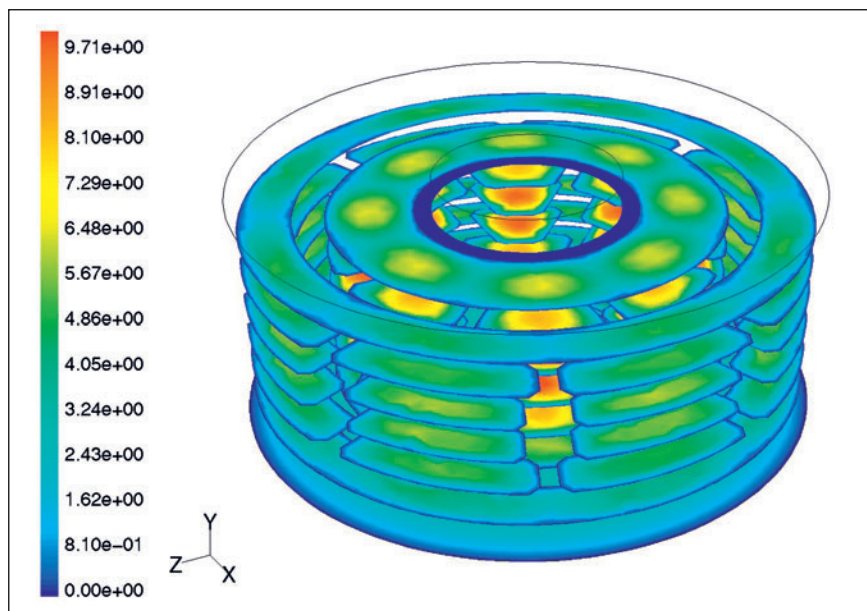


Variety by the Meter

Flow velocity in the region of the double spider head of a pipe die (source: Institut für Kunststofftechnik Paderborn); simulation software: Polyflow (Fluent Deutschland GmbH)



Extrusion Dies. Production of high-quality semi-finished plastic goods requires product-specific extrusion lines that incorporate a number of critical processing operations. Regardless of where the extrusion die is located in this sequence of important components, there is no doubt that it is ultimately responsible for the shape of the product. It is this responsibility that results in the variety of products that can be produced via extrusion.

STEFAN SEIBEL

Within the plastics processing industry, the extrusion process is one of the most common for producing useful semi-finished goods from plastic raw materials. Innovations in this sector result from competition with other manufacturing processes, new product ideas and economic pressures. The consequence is that manufacturers of extrusion equipment are faced with the challenge of continually improving their own technology. By classifying extrusion systems on the basis of the outlet geometry of their dies, four groups can be distinguished and identified accordingly: circular, slot, annular and freely two-dimensional (Fig. 1).

In all of these groups, shaping of the plastics occurs while it is in the molten state. From the standpoint of fluid dynamics, this melt condition is determined by a number of rheological phenomena. Many of these phenomena are not yet understood fully [1] and only a few can be

characterized satisfactorily. The technique employed in industry to characterize flow properties range from single measurements such as the MFI value, for instance, through determination of the relationships between the viscous and elastic properties as a function of temperature and time, to in-line measurement techniques utilising ultrasonics. The theoretical and practical research of recent years aimed at describing the flow

behaviour in extrusion dies with the aid of material data and flow models has increased understanding of the processes occurring in extrusion dies.

Basically, the extrusion die serves to form the required product cross-section from the usually circular melt stream provided by the extruder. The basic geometry of the semi-finished item is thus already determined by the die while the plastic is in the melt state. The process step

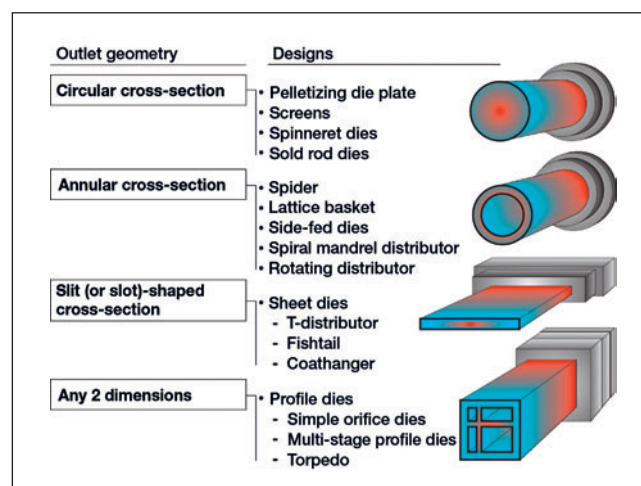


Fig. 1. Overview of extrusion die designs

Translated from Kunststoffe 12/2005, pp. 38–46

is associated with a pressure drop, so that the extrusion die also affects the pressure-throughput relationship of the extruder. The two components should be matched to one another as closely as possible, since in addition to the quality of the extrudate the economics of the entire extrusion line depends on this symbiosis.

Likewise, it is necessary to match the die to the downstream equipment, as expansion of the melt and/or temperature differences must be corrected and compensated for via calibration to stabilize the dimensions of the product.

