

HANSER

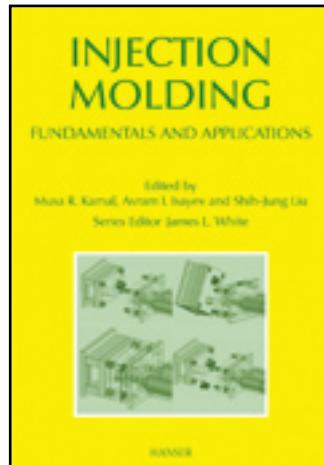


Table of Contents

Injection Molding

Technology and Fundamentals

Herausgegeben von Musa R. Kamal, Avram I. Isayev

ISBN: 978-3-446-41685-7

For further information and order see

<http://www.hanser.de/978-3-446-41685-7>
or contact your bookseller.

Contents

Preface	V
Part I: Background and Overview	1
1 Injection Molding: Introduction and General Background	3
<i>Musa R. Kamal</i>	
1.1 Scope	3
1.2 Introduction	3
1.2.1 Polymer Processing	3
1.2.1.1 The Plastics Processing System	4
1.2.1.2 Processing Properties of Polymers and Their Compounds	5
1.2.2 Injection Molding	5
1.2.2.1 Introduction	5
1.2.2.2 General Injection Molding Process Sequence	6
1.3 Injection Molding Process Characteristics	9
1.3.1 The Plastication Stage	9
1.3.1.1 The Melting Zone	11
1.3.1.2 Temperature distribution in the nozzle	13
1.3.2 The Filling Stage	17
1.3.2.1 Flow Lines and Weld Lines	17
1.3.2.2 Jetting	19
1.3.2.3 Fountain Flow	20
1.3.3 Heat Transfer in the Cavity	24
1.3.3.1 Measurement of Temperature Distribution in the Cavity	24
1.3.3.2 Numerical Simulation of Heat Transfer in Injection Molding	28
1.3.3.3 Crystallization Kinetics	30
1.4 Microstructure of Injection Molded Parts	31
1.4.1 Crystallinity	32
1.4.1.1 Effect of Crystallinity and Orientation on Birefringence and Tensile Modulus	33
1.4.2 Morphology	36
1.4.3 Residual Stresses	40
1.4.3.1 Calculation of Residual Stresses	42
1.4.4 Microstructure of Fiber Reinforced Thermoplastics	46
1.4.4.1 Fiber Length and Concentration Distributions	46
1.4.4.2 Matrix Crystallinity	47
1.4.4.3 Fiber and Matrix Orientation	48
1.4.4.4 Composites Incorporating Conductive Fibers	51
1.4.5 Distribution of Cure in Thermosets	51
1.5 Properties of Injection Molding Compounds and Products	54
Symbol List	61
References	63

Part II:	Injection Molding Machinery and Systems	71
2	Injection Molding Machines, Tools, and Processes	73
	<i>Tadamoto Sakai and Kenji Kikugawa</i>	
2.1	Injection Molding Machines	73
2.1.1	Types of Injection Molding Machines	73
2.1.1.1	Horizontal Injection Molding Machines	73
2.1.1.2	Vertical Injection Molding Machines	74
2.1.1.3	Hybrid Injection Molding Machine Composed of Vertical and Horizontal Units	75
2.1.2	Screw and Barrel Unit	75
2.1.2.1	In-Line Screw Type Injection Molding Machines	76
2.1.2.2	Screw Design for Injection Molding Machines	76
2.1.2.3	Barrels for Injection Molding Machines	77
2.1.3	Driving Principles	79
2.1.3.1	Hydraulic Injection Molding Machines	80
2.1.3.2	Electric Injection Molding Machines	80
2.1.3.2.1	Control Systems for an Electric Injection Molding Machine	81
2.1.3.2.2	Injection Mechanism for an Electric Machine	82
2.1.3.2.3	Nozzle Contact Mechanism for an Electric Injection Molding Machine	83
2.1.3.2.4	Electric Clamping Mechanism	83
2.1.3.2.5	Electric Ejection Mechanism	84
2.1.3.3	Man-Machine Interface and Communication Control	84
2.1.3.3.1	Man-Machine Interface for an Injection Molding Machine	84
2.1.3.3.2	Communication Control	86
2.1.4	Process Control	86
2.1.4.1	Control of the Filling Process	87
2.1.4.2	Control of the Hold-Pressure Switching Process	87
2.1.4.3	Control of the Hold-Pressure Process	88
2.1.4.4	Control of the Metering Process	89
2.1.4.5	Control of the Mold Opening/Closing Process	89
2.1.4.6	Temperature Control of Each Barrel And Nozzle	89
2.1.4.7	Control of the Injection Compression Process	89
2.2	Molds for Injection Molding	90
2.2.1	Functions of Mold Components	91
2.2.2	Classification of Molds	94
2.2.2.1	Cold Runner Mold Systems	94
2.2.2.1.1	2-Plate Molds	94
2.2.2.1.2	3-Plate Molds	94
2.2.2.2	Hot Runner Mold Systems	96
2.2.3	Sprue, Runners, and Gates	98
2.2.3.1	Runners	98
2.2.3.2	Gates	98
2.2.3.3	Gate Balance	102

