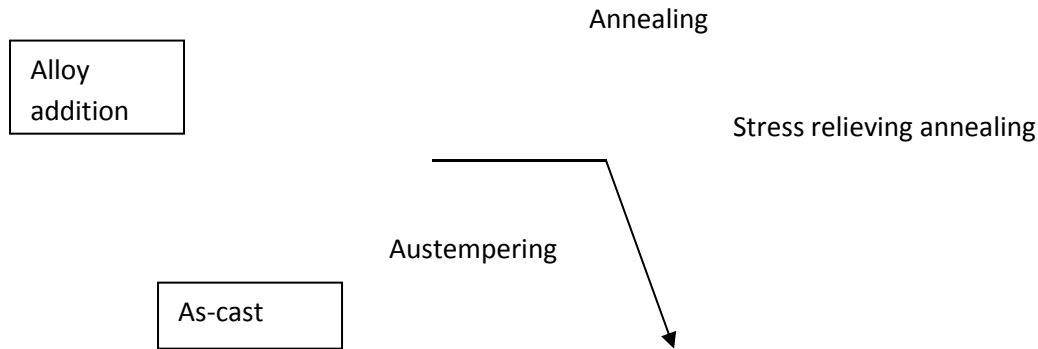
Improvement of the characteristic is often made by alloy addition.

Main Heat Treatment

- Annealing for high ductility
- Stress relieving annealing for prevention of passage-of-time change
- Normalizing, austempering for high strength
- Annealing after welding repair

Cast iron





Heat Treatment of Aluminum Alloy Castings

Solution Treatment and Aging of Aluminum Alloy Casting

Since many aluminum alloys such as Al-Cu, Al-Si-Mg, Al-Zn-Mg based alloys or the like have precipitation phenomenon in the ageing process, the enhancement of the mechanical properties due to heat treatment is contemplated. The heat treatment for ageing precipitation consists of the following operations:

- i. **Solution heat treatment:** casting is heated to a high temperature of around 800k (527°C) to make the structure uniform by deleting segregation during the casting, and at the same time, to sufficiently dissolve crystallization phase, precipitation phase or the like in the mother phase in order to obtain supersaturated solid solution.
- ii. **Quenching treatment:** by submerging supersaturated solid solution at a high temperature into water, the state of the high temperature is rapidly cooled and brought to the room temperature.

- iii. **Ageing hardening treatment:** after the solution heat treatment has been carried out, it is reheated to and retained at a comparatively low temperature around 440k (167°C), and the precipitation is promoted.

The operation described above will be explained with reference to Fig.11.26. if alloy of the composition q in the phase equilibrium diagram is cast, the concentration is different at the respective positions of α -dendrite internal within the crystal grain, non-equilibrium eutectic phase ($\alpha + \beta$) is crystallized at the interstices of branches of the respective dendrites and at the grain boundary, and micro-segregation is generated. At this time, if the casting material is heated to a temperature of p point and retained, alloy element is dissolved into the matrix, and the solid solution is formed. This operation is referred to as solution heat treatment. If the alloy is cooled from this state to a temperature lower than the solubility limit, the entire alloy element cannot be solid soluble, and β phase (compound) is precipitated.

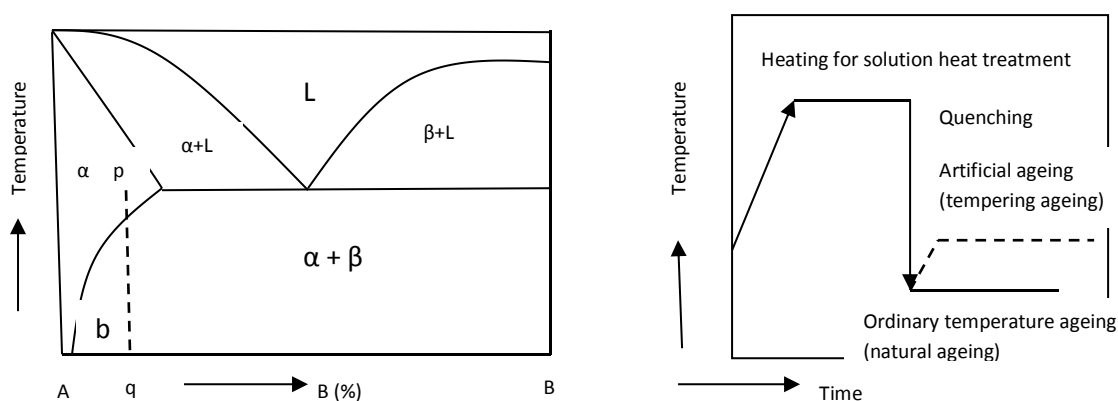


Fig.12.26 Heat Treatment Operation

In this way, since the precipitated β phase is coarse, it does not contribute to the hardening. After the solution heat treatment, if the casting material is submerged into water, warm water or oil to cool rapidly, in this case, the compound does not have any time to precipitate from solid solution, and supersaturated solid solution in which the alloy element has been excessively solid soluble is obtained at room temperature. Since this supersaturated solid solution is unstable, if it is left for a long time at room

temperature, the excessive portion is precipitated (room temperature ageing, or natural ageing). In this case, the precipitation is very fine and occurs uniformly, and makes the matrix hard, since in the natural ageing, it requires a long time for hardening, an artificial ageing treatment (ageing hardening treatment, tempering treatment) in which the precipitation is promoted by heating to a temperature in the range from about 400k to 490 k (127°C- 217°C) is carried out. The following processes are shown in Fig.12.27 with reference to an example of Al - 4.5%Cu alloy. The stabilization phase of the precipitation of Al-Cu based alloy is Al_2Cu compound, in Al-Cu-Mg based alloy, the precipitation phase is seen in Al_2CuMg compound, in Al-Si-Mg based alloy, the precipitation phase is Mg_2Si compound. The precipitation phase precipitated by age hardening treatment is a fine phase of the order that the electron microscope can observe. The processes of the precipitation accompanying heating are as follows:

Supersaturated solid solution $\longrightarrow$ GP zone $\longrightarrow$ (intermediate phase) $\longrightarrow$
stabilization phase

At the time when it is in the state of GP zone and intermediate state of precipitation processes, the strain of crystal lattice is enlarged and hardened. When it is in the stabilization phase, it does not contribute to the hardening

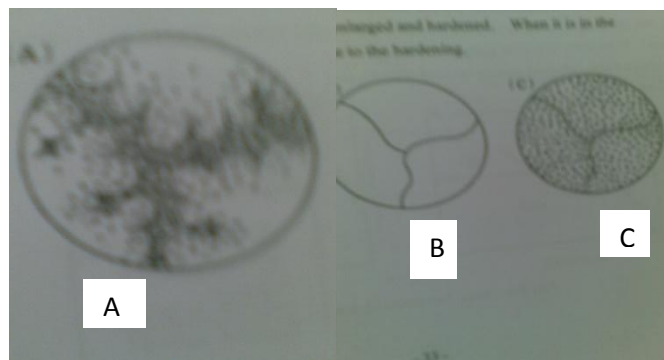


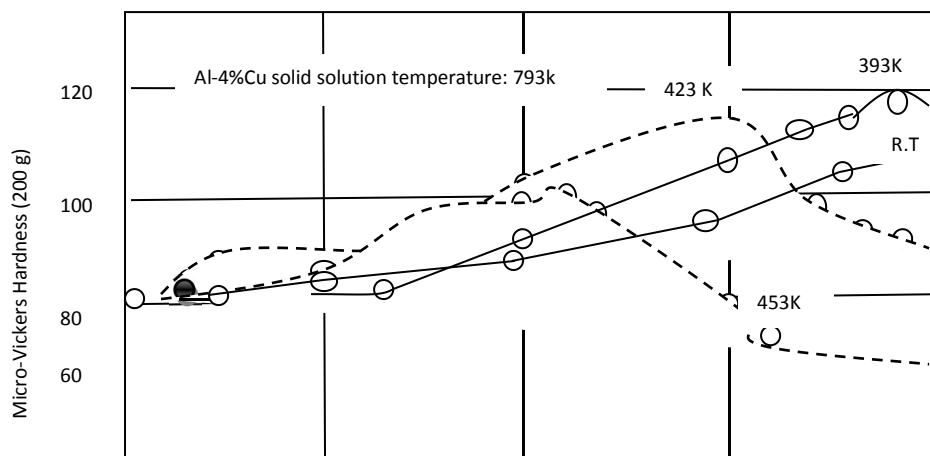
Fig 12.27 Structure of Al-4.5%Cu Alloy, and Influence of solution Heat treatment and Ageing Influence on Mechanical Properties

(note: the precipitation of ageing sample (C) cannot be observed by an optical microscope, but it can be observed by an electron microscope and can be seen as uniformly and finely distributed)

Table 12.8 Mechanical properties of solution heat treatment and water quenched Al-4.5%Cu alloy

	As –cast	Quenching	Ageing
Structure	primary crystal α Primary crystal $\alpha+\beta$ Precipitation phase θ	primary crystal α	primary crystal α primary crystal θ
Tensile strength kg/mm²	16.8	22.4	25.4
Proof stress kg/mm²	9.1	11.2	16.8
Elongation %	5	8.5	5
Hardness HB	5.5	60	75

In Fig.12.28 ageing curves are shown representing the change of hardness accompanying, the ageing time for Al- 4.5%Cu alloy aged at a variety of temperatures. With the elapse of the time, the hardening is initiated by the precipitation of GP zone, and the intermediate phase precipitates from the stage prior to the peak. After achieving the maximum hardness by fine precipitation phase. The hardness begins to be lowered as the intermediate phase becomes coarse. Although at a lower ageing temperature there is a delayed in rise of hardness, the value of the maximum hardness becomes higher when the ageing temperature is higher and precipitation hardening is promoted and the time period for achieving the maximum hardness becomes shorter, however, the value of the maximum hardness is lowered. An ageing in which the hardness (strength) indicates the maximum value is referred to as a peak ageing. The state prior to achieving the peak ageing is referred to as sub-ageing, and the state in which the softening is progressing after the peak ageing is referred to as over-ageing.



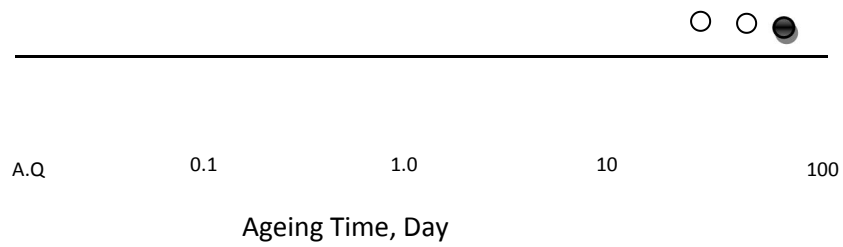


Fig. 12.28 Ageing hardening curves of Al-4.5%Cu Alloy

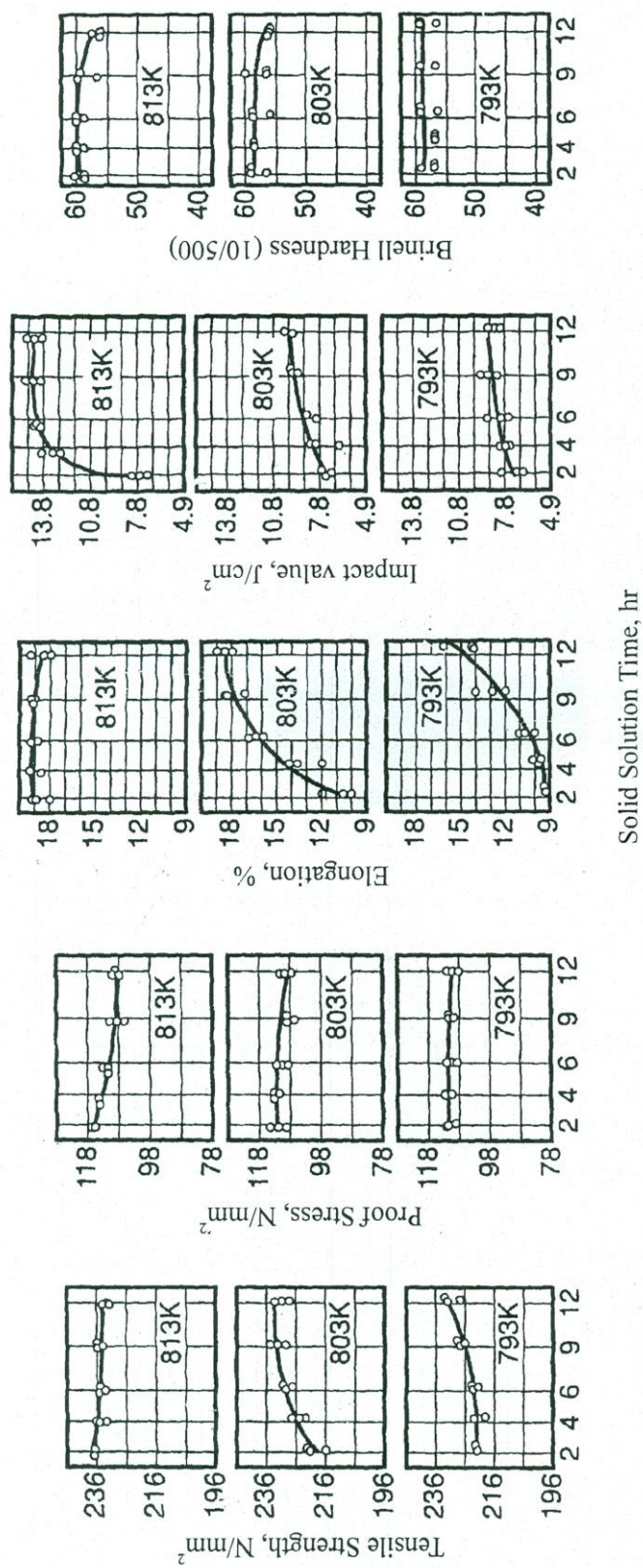


Fig. 7.29 Solid Solution Temperature, Time and Mechanical Nature of AC4C (Al-6.85%Si-0.30%Mg-0.20%Fe-0.12%Ti) T4 Member