Dies with a Circular Cross-section

Dies with a circular cross-section are used for production of fibre, pellets, filaments and solid rods. The smallest outlet cross-sections with diameters starting at 0.05 mm and tolerances of $\pm 1 \mu\text{m}$ are found in the so-called spinnerets. In this area, both single dies and spinneret packs, e.g. for nonwovens production, with several thousand openings find use. Every spinneret capillary is preceded by transition zones with several entry angles as well as depressions or recesses in the inlet region, as shown in Fig. 2. The entry angles α and β are often trumpet- or chalice-shaped in order to introduce as little deformation into the melt as possible. Matching of material and product is accomplished via specific variation of the L/D ratio and the entry angles.

In pelletizer dies, the individual outlet cross-sections or openings are arranged either linearly or circularly. The arrangement of these openings (usually 2.4–3.5 mm in diameter) depends on whether hot or cold pelletizing follows and the manner in which melt is supplied. In addition to the mechanical resistance to widening, supplying the melt uniformly to all openings is decisive for the

operation of this die type. In the region of the discharge outlet, the die plates are subject to extreme wear from the cutting

vestigations of flow phenomena in capillaries in order to improve existing mathematical models, optimise inlet and out-

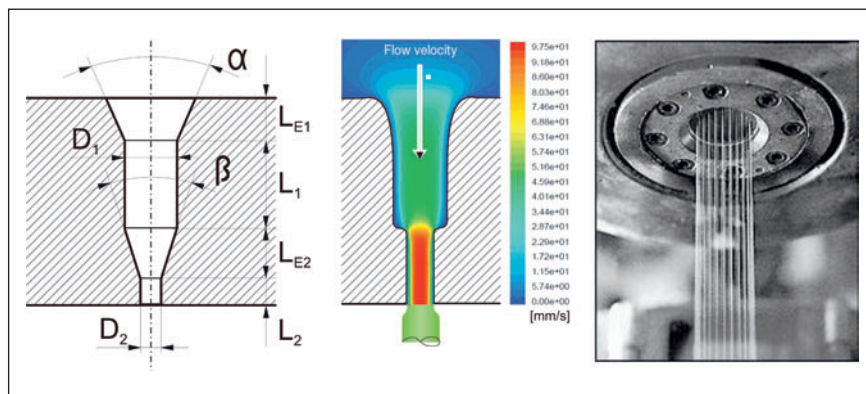


Fig. 2. Sectional representation of a simple type of spinning die with the typical geometric parameters (left); illustration showing the flow velocities (centre); melt exiting from a spinneret nozzle pack (right) (source: www.etn-net.org)

knives and the change in flow. This is counteracted through the use of special die designs (knife-side) or, even more effectively, through use of 3–5 mm thick ceramic or hardmetal die plates as “die armour”, as shown in Fig. 3.

Furthermore, the relatively poor thermal conductivity of these ceramic/hardmetal plates provides good thermal insulation and prevents premature “freezing” of the melt prior to exiting the die. Because of the sometimes very high mass throughputs of up to 25 kg/h with PP materials, which each opening must accommodate, melt deformation due to extension/elongation, in particular, must be taken into consideration in addition to the shear deformations. In order to keep the load on the melt due to dissipation just within acceptable material-specific limits, on the one hand, and still control the resultant die pressures, on the other, the entry angles are normally $< 30^\circ$ and the L/D ratio between 4.5 and 7.5.

In recent years, industry and research facilities alike have intensified their in-

let zones from a fluid dynamics standpoint and promote new surface coatings.

Dies with a Slit (or Slot)-shaped Cross-section

Extrusion dies with a slot, or slit, outlet are used to produce sheet and film as well as to coat flat webs. The function of these so-called sheet dies is to convert the melt flow from a circular cross-section to a narrow rectangular cross-section, so that melt has the most uniform velocity distribution possible over the width of the outlet. To achieve a symmetrical melt distribution over the entire width of the die, rheologically optimised flow channels are employed that can take various shapes, depending on the application. The most commonly encountered distribution shape is that of the coathanger die, in which the cross-section of the distribution channel decreases continuously (Fig. 4).