2.2.3.4	Air Vents.....	103
2.2.4	Ejection Mechanisms.....	103
2.2.4.1	Ejector Pins	104
2.2.4.2	Sleeve and a Stripper Plate	104
2.2.4.3	Air Ejector	104
2.2.5	Mold Cooling	106
2.2.6	Temperature Control Methods and Mechanisms.....	106
2.2.6.1	Liquid Medium Control	106
2.2.6.2	Electric Heater Control.....	107
2.3	Injection Molding Processes	107
2.3.1	In-Mold Build-Up Injection Molding (DSI)	107
2.3.2	Conventional Processes	108
2.3.3	DSI Molding Process.....	108
2.3.3.1	Injection Welding Mechanism	108
2.3.3.2	Advantages of the DSI molding process	109
2.3.3.3	Product Examples of the DSI Molding Process.....	110
2.3.4	Multi-Material Injection Molding	111
2.3.4.1	Multi-Material Molding Techniques	111
2.3.4.2	Application Examples for the M-DSI Molding Process	114
2.3.5	Super-High Speed Injection Molding	115
2.3.5.1	Effects of High-Speed Injection	115
2.3.5.2	High-Speed Injection Molding Machines	116
2.3.5.3	Example of Ultra High-Speed Injection Molding.....	117
2.3.6	In-Mold Coating Injection Molding	117
2.3.6.1	Surface Decoration Techniques.....	117
2.3.6.2	Simultaneous Transfer Molding	118
2.3.7	Insert Injection Molding Process	120
2.3.7.1	Insert Molding Machines	121
2.3.8	Sandwich Injection Molding	122
2.3.8.1	Process Outline.....	122
2.3.8.2	Construction of Sandwich Nozzles	122
2.3.8.3	Features of Sandwich Molding	124
2.3.9	Plastic Magnet Injection Molding	125
2.3.9.1	Molding System and Magnetic Field Generating Methods	126
2.3.9.2	Important Issues with Injection Molding of Plastic Magnets	127
2.3.9.3	Key Points of Mold Design for Plastic Magnets	128
2.3.10	Long-Glass Fiber Reinforced Injection Molding	128
2.3.10.1	Long Fiber Reinforced Plastics Injection Molding.....	129
2.3.10.2	Properties of Long Glass Fiber (GF) Reinforced Plastics	129
2.3.10.3	Applications of Long-Fiber Molding to Large-Size Products	130
	References.....	130