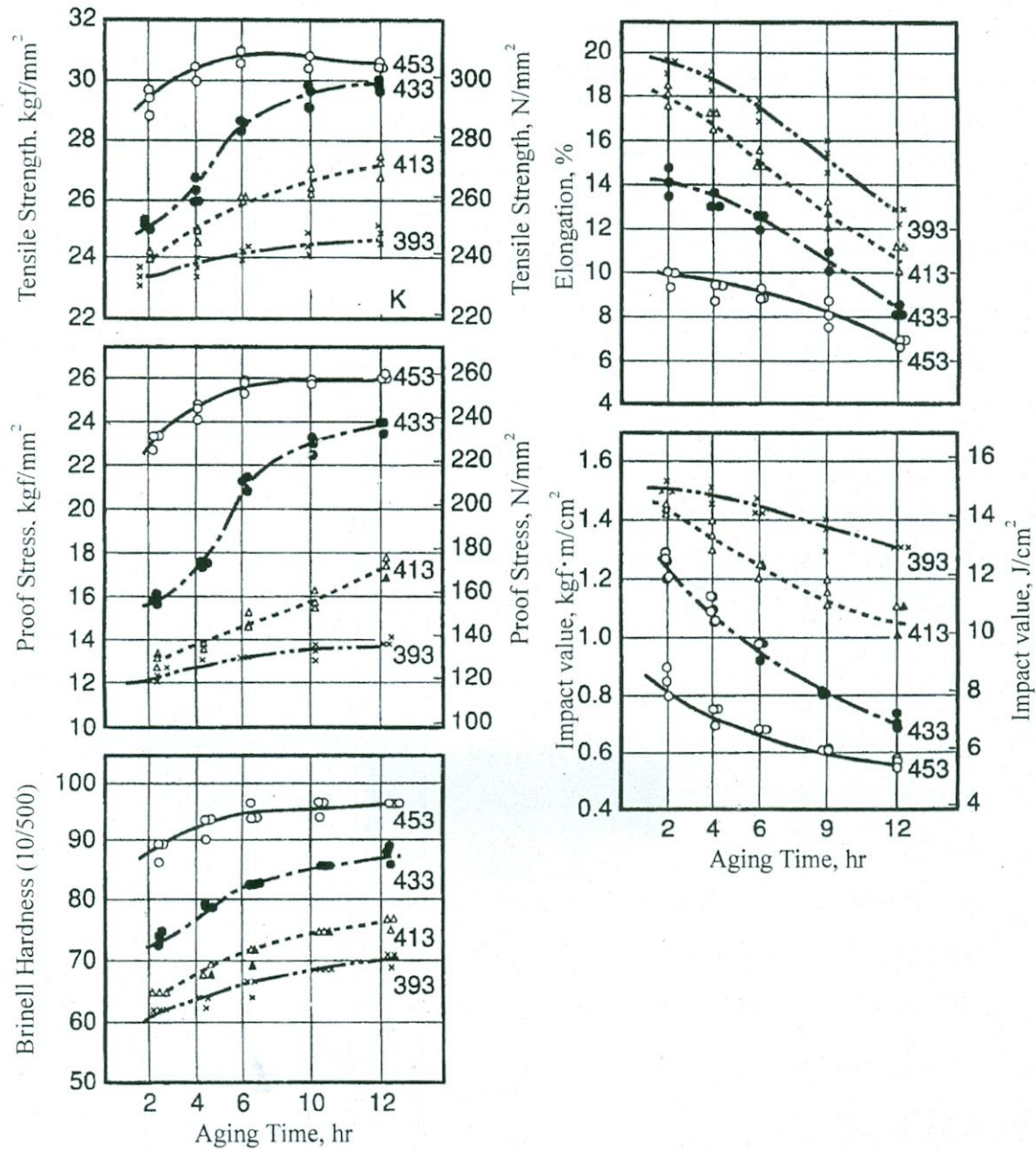


Fig 12.30 Aging Conditions and Mechanical Property of AC4C
(Al-6.85%Si-0.30%Mg-0.20%Fe-0.12%Ti)(813 K × 9 hr, 288K Water Cooling)

AC4C as a typical aluminum alloy is exemplified, the influence of temperatures and time periods in the solution heat treatment and artificial aging treatment upon the mechanical property is shown in Fig.12.29 and Fig.12.30. In general, there is shape change of eutectic silicon during solution heat treatment. Eutectic silicon becomes round with higher temperature or the longer the time of holding. This, in many cases, leads to elongation improvement and the tensile strength increases to some extent. If the

temperature is too high and ‘‘local melting phenomenon (burning)’’ that is partial dissolution begins, the lowering of the elongation may be significant.

In an artificial aging treatment, the mechanical properties are largely changed depending upon the temperature and time periods. Although it is necessary to set the most suitable conditions according to the object, usually, as the tensile strength, proof stress, hardness and the like are enhanced, the elongation and impact value are lowered. Castings such as wheels or parts of the suspension system, which attaches importance to toughness are treated in many cases, at a low temperature. Besides the above described heat treatment for the purpose of enhancing the mechanical properties, Other heat treatments for removing the strains such as casting strain, heat treatment strain or the like are used. The heat treatment for removing the generation of a minute dimensional change during use, and heat treatment for softening the material to add plastic deformation such as forging or caulking are also utilized. These are distinguished by the heat treatment symbols. The heat treatment symbols are indicated as follows:

F: as cast (as produced)

O: Heat treatments for the purpose of increasing the elongation as the pre-treatment before plastic working, and for the purpose of stabilizing the dimension, removing the residual stress such as casting straining, working strain, welding strain or the like. In general, the material is heated at about 620 K (347°C) for about 2 hours and slowly cooled to be annealed.

T4: Heat treatment in which natural aging treatment is carried out to a sufficient stable state after solution heat treatment. The toughness out of the mechanical properties is most enhanced, the corrosion resistance is improved. As for the strength, it is somewhat lower compared to T6 Treatment.

T5: Heat treatment where the casting cooled to room temperature after the casting is subjected only to an artificial aging treatment for the sake of enhancing the strength and stabilizing the dimension. Usually, since the casting whose thickness is thin or which has been quenched by metal mould or chilling block is to some extent in a supersaturated solid soluble state even if the solution heat treatment is not carried out, the precipitation is generated by an artificial ageing. Since the supersaturated degree is

low, the amount of precipitation is slight. This is a heat treatment for carrying out only aging hardening treatment (tempering treatment) for the purpose of raising the strength.

T6: Heat treatment in which hardening is carried out after the solution heat treatment, then an artificial hardening treatment is performed. It is carried out for the sake of obtaining high values particularly in strength and hardness. Accompanying the rise of the hardness, the toughness as well as elongation, impact value and the like are lowered.

T7: heat treatment in which the hardening is carried out after the solution heat treatment, and the precipitation is promoted at a higher temperature than the artificial aging temperature that gives the maximum strength to obtain the over-aging state. The internal strain is reduced, the dimension is stabilized, and corrosion resistance is improved. The strength is lower than T6, but the toughness is higher.

Concerning alloys of JIS standards, the heat treatment conditions of the respective alloys recommended in the standards are shown in Table 12.9

Table 12.9 Heat treatment Conditions of JIS Aluminum Alloy Test Pieces cast in Metal Mould

Kinds	Classification of Qualities	Symbols	References					
			Heat treatments					
			Annealing		Solution heat treatment		Tempering	
			Temp. (K)	Time (h)	Temperature (K)	Time (h)	Temperature (K)	Time (h)
First kind A	As cast	AC1A-F	-	-	-	-	-	-
	Solution treatment quenching	AC1A-TA	-	-	About 788	About 10		
	Solution treatment quenching-tempering	AC1A-T6	-	-	About 788	About 10	About 433	About 6
First kind B	As cast	AC1B-F	-	-	-	-	-	-
	Solution treatment quenching	AC1B-T4			About 788	About 10	-	-
	Solution treatment quenching-tempering	AC1B-T6			About 788	About 10	About 433	About 4
Second kind A	As cast	AC2A-F	-	-	-	-	-	-
	Solution treatment quenching-tempering	AC2A-T6	-	-	About 783	About 8	About 433	About 9
Second kind B	As cast	AC2B-F	-	-	-	-	-	-
	Solution treatment quenching-tempering	AC2B-T6	-	-	About 773	About 10	About 433	About 6
Third kind A	As cast	AC3A-F	-	-	-	-	-	-
Fourth kind A	As cast	AC4A-F	-	-	-	-	-	-
	Solution treatment quenching-tempering	AC4A-T6	-	-	About 798	About 10	About 433	About 9
Fourth kind B	As cast	AC4B-F	-	-	-	-	-	-

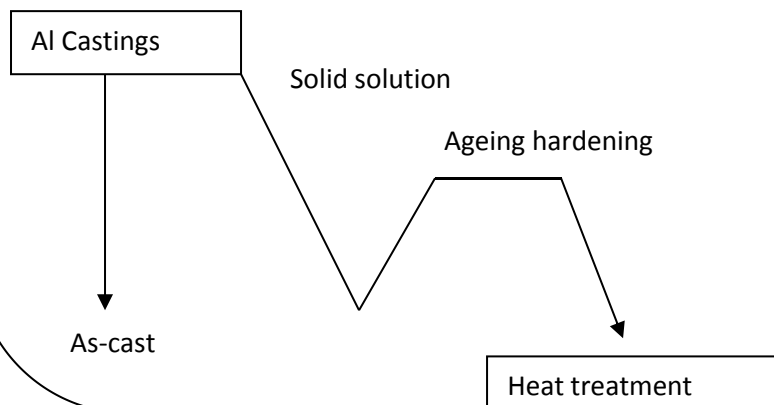
	Solution treatment quenching-tempering	AC4B-T6	-	-	About 773	About 10	About 433	About 7
Fourth kind C	As cast	AC4C-F	-	-	-	-		
	Tempering	AC4C-T5	-	-	-	-	About 498	About 5
	Solution treatment quenching-tempering	AC4C-T6	-	-	About 798	About 8	About 433	About 6
	Solution treatment quenching-tempering	AC4C-T61	-	-	About 798	About 8	About 433	About 7
Fourth kind CH	As cast	AC4CH-F	-	-	-	-	-	-
	Tempering	AC4CH-T5	-	-	-	-	About 498	About 8
	Solution treatment quenching-tempering	AC4CH-T6	-	-	About 808	About 8	About 428	About 6
	Solution treatment quenching-tempering	AC4CH-T61	-	-	About 808	About 8	About 443	About 7
Fourth kind D	As cast	AC4D-F	-	-	-	-	-	--
	Tempering	AC4D-T5	-	-	-	-	About 498	About 5
	Solution treatment quenching-tempering	AC4D-T6	-	-	About 798	About 10	About 433	About 10
Fifth kind A	As cast	AC5A-O	About 623	About 2	-	-	-	-
	Solution treatment quenching-tempering	AC5A-T6	-	-	About 793	About 7	About 473	About 5
Seventh kind A	As cast	AC7A-F	-	-	-	-	-	-
Seventh kind B	Solution treatment quenching (air cooling)	AC7B-T4	-	-	About 703	About 18	-	-
Eight kind A	As cast	AC8A-F	-	-	-	-	-	-
	Tempering	AC8A-T5	-	-	-	-	About 473	About 4
	Solution treatment quenching-tempering	AC8A-T6	-	-	About 793	About 4	About 443	About 10
Eight kind B	As cast	AC8B-F	-	-	-	-	-	-
	Tempering	AC8B-T5	-	-	-	-	About 473	About 4
	Solution treatment quenching-tempering	AC8B-T6	-	-	About 783	About 4	About 443	About 10
Eight kind C	As cast	AC8C-F	-	-	-	-	-	-
	Tempering	AC8C-T5	-	-	-	-	About 493	About 4
	Solution treatment quenching-tempering	AC8C-T6	-	-	About 783	About 4	About 443	About 10
Ninth kind A	Tempering	AC9A-F5	-	-	-	-	About 523	About 4
	Solution treatment quenching-tempering	AC9A-T6	-	-	About 743	About 4	About 473	About 4
	Solution treatment quenching-tempering	AC9A-T7	-	-	About 773	About 4	About 523	About 4
Ninth kind B	Tempering	AC9B-F5	-	-	-	-	About 523	About 4
	Solution treatment quenching-tempering	AC9B-T6	-	-	About 773	About 4	About 473	About 4

	Solution treatment- quenching- tempering	AC9B-T7	-	-	About 773	About 4	About 523	About 4
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Summary of Aluminum Casting

Aluminum casting is subjected to heat treatment depending on production process. Gravity die casting and low pressure die castings can change their property by the method of heat treatment.

Die castings are not heat treated. Recently high vacuum die-casting process which can adopt heat treatment is introduced.



Heat Treatment of Magnesium Alloy Castings

Magnesium Alloy for Casting and Condition of Heat treatment

The typical magnesium casting alloy are shown in Table 12.10. The corrosion resistance of the Mg-Al alloy improves by the restraint of impurity elements drastically. The die-casting manufacturing method is the mainstream, but a high strength magnesium casting is expected by heat-treatment after gravity die-casting or low pressure die-casting.

Table 12.10 Heat Treatment Condition and Property of Typical Magnesium Casting Alloy

Symbol		HT	Tensile Test			References				
			TS N/mm ²	Ty 0.2% (N/mm ²)	Elong.. %	Solution anneal			Aging	
						Temp± 6 °C	max. Temp °C	Time (h)	Temp ± 6 °C	Time (h)
MC1	AZ63A	F	180≤	70≤	4≤	-	-	-	-	
		T4	240≤	70≤	7≤	385	391	10-14	-	
		T5	180≤	80≤	2 ≤	-	-	-	260	4
									232	5
		T6	240≤	110≤	3 ≤	385	391	10-14	218	5
									232	5
MC2E	AZ91E	F	160≤	70≤	—	-	-	-	-	-
		T4	240≤	70≤	7 ≤	413	418	16-24	-	-
		T5	160≤	80≤	2 ≤	-	-	-	168	16
									216	4
		T6	240≤	110≤	3 ≤	413	418	16-24	168	16
									216	5-6
MC3	AZ92A	F	140≤	75≤	1 ≤	-	-	-	-	-
		T4	230≤	75≤	6 ≤	407	413	16-24	-	-
		T5	160≤	80≤	—	-	-	-	260	4
		T6	235≤	110≤	1 ≤	407	413	16-24	218	5
MC5	AM100	F	140≤	70≤	—	-	-	-	-	-
		T4	240≤	70≤	6 ≤	424	432	16-24	-	-
		T5	160≤	80≤	—	-	-	-	232	5
		T6	240≤	110≤	2 ≤	424	432	16-24	232	5

Fundamentally, heat treatment of magnesium castings is similar to aluminum castings. However, in the case of magnesium alloy castings it is important to take care or prevent ignition during heat treatment. When magnesium casting is heat treated, the atmosphere of the heat-treatment furnace inside is filled with SF₆ gas which flows to suppress the burning. Usually mix gas with 0.2-0.3% SF₆ and CO₂ gas flow in the furnace. It is necessary to operate it carefully because the product burns when gas is cut during heat treatment. Magnesium castings have improved grain refining by inoculation or superheat treatment before the pouring. As crystal grain becomes fine, strength and elongation is equal to aluminum alloy casting.

REVIEW QUESTIONS FOR CHAPTER TWELVE

1. List the types of heat treatment administered on steel castings
2. Explain five types of heat treatment administered on steel castings

3. Mention some types of steels and indicate the type of heat treatment for the steel type
4. Explaining annealing types for steel castings
5. Explain the following: quenching, solution treatment, and surface structure change by mould reaction
6. List some characteristics of cast irons that makes them suitable as castings
7. Does reducing impurity and heat treatment of Al-Mg alloy increase strength? Explain
8. Explain the alphabets, F, O, T4, T5, and T6 as it relates to heat treatment.
9. What is ageing?
10. What do you understand by precipitation hardening process? Explain
11. How does solution heat treatment and ageing influence mechanical properties of Al-4.5%Cu alloy?
12. What are the principal stages in the heat treatment of aluminium alloy castings?
13. What are the main heat treatment given to cast iron castings?
14. List and explain the surface hardening methods carried out on castings that you know
15. Draw the heat treatment pattern for austempered ductile cast iron and explain
16. Draw a heat treatment pattern for quenching and tempering of spheroidal graphite cast iron and explain
17. Draw the heat treatment pattern for normalizing cycle for cast iron
18. Draw the stress relieving annealing cycle for cast iron and explain
19. Draw the annealing cycle for ductile cast iron and explain
20. What is soft annealing?
21. Write a short note on ductile cast iron.
22. Write on general characteristics and classification of cast iron
23. Draw the heat cycle for hardening of steel

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CHAPTER THIRTEEN

INSPECTION AND QUALITY CONTROL OF CASTINGS IN THE FOUNDRY

According to Beeley (1982) the inspection of castings has the dual purpose of ensuring that the product conforms to design requirements, and of providing information needed for quality control in the foundry. Although foundry production and technical staff are concerned in many aspects of quality control, the systematic collection and interpretation of quality data is frequently channeled through an inspection department, which has a special responsibility for the administration of standards embodied in contracts and commercial relationships.