The fishtail shape is also fairly common, as is the T-shape, which is preferred

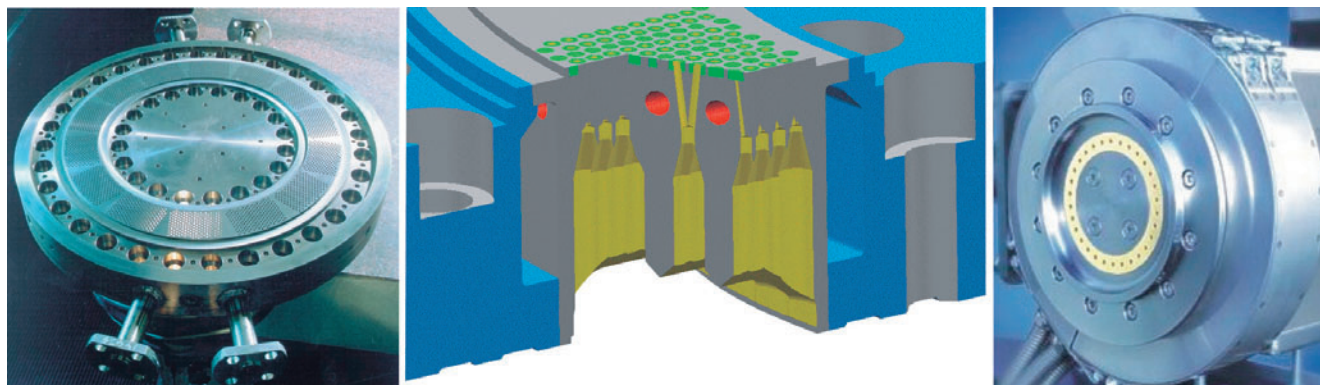


Fig. 3. Die plate designs; left: pelletizer die plate with annular arrangement of openings, centre: sketch of the inlet to the die orifice (source: Coperion Werner & Pfleiderer); right: hardfaced pelletizing die plate (source: Econ Maschinenbau und Steuerungstechnik)

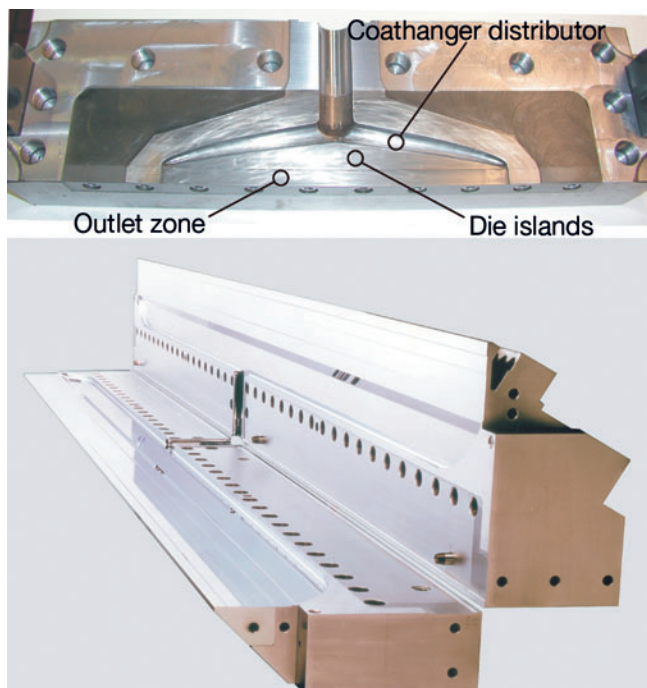


Fig. 4. Above: Half of a sheet die with a coathanger distributor (source: Institut für Kunststofftechnik Paderborn); **below: T-distributor die** (source: Verbruggen N.V.)

for extremely wide dies. In 95 % of the applications today, the die surfaces are hard chrome-plated or polished and only rarely have special surface coatings. The design of the distribution channel in a sheet die is usually intended for only a narrow operating window – with regard to material and process parameters. In the event of deviations from the operating point, non-uniform flow velocities that cause variations in thickness transverse to the take-off direction result at the outlet of the die. To level out such thickness variations, restrictor bars (sometimes called choker bars) and/or flexible die lips are employed in sheet dies. For this purpose, adjustment screws with which the die gap can be adjusted are positioned with a uniform spacing across the width of the die. This change in flow channel height affects the local flow velocity. Many highly automated film and packaging lines use automatic dies today. In these, adjustment of the die lips takes place automatically, so that the die gap and product thickness distribution are linked. Thermal expansion bolts, translators or motorised actuators are available as actuating element [2].

The width of the die gap, and thus the width of the die, depends on the downstream equipment and products. Die widths today range from 100 to 8000 mm, with die gaps of 0.5 to 70 mm. In order to permit some variation of the product width within at least a certain range, deckle bars that are introduced into the flow channel from the side or edge adjustment strips that are installed upstream of the outlet permit the working width of the die to

be reduced. These deckling systems are used successfully for extrusion of mono-layer and multi-layer products and, above all, for coating. As a rule, electric heater cartridges and heating platens are used to heat the die body. Insulation of exterior surfaces and even complete encapsulation of the die are becoming more and more common as a means of reducing heat losses.

This extrusion die type is witnessing a great deal of activity regarding innova-

tions in many areas. For instance, scale-up/scale-down rules for designing sheet dies with the aid of simple equations are being developed at the Institute for Plastics Technology (Institut für Kunststofftechnik) at the University of Paderborn. The equations are based on the coathanger distributor geometry. Once a sheet die with good melt distribution has been designed, it is then possible to resize the width and height of the die gap in the die. Moreover, it is also possible to change the resin to be processed by varying the exponent n in the application rules. In general, network methods and numerical flow simulations are employed when designing this type of extrusion die. This work has two objectives: on the one hand, to improve quality by optimising flow and, on the other, to achieve the most compact die design. Developments in the area of coextrusion are, in most cases, initiated by demands for increased functionality in packaging films and result in new feedblock systems with matching sheet die distributors whose function is to maintain stability of the multi-layer distribution up to the die outlet.