3	The Plasticating System for Injection Molding Machines	133
	<i>Mark A. Spalding and Kun Sup Hyun</i>	
3.1	Introduction	133
3.2	The Plasticating System	134
3.3	Operation of Plasticating Screw Machines	136
3.3.1	Proper Operation	138
3.4	The Melting Process	138
3.5	Basic Screw Design	146
3.5.1	PS Injection Molding Case Study	147
3.6	High-Performance Screw Designs	148
3.7	Secondary Mixing Processes and Devices	154
3.7.1	Dynamic Mixers	161
3.8	Screw Design Issues Causing Resin Degradation	163
3.9	Non-Return Valve	165
	Nomenclature	166
	References	168
4	Non-Conventional Injection Molds	171
	<i>António M. Cunha, António J. Pontes</i>	
4.1	Introduction	171
4.2	Molds for Multi-Material Molding	173
4.2.1	Co-Injection	173
4.2.2	Overmolding	176
4.3	Injection Units, Layout, and Runner System	181
4.3.1	Equipment	181
4.3.2	Hot Runners	183
4.3.3	Material Interactions	183
4.4	Molds for Injection-Welding	184
4.5	Molds for Backmolding	186
4.5.1	Molding over Textiles or Fabrics	186
4.5.2	In-Mold Labeling	191
4.5.3	In-Mold Decoration	192
	References	194
5	Gas Assisted Injection Molding	195
	<i>Shih-Jung Liu</i>	
5.1	Introduction	195
5.1.1	Gas Assisted Injection Molding	195
5.1.2	Advantages and Limitations of GAIM	198
5.1.3	Materials for GAIM	199
5.2	Molding Equipment and Process	199
5.2.1	Gas Injection Unit and Injection Nozzle	199
5.2.2	Gas Injection into the Part	200
5.2.3	Gas Nozzle	202

5.2.4	Pressure Development during the Molding Process	202
5.2.5	Gas Penetration Behavior in Molded Parts	203
5.2.6	Gas Venting and Recycling.....	205
5.2.7	Moldability Diagram for GAIM	206
5.3	Process Modeling	207
5.4	Part/Mold Designs and Molding Guidelines.....	209
5.4.1	Gas Channel Geometry.....	209
5.4.2	Gas Channel Layout.....	211
5.4.3	Effect of Gravity	211
5.4.4	Residual Wall Thickness Distribution.....	212
5.4.5	Gas Dissolution into the Polymer.....	213
5.4.6	Gas F fingering	215
5.4.7	Unstable Gas Penetrations	216
5.4.8	Weld Lines Caused by the Flow-Lead Effect	217
5.4.9	Molding of Fiber Reinforced Materials.....	218
5.5	Concluding Remarks.....	220
	List of symbols.....	220
	References.....	221
6	Water Injection Techniques (WIT)	223
	<i>Walter Michaeli</i>	
6.1	Introduction.....	223
6.2	Processing Technology	224
6.2.1	Course of Process	224
6.2.2	Process Variants	225
6.2.2.1	Short-Shot Process	226
6.2.2.2	Full-Shot Process	226
6.2.2.3	Full-Shot Process with Overspill.....	226
6.2.2.4	Melt Push Back Process	226
6.2.2.5	Core Pulling Process	227
6.2.2.6	Rinsing/Flushing Process	227
6.2.3	Comparison between GAIM and WIT	228
6.2.3.1	Limitations of GAIM	229
6.2.3.2	Cycle Times	229
6.2.3.3	Part Properties.....	230
6.2.3.3.1	Residual Wall Thicknesses (RWT).....	230
6.2.3.3.2	Shrinkage/Warpage	232
6.2.3.3.3	Fluid-Sided Surface Qualities	232
6.2.3.3.4	Typical Part Defects	233
6.3	Plant and Injector Technology	234
6.3.1	Concepts and Operation Technology for Water Pressure Generating Units ..	234
6.3.2	Injector Technology for Water Injection Technique	237
6.3.2.1	Demands on WIT Injectors	237
6.3.3	Classification and Presentation of Different WIT-Injectors	239

6.3.3.1	Operating Method	239
6.3.3.2	Operating Direction.....	241
6.3.3.3	Alignment in the Mold	242
6.3.4	General Design Remarks for WIT Injectors	242
6.3.4.1	Excellent Process Reliability.....	243
6.3.4.2	Specific Controllability	243
6.4	WIT Compatible Part Design	243
6.4.1	Injector Embedding.....	243
6.4.2	General Design Guidelines for WIT Articles	244
6.4.3	Tubular Articles	245
6.4.3.1	Cross Sections	245
6.4.3.2	Aspect Ratio.....	246
6.4.3.3	Curves and Redirections.....	246
6.4.3.4	Change of Diameter.....	247
6.4.4	Compact Parts with Integrated Thick-Walled Sections	248
	List of Abbreviations and Symbols.....	248
	References.....	249