A modern quality control organization is concerned with a great deal more than the routine sorting of properties in relation to specified limits. Much data is obtained by the use of highly sophisticated equipment and techniques and more detailed treatment than simple go or no-go tests is required in interpreting the results. Adverse trends may then be detected before quality determination leads to a high proportion of rejects (Quilter, 1969).

With the information from current production should be integrated findings from complaints and customer rejects, although such information is often of limited value on account of the delay before its receipt. This emphasizes the need to minimize delays in the further processing of castings; where this is impracticable, a system of scheduled proof machining of representative sample batches reduces the risk of accumulating undetected defects.

During the twentieth century running through this twenty first century, great strides have been made in foundry science and technology. The nature of metals is much better understood, thanks to much research and to new instrumentation. Foundry equipment has undergone a major revolution, permitting a high degree of mechanization, with better controls and uniformity. The concept of quality control by data analysis has gained a foot-hold. Nevertheless, there remain many variables which are still handled by empirical methods. Most important, applying the available scientific knowledge still runs into formidable cultural resistance, since the industry has long been rooted in empiricism. The computer has become a valuable tool in producing quality castings. Computers are used at the design stage of the casting for both the drawing and to carryout simulations. Simulations can be carried out for thermal analysis, solidification simulation and flow pattern in the gating system, and mould cavity. The simulation process helps in predicting shrinkages and other defects

that would occur in the actual casting process and necessary corrective measures are taken to avoid the occurrence of such defects (Brown, 1994).

According to Ihom (2003) quality control and inspection are important technical and economic considerations in manufacturing. Though engineers and customers specify quality standards it is the responsibility of the manufacturing division to produce work of satisfactory quality. For a better understanding of our topic it is important for us to define some key words.

The quality of a product: is defined by a set of specifications governing functional performance, composition, strength, shape dimensions, workmanship, colour, and finish. Quality is meaningful only in relation to the purpose and end use of the product. "Good quality" is attained when a product or service fully satisfies the purpose for which it is designed. To the user, quality is fitness for use, not conformance to specifications.

Quality Planning: the quality planning process is a series of events requiring close collaboration between the foundry and its customers. It involves product specification, casting design, design review, samples for qualification testing, trial runs and formal manufacturing planning.

Control: is the process through which we prevent change or retain the status quo (Juran, 1979). The process through which we establish and meet standards is commonly called "control".

Quality control: means the recognition and removal of identifiable causes of defects and variations from the set standards. When a product is substandard, statistical techniques can be used for the systematic observation of quality and interpretation of variability; the corrective action can be undertaken. Proper standardization and effective control of materials, machines, and workmanship insure uniform quality in the product (Ihom, 2003). According to Juran (1979) when the universal process is applied to problems of product quality, it is often "quality control". Quality control is the regulatory process through which we measure actual quality performance, compare it with standards, and act on the difference.

Inspection: is the application of tests and measuring devices to compare products and performance with specified standard; specified limits of variability and, therefore, is acceptable or unacceptable (defective) (Ihom, 2003). According to Parker and Truckenmiller (1979) foundry inspection and tests are done both as controls on the process and as checks on the product. Inspection always involves evaluating the quality of some characteristic in relation to a standard.

Castings: are products of the foundry-shop; they are metal objects formed by melting and pouring molten metal into a mould box with preformed cavity, where it solidifies to form the metal object.

INSPECTION

The inspection of castings has the dual purpose of ensuring that the product conforms to design requirements and of providing information needed for quality control in the foundry. This has been explained in details in the introduction. We will now look at standards and their commercial implication (Beeley, 1982).

Standards and their Commercial Implication

The initial requirement for inspection is the establishment of standards reflecting the intentions of the designer. Design in the broadest sense requires definition of the product in terms of physical shape and dimensions, composition and properties, and general quality. Inspection is based on permissible standards of deviation from the ideal. Some factors, for example dimensions, composition, and mechanical properties, are capable of precise quantitative definition so that numerical tolerance limits can be prescribed: in other cases subjective judgments are needed.

Many explicit design requirements can be conveyed in drawings and specifications. Castings may, for example, be manufactured to a widely recognized specification such as a British standard, in conjunction with drawings or patterns provided by the purchaser. Many formal specifications are, however, confined the definition of chemical composition and/ or mechanical properties, whereas castings require further qualities implicit in the capabilities of the process: the maintenance of these qualities, for example soundness and surface finish, is frequently dependent on internal standards instituted by the manufacturer. These standards are closely associated with commercial policy and may be set at a higher level than strictly necessary to meet the formal specification. Standards must not, on the other hand, be set at an unrealistic level in relation to the basic capability of the particular casting process; the economic implications of high standards must also be appreciated. Unnecessary tight compositional tolerances, for example, may entail additional raw material costs or higher rejection rates, whilst the cost of more rigorous inspection procedures must itself be reflected in the selling price of the casting.

Radiographic and other special techniques are particularly expensive and should not be formally specified unless absolutely necessary. It is important that the significance and cost of these techniques be fully appreciated by the purchaser. Whilst of great value to the founder for methods development and for sample checks on quality during production; they should, where stipulated for routine inspection, be separately quoted and invoiced wherever possible.

Material and Product Testing Procedures

Routine casting inspection normally involves geometric checking for shape and dimensions. Representative chemical analysis and mechanical properties are also often available.

These measures are increasingly supplemented by various forms of no-destructive testing, hydraulic testing and proof loading. Since all such measures add to the cost of the product, the first consideration must be to determine the amount of inspection needed to maintain adequate control over quality. In some cases this may require full examination of each individual casting but in other cases sampling procedures may suffice.

Whilst it is customary to perform at least a limited visual inspection on all castings, detailed inspection may be confined to critical points at which variations are likely to occur: it is in this respect that a full understanding of the foundry method on the part of the inspector can eliminate unnecessary routine. Certain cast dimensions are susceptible to variation from mould and core movement, whilst others, depend primarily on a single element of the pattern, are liable to vary only within narrow limits. Similarly, detailed understanding of the service function of a casting clarifies the relative importance of its dimensions and the significance of defects in different zones. According to Clegg, (1991) for those mould materials based on the use of sand, a variety of established tests are used to monitor and control their quality. These tests include grain size distribution and grain fineness number, which determine the base sand's permeability, binder demand and influence on surface finish and are therefore important in the inorganic and organic bonded systems and even the unbonded sand systems. Beyond these tests the requirements will be different, depending upon the specific bonding agent. For the clay-bonded green sand system, tests to establish the moisture content, active clay level, compactability, compression strength, deformation characteristics, and permeability of the sand are widely practised (Clegg, 1991).

The inspection procedure must therefore be adjusted to suit the particular circumstances surrounding each type of casting. If sampling is used it must be appreciated that there can be no absolute assurance of freedom from defects in an individual case, so that complete coverage is needed in critical applications where no further sorting will occur. In those cases where inspection is to be limited to certain features or to a proportion of total production, full inspection may be carried out on preliminary samples and during the early

stages of production, and may be resumed if trouble is encountered during later production runs.

An important element in inspection and quality control concerns the identity of the castings examined. Whilst many castings are manufactured with no attempt at prolonged identification, a distinguishing mark of origin on each casting is a valuable aid to the maintenance of quality records. Abbreviated cast and serial numbers can be stamped at an early stage on all save the smallest castings: the marking can often be retained throughout the life of the casting to provide permanent reference to its production and inspection history. Metal stamping must be applied with discretion in view of the frequent incidence of fatigue failures initiated at such stamps: it is essential to position them away from highly stressed regions (Beeley,1982).

Shape and Dimensions

Brief visual inspection of each casting ensures that none of its features has been omitted or malformed by moulding errors, short running or mistakes in fettling. Serious surface defects and roughness can be observed at this stage.

Dimensional examination is then carried out against the drawings, aided by gauges, jigs and templates: tolerances on the cast dimensions are normally included on the drawing. In some cases this operation can be combined with marking out for subsequent machining. Where castings are destined for machining without individual marking out, particular care is needed in respect of dimensions incorporating datum surfaces. Errors involving these surfaces can produce consequential errors or inadequate machining cuts elsewhere on the casting. In cases where the weight of the component is critical a specific weight check may be included: this may also be required for costing purposes (Beeley, 1982).

Where dimensional errors are detected in relation to general drawing tolerances, their true significance must be determined. A particular dimension may be of vital importance, but may on the other hand have been fortuitously included in blanket tolerances needed primarily elsewhere. A recommendation of the international organization for standardization stresses the desirability of stating functional dimensions on drawings so that tolerances are not restricted unnecessarily.

In cases where castings have been produced from patterns supplied by the purchaser, these may, subject to the recognized contraction allowances, form the direct basis for the dimensional examination. The owner of the pattern is then implicitly responsible for the cast dimensions, apart from errors due to distortion or fettling. It is nevertheless usual for most

foundries to verify the patterns against drawings when these are also available. Plate 1 shows a shape and dimensional defect.



(a)

(b)

Plate 1: Shows (a) Shape and Dimensional Defect (b) surface defect and shape defect arising from core movement.

Surface Quality and Finish

Quantitative standards are seldom adopted for the surface finish of castings, which are normally judged from visual examination alone. Numerical standards may, however, be specified if required. The simplest evaluation is by visual comparison with a series of standard surfaces: these may be arbitrarily graded, or may themselves have been

quantitatively assessed by other means. Alternatively, a stylus measuring instrument may be used to obtain representations of surface profiles. Such instruments are usually only suitable, however, for distinguishing between relatively smooth surfaces such as those obtained in precision casting processes: they provide graphical representation of the profile or an integrated numerical value derived from the total vertical movement of the stylus relative to a datum during a fixed length of traverse.

Composition and Mechanical Properties

Melting: The importance of the metal melting stage was described earlier on in chapter 7. Regardless of the alloy being cast, metal temperature is an important variable to monitor and control. Incorrect control can result in a variety of problems such as the loss of volatile elements, absorption of gases, metal penetration of the mould when the temperature is too high, and misrun castings when the temperature is too low. The most popular method of measuring metal temperature is that based on the immersion of a thermocouple but optical and radiation pyrometers are also used (Clegg 1991)

Quality control tests to establish the level of gas in the molten metal are important for those alloys which are especially susceptible to gas absorption during melting. These include aluminium and copper-base alloys, which are susceptible to hydrogen absorption. The tests available range from simple and effective qualitative methods, such as solidification of samples under reduced pressure followed by sectioning to identify gas porosity, to quantitative methods based on vacuum diffusion extraction of a gas from a solid sample followed by a measurement technique.

The composition and mechanical properties of castings are normally determined by tests carried-out on specimens cast from the same heat of metal.

Composition: chemical composition is usually determined on separately cast analytical samples identified by cast-in tags or by stamping. To be truly representative the sample must be drawn at the same time as the castings are poured, since losses of volatile or readily oxidized elements may otherwise cause the compositions to diverge. Where casting operations are prolonged, or where successive ladles need to be drawn from a single heat or from a holding furnace, frequent sampling is needed at the casting point. Analysis may also be carried out on discard metal from heads and runners.

Composition is normally assessed in relation to specified limits for the major alloying elements and expected impurities, but watch also needs to be kept on occasional tramp elements and on gas content. The need for a particular balance of composition, as required, for example, to maintain a carbon or zinc equivalent, may be superimposed on the limits for individual elements. The increasing use of spectrographic, X-ray fluorescence and other physical techniques to replace wet analysis enables a comprehensive range of elements to be simultaneously and rapidly determined. Apart from the advantage for routine analysis, this permits more extensive bath sample analysis and thereby improves control in melting. The composition of each cast can also be verified before the castings are further processed, minimizing loss of production time.

Qualitative Tests: in the case of cast iron, for example, it is possible to obtain a guide to the alloy's composition from two simple shop-floor tests. In the first, known as the chill test, a sample of metal is poured into a wedge-shaped cavity in a sand mould. The alloy solidifies quickly in the thinnest section as white iron. The lower the carbon and/or silicon content of the melt, the greater will be the depth of this chill layer. By calibrating the depth of chill against known compositions, the foundry has a rapid guide to a melt's suitability. In the carbon equivalent test a sample of cast iron is poured into a special cup containing a thermocouple. From the cooling curve it is possible to establish the iron's carbon equivalent value, which is a function of its carbon, silicon and phosphorus contents. This value correlates closely with the alloy's mechanical properties and provides a guide to the alloy's acceptability before pouring. The technique of thermal analysis can be extended to provide a good estimate of carbon and silicon content when the phosphorus content is consistent and low

Wet Analysis: The traditional method of analysis requires that the alloy be reduced to an aqueous solution using treatments appropriate for each element to be analysed. Gravimetric or volumetric techniques may then be used to establish an element's concentration to a high degree of accuracy. Such procedures are most effective when used to establish the major constituents present in an alloy. The procedures require skilled chemists and are often time consuming.

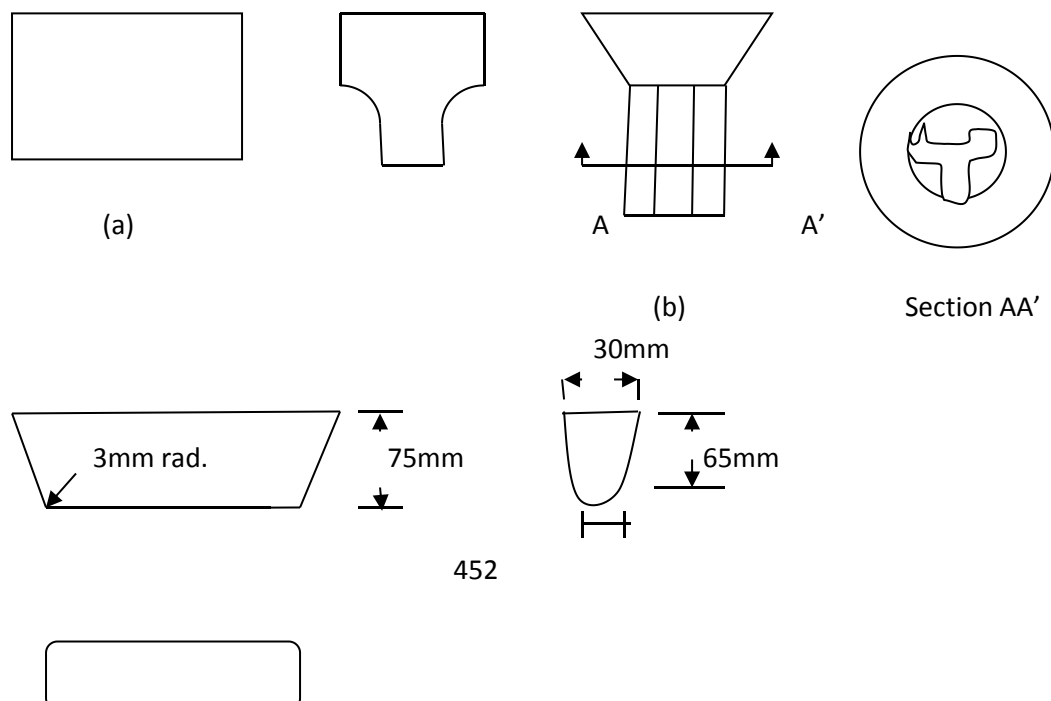
Spark Emission Spectrometry: In this technique a high energy spark vaporizes metal from the surface of a prepared cast sample in an evacuated chamber. Diffraction gratings are used to separate the wavelengths of light emitted from the elements of interests and the amount of light energy emitted by each element is analysed and converted to a concentration value for that element. Property standardized equipment can with the incorporation of a

powerful computing program, routinely provide the analysis of a sample within 5 minutes. The equipment is relatively expensive, but has the potential to provide an analysis for up to 48 elements.