Dies with an Annular Cross-section

Dies with an annular cross-section are used for extrusion of pipe, tubing, blown film, blow moulding parisons and for

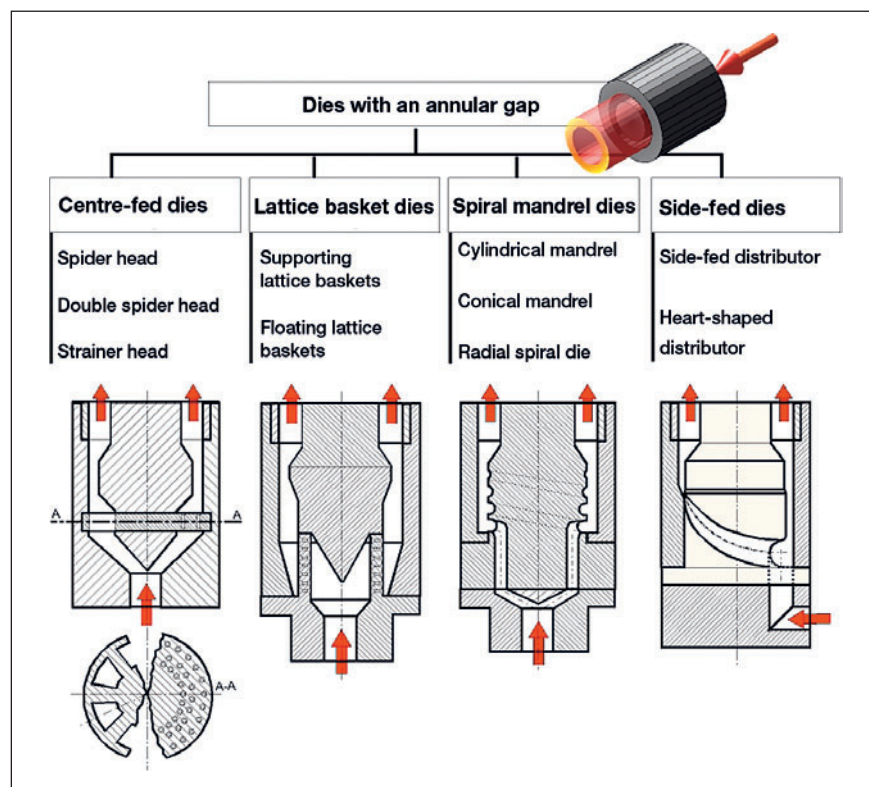


Fig. 5. Classification of die with an annular gap

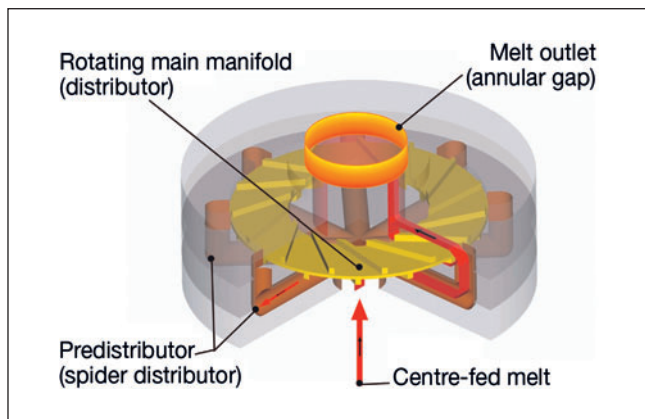


Fig. 6. Schematic of die with rotating distributor showing view of flow at the distributor element (source: Institut für Kunststofftechnik Paderborn)

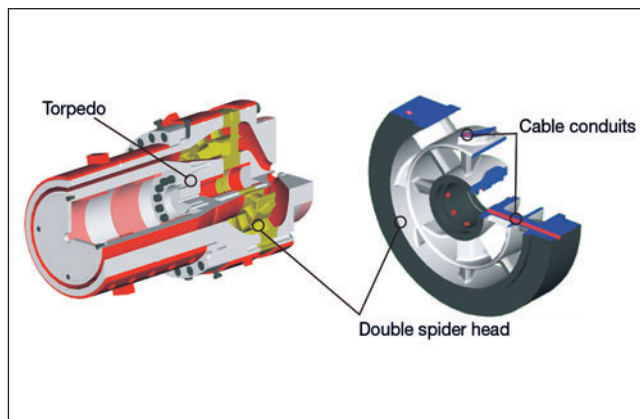


Fig. 7. Sketch of a centre-fed die with double spider head (source: Battenfeld Extrusionstechnik)

coating of wire and cable. Production of semi-finished goods with a seamless annular cross-section involves primarily the four extrusion die types shown in Fig. 5. What these have in common is the approach taken for melt distribution. This is accomplished statically via the type-specific flow channel structure, i.e. the melt is forced through a predistributor and then spread out by one or more distributor systems. In contrast to this classical approach to static melt distribution, the University of Paderborn is testing and refining a new type of dynamic die concept for extrusion of film and pipe.