Part III:	Injection Molding of Complex Materials.....	251
------------------	--	-----

7	Flow Induced Fiber Micro-Structure in Injection Molding of Fiber Reinforced Materials	253
	<i>Michel Vincent</i>	
7.1	Introduction.....	253
7.2	Observations	254
7.2.1	Fiber Length Distribution	254
7.2.2	Fiber Concentration.....	255
7.2.3	Fiber Orientation	256
7.2.3.1	Orientation Mechanisms	256
7.2.3.2	Qualitative Observations	256
7.2.3.3	Quantification Tools: Orientation Distribution Function, Orientation Tensors	258
7.2.3.4	Experimental Methods	258
7.2.3.5	Results	260
7.3	Calculation of Fiber Orientation	261
7.3.1	Orientation Models	261
7.3.1.1	The Standard Model	261
7.3.1.2	Choice of the Interaction Coefficient and the Closure Approximation	263
7.3.1.2.1	Value of the Interaction Coefficient.....	263
7.3.1.2.2	The Closure Approximation Issue	264
7.3.1.3	Discussion of the Standard Model	265
7.3.1.4	Application to Injection Molding.....	265
7.3.2	Rheological Models	266
7.3.2.1	Overview on Rheological Measurements.....	266

7.3.2.2	Introduction to Behavior Laws	267
7.4	Conclusions	268
	List of Symbols	269
	References.....	270
8	Injection Foam Molding.....	273
	<i>X. Xu and C. B. Park</i>	
8.1	Introduction.....	273
8.2	Injection Foam Molding Technologies: Background.....	274
8.2.1	Structural-Foam Molding.....	274
8.2.1.1	Low-Pressure Foam Molding	274
8.2.2	High-Pressure Foam Molding.....	275
8.2.2.1	Co-Injection Foam Molding	276
8.2.2.2	Gas Counter-Pressure Foam Molding.....	277
8.2.2.3	Sequential Injection Foam Molding.....	278
8.2.3	Microcellular Injection Foam Molding.....	279
8.2.3.1	Background on Microcellular Foam Processing.....	279
8.2.3.2	Development of Microcellular Injection Foam Molding	280
8.2.3.2.1	Batch Microcellular Processing.....	280
8.2.3.2.2	Semi-Continuous Microcellular Processing	281
8.2.3.2.3	Continuous Microcellular Processing	281
8.2.3.2.4	Microcellular Injection Foam Molding.....	282
8.3	Fundamentals of Foam Injection Molding.....	284
8.3.1	Foaming Additives	284
8.3.1.1	Cell-Nucleating Agents.....	284
8.3.1.2	Blowing Agents.....	285
8.3.1.2.1	Chemical Blowing Agents	285
8.3.1.2.2	Physical Blowing Agents.....	285
8.3.2	Thermophysical and Rheological Properties of Polymer/Gas Mixtures.....	285
8.3.2.1	Solubility and Diffusivity	285
8.3.2.1.1	Solubility.....	285
8.3.2.1.2	Diffusivity.....	288
8.3.2.2	Viscosity of Polymer/Gas Mixtures	289
8.3.2.3	Surface Tension of Polymer/Gas Mixtures.....	291
8.3.3	Formation of Foamable Compositions	291
8.3.3.1	Foamable Compositions in CBA Processing	291
8.3.3.2	Foamable Compositions in PBA Processing	292
8.3.3.3	Dissolution of Gas in Polymers.....	292
8.3.4	Cell Nucleation	293
8.3.4.1	Homogeneous and Heterogeneous Nucleation.....	293
8.3.4.1.1	Homogeneous Nucleation	293
8.3.4.1.2	Heterogeneous Nucleation.....	295
8.3.4.2	Nucleation and Pressure Profiles during Filling.....	295
8.3.5	Filling and Cell Growth	298