X-Ray Fluorescence Spectrometry (XRF): This technique utilizes the interaction of the inner-shell elements with primary X-ray. The secondary x-rays produced are separated into the wavelengths related to the elements to be measured, using either energy dispersive or wavelength dispersive methods, and the intensity of each is recorded. Although expensive, the equipment is versatile and widely used in the non-ferrous industry (Clegg, 1991).

Mechanical Properties: specimens for mechanical testing are normally machined from specially designed cast test bars. These may be poured separately from the same heat of metal or may, especially in the case of heavy castings, be directly attached to the casting itself.

The status of the test bar should be free from ambiguity: it is intended, with certain exceptions, to be representative of the particular heat of metal and not of any individual casting. The measured properties will reflect influences of dissolved gas, inclusions and melt treatments but will not necessarily be those which would be obtained from test pieces cut from actual castings, since there may be differences in section, structure and degree of feeding. Standardization of test bar conditions permit the use of measures to ensure perfect soundness of the test specimen so that yield is largely disregarded and most test bars are heavily overfed. Keel block and other typical test bar designs showing this feature are illustrated in Figure 13.1.



19mm

180mm

(c)

Figure 13.1: Some Designs for Cast test Bar (a) General Purpose Keel Block (b) Clover Leaf Test Bar (c) Chill Cast Test Bar for Light Alloys. Source: Beeley (1982).

However, more benefit is to be derived from the retention of cast surfaces in close proximity to the final test piece, hence the use in certain test bar designs of a cast shape conforming closely to the contour of the machined test specimen. It should be added that to avoid major differences in cooling conditions, all test bars are normally cast in moulds of similar material to that used for the groups of castings they represent; casting temperature should also be standardized as far as possible. Special conditions exist in the case of cast iron owing to the marked dependence of structure and properties upon section thickness and cooling rate. It is therefore desirable for the test piece to be reasonably representative of general section thickness as well as composition: various test bar sizes are accordingly specified with cast diameters ranging from 15-53 mm.

Castings may be evaluated on the basis of a wide range of mechanical tests. Tensile test is normally carried out on the universal type of testing machine, results for proof or yield stress, tensile strength, elongation and reduction of area being obtained. Other tests include hardness testing, this test apart from its value as a guide to wear resistance and machinability, is frequently used to verify the effectiveness of heat treatment applied to actual castings; its general correlation with tensile strength enables a rough prediction of that property to be made, notched bar impact values are induced in some casting specifications, even though the results have no direct quantitative design significance. Both Charpy and Izod tests are used; bend, transverse and compression tests are other tests normally specified. For routine inspection, fatigue, stress rupture or creep tests are not used. Various special tests like test for weld decay as applied to austenitic stainless steels, ballistic tests on plates, and weldability tests may be applied to establish the response of the cast material to subsequent manufacturing and service conditions.

Destructive Tests on Castings

Mechanical test results from cast-on or separately cast bars may be supplemented by tests carried out on specimens removed from actual castings, variation of properties within a single casting, results from inevitable differences in microstructure, density, and composition produced by local differences in freezing conditions. Whereas the normal test block is designed to evaluate the metal under ideal conditions of feeding, tests on sectioned castings can provide a more direct indication of properties within a particular design.

Systematic sectioning also facilitates the direct investigation of structure and internal soundness by metallographic techniques and aids the accurate interpretation of results of radiographic and other methods of non-destructive testing.

Another form of destructive testing involves the direct loading of representative castings to failure in special fixtures.

Simulating service stresses: the deformation and breaking load and the position and nature of the fracture provide a guide to material quality and to the behavior of the design under highly stressed conditions. In a simpler form of test the casting can be fractured by compression in a press.

Castings for destructive testing may be selected from rejects from other causes, but it may in some cases be necessary to sample a proportion of castings from normal production. Such techniques can form a vital aid to the interpretation of test results and inspection findings derived by more conventional means.

Soundness: The Non-Destructive Testing of Castings

Various methods are available for determining the internal soundness of castings without recourse to sectioning. The ability to detect invisible flaws not only assists in maintaining high quality standards, but provides a valuable aid to the development of foundry methods. These factors have greatly enhanced the position of the casting in engineering. However, since non-destructive testing greatly increases sensitivity of the inspection operation, the techniques need to be adopted and interpreted with discretion if unnecessary rejections are to be avoided.

It will be the object in the following section to review the methods which have become well established in the foundry field. These include a number of techniques of surface flaw detection and the two main forms of internal examination, namely radiography and ultrasonic testing.

Tests for Defects in the Surface Zone

Cracks and other flaws communicating directly with the surface of the casting can be detected by a number of techniques including penetrant methods, chemical etching and magnetic flaw detection; the latter method is also capable of revealing flaws situated immediately below the surface. All the methods require clean and reasonably smooth surfaces for effective detection.

The penetrant methods are based on the use of fluids to permeate and highlight defects by increasing their contrast with the surrounding surface. The methods are also particularly useful for establishing the soundness and integrity of thin walled castings in cases where pressure testing is not readily applicable. Penetrant solution can be applied to one face and the opposite face examined for signs of seepage.

Dye Penetrant Testing

The surface of the casting is in this case treated with a dye solution based on a low viscosity solvent. The solution can be applied by brush or aerosol spray or the casting can be entirely immersed in a tank of solution; the casting is then thoroughly rinsed and dried. After a time, seepage of residual fluid occurs from cracks and other narrow surface defects to produce a visible stain. A widely used variation of the technique utilizes fluorescent dyes, enabling the search for flaws to be carried out with an ultraviolet source in a darkened cubicle.

Oil and Chalk Testing

This long established technique uses paraffin oil as the penetrant medium. The casting is treated, usually by immersion with heated paraffin; it is then rinsed in detergent solution and water and dried. Using a low pressure air dispenser the surface is coated with dry powder chalk, which becomes marked after a time by seepage of paraffin from cracks or porous zones.

Chemical Etching

Very fine surface cracks, laps and similar defects may be masked by a very thin layer of metal resulting from superficial plastic deformation. This can occur in shot blasting, in fettling or even in the machining of a casting. In other cases the masking layer may consist of oxide scale formed in heat treatment. Normal penetrant methods are not always effective in such cases.

Controlled corrosive attack in a picking solution offers a method of revealing these hidden surface defects and at the same time of exposing subcutaneous pinholes. The technique employs acid or acid salt mixtures developed for particular alloys, the casting being immersed in the etching

bath, rinsed and dried. Defects are rendered visible by local staining against the clean, matt surface produced by the etch. Care must be taken to neutralize excess acid and rinse after completion (Beeley,1982).

Magnetic Flaw Detection

Ferromagnetic materials, notably iron and steel, respond to magnetic flaw detection, a highly effective and sensitive technique for revealing cracks and similar defects on or just beneath the casting surface. When a piece of metal is placed in a magnetic field and the lines of magnetic flux are intersected by a discontinuity such as a crack, poles are induced on either side of the discontinuity. The resulting local flux disturbance can be detected by its effect upon magnetic particles, which become attracted to the region of the defects. Maximum sensitivity of indication is obtained when a crack runs in a direction normal to the applied field and when the strength of this field is just enough to saturate the section being examined. A defect just below the surface can still exert a visible influence upon magnetic particles at the surface.

The magnetic particles for flaw detection may be applied directly to the surface as a dry powder, but are more commonly suspended in a suitable fluid as an “ink”. The particles in such inks must be large enough, and the flow of fluid over the surface sufficiently slow to facilitate rapid settling under the influence of light magnetic forces. The magnetic powder base may be treated with a dye or fluorescent coating to assist observation against dark surfaces.

As the most sensitive available method of crack detection the magnetic particle technique predominates in ferrous metal casting, penetrant methods being required for non-ferrous metals and austenitic steels.

The Detection of Internal Defects

Two principal methods have been applied to the detection of internal defects in castings, namely radiography and ultrasonic testing. Of these, radiography is the more highly developed as a technique for detail examination, being capable of providing pictorial representation of the form and extent of most types of internal defects. Ultrasonic testing, less universally applicable, can give qualitative indications of many defects, its value being enhanced in the case of castings of relatively simple design, for which the signal patterns can be most reliably interpreted.

The scope of both methods is being continuously developed, radiography being extended to the examination of castings of great thickness and ultrasonic testing to the determination of important structural characteristics in cast alloys. For both techniques, skilled interpretation is the key to full

exploitation. The principle of radiography is also being extended to the study of foundry processes: eg the use of high energy x-ray fluoroscopy in studies of liquid metal flow and solidification phenomena.

Radiography

Radiographic examination is based upon exposure of the casting to short wavelength radiation in the form of x-ray or gamma rays from a suitable source. The amount of radiation absorbed by a particular alloy is a direct function of its total thickness so that transmission is influenced by the presence of internal cavities or by inclusions of substances possessing different radiographic density from that of the parent material. The emergent radiation is consequently subject to local variations in intensity, or shadow effects which can be detected with the aid of photographic films, fluorescent screen, or counting equipment. The production of radiographs on film is the technique most commonly applied to castings, although the less sensitive fluorescent screen offers a convenient means for the rapid examination of light alloys in thin section. Figure 13.2 shows the production of radiographic image on film. The dark shadow represent the defect. Whereas, light contrast areas represent nonmetallic inclusions.

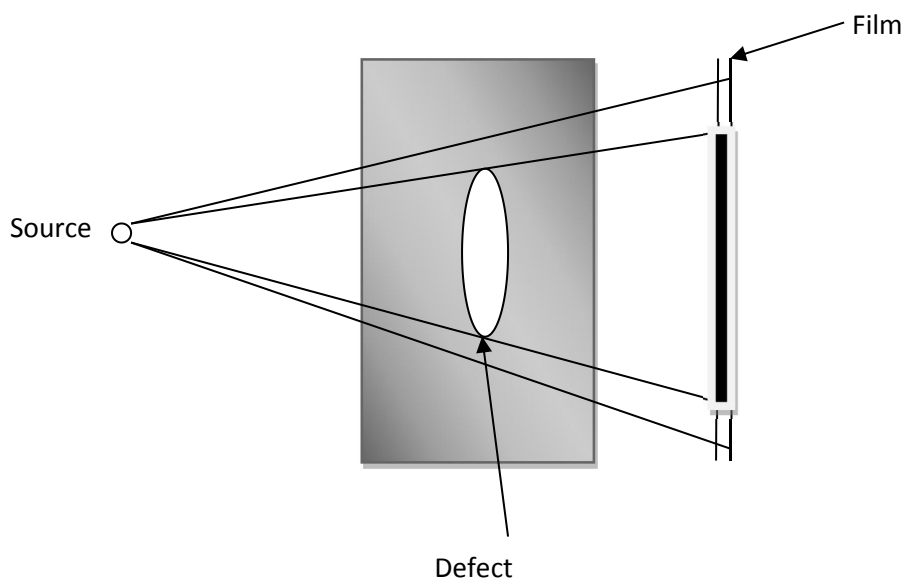


Figure 13.2: Production of Radiographic Image on Film

Gamma Radiography

Gamma radiation, a product of radioactive decay, is extensively used in the non-destructive testing of castings, the general technique being similar to that employed in x-ray work. Radium and Radon were originally employed as gamma ray sources, but more convenient sources have been

available in recent years in the shape of artificial isotopes possessing the appropriate characteristics. The small size and portable nature of the source, as compared with the x-ray tube and its ancillary generating equipment, is a valuable feature of gamma radiography. A gamma source from cobalt 60 which has main energy of 1300kv is capable of penetrating several inches of steel and is used for steel with the thickness range of 40-200mm.

Ultrasonic Testing

Ultrasonic flaw detection is based on the use of acoustic waves with frequencies in the range between 20kHz and 20MHZ. These waves have the property of being transmitted by solids but reflected by internal surfaces such as those present at defects; the behavior of an ultrasonic beam thus affords a basis for the detection, location, and size estimation of defects. When the waves meet a discontinuity, for example the metal-air interface at a crack, a reflection is obtained and can be detected by an appropriately positioned receiver: a further echo is generated at the opposite surface of the section. See Figure13. 3.

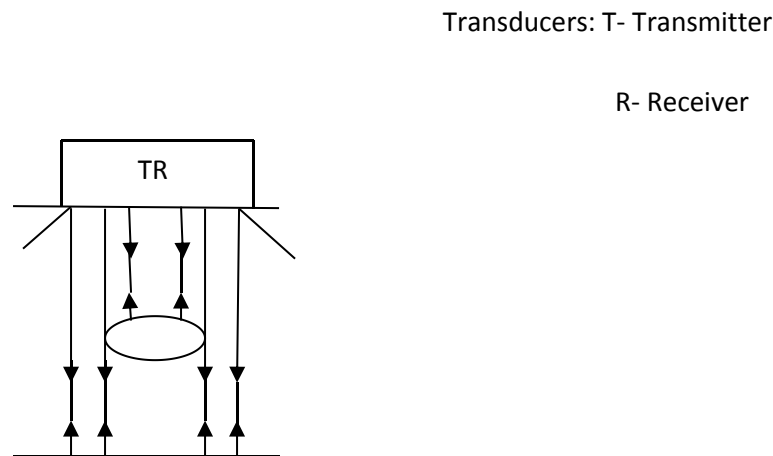


Figure 13. 3: Ultrasonic Testing: Single Probe Reflection Technique

Other Methods of Non-Destructive Testing

These include a group of electromagnetic methods in which detector coils are employed to register dissimilarity between a specimen and a standard. The principle can be used for flaw detection or as a means of sensing dimensional errors. In the case of small investment castings an

encircling coil can be used, whilst in other cases a probe coil can be placed closed to the zone being inspected: a defect is then revealed by a local change in electromagnetic characteristics.

Proof Loading and Pressure Testing

Certain inspection procedures are designed to subject a casting to conditions resembling those which will be encountered in service. Castings may be mechanically loaded in special fixtures to simulate service stresses, but much more common is the pressure testing carried out to verify hydraulic soundness in castings required to contain fluids under pressure. Equipment for pressure testing is designed to seal the apertures in valves, pipe sections and similar castings for the application of hydraulic or pneumatic pressure. In the latter case the casting is submerged in a water tank or its surface treated with detergent solution to induce visible bubbles at leaks; great care is required in case of explosive failure.

QUALITY AND PROCESS CONTROL IN THE FOUNDRY

As emphasized at the beginning of the paper, casting inspection can provide the basis of a quality control system in which feedback of information is used to improve quality and to detect significant changes in the manufacturing process at an early stage. Similar objectives are served by systematic observation of process variables from raw materials to final product.

The operation of a quality control system simplifies the task of meeting specifications and can reduce the amount of inspection required, whilst the presentation of data in the form of visual control charts reveals trends not readily evident from examination of data itself. The use of such systems focuses attention on quality and provides a platform for cooperation between inspection and production departments.