In the type of die depicted schematically in Fig. 6, distribution of the melt occurs with the aid of a rotating distributor geometry (which represents the heart of this dynamic melt distributor system) that is driven solely by the incoming melt.

For extrusion of pipe and tubing, centre-fed dies are used for the most part. For extrusion of blown film, reinforced tubing, blow moulding parisons and for coating of wire and cable, the dies must generally be fed from the side at an angle of 90°. When designing coextrusion dies,

combinations of the various die types and feed directions are often employed.

Regardless of the design, nozzle assemblies the flow channels of which recombine, stabilize and direct the melt streams toward the outlet of the die must be attached to the base die body – either directly or via replaceable adapters. The design of these flow channel regions is very product- and material-dependent and shows little standardisation. For instance, when producing PVC pipe via spider heads, compression to smaller outlet cross-sections is essential to guarantee product quality. In most cases, pipe extrusion and production of blow moulding parisons involves a reduction in diameter. Typical reduction factors range here from 2:1 to 6.5:1. In contrast, blown film dies and dies for large-diameter pipe involve an increase towards the die outlet. The expanding cross-sectional area can be as much as 1:2.5. In any case, a continually accelerating flow should always be the objective in the nozzle region.

A parallel zone that in many cases is adjustable regarding gap width and centering follows at the end of the nozzle zone.

The so-called flexring technology with which a more exact adjustment of the die gap is possible – and thus the thickness tolerance – has found acceptance in the pipe and blown film sectors only in recent years. This technology involves placement of a flexible sleeve in the solid outer die ring near the discharge opening. Adjustment screws – placed uniformly around the circumference – are incorporated into the outer die ring for the purpose of adjustment. These screws permit reversible deformation of the flexible sleeve and thus a very precise adjustment of the local resistance to flow through the annular die gap [3].

The ratio of the die land length to the die gap depends on the material being processed and ranges from about 2:1 to 30:1 in pipe dies.

Centre-fed Dies

The primary field of application for this type of extrusion die is the extrusion of pipe and parisons. In terms of volume processed, the most important resins are polyvinylchloride (PVC), the polyolefins (e.g. PE-HD) and the polyamides (PA). Generally, this type of die is quite forgiving with regard to residence time distribution and required pressure.

The torpedo is held and positioned in the die by a spider, so that the centre-fed melt stream forms an annular flow around it. Downstream in the die, the melt flows around the spider legs and is divided into several streams. Instead of legs, a breaker plate can also be employed. Because the melt stream is divided, a subsequent compression zone is essential in order to suppress weld lines and streaks. For higher throughputs and to improve the physical properties of the product, a double spider head is finding increasing use in recent years. In this design, two sets

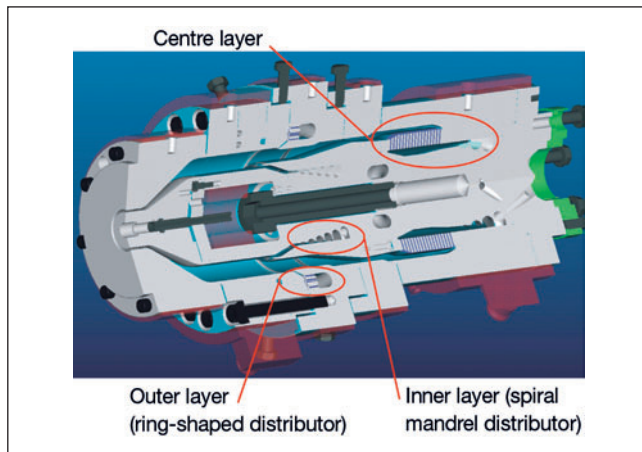


Fig. 8. 3-layer extrusion die with floating lattice basket (centre layer) for production of PP foam-core pipe

(source: Battenfeld Extrusionstechnik)

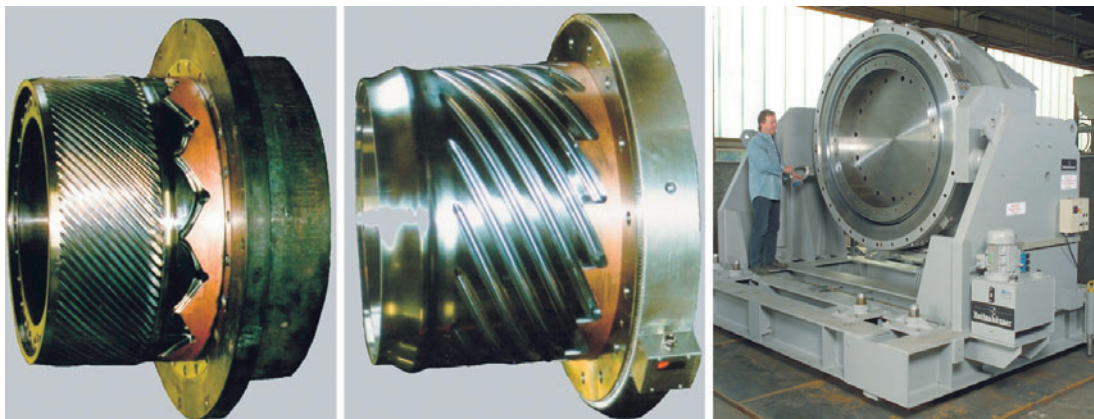


Fig. 9. Spiral mandrel distributor designs; left: torpedo with coathanger pre-distributors, centre: torpedo with starlike (star-shaped) pre-distributor (source: ETA); right: die for pipe with diameter of up to 2000 mm (source: Reifenhäuser)

of legs that are offset with respect to one another are placed around the circumference. As shown in Fig. 7, a backing ring supports the two spider heads against one another. A major benefit of this design is the manner in which the melt is divided, which results in a significant improvement in the physical properties of the extruded product [4].