8.3.5.1	Geometric Singularity and Weld Lines	299
8.3.5.2	Void Fraction Control	299
8.3.5.3	Cell Growth in a Mold	299
8.4	Foam Molding Machines and Applications	300
8.4.1	Foam Molding Machines	300
8.4.2	Applications	302
8.5	Future Developments	302
	List of Symbols and Abbreviation	303
	References	304
9	Powder Metal Injection Molding	309
	<i>James F. Stevenson</i>	
9.1	Opportunity	309
9.2	Process Overview	310
9.3	Feedstock	313
9.3.1	Powders	313
9.3.2	Binders	314
9.3.3	Compounds	316
9.4	Part and Tool Design	317
9.4.1	Part Design	317
9.4.2	Mold Design	319
9.5	Molding	322
9.5.1	Equipment	322
9.5.2	Operations	322
9.6	Debinding	323
9.7	Sintering	324
9.7.1	Fundamentals	324
9.7.2	Furnaces	329
9.7.3	Setters	332
9.8	Post Sintering Treatments	333
9.8.1	Heat Treatment	333
9.8.2	Hot Isostatic Pressing	335
9.8.3	Secondary Operations	335
9.9	Material Properties	336
	List of Symbols	338
	References	338
	Acknowledgements	339
10	Micro Injection Molding	341
	<i>Volker Piotter, Guido Finnah, Thomas Hanemann, Robert Ruprecht</i>	
10.1	Introduction	341
10.2	Why Is Polymer Processing so Interesting for Microsystems Engineering? ..	342
10.3	The Process Specialties of Micro Injection Molding	343
10.3.1	Types of Micro Components	345

10.3.2	Machine Technology for Micro Injection Molding	346
10.3.3	Fabrication of Microstructured Mold Inserts For Micro Injection Molding..	349
10.3.4	Special Types of Micro Injection Molding.....	350
10.3.5	Simulation	351
10.4	Micro Reaction Injection Molding.....	353
10.4.1	Reactive Resin Polymerization Methods	353
10.4.2	Thermally Initiated Reaction Injection Molding of LIGA-Structures.....	354
10.4.3	Development of Light Induced Reaction Molding (Photomolding) Techniques	356
10.4.4	UV-Embossing of Photocurable Systems.....	358
10.4.5	Photomolding of Composites	360
10.5	Micro Powder Injection Molding (MicroPIM).....	362
10.5.1	Introduction to MicroPIM.....	362
10.5.2	Metal and Ceramic Powders for PIM	365
10.5.3	Commercially Available PIM Feedstocks and Binders	366
10.5.4	Binder Systems for MicroPIM.....	367
10.5.5	Compounding Feedstocks for MicroPIM	368
10.5.6	Rheology Measurements of PIM Feedstocks.....	369
10.5.7	Machinery for MicroPIM.....	371
10.5.8	Molding Tools for MicroPIM	371
10.5.9	Patterning Process for PIM Microparts	375
10.5.9.1	Debinding of MicroPIM Green Compacts.....	376
10.5.9.2	Sintering Process for MicroPIM Parts.....	378
10.5.10	MicroPIM Research.....	378
10.6	Two-Component Micro Injection Molding (2C-MicroPIM)	378
10.6.1	Machine Technology for Micro Two-Component Injection Molding	379
10.6.2	Mold Technology for Two-Component Micro Injection Molding.....	381
10.6.3	Contact-Strength for the Multi-Component Injection Molding	381
10.6.4	Sequence of the Two-Component Micro Injection Molding Process	382
10.6.5	Variothermal Mold Temperature Control for Two-Component Injection Molding.....	383
10.6.6	Applications of Multi-Component Injection Molding	384
10.6.6.1	Insert Injection Molding.....	384
10.6.6.2	Overmolding	384
10.6.6.3	In-Mold Assembly	385
10.6.6.4	3D-MID-Technology.....	385
10.6.6.5	Two-Component Powder Injection Molding	385
10.7	Summary and Outlook	386
	List of Abbreviations	387
	References.....	389