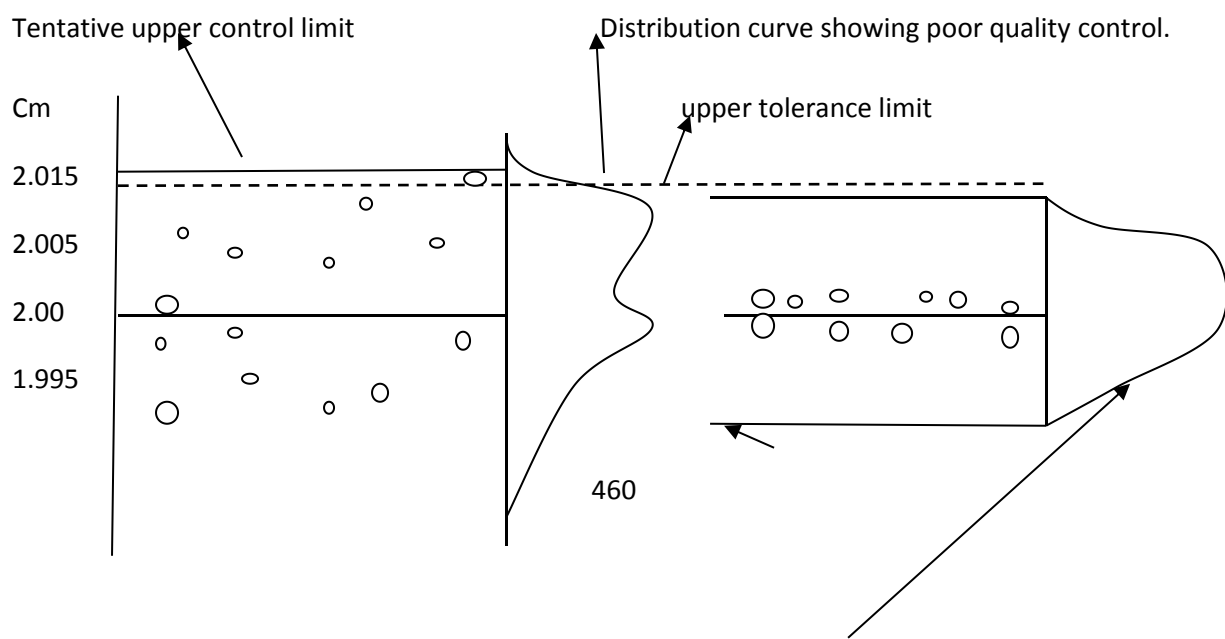
Quality control is concerned with variation of a process or product characteristic about some hypothetical standard state. In assessing the significance of deviations from this state, distinction must be drawn between variations due to chance and those resulting from definite changes in production conditions and requiring corrective action. Control charts are provided with limits designed to show when these conditions are reached, the limits being established by statistical methods which take into account the natural variations arising in process and product. These methods also give guidance in the use of sampling techniques to minimize the task of measurement (Beeley, 1982). The issue of quality control in castings is very important and must be taken serious, according to Peters (1991) most quality programs fail for one of two reasons: they have system without passion , or passion without system. You must have both. There is a lot of controversy here:

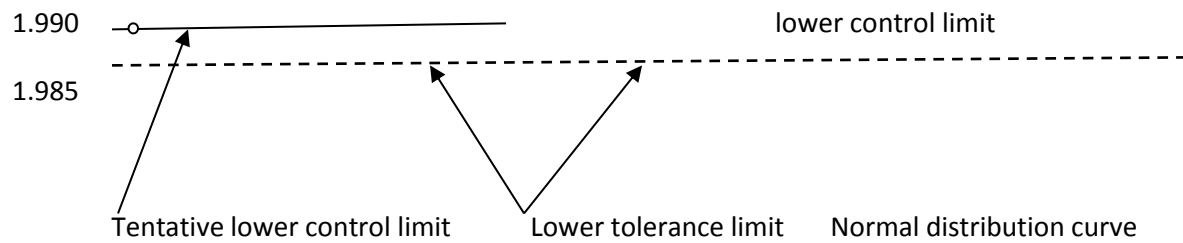
should you follow Prof. W. Edwards Deming, father of the Japanese quality revolution via statistical process control? Or Phil Crosby, author of “Quality is Free”, and so prominent that GM bought a 10 percent stake in his firm? Or Armand Feigenbaum’s “Total Quality Control”? or Joseph Juran? Or invent a system of your own? Eventually you will develop your own scheme if you are successful. But I strongly recommend that you not begin with a Chinese menu. Pick one system and implement it religiously (Peters, 1991). Quality is measured and “what gets measured gets done” is a wonderful old saying. Measurement is the heart of any improvement process. We now look at some quality control principles which are applicable to castings.

Statistical Quality Control (SQC)

Statistical quality control was introduced by Deming, at the time it was like quality control was all about statistical quality control; the period was over and then came principles like total quality control and other principles which lay emphasis on passion, motivation and man. The problem is actually not with the principle but how well the principle is applied. Statistical quality control, which is based on the mathematical law of probability, indicates the limits beyond which variations in the quality of the product should not go without correction. The law of probability applies to the behavior of the chanced variation in a standardized process. Variation in quality beyond the limits based on probability; are attributed to factors which can be brought under control or eliminated.

Setting up statistical quality control requires the measurement of samples of the product for quality. By means of a simple statistical computation involving the use of tables, the measurements are plotted on a chart to show the range or control limits for the quality measurement of subsequent production. Figure 13.4 shows statistical quality control chart used to identify assignable causes of defective work that can be removed, thus bringing the process into control and reducing defective work (Ihom, 2003).





Sample measurement of parts shows that the process is not in control and not under tolerance

Proper adjustment.

Process has been brought under proper level of control and can produce within limits-control limits are narrower and dots are within the limits.

Figure 13.4: Statistical Quality Control Chart used to Identify Assignable Causes of Defective Work that can be removed, thus bringing the Process into Control and Reducing Defective Work (Ihom, 2003)

According to Deming in Ihom (2003), the major cause of poor quality is variation. Thus a key tenet of Deming approach is to reduce variability in the manufacturing process.

Zero Defect

A program developed in the aerospace industry in 1962. This program attempted to prevent errors by eliminating their cause, rather than remedying them after they had been made. However, Philip Crosby, another quality advocate, suggested that zero defects was the only meaningful performance standard and the cost of quality (including the cost of non-conformance) the only performance measure. To Crosby, quality meant not elegance but conformance to requirement. He believed that a problem with quality did not exist per se, but rather that the organization had functional problems. Crosby also argued that it was always more cost effective to perform an activity right the first time. In contrast to Deming, Crosby focused more on management, organizational processes, and changing corporate culture than on the use of statistical techniques.

Total Quality Control (TQC)

This concept is a more recent concept that the Japanese and the Americans have embraced. The basic idea of TQC is that it is extremely expensive to “inspect” quality into a company’s outputs and much more efficient and effective to produce it right the first time. As a result, responsibility for

quality has been taken away from the quality control department and placed where it belongs – with the workers who produce the parts or provide the services in the first place. This is called quality at the source. It is the heart of statistical quality control (SQC), sometimes called statistical process control (SPC). The beginning of TQM dates back to the 1930s when Dr. Shewart began using statistical control at the Bell Institute. Infact, both Juran and Deming were students of Shewart. There are so many other quality control versions which time and space will not allow to mention here.

In –Process Controls in the Foundry.

The operations of melting, moulding , and pouring are critical to casting quality and are mainly in the hands of the production workforce. These men have numerous standards to meet aside from quality. The in-process controls are designed to assist these men in the attainment of product quality as well as to provide assurance that the quality standards have been met.

Amongst the more important uses of these techniques in the foundry are the control of incoming materials, for example melting stock, fuels, base moulding sands and binders, by chemical analysis and physical testing. Process control during manufacture can embrace sand testing both at the mill and the moulding station, with particular emphasis on moisture content and green strength: Davies in Beeley (1982) has described the practical application of statistical quality control (control charts) in this field. Metal temperature and composition, including gas content, are further characteristics suitable for continuous observation and chart control. Although dimensional examination, mechanical properties and the incidence of defects are the most obvious points of interest, it is to be expected that there will be increasing attention to the control of metallurgical characteristics, as determined for example in non-metallic inclusion and grain size counts.

USE OF COMPUTERS IN QUALITY CONTROL

Today's talk on quality control of castings will not be complete without the mention of computers and the role they are playing in quality control of casting. Computers are helping in Crosby principle of zero defect, which stresses that it was more cost effective to perform an activity right the first time. Computer modeling and simulation of solidification of castings is presently assisting in the reduction of defects in castings. Casting process is simulated using the computer before the actual pouring and solidification. The computer is used for casting design, gating system design, thermal analysis and by extension the solidification process. There are software packages like Ansys,

solidworks, matlab, metallurgy, and the SOLSTAR system with which it is possible to carry out design in both 2D and 3D. These programs can be used for modeling the entire casting process. With this it is possible to detect a problem before the actual casting process takes place.

According to Brown (1994) since computers became widely available in industry, researchers have been working on the development of programs to simulate the solidification of castings.

The aim of computer modeling is to :

- Predict the pattern of solidification, indicating where shrinkage cavity associated defects may arise
- Simulate solidification with the casting in various positions so that the optimum position may be selected .
- Calculate the volumes and weights of all the different materials in the solid model.
- Provide a choice of quality levels, allowing, for example, the highlighting or ignoring of micro-porosity.
- Perform over a range of metals, including steel, white iron, grey and ductile iron and non-ferrous metals.

The SOLSTAR System

As mentioned above many such programs now exist; we will however look at the SOLSTAR system. Some of these programs require computers of a power not generally available to practical foundrymen, while others take an unacceptably long time to obtain meaningful results. The SOLSTAR system, marketed by Foseco, is designed to run on an IBM PC or compatible desk-top computer and to produce simulations in a matter of minutes. The SOLSTAR system can be perceived as a form of "electronic- sampling", whereby the foundryman can test his production methods on the computer, until he attains a "SOLSTAR-approved" technique. He can then begin casting production with greatly enhanced chances of getting it "right first time". The speed of the program allows the operator time to carry out a number of "what if" experiments on the computer, enabling him to attain the required casting quality at minimum cost.

Procedure for Applying the Solidification Program

1. Using the casting drawing, determine model scale and element size
2. Make the solid model of the casting

3. Make the solid model of the proposed production method (feeders, chills, insulators etc) use the program's own feeder-size calculator if required.
4. Carry out thermal analysis to establish the order of solidification
5. Carry out solidification simulation to a set quality standard, for the selected alloy incorporating shrinkage percentage, ingate effects, etc. This results in the model being changed to the predicted final shape (internal and external) of the casting showing size shape and location of shrinkage cavities in casting and feeders.
6. Examine the predicted shrinkage (the equivalent of non-destructive testing) by viewing and plotting of 3D "X- rays" and sections of the model in 2D slices or 3D section and relating predicted defects to solidification contours and required quality standards
7. If the predicted defects do not meet the required quality standard, develop an improved production method and repeat the procedures. These trial-and –error sampling procedure can be carried out very rapidly, allowing the operator to indulge in any number of "what if experiments".

During the solidification simulation, the effect of varying moulding, position, ingate position, ingate position, mould materials, chills, insulating and exothermic materials can be modeled, allowing the optimum method of making the casting to be predicted.

Feed –Size and Weight Calculations

The program can calculate the volume, weight and surface area of each material in any selected part of the model, so that casting yield is readily obtained. The program can also calculate feeder sizes for steel and ductile iron, giving a selection of feeder options (height / diameter ratios, sand or insulating / exothermic materials). This data allows more accurate estimation of production costs to be made.

Applications

The SOLSTAR solidification simulation software is in regular use by aluminium, copper, iron, and steel foundries using processes ranging from green –sand resin-and-shell-bonded sand to investment and gravity diecasting. Applications include: large steel castings such as a 20 tonne turbine housing and a 46 tonne stern frame where improved yields and reduced fettling costs were achieved, critical high pressure value castings etc. The SOLSTAR program is not only used by foundry method engineers but also casting designers and purchasers are using the software having experienced significant improved quality from their SOLSTAR using suppliers. The SOLSTAR is the subject of

constant improvement in terms of accuracy, speed and ease of use and addition of more alloys, processes and facilitation.

The use of computer modeling of solidification is growing since it allows the pattern of solidification of a casting to be predicted and several alternative casting methods can be simulated before the final method is chosen (Brown, 1994, Beeley, 1982).

SUMMARY

The Chapter has looked at inspection and quality control in casting. The two components of the chapter (inspection and quality control) have been individually reviewed. The chapter has clearly posited that inspection of castings has the dual purpose of ensuring that the product conforms to design requirements and of providing information needed for quality control in the foundry. The inspection process is made up of visual inspection and instrumental inspection. The two methods of instrumental inspection which are destructive and nondestructive methods have been reviewed and their importance to quality control has been stressed. In conclusion quality of castings is very important and to achieve the production of quality castings adherence to quality control principles is very important also the use of computer for quality control has become necessary particularly as regarding the prediction of solidification patterns of a casting, and several alternative casting methods can be simulated before the final method is chosen. This will make it possible for casting to be done right the first time.

REVIEW QUESTIONS FOR CHAPTER THIRTEEN

1. What is the purpose of inspection of castings?
2. What is the duty of quality control in a foundry?
3. What is the quality of a product?
4. Explain the following terms: Quality planning, quality control, inspection, and castings
5. Explain standards and their commercial implication
6. Write short note on material and product testing procedures
7. How is shape and dimensional inspection carried out?
8. How is surface quality and finish inspection carried out?
9. Write on composition and mechanical properties inspection
10. Explain X-ray Fluorescence spectrometry (XRF) technique
11. Write on the various destructive testing methods that you know
12. Write on non-destructive testing methods that you know are used for the testing of casting soundness
13. Explain Gamma Radiography technique also explain in brief ultrasonic testing
14. Describe how proof loading and pressure testing is carried out on castings
15. What is the main thrust of quality control of castings?

16. What do you understand by statistical quality control?
17. Explain the concept of zero defects of castings in quality control
18. What do we mean by in-process controls in foundry? Elaborate
19. Explain and elaborate on total quality control
20. Write on the use of computers in quality control
21. Explain how the SOLSTAR System works.

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CHAPTER FOURTEEN

MODERNISATION AND MECHANISATION OF FOUNDRIES

The 21st century and beyond is said to be the era of excellence and sophistication in technology with application of intelligent systems and machines in manufacturing. Every manufacturing process today is witnessing drastic changes with the introduction of manufacturing devices with artificial intelligence and we do expect to see much more in the near future. Today we have amazing processes like the 3D printing (layer by layer printing) where components and spare parts can be printed in one single piece. This technology has already taken root in the advanced countries of the world. The technology is also used for the production of spare parts by astronauts on spaceships. The foundry sector is not left out of the current modernization as a matter of fact the introduction of levitation furnaces, plasma technology, intelligent machineries, and the computer has greatly revolutionize foundry technology (Ihom, *et al.*, 2014).

According to Jain (2009) mechanization of foundries is necessary, where permitted (depending on the quantity and type of production) in order to improve the working conditions in foundry, increased production and quality of casting lowering down the cost,

elimination of laborious manual operations like preparation of sands, moulds and various other material handling operations. Mechanization can be applied to preparation of sand moulds, cores, transporting sand, moulds and molten metals etc. it is best suited where a repetitive work and mass production of small size parts is involved.