In order to prevent dead areas and deposits, the flow cross-section following the spider head (also called spider strainer) and extending to the outlet from the die should not be divergent. Usually, the nozzle region exhibits continuous compression – up to the entrance to the parallel zone. When processing PVC, a cross-sectional compression of up to 50:1 is common.

Lattice Basket Dies

Lattice basket dies find use in a great variety of applications, but most often in concepts for pipe and coating extrusion lines. As the die name already indicates, the torpedo is not held by legs, but rather by a lattice basket. In this case, the expression supporting lattice basket is used. If the lattice basket fulfills only processing-related requirements, the design is designated as a floating system. The lattice basket itself is a tubular, quasi-perforated body with a very large number of openings (1–3 mm in diameter) that divides the melt stream into many smaller streams. As the illustration in Fig. 8 shows, the floating, horizontal orientation of the lattice basket diverts the melt stream by 90° twice.

After being diverted the second time, the melt passes through a so-called “compression zone” in which the melt steams from the individual openings are “welded” back together. Following the compression zone there is a relaxation zone. In this large parallel-walled region, the melt stream relaxes and stabilizes prior to entering the nozzle zone. Lattice basket

dies are employed for extrusion of PE-HD, PE-LD, PP, ABS and PS. Compared to centre-fed dies, lattice basket dies are considerably more compact, which makes them lighter and easier to handle. By working with only one short but significant source of a pressure drop – the lattice basket – this die type exhibits only relatively small overall pressure losses. Recently, lattice basket dies that work with a combination of a wiping spiral – for pre-distribution – followed by a lattice basket (Fig. 8 centre) have become available on the market.

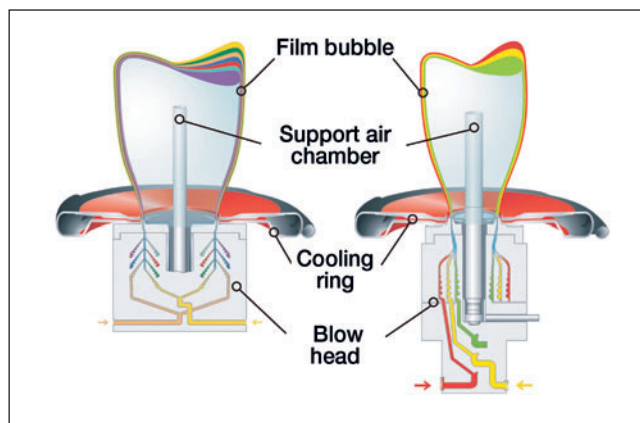
Spiral Mandrel Dies

Spiral mandrel dies are employed for extrusion of pipe, blown film, and blow moulding parisons as well as for coating. In conventional spiral mandrel dies, each individual spiral is supplied with melt by the pre-distributor – a so-called starlike (or star-shaped) pre-distributor. As a result of this pre-distributor design, it is not possible to have a large number of concentrically arranged main manifolds, because the pre-distributors would otherwise affect one another (thermally) too much or the space available is simply inadequate. More than 5 layers are seldom offered in a classical design. In order to overcome this restriction, die designers have increasingly

concentrated on development of pre-distributors. Today, designs with multiple prebranching and one or more side-fed pre-distributors to feed the actual spiral distributor have become standard. For side-fed dies with limited wall thickness – in order to create space in the centre – annular pre-distributors that feed each spiral channel with melt are available. The spiral-shaped channels that are machined into the mandrel in the form of a multiple thread follow these primary distributors, or pre-distributors. The channel depth decreases continuously, so that the leakage gap between the mandrel and outer die wall increases continuously. The designs range from a lot of shallow and narrow spirals at a steep helix angle to designs with a few spirals having a large cross-sectional area at a smaller helix angle (Fig. 9).