Part IV: Process Visualization, Control, Optimization, and Simulation	395
11 Internal Visualization of Mold Cavity and Heating Cylinder	397
<i>Hidetoshi Yokoi</i>	
11.1 Introduction	397
11.2 Dynamic Visualization Techniques for the Inside of the Mold Cavity	397
11.2.1 Overview of Dynamic Visualization Techniques	398
11.2.1.1 Light transmission method	398
11.2.1.2 Light Reflection Method	399
11.2.1.3 Light-Section Method	401
11.2.2 Glass-Inserted Mold (2D, 3D)	401
11.2.3 Back-Lighting Mold	406
11.2.4 Laser-Light-Sheet Mold	408
11.2.5 Runner-Exchanging System	411
11.2.6 Automatic Tracking System under High Magnifications	414
11.2.7 Visualization Technique for Ultra-High-Speed Injection Molding	416
11.3 Static Visualization Techniques for the Inside of a Mold Cavity	418
11.3.1 Overview of Static Visualization Techniques	418
11.3.1.1 Plugging of Colored Materials	418
11.3.1.2 Lamination of Colored Materials	419
11.3.2 Runner-Exchanging System and Gate-Magnetization Method	420
11.4 Visualization Heating Cylinder	424
11.4.1 Overview of Visualization Techniques for the Inside of a Heating Cylinder ..	425
11.4.2 Glass-Inserted Heating Cylinder	428
11.4.3 Visualization Unit inside Hopper Throat, Check-Ring, and Reservoir Areas ..	431
11.4.4 Image Processing Method for Laminated Slit Images	434
References	435
12 Injection Molding Control	439
<i>Furong Gao and Yi Yang</i>	
12.1 Introduction	439
12.2 Basic Concepts and Elements of Control Systems	440
12.2.1 Basic Control System Structure	440
12.2.1.1 Open Loop System	441
12.2.1.2 Closed-Loop System	441
12.2.2 Basic Elements of Control Systems	442
12.2.2.1 Controlled Variables in Injection Molding	442
12.2.2.2 Actuators in Injection Molding	443
12.2.2.3 Measurement of Output Variables	444
12.2.2.4 The Controller	444
12.3 Control Applications	445
12.3.1 Machine Sequence Control	445
12.3.2 Adaptive Control	446
12.3.2.1 Dynamic Analysis of Injection Molding Process Variables	446

12.3.2.2	Adaptive Control Background	450
12.3.2.3	RLS Estimation	450
12.3.2.4	Pole Placement Design	451
12.3.2.5	Solving the Diophantine Equation.....	452
12.3.2.6	Direct Implementation of Adaptive Pole-Placement Control.....	454
12.3.2.7	Improvement I – Anti-Windup Estimation.....	454
12.3.2.8	Improvement II – Adaptive Feedforward Control.....	457
12.3.2.9	Improvement III – Cycle-To-Cycle Adaptation	459
12.3.2.10	Test of Different Conditions	460
12.3.2.11	Summary	461
12.3.3	Model Predictive Control.....	462
12.3.3.1	MPC Background.....	462
12.3.3.2	GPC Design for Injection Velocity.....	464
12.3.3.3	Step Response Comparison of GPC and Pole-Placement	465
12.3.3.4	Adaptive GPC Experiments with Different Conditions	465
12.3.3.5	Summary	467
12.3.4	Fuzzy Model Based Control [16]	468
12.3.4.1	Fuzzy Inference System.....	468
12.3.4.2	Fuzzy Multi-Model and Application to Injection Velocity.....	469
12.3.4.3	Fuzzy Multi-Model Predictive Control.....	474
12.3.4.4	On-Line Identification of Model Parameters of Rule Consequents.....	474
12.3.4.5	Batch Learning of Membership Function Parameters of Rule Premises	475
12.3.4.6	Experimental Test of Fuzzy Multi-Model Based Predictive Control.....	476
12.3.4.7	Summary	481
12.3.5	Iterative Learning Control [18].....	481
12.3.5.1	Iterative Learning Control Background	482
12.3.5.2	P-Type Learning Control Algorithm.....	483
12.3.5.3	Optimal Iterative Learning Controller	485
12.3.5.4	Robust and Convergence Analysis.....	488
12.3.5.5	Selection of the Weighting Matrices	490
12.3.5.6	Injection Velocity Control with Optimal ILC	491
12.3.5.7	Summary	494
12.3.6	Statistical Process Monitoring of Injection Molding.....	494
12.3.7	Statistical Process Monitoring for Continuous Processes.....	494
12.3.8	Statistical Monitoring of Batch Processes.....	497
12.3.9	Stage-Based Statistical Monitoring of Injection Molding [61–63]	499
12.3.9.1	Fault #1: Material Disturbance	501
12.3.9.2	Fault #2: Check-Ring Failure	503
12.4	Control Perspective and Challenges for Injection Molding.....	504
12.4.1	Control Perspective	504
12.4.2	Major Challenges of Injection Molding Control	506
12.4.2.1	Implementation of Robust Control Algorithms	506
12.4.2.2	New Measurements	506
12.4.2.3	Comprehensive Quality Modeling.....	506