Materials handling mechanization increases efficiency, saves lot of man-hours, keeps production costs low, promotes safety of personnel and reduces damage. The material (sand, flasks, patterns etc) are moved automatically at a fast speed. Heavy-lifting and laborious operations are done by machines. Given floor space is utilized in optimal way, dust nuisance is minimised, and castings with closer dimensional tolerances and with fewer defects are produced.

Mechanical equipment for sand preparation comprises of magnetic separator (to separate iron pieces, wire, nails, iron shots etc), gyratory riddle (which removes pieces of dry sand cores, hard lumps etc), rotary sand kicker (which straddles long heaps of sand, previously moisten with water, and mixes the mass with vigorously rotating blades), sand muller (which distributes the various ingredients of sand to make homogeneous mixture), sand aerator (which separates sand grains by whirling it at high speed by an impeller so that each grain can flow freely and smoothly in the direction of ramming), reclamation unit (which make used sand fit for reuse after some treatment on it and using some additives), use of fume and dust extraction equipment is essential in mechanized foundries at screens, chipping or fettling benches, knock out belts, turning point etc.

Large overhead bridge cranes are used to convey all parts on a large floor area. Moulding sand distribution conveyor belt is used to convey sand from sand preparation unit to individual sand hoppers, located directly above the moulding machines. For filling sand into flask, the operator pulls a lever and desired amount of sand falls down. Roller conveyor system is used to carry moulds and flasks from one place to another.

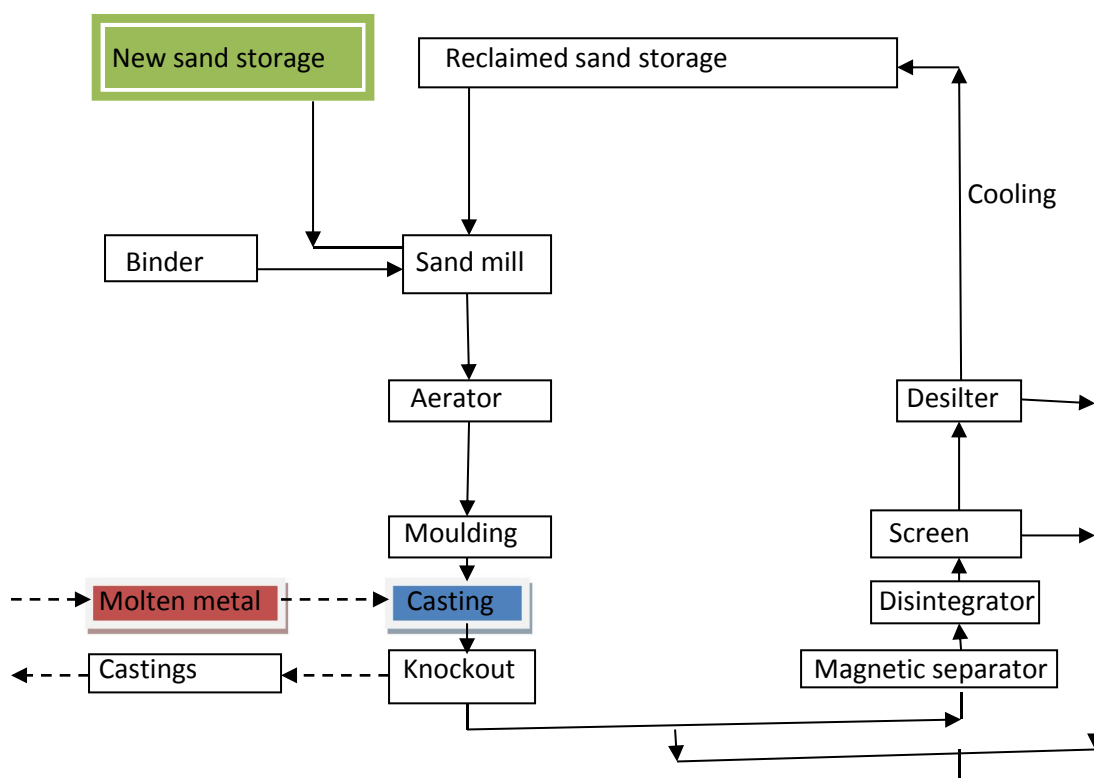
Several types of moulding machines (jolting, squeezing, slinging, jolting and squeezing etc) are used. Use of turn tables (circular revolving table having number of moulding machines) provides highly mechanized system. Turntable revolves at a slow speed and several operations are carried out at various stations, each worker doing his predefined work on each station. The operation of melting, pouring of metal is also mechanized to the extent possible. The material handling equipment like belt conveyors, bucket elevators, mono rail conveyors, crane etc are used for handling sand, cores and core sand, castings, furnace charge etc. moulds from the mould production area are conveyed for pouring by either roller conveyors, or pallet conveyor or overhead conveyor. Molten metal may be poured while moulds are in motion, (or mould transported to pouring ladle where metal is poured) and after pouring and cooling, the moulds are conveyed to shake-out operation, the castings removed and transported to fettling shops, and the emptied flasks, moulding boards etc. are returned to the moulding shop. In pouring of the molten metal, it is brought in ladles from the furnace on a mono-rail type overhead conveyor and is moved in synchronism with mould so that metal can be poured continuously as the mould is moving.

Sand Systems

The mixing plant is frequently incorporated in a comprehensive reconditioning system through which the main bulk of the foundry sand circulates in a continuous cycle. The most primitive system is based upon simple batch reconditioning without the refinement of automatic handling and reclamation plant. The moulding sand is prepared by milling or even by hand. After casting, the moulds are knocked out, the floor sand being watered and reused after riddling, aeration, or remilling. At intervals the sand heap is reconditioned with additions of new sand and binder. Natural moulding sands are best adapted to this practice since the binder is already well distributed and the moisture content less critical. The practice still finds some application in small jobbing foundries.

In contrast with such simple systems are the fully integrated sand processing plants used in modern mechanized foundries: a typical sequence of elements in such a system is shown in Figure 14.1. Closely controlled mixtures are produced from blends of new and reclaimed sand, binders and other additions, the mixture being delivered by skip or conveyor directly to the moulding stations: moulding machines and sandslingers are served through feed hoppers. After casting, sand from the knock-out is fed into the reclamation system. Sand systems of this type can be highly automated, with centralized push button control of the entire handling mixing and distribution cycle.

The operations embodied in the system vary greatly with the type of production and with the sand practice, but the aims are to remove metal spillage, nails, and core irons, break down lumps and achieve maximum cooling. Whilst it is desirable to minimize the amounts of core sand and spent binder recirculating through the system, recovery of unchanged binder in the moulding sand should be one of the main objectives.



Discarded sand and residues

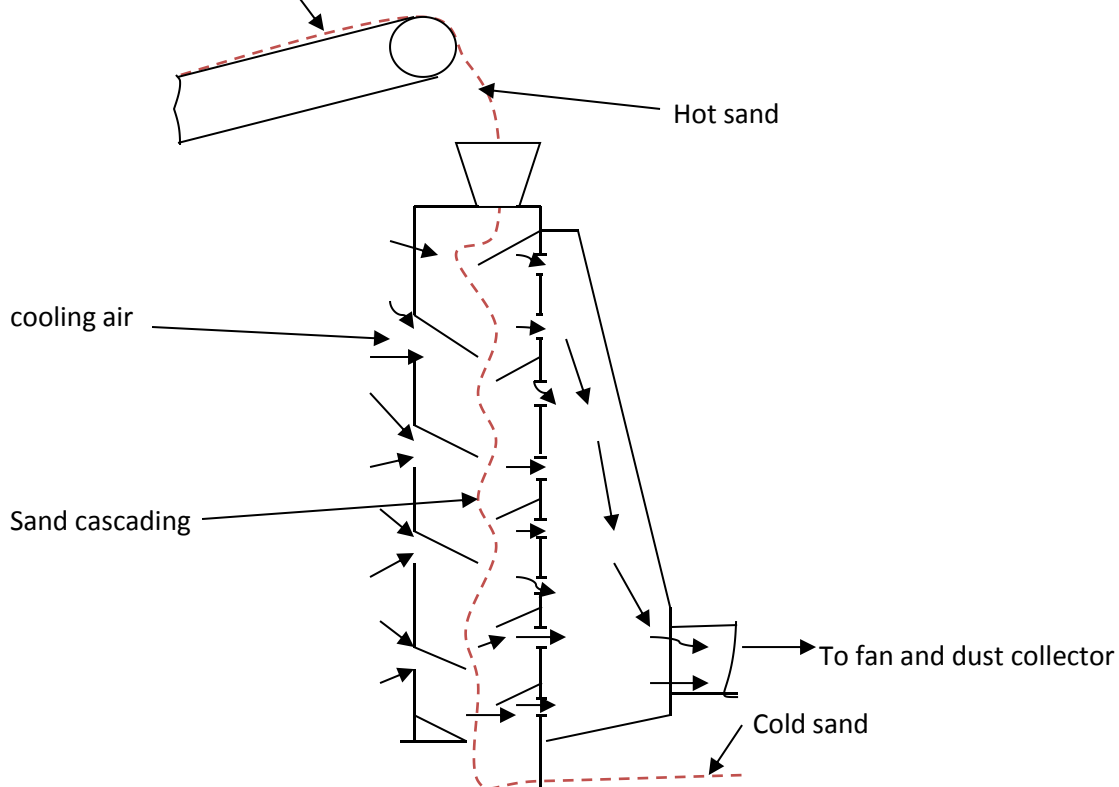


Figure 14.1 Flow Diagram for Typical Moulding Sand System

Plant equipment employed in reclamation includes magnetic separators, disintegrators, screens and de-silters, the sand being transported between the stages by belt conveyor and bucket elevator. The processed sand is finally fed into a storage hopper from which it can be discharged directly into the mixing plant for the next cycle. The normal movement of the sand through the system provides some opportunity for air cooling, but water sprays may be used for very hot sand. Forced air cooling is combined with desilting in some plants by counterflow currents in a cascade system (figure 3.4).

The strength properties of the reconditioned sand in systems can be maintained at an equilibrium level with very small additions of binder on each passage through the mixer. Since adsorption of water by the clay bond is reversible up to temperatures in the range 400-700°C, the only permanent loss of bond occurs in the zone immediately adjacent to the casting: the extent of this zone depends on the mass and temperature of the casting and the interval before knockout. Rapid knockout, therefore, is an important means both of conserving binder and of minimizing the serious problem of hot sand in systems. Such losses of bond as do occur, apart from that in the layer against the casting, are caused by physical loss of sand from the system, by dilution with coresand which contributes no renewable bond, and by separation of unchanged binder during screening and desilting: this loss increases with drying and is at a minimum in high production light greensand systems.

Conveyor from rotary screen



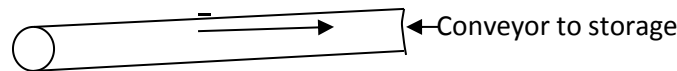


Figure 14.2. Sand Cooling and Desilting Plant (Beeley, 1982)

The properties of the reconditioned sand are also influenced by changes in the sand grains and by contamination with metal oxides, slag reaction products, spent binder and core sand which have not been eliminated in reclamation. Breakdown of quartz grains and accumulation of fusible fines reduce both permeability and refractoriness. These changes can be kept under control by systematic additions of new sand. This may be introduced either as a regular constituent of the reconditioned mixtures or in reclaimed facing sand containing a high proportion both of new sand and of binder. Less systematic is the sporadic renewal of larger masses of sand, the system being allowed to continue for long periods with binder additions alone. Although feasible where refractoriness is relatively unimportant, the periodic fluctuation of sand quality is an undesirable feature of the latter practice.

Systematic introduction of new sand into the plant requires regular dumping of used sand in quantities equivalent to those of the incoming material, maintaining an equilibrium volume in circulation.

In fully integrated sand systems, characterized by close control, synthetic mixtures based entirely on silica sands are most suitable, bentonite clays being frequently employed as the primary binder. Table 14.1 gives the composition and properties of two synthetic system sands used for the production of machines moulded steel castings. The first is unit mixture based on regular additions of sand as well as of binder, whilst the second mixture is primarily used as a backing sand and derives its properties from regular influx of the facing mix also shown in the table. The synthetic unit sands employed in cast iron and nonferrous practice differ principally in their use of finer base sands; coal dust is also usually present in the former case.

Table 14.1 Reconditioned System Sands

1 System unit sand	2A System backing sand	2B New facing mixture
90% Reclaimed sand	Reclaimed sand	50% Chelford silica
5% Chelford silica	0.35% Bentonite	50% Arnolds 52 silica
5% Arnolds 52 silica		4.0% Bentonite
0.65% Bentonite		0.5% starch
0.15% starch		
Moisture content, % 4.3	3.5	4.0
Permeability 130	160	150
Green compression		
Strength 6.5lbf/in ² (45kN/m ²)	7.5lbf/in ² (52kN/m ²)	7.0lbf/in ² (48kN/m ²)
Dry compression		
Strength 100lbf/in ² (690kN/m ²)	110lbf/in ² (760kN/m ²)	100 lbf/in ² (690 kN/m ²)

Source : Beeley, 1982

Davies in Beeley, 1982 has applied a theoretical treatment to the maintenance of bond in sand systems, demonstrating the eventual stabilization of effective binder content at a level determined purely by the cyclical addition and independent of initial content, assuming stable loss rates. The loss of bond in each cycle, due to irreversible dehydration and physical separation, is stated to fall normally in the range 5-20%, representing a requirement for additions of 0.2-0.8% of binder to maintain the properties of a 4% mixture.

Comparing the unit mixture in Table 3.4 with the equivalent 'starter' facing mix, 0.4% of the 0.65% clay addition could be regarded as being required to balance the 10% addition of new unbounded sand, the remaining 0.25% being sufficient to maintain equilibrium in respect of bond losses in the 90% of reclaimed sand. This, the equivalent of an addition of 0.28% when expressed as a percentage of the reclaimed sand fraction, represents a renewal of 7% of the original clay binder content in each cycle, or a 'life factor' of approximately 14 cycles. In this case, therefore, the major part of the overall 16% clay renewal addition arises from dumping loss necessitated by the new sand addition rather than from deterioration of the binder in casting. As might be expected from the lower decomposition temperature of the cereal binder, its consumption rate is approximately three times that of the clay binder, proportionately greater cyclical additions being required. The above conditions, encountered in the production of machine moulded steel castings in the weight range 20-50kg, would be modified in the direction of increased binder life in systems with lighter castings and more rapid knockout. Reduction in the new sand addition, with corresponding conservation of binder, can be made in cases where refractoriness of the mixture is of less consequence.

Controlled experiments on rate of bentonite loss have been carried out by Zrimsek and Vingas in Beeley, 1982 and the results presented in graphical form: the shape and size of casting were shown to be critical in determining the rate of new addition required.

Unit and Duplex Sand Practice

Integrated sand systems can most conveniently be operated using a single or unit sand mixture which passes round the cycle of mixing, handling, moulding and reconditioning in the manner already discussed. Such a system is ideally adapted to mechanized production; sand hoppers can discharge directly into the moulding boxes and both mixing plant and moulders are only concerned with a single material.

Unit sand thus offers the customary features of standardization and where refractoriness is not an overriding consideration the advantages are great. Its use, however, does represent a compromise. Apart from reduced refractoriness compared with uncontaminated sand containing a high proportion of new quartz grain, the material may contain metal shot too small for separation by the system: this can cause surface blemishes on the castings. The system sand also tends to be warm, producing drying out at the mould face.