That the die designers and machine builders are fully exploiting the numerous degrees of freedom that this die type offers is shown by the variety of dies available on the market. In addition to the cylindrical version, “radial” or “conical” spiral distributors with upstream prebranching systems and side-fed melt are offered, especially for coextrusion of blown film [5]. In these designs, the spirals do not run around a cylindrical mandrel, but rather are machined into a cone

Fig. 10. Left: conical spiral mandrel distributor Vorex Maxicone blow head; right: Vorex three-layer blow head with starlike (star-shaped) pre-distributor (source: Windmüller & Hölscher KG)



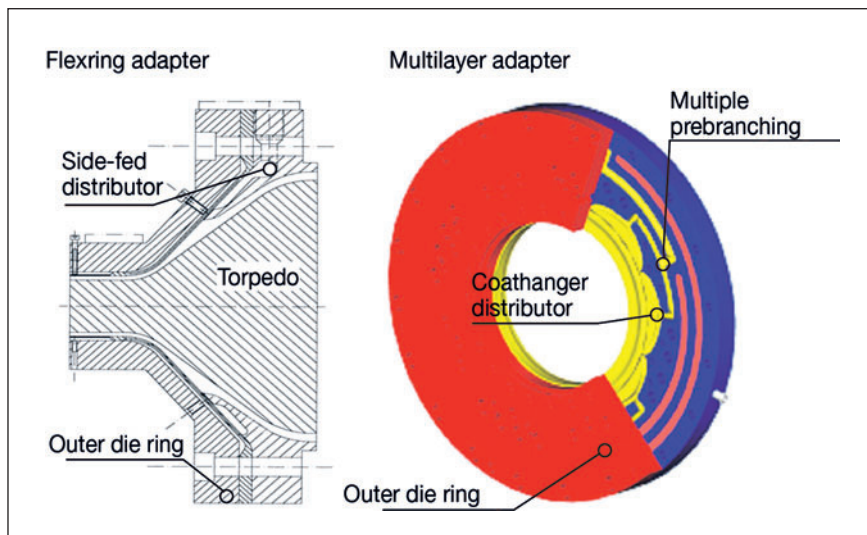


Fig. 11. Flexring adapter with side-fed predistributor for the outer layer (left) (source: Heinz Groß); multi-layer adapter (right) (source: Krauss Maffei)

or flat die plate. As a result of this flat design, several of these spiral plates can be placed on top of one another. Thanks to this arrangement, the radial spiral die is also called a “stack die” or “pancake die”.

In conical spiral distributors, the melt is also side-fed, so that, for instance, supporting and cooling air can be conveyed centrally in blow heads. The blow head shown in Fig. 10 for 5 to 7 layers has been used successfully in actual practice for wide multi-layer films of up to 2200 mm dfl (lay-flat width of the blown film). The patented conical distributor system permits exceptionally compact construction. Thanks to the low pressure loss, this translates into high machine outputs with optimal film tolerances. The conical design combines the advantage of the radial distributor with regard to high flexibility in terms of the number of layers without its sealing problems as the result of excessive deflection in the die.

Side-fed Dies

Side-fed dies find use for extrusion of pipe and blown film as well as for coating.

These dies are often supplied with melt from the extruder at an angle of 90°. The side-fed melt is transformed into an axial flow by a distributor channel that is machined into the torpedo head. This flow around the torpedo gives rise to at least one, and in the case of several distributors, correspondingly more characteristic flow lines.

There are basically two different flow channel designs to distribute the melt: on the one hand, the classical coathanger design – if the base is unwound, a shape similar to that of the coathanger distributor results – and, on the other, the heart-shaped curve. The latter utilises a heart-shaped torpedo around which the melt flows. The torpedo is designed in a manner that produces almost equally long flow paths. Dividing and subsequently recombining the melt streams results in two flow lines that can weaken the product [6].

The know-how of designers and process technicians involves largely configuring the geometry of the distributor channel and and/or torpedo in a way that yields a uniform flow velocity at the outlet.

A major advantage of this distributor type is the possibility of a space-saving and functional retrofit of existing extrusion dies. A conical torpedo (mandrel) is often integrated in the nozzle region or before the main distributor. So-called “multi-layer adapters” for extrusion of one or more outer melt layers have also become available recently (Fig. 11). These adapters with multiple coathanger regions are incorporated between the main distributor and nozzle zone.

Dies with a Profile Cross-section

The plastic profiles produced by means of extrusion can be classified roughly as solid rod profiles, open profiles and hollow profiles. In terms of volume processed, the most important resin in profile production still remains polyvinylchloride (PVC). PVC profiles are employed in the manufacturing of window and door frames, rolling shutters, cable conduits, cladding and other semi-finished goods for the construction industry. Other materials, such as ABS, PS, PP, PE and PM-MA, find use in the furniture, automotive and electrical/electronics industries.

The melt is shaped initially in the profile zone, while the final shape is formed in the subsequent calibration zone with simultaneous cooling. Matching the die outlet to the calibration section is more critical here than with any of the previously discussed dies for a stable melt-shaping process, and thus the dimensional accuracy and stability of the profile.

The simplest form of profile die consists of a single flow channel at the end of which an orifice is placed with the shape of the desired profile. This design, with a suitable inlet to the orifice, is often employed in crosshead dies for production of rubber profiles (coating).

More favourable from the standpoint of fluid dynamics are the multi-stage profile dies consisting of several plates arranged in succession. Viewed from the infeed end, each plate holds a shape that more and more closely resembles the final shape of the profile. The transitions between the plates are tapered or have shapes that promote good flow, so that no dead zones result. The multi-stage construction largely prevents undesirable dead regions, but leads to considerably higher costs than for a simple die with a shaped orifice. Multi-stage dies do not incorporate a torpedo.