The binder addition to a unit sand must be maintained at a level determined by its strength requirements as a facing material, when lower properties might suffice in the main bulk of the mould. There is, moreover, no opportunity to tailor the properties of the standard mixture to the varying requirements of individual types of casting. Most of these disadvantages can be overcome by separate facing and backing mixtures; the choice of practice must be determined by the relative importance accorded to standardization.

Facing sands may consist wholly of new sand or may contain proportions of reclaimed sand smaller than those in unit sands. The backing sand usually consists of reclaimed sand with the sole addition of moisture. In duplex practice, therefore, the new sand and binder additions are deployed to maximum advantage by being introduced into the system at the point where refractoriness and high strength are most required. The chief disadvantage lies in the need for separate handling of the small quantities of facing sand.

The economics of facing-backing sand practice and the balance of properties in such systems depend heavily upon the relative consumption of the two materials. Facing sand consumption partly depends on the type of casting being produced and tends to form a greater proportion of the whole in small moulding box production. Usage also depends on the discretion of the operator, so that cost control requires close watch to be kept on the relative consumption.

Full Sand Grain Reclamation

The foregoing discussion has been concerned with reclamation and processing of used sand to form fully bonded reconditioned mixtures. One objective in such practice is to retain the maximum quantity of unchanged binder, so minimizing the addition of new binder needed to restore the properties of the material.

Limited attention has been given to a different aspect of reclamation, namely the full recovery of the sand grade for use as a direct substitute for new sand. The primary aim of full reclamation is the economic utilization of material which would otherwise need to be dumped to make way for new sand: it thus offers a closer approach to complete self-sufficiency of the system.

For full reclamation a more exacting process cycle is required than that used in reconditioning, since the aim is separation of the whole of the fines and removal of the coatings of spent binder adhering to the grains. Processes of pneumatic or wet scrubbing and separation are effective in removing clay, but thermal reclamation, involving high temperature oxidation, is needed for complete elimination of the carbonaceous residues in core sands. Mechanical attrition method of sand reclamation is the commonly practiced, because it has the lowest cost. The steps in the process are:

- Lump breaking; large sand lumps must be reduced in size to allow the removal of metal, etc
- Separation of metal from the sand by magnet or screen
- Disintegration of the sand lumps to grain size and mechanical scrubbing to remove as much binder as possible, while avoiding breakage of grains
- Air classification to remove dust, fines and binder residue
- Cooling the sand to usable temperature
- Addition of new sand to make up losses and maintain the quality of the reclaimed sand.

Wet reclamation comes in when dealing with difficult to reclaim sands for instance some silicate-bonded sands are particularly difficult to reclaim mechanically because Na_2O builds up and lowers refractoriness. Thermal reclamation is ineffective but water washing can be used. The steps in the processes are:

- Lump breaking
 - Metal separation by magnet or screen
 - Disintegration to grain size
 - Water wash with mechanical agitation to wash off the silicate residues
 - Separation of sand and water
 - Drying of the sand
 - Agglomeration of the alkaline residues in the water to allow settlement and separation
 - Water treatment to permit safe disposal of the water
- Wet reclamation is expensive and its use is not common.

Microwave processing of ceramic materials is a technology that has found application in various areas. Microwave rapid heating technology is currently used for sand reclamation where the selective heating of the binder takes place leaving the sand grains. Details on the various forms of reclamation can be gotten from the following literatures, Minowa, 2008, Liu *et al.*, 1994, Leidel, 1994, Murray, 1994, Jain, 2009, Brown, 1994 .

The economics of such methods must depend upon comparison with the true cost of new sand, including stock maintenance, transport and dumping costs; full reclamation techniques have not so far been widely adopted where new sand supplies are readily available

Trends in Casting Technology

- Argon oxygen decarburization and deoxidation, as well as electroslag remelting, ladle metallurgy, plasma refining, and calcium wire injection for producing high-quality steels, are being practiced in modern foundries.
- Electromagnetic stirring of the molten metal in the mould and vibrating the mould to obtain smaller and more uniform grain size during solidification, counter-gravity pouring, and shrouding the pouring stream are being contemplated.
- Computer aided design and manufacturing techniques are being used to predict solidification patterns, prevent casting defects, and calculate volumes, weights and dimensions for proper mould design and economic production.
- Computer-aided design and manufacturing of castings, moulds and dies, and gating and runner systems are being implemented at a rapid rate.
- Developments are taking place in automation of moulding and casting processes to reduce costs, using computer controls, sensors, and industrial robots.
- Research is in progress on automated inspection of castings using machine vision and fibre optics.
- Improvements in melting and remelting techniques and refining the molten metal prior to pouring are in progress, including the use of exothermic materials to prevent choking of runners.

REVIEW QUESTIONS FOR CHAPTER FOURTEEN

1. What do you understand by foundry mechanization?
2. Explain how the various processes are integrated in a modern mechanized foundry
3. Explain sand circulation system in a foundry

4. Explain unit and duplex sand practice
5. Write a short note on full sand grain reclamation
6. Write on current trends in casting technology

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CHAPTER FIFTEEN

HEALTH AND ENVIRONMENTAL PROTECTION IN INDUSTRIAL PLANT

Introduction

Foundry industry produces heat, gases, dust, noise and a large quantity of waste such as irreclaimable sands, ashes and slag. These individual elements have considerable effect on environment degradation and cause condition unsuitable for human's health.

In Nigeria, the factories ACTS of 1955, came into force on 1st September 1956, the factories (Amendment) ordinance, 1458, which came into operation on 1st April, 1959 made slight changes in some section of the original Act. And again in 1984, yet more changes were made in the factories Act. The factory Act lays down in general terms the minimum standard for safety, health and welfare of factory workers to be maintained in all factories in Nigeria (HHSAR, 1955).

Relevant Section of the Acts and Regulation

Part III contains some safety requirements for special causes such as injury to eyes (section 53), but is largely concerned with possible damage to health, such as the effect of abrasive dust on the lungs (section 50) and of harmful substances on the (section 52) of Part IV contains conditions required in the factory for health of the workers (section 13-19). The requirement as to safety of personnel at the work place i.e. safety from personal injuries is contained in Part V of the Act sub-sections 20-44. Part VI has to do with welfare matters (sections 45-49).

Health Hazards

The hazards arise from inhalation of dust and fumes in foundry environment. Silicosis, due to inhalation of silica dust of 0.5 to 3 micron size is the most serious health hazard. Prolong inhalation from a few months to about six years can reduce the breathing capacity of human lungs. The common symptoms of silicosis are; heavy breathing, persistent cough, chest pain and blood in the mucus. The lungs affected by silicosis are prone to tuberculosis infection, leading to silicon-tuberculosis. Silicosis is a pulmonary disease caused by inhalation of silica dust. It is considered that there is no permanent cure of silicosis; therefore every effort must be made to avoid inhalation of silica dust. The practice of using silica flour or quartz powder as a parting compound in moulding has been banned in several countries (Agarwal, *et al.*, 1996, Flinn, 1963, Mikhailvo, 1987).

Inhalation of metallic vapour or fumes in melting and pouring station can lead to severe health problem. This can be serious hazard when metals with high vapour pressures are melted. In a case of the foundry shop of the Ajaokuta Steel Company, the most preventive measures are that fume exhaust systems near the melting unit which was installed and suitable gas masks were also used by the workers. The foundry ventilation system can greatly reduce these health hazards. High ceiling with high wall ventilators can reduce accumulation of dust and fumes (Ocheri, 2006).

Noise in the Foundry

Noise plays an important part in everyday life and hearing is one of the two major senses with which we relate to our surroundings and communicate with fellow human, noise over a period of time can cause permanent and irreparable damage to hearing.

Such damage develops slowly and is unlikely to be noticed from day to day but the accumulation of damage over the years, when combined with the normal reduction of hearing

ability due to ageing, will eventually result in serious hearing difficult. Judgment of loudness of noise may be impaired-sufferers may ask people to speak up and then complain that they are shouting.

People suffering from noise damaged hearing may also be afflicted by **tinnitus (persistent noise in the ear)**, a particularly distressing ringing or buzzing sound in the ears which may be intermittent but in some cases can be continuous 24hours per day.

Noise Pollution and Its Effects on Man (Worker)

The problem of human response to noise is complex and individual judgments with respect to loudness or noise tend to vary over a relatively wide range, and this has been a very serious problem in the foundry shop of ASCL (Ocheri, 2006).

An excessive noise tends to decrease the efficiency of workers.

- (a) It can lead to loss of hearing
- (b) Speech communicate among worker becomes difficult.
- (c) The mental health of the worker may be affected.

The important sources of noise are grinders, the knock out grids, tumbling drums and ventilation in the fettling section for these reasons; the fettling section of the Ajaokuta Steel Company's foundry is built in a separate area from the foundry shop proper.

The other sources of noise are compressed –air operated machines and tools, the cranes, the Electric Arc furnace during the process of melting, the mouldings machines are not left out in noise pollution others are the pneumatic rammers, the jolting machine and the Muller mixers.

Vibration at Work Place

Exposure to vibration at work through the use of hand held power tools and machinery such as chipping hammers, grinders, chain saws, pneumatic rammers, can give rise to an industrial disease known as the Hand Arm Vibration Syndrome (HAVS). Its best known effect is Vibration White Finger (VWF) or Dead Hand, an impairment of the blood circulation in the hands and fingers, but damage to nerves and muscles can also occur. The symptoms include the balancing of the fingers, numbness, tingling and reduced grip strength and manual dexterity.

Hand Transmitted Vibration

Hand Transmitted Vibration (HTV) may also result in pain and stiffness in the hands, joints, wrists and elbows. Operators of vehicles such as tractors, fork lift trucks, overhead cranes and other machines, may be exposed to vibration received through other parts of the body, chiefly the seat. This ‘Whole Body Vibration or (WBV) as it is called, has been associated with the development of such disorder as lower back pain and spinal complaints. There is a risk that those exposed may have to retire early as a result of back problems.

Inform Workers and Control the Risk

The workstation platform is the last stage at which vibration reduction can be applied where, practicable; the installation of carefully selected, ergonomically well designed, suspension seats can reduce vibration significantly. Mechanical and pneumatic suspension seats, which reduce the vibration exposure of the user, are available for many vehicles. In many cases they can be retro-fitted.

Person exposed to vibration and their supervisors can play an important part in minimizing vibration health risk. To participate effectively they will need to know:

- (a) About the hazard and the risk;
- (b) What action is being taken to minimize the risks;
- (c) How to recognize and report signs of injury
- (d) What they can do to help

If vibration exposure cannot be reduced to below recommended action levels by engineering controls, the use of management and ergonomic measures could be considered. Vibration exposure and associated risks to health could for example, be reduced by.

- (i) Improving the ergonomic design of workplaces, processes, equipment and tasks;
- (ii) Reducing the duration of exposure by job rotation.
- (iii) Avoiding uninterrupted exposure over a long period

Environmental Concern of Metal Casting Facilities and Binders Emissions.

Metal casting facilities have long been known as ‘recyclers’ because of their basic function of taking scrap metal, and turning it into useful products. Unfortunately, because of the other material needs of these processes, which include binders, castings, washers etc, metal casting facilities had also earned the reputation of being very dirty place to work in or live near. This reputation has changed, however, with governmental pressure responding to people’s

physical and health needs as well as drive for environmental responsibility on the part of industry (Bolton, 2000). Today several counter measures are on ground to check environmental pollution. In Nigeria today NESREA is at the forefront of environmental pollution prevention and control. NESREA is National Environmental Standards and Regulations Enforcement Agency; it is an agency of government saddled with the responsibility of promulgating environmental pollution protection laws and ensuring that they are implemented. They enforce environmental laws in conjunction with the state environmental protection agencies (Ihom, 2014). There are several environmental policies put in place by government all over the world to protect the environment and this include; reduction in emissions released to the atmosphere, refuse gathering, sorting, disposal, recycling, solid waste conversion to energy, effluent treatment / waste water treatment, use of renewable energy, green chemistry, zero waste manufacturing system etc all of these policies must be implemented in conformity with standard sets by nations' environmental regulatory bodies. It has long been realized by governments of the world that for environmental pollution control and abatement to be effective it must be targeted at the industrial sector. This is because the activities of companies can lead to serious pollution problems. Environmental standards have to be set to which the regulatory bodies of government must ensure that industries or the industrial sector conform to. Energy conversion processes produce by-products that constitute environmental pollution. The manufacturing process produces by-products in the form of gases, liquid and solid wastes. These all constitute serious pollution problems. The transport sector accounts for 74% of the entire global CO emission. Industrial operations such as electric and blast furnaces in iron and steel industry, petroleum refining, paper industry, gas manufacture, and coal mining accounts for 9.6% of CO emission. The concentration of CO in city air is about 55 ppm. Measures that are currently being taken to reduce CO emission at the industrial level include modification of engine design, fuel modification and development of substitute fuels, treatment of exhaust gases, and exhaust gas recirculation, is another approach that is being studied for the purpose of automobile pollution abatement. The annual global release of NO_x from man-made sources is about 5×10^7 tonnes, which is only slightly less than that discharged by natural bacterial activity. Oxides of nitrogen are produced by the combustion of coal, oil, natural gas and other organic matter. This NO_x is also introduced into the atmosphere from automobile exhausts, incinerators, furnace stacks, coal fired power plants and other similar sources. The control of NO_x in automobile emissions can be minimized in automobile by the use of two stage catalytic converters. Similarly, NO_x from power plant emissions can be reduced by 90% by using a two-stage combustion process. 33% of SO₂ emission is due to human activities such as combustion of fuels, coal-fired power stations,

transportation, refineries, metallurgical operations such as smelting of sulphide ores and chemical plants (Ihom, 2014).

As a result of these pressures, significant federal legislation of USA has been passed which has been directed at forcing companies to recycle most of their waste. Legislation dealing with clean water, clean air, and the generation and disposal of solid waste, both hazardous and non-hazardous, has been formulated. These acts though formulated in the USA are not different from what is obtainable in most countries including Nigeria. A partial summary of the most significant of these legislation is given below:

1963- Clean Air Act (CAA)

1965- Solid waste disposal act-first law dealing with safe disposal of household, municipal, commercial, and industrial waste

1970- resource recovery act

1970- clean air act (CAA), amendments to CAA, most of basic structure of CAA were established in these amendment-emission standards for industrial plant and automobiles.

1970- clean water act (CWA)

1976- Resource conservation and recovery act (RCRA) – regulates generation, storage, transportation, treatment and disposal of hazardous waste.

1977- clean air act, amendments to CAA

1977- Clean water act, requires at least secondary treatment of all publicly owned treatment works, stipulating that such facilities provide at least 85% BOD (Biochemical oxygen demand) removal.

1980- comprehensive environmental response, compensation and liability act (CERCLA), requires clean up of sites which pose a threat to human health or the environment (superfund), amendment to RCRA

1984-Hazardous and solid waste amendments, amendment to RCRA

1986- Superfund amendments and reauthorization acts (SARA)

1990- Clean air act amendments (goal to reduce air pollution by 90% by year 2000).

EPA (Environmental Protection Agency) identified Iron and Steel Foundries as potential major source categories of acrolein, benzene, Cr, Co, Pb, Mn, Ni, Se, formaldehyde, phenol, toluene, xylene, polycyclic organic matter. This forms a list of 189 hazardous air pollutants (HAPs) added to existing list from 1970 (Karl, 2000).