Dies for hollow profiles always incorporate a torpedo. This type of profile die

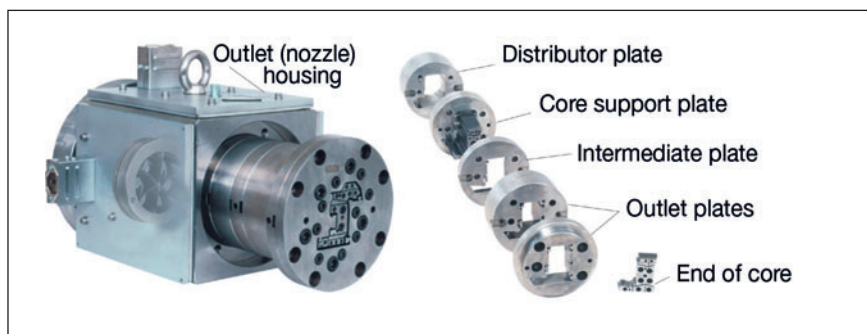


Fig. 12. Hollow chamber die for a frame profile (source: Gruber & Co Extrusionstechnik)

consists of several plates the openings in which describe the approaching outer shape of the extrudate. The interior contains a torpedo (held by legs) that spreads the incoming melt and forms the hollow shape. These plates form the individual functional zones of the die and are designated the feed, distribution, compression and parallel zones (Fig. 12).

The diskpack profile die represents an additional concept for production of hollow profiles. The segmented construction (disks) and the design of the flow channels are similar to that found in the die described above. The difference lies in the design of the torpedo, which is also divided into segments each of which is held by legs [4].

As a result of its flow channel configuration, this die class is extremely complex and can be described from the standpoint of fluid dynamics only with the aid of CFD programs. The possibilities for design offered by simulation programs, however, are limited by the rheologically difficult to characterize materials, such as PVC and rubber systems, for example.

Summary

New trends and technologies in the field of extrusion dies are rare, but can still be found, even though some areas of extrusion are less generous with their information than others. Apparently, Germany – recognised as the world's leading exporter – also assumes a key role when it comes to the development of extrusion dies. It should be possible to detect trends and new developments from market developments. Even if this is difficult, according to suppliers of machinery and tooling, such new developments are bound to reflect in some way the many demands of processors. To be mentioned here in this regard above all is the necessity to produce small lot sizes, to participate in and contribute to new developments (from both the product and material standpoints) and to satisfy the ever more stringent quality requirements.

For instance, two German machinery suppliers and their cooperation partners have recently started to offer pipe line concepts that permit a continuous change of dimensions without stopping the system. To accomplish this, the extrusion die has been modified, as in blow moulding, to have an adjustable die gap. In addition to the outside diameter, the wall thickness is variable within certain limits as well. To avoid instabilities and simultaneously reduce build-up, it is important in this re-

! In Profile

The cornerstone for the founding of **3 Pi Consulting & Management GmbH** in 2003 was laid already at the beginning of 2002. The team at 3Pi views itself as a structured, fundamentals-oriented service provider for engineering in plastics processing. Activities focus above all on process optimisation, process development and product analysis. These services are offered in the fields of joining/assembly technology, injection moulding, extrusion and quality management.
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gard to create a defined and consistent transition point – from wall adhesion to plug flow – from the torpedo and the nozzle. Special shapes and surfaces at the end of the nozzle zone are offered for this purpose [7].

The economic requirement to conserve raw materials is leading in some areas to the use of higher-grade materials or the use of reinforced mixtures and blends in order to ensure the same mechanical properties with reduced material usage [5]. The other way to satisfy this requirement is through use of less expensive materials, such as recycled or mineral-filled or foamed plastics. In addition to processing of ready-to-use compounds, direct extrusion from the compounder into the centre layer is used. Extrusion of foamed inner layers represents a third possibility for production of pipe and sheet. According to information from machinery suppliers, this variation is employed also for processing of PVC and polyolefins. Most of these requirements are addressed with the development of product-specific multi-layer dies.

On the basis of the last-mentioned information regarding material variations, but also from the quality standpoint, extrusion die suppliers are attempting to optimise the surfaces that come into contact with the melt layers. At present, PVD (Physical Vapour Deposition) coatings are preferred because of their advantages regarding the variety of materials that can be deposited and the low coating temperatures of 200–500°C. Coating materials include TiN, TiCN, TiAlN, TiAlN/CRN.

Because of the great variety available, many suppliers of machinery and extrusion dies are now working with the aid of computer-aided design methods. Furthermore, experience relating to permis-

sible residence times and melt stresses is making an important contribution to die design. At the same time, physical and mechanical characteristics as well as production-related requirements and manufacturing know-how are having a significant impact on die concepts.

As indicated at the outset, the extrusion die is one component in the concept for an extrusion line and must also satisfy requirements regarding "handling". Designs and process technology can address these requirements by integrating quick-change mechanisms for die nozzles, providing special devices for rapid material changes, considering possible interactions with the surroundings and even planning for quick die changes. ■

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