All of these legislations do affect the manner in which metal casting facilities deal with their own solid, liquid, and gaseous waste, and therefore their own processes. The net result of these far-reaching environmental laws has been that metal casting facilities are very sensitive to any change or potential change in their process which could improve their current environmental position (Karl, 2000). It is clear that minimizing the potentially dangerous emissions from each process will require knowing much more about the materials

which are going into the process and understanding what happens to the materials during the process. The inputs, outputs and the processes involved in a hypothetical green sand foundry is illustrated in Figure 15.1. The figure shows the inputs that go into a metal casting foundry and the output that is released from the foundry. The output include volatiles (gases), dusts, sludges, slags, spent sands, and castings.

The granting of an operating permit or the use of a newly developed binder will depend upon the individual state's law and on the total amount of HAP emitted per annum. It is the responsibility of the designer to consider the environmental envelope at the beginning of the product life cycle, to minimize the impact of the product manufacturing and usage on the environment by minimizing energy and materials requirements and minimizing deleterious materials outputs. Obviously the goal of the designer will be to produce a product with zero negative discharges, to select and help design products and processes, which generate useful by-products instead of outputs which will materially harm the environment (Karl, 2000).

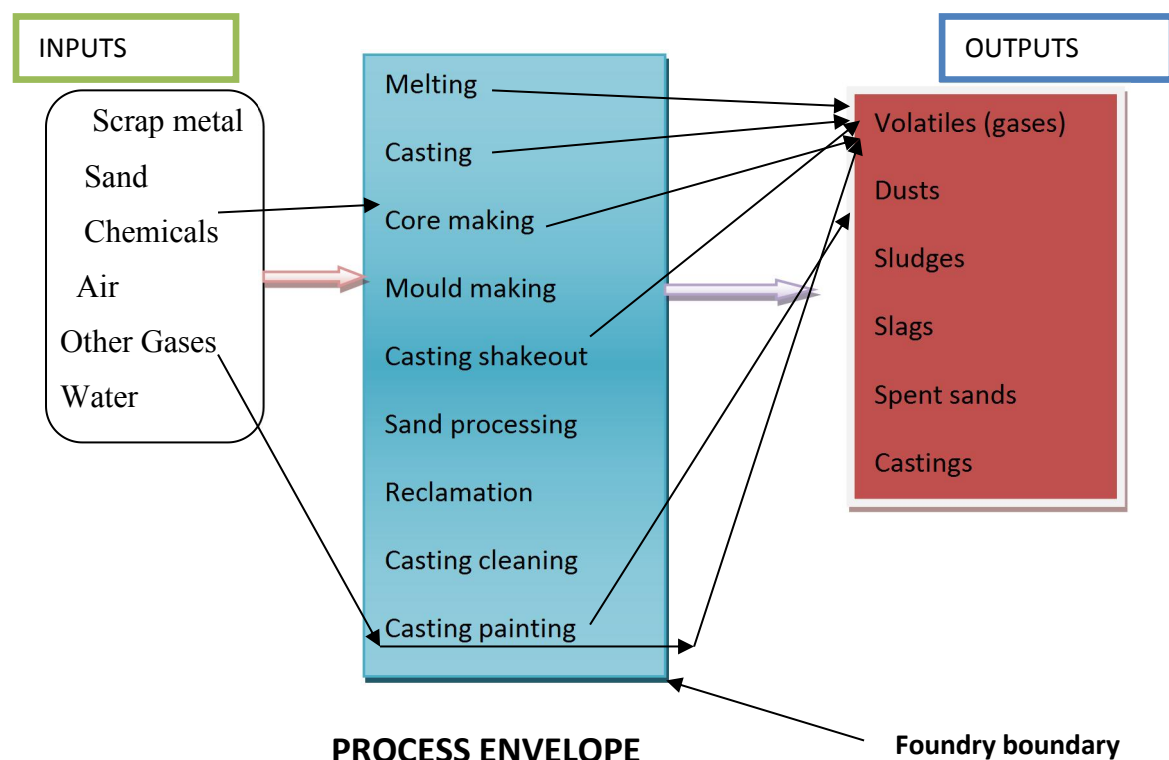


Fig.15.1 Inputs and Outputs Illustrating the Sources of Volatiles in a Typical Foundry.

Source: Karl, 2000

Binder Emissions

According to Tinebra and Wilson (1993), the gas evolution from UFFA-BSA (Furan) binder amounts to 3.8cc/g and the binder has a residual carbon of 62% after decomposition. Mckinley, *et al.*, (1993), said that chemical binder emission are classified into hazardous air pollutants (HAPs), and non-hazardous air pollutants (non-HAPs). According to him non-HAPs emissions include: ethyl alcohol, carbondioxide, furfuryl alcohol, ammonia, sulphurdioxide, nitrous oxide, furans, acetones, methyl formate etc. HAP emissions include: formaldehyde, benzene, methanol, toluene, cresole/cresylic acid, phenol, carbonmonoxide, polycyclic-organic matter and cyanide compounds.

Archibald (1993), in his work “Nobake Binder System” said that formaldehyde is a potent skin, eye and mucous membrane irritant. It is considered a potential skin sensitizer. Employee exposure to formaldehyde should be controlled to within 1ppm for an eight-hour time weighted average (TWA), per USA regulation. Elwood (1993), said that one of the substances that is in most organic binder system is formaldehyde. OSHA (Occupational Safety and Health Administration) developed a substance specific standard of 0.75ppm threshold limit value (TLV), and called for the monitoring of employees working with the material. OSHA limits are known as permissible exposure limits (PELs).

Materials and OSHA Limits

Formaldehyde = 0.75ppm 8-hr TWA (Time-weighted-average)

Sulphurdioxide = 2.0 ppm 8-hr TWA

Carbonmonoxide = 35 ppm 8-hr TWA

Furfuryl alcohol = 10 ppm 8-hr TWA

Phenol = 5 ppm 8-hr TWA

Benzene = 1.0ppm 8-hr TWA

Toluene = 100ppm 8-hr TWA

Xylene = 100ppm 8-hr TWA

According to Archibald (1993), air borne emissions of industrial hygiene interest during mould and core production are formaldehyde and furfuryl alcohol, while the decomposition emissions of industrial hygiene interest are carbonmonoxide and formaldehyde. Geoffrey (1993) also agreed that free formaldehyde, aerated during mixing, is associated with irritation of the eyes, nose, and throat. According to the author, low free formaldehyde binders help foundries meet the new OSHA formaldehyde standard and the new EPA emission standard.

Starch binders from manihot esculenta has as their chief emission products water vapour, carbondioxide and a residual carbon of almost 70%. According to Moore and Mason (1981), manihot esculenta (starch) binder has a decomposition temperature of 121°C, with volume of gas evolved at decomposition temperature being equivalent to 113.76m³ gas evolved per m³ sand. Urea formaldehyde binder has a decomposition temperature of 163°C with volume of gas evolved at decomposition temperature as 96.48 m³ gas evolved per m³ sand. Linseed oil has a decomposition temperature of 427°C with a volume of gas evolved at decomposition temperature as 350.88m³ gas evolved per m³ sand. Table 15. 1 shows the chemical formulae of common binder components. Manihot eculenta on combustion releases carbondioxide and water into the environment. Reaction is shown below:

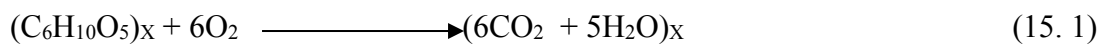


Table 15.1:Chemical Formulae of Common Binder Components

Material	Chemical Formula
Linseed oil	C ₅₄ H ₉₈ O ₁₆
Phenol formaldehyde	(C ₇ H ₈ O ₂) _x
Urea formaldehyde	(C ₂ H ₆ O ₂ N ₂) _x
Starch	(C ₆ H ₁₀ O ₅) _x

Source: Moore and Mason (1981)

Atmospheric Pollution

The foundry operations burns significant portion of chemicals and particulate matter as released into the atmosphere. Although a vast number of substances contribute to air pollution, the most common air pollutants contain carbon, sulphur, and nitrogen. These chemicals interact with one another and with ultraviolet radiation in heat emission from the melting process in dangerous ways that can cause serious health problems to the workers

Industrial effluents

The organization of castings of either steel or cast iron products are associated with consumption of industrial quantities of charging and additional metals, fuels, oxygen, electric energy and water. Apart from the final cast products the products of castings are slag, exhaust gases, water from cooling systems and melting dust.

In general sense, the term industrial effluents covers all forms of industrial waste products, gaseous, liquid and solids. In a narrower sense, industrial effluent as result of factory production into streams or reservoirs.

Sources of Atmospheric Pollution

In the foundry shop of the Ajaokuta Steel Company, there are some types of furnaces that are used for the process of melting all kinds of steel and cast iron products. (Two 6T Electric Arc Furnaces, One 10T Induction Furnace, One 1T Induction Furnace, Centrifugal Casting Machine and 100Kg Crucible Furnace).

During the melting process large quantity of melting dust are emitted which worsen labour condition in the shop and is the source of atmospheric pollution. The melting dust formed during the melting process consists mainly of iron oxides, but in some cases non-ferrous metal may be present in it.

For instance the use of scrap containing zinc plated iron results in an elevated concentration of zinc in the dust, in the form the other sources of atmospheric pollution in the foundry shop include exhaust wastes from the charge materials, like pig iron, scrap, charcoal, limestone, graphite electrode and the Ferro-alloys, the stock yard, the teeming section and ladle preparation and inspection section also constitute to atmospheric pollution because of the gaseous waste discharge.

Thus sulphur compounds, cyanide concentration, inorganic and organic synthetic chemical and melting dust are some of the main pollutions of the atmosphere from the foundry shop. These elements are very dangerous to the health and also constitute problems to the environment.

Methods of Controlling Atmospheric Pollution

Many methods of controlling atmospheric pollution are available and practiced. The method of removal of pollutants after generation and before dispersion is the most useful for an effective control of air pollutant in the foundry shop. Dust collectors of the following main types are mostly employed for the purpose:-

(a) Inertia dust collectors of this type can be divided into two groups.

(b) Dust collectors with settling chambers whose operation are based on gravitational settling of dust particules from the gas flow due to deceleration of the flow motion (which is attained by abrupt widening of the cross-section of a gas dust) the dust further moves to a scrubber underground and there the dust are filtered before the dust are sent through the provision for the distribution of the dust through the exhauster and to the atmosphere.

The gas flows around that body while solid particles carried by it impinge the body surface owing to their inertia and retained on it. The principle underlies the operation of a scrubber and cloths filters. Exhaust gases from the foundry melting process are often purified by scrubber of the Ventura-type.

Workers' Safety

Workers must be trained in personal safety measures. They must be trained to wear gloves, apron (asbestos heat resistant material) and suitable shoes, nose respiratory masks and helmets. The general tendency, however is to avoid wearing them, as they are uncomfortable in a hot environment, workers must wear suitable goggles in pouring and fettling section to avoid eye injuries.

Workers are also prone to accidents during pouring while handling hot metal, improper lifting of heavy weights (in moulds for instance) in normal foundry shop can lead to spinal injuries. Proper and adequate lighting, particularly at moulding and pouring stations is essential to avoid accidents and to improve quality of work. A periodical review (at least once in three months) of accidents, safety measure and worker safety training program should be undertaken by foundry engineer.

Some Ways of Dealing with Environmental Pollution and Health Hazards

- (a) Based on the data pertaining to the emissions it will be required to calculate the ground – level concentrations for each component / equipment before installation. The obtained results must be analyzed and compared with the ones adopted in Nigeria air quality standards.
- (b) Machinery must be so designed and constructed that risks resulting from the emission of airborne noise are reduced to the lowest level taking account of technical progress and the availability of means of reducing noise, in particular at source.
- (c) Health surveillance-where there is a significant risk to the health of employee as a result of exposure to vibration at work a program of appropriate health surveillance might need to be provided in accordance with the requirements of management of health and safety at work regulations.
- (d) The key point for foundry management is that foundry equipment and machinery should in future be supplied with better and more detailed information on noise and vibration level than is currently the case allowing a positive and informed machinery purchasing policy to operate effectively.
- (e) The noise assessment should advise the employer on which part of his premises need to be marked as ear protection zone.
- (f) Ear protection must be suitable to protect against the level of noise to which employee are exposed.
- (g) The management has a duty to ensure the full and proper use of anything provided in complying with the regulation for those employee exposed between the first and second action level.

- (h) The management also has a duty to ensure that anything provided under the regulations is properly maintained. This would cover, for example, ear protection, signs, indicating ear protection zones, noise control measures, e.g. noise enclosure, pneumatic silencers e. t. c.
- (i) The management of the Steel Company and that of Foundry shop must not compromise standard as regards the use of faulty equipment particularly the industrial exhauster as this could be inimical to the health and safety of the workers.
- (j) The inhalation of silica dust may also result to difficulty in breathing, persistent cough, chest pain and blood in the mucus, therefore the management of the foundry shop should make a yearly chest x-ray to reveal the incidence of these diseases.
- (k) To reduce the air pollutants emissions to the atmosphere in the process of operation of the Foundry equipment, dust- generating main process and auxiliary equipment with dust catcher should be provided.

Summary

In summary, it is worthy to state here that foundry environment can be extremely harsh and the importance of maintaining noise control measures, controlling of atmospheric environment, minimizing the vibration effect on the workers and ear protection is crucial to continuing effective control of noise exposure.

However, the subject of noise and its transmission is complex; hearing loss often goes unnoticed being confined initially to a limited frequency range, before becoming more severe and extensive. The management of foundry should make the right choices in its efforts to reduce generation of an exposure to noise and vibration at the shakeout, Electric Arc Furnace, Muller mixers and other equipment.

The characteristic feature of any modern production process is the generation of a considerable amount of various types of waste which differ from each other by physical and chemical properties, quantities, by the character of their influence on the environment and population. Part of these wastes may be used by own plant as in their production or in some other industries. The rest of the waste should be managed in a manner that would exclude or minimize as far as possible the adverse impact of waste on the environment. Finally, the

management should envisage an air pollution monitoring system, to give recommendations on arrangement of stationary monitoring stations.

REVIEW QUESTIONS FOR CHAPTER FIFTEEN

1. Why was it necessary for the government of Nigeria to establish the factories Acts of 1955?
2. Write on relevant sections of the factories Acts and regulation
3. Write on health hazards associated with the foundry environment
4. Write on noise in the foundry and the effect of noise on the foundry worker
5. What is Hand Arm Vibration Syndrome (HAVS)? Expatiate.
6. What are the effects of hand transmitted vibration (HTV) on the foundry worker?
7. Write on the existing remedies for controlling the effects of vibrations on the foundry worker
8. Write on binder emissions in the foundry and its effect on the foundrymen and the environment
9. Draw the process envelope of a typical foundry showing the inputs and outputs
10. What is the meaning of binder emissions?
11. List some emissions in the foundry and indicate their OSHA limits
12. What is the chemical formula for linseed oil, starch, urea formaldehyde and phenol formaldehyde?
13. How does the foundry pollute the atmosphere and what are the common effluents associated with the foundry shop?
14. List some sources of pollution in the foundryshop
15. Write on some methods of controlling atmospheric pollution in the foundry.
16. Write on methods of achieving workers safety in the foundry

17. What are your suggestions for reducing environmental pollution associated with the foundryshop?

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