12.4.2.4	Closed-Loop Quality Control	507
12.4.2.5	Process and Control Performance Monitoring.....	507
	References.....	507
13	Optimal Design for Injection Molding	511
	<i>Kalonji K. Kabanemi, Abdessalem Derdouri and Jean-François Hétu</i>	
13.1	Introduction.....	511
13.2	Basic Equations for the Mold Filling Problem	513
13.2.1	Mathematical Model: Hele-Shaw and Energy Equations	513
13.2.2	Boundary Conditions	514
13.2.3	Numerical Discretization	515
13.3	Optimization Techniques.....	516
13.3.1	Optimization Concept.....	516
13.3.2	Optimization Problems.....	516
13.3.3	Numerical Solution of Optimization Problems	517
13.3.3.1	Zero-Order Methods.....	518
13.3.3.2	First- and Second-Order Methods.....	519
13.3.3.3	Combination of Zero-Order and Gradient-Based Methods	520
13.4	Gradient-Based Methods and Sensitivity Analysis	521
13.4.1	Direct Sensitivity Equation Method	521
13.4.2	Adjoint Equation Method	522
13.4.3	Comparison of Solution Methods	524
13.4.4	Choice of a Method	524
13.5	Optimal Design for Injection Molding.....	525
13.5.1	Problem Parameters.....	525
13.5.2	Problem Definition	525
13.5.3	Direct Sensitivity of the State Equations.....	526
13.5.4	Sensitivity Formulation of the Objective Function	528
13.5.5	Parameterization of the Injection Pressure and Sensitivities.....	528
13.5.6	Sensitivities of the Function Constraints	530
13.5.7	Flow-Front Tracking and Sensitivities.....	530
13.5.8	Parameterization of the Flow Domain and Sensitivities.....	531
13.6	Algorithm.....	534
13.7	Illustrative Applications	534
13.7.1	Automotive Part: Single Gate Optimization	534
13.7.2	Automotive Lens: Multiple Gate Optimization.....	541
13.7.3	Multiple Gate Optimization: More than One Optimal Solution	545
13.8	Conclusions	547
	List of Symbols and Abbreviations.....	547
	References.....	549
14	Development of Injection Molding Simulation	553
	<i>Peter Kennedy</i>	
14.1	Introduction	553

14.2	The Molding Process.....	553
14.3	The Problem	554
14.3.1	Basic Physics of the Process.....	555
14.3.2	Material Properties.....	555
14.3.3	Geometric Complexity of Mold and Part.....	556
14.3.4	Process Stability	556
14.4	Why Simulate Injection Molding?	556
14.5	Early Academic Work on Simulation	557
14.5.1	Boundary Conditions and Solidification	558
14.6	Early Commercial Simulation.....	559
14.7	Simulation in the 1980s.....	561
14.8	Academic Work in the 1980s.....	562
14.8.1	Mold Filling	562
14.8.2	Mold Cooling	565
14.8.3	Warpage Analysis.....	565
14.8.4	Fiber Orientation	566
14.9	Commercial Simulation in the 1980s	568
14.9.1	Codes Developed by Large Industrials and not for Sale	570
14.9.1.1	General Electric	570
14.9.1.2	Philips/Technical University of Eindhoven	570
14.9.2	Codes developed by Large Industrials for Sale in the Marketplace	571
14.9.2.1	SDRC.....	571
14.9.2.2	GRAFTEK	571
14.9.3	Companies Devoted to Developing and Selling Simulation Codes.....	571
14.9.3.1	AC Technology	571
14.9.3.2	Moldflow	572
14.9.3.3	Simcon Kunststofftechnische Software GmbH.....	573
14.10	Simulation in the 1990s.....	573
14.11	Academic Work in the 1990s.....	574
14.12	Commercial Developments in the 1990s	575
14.12.1	SDRC.....	575
14.12.2	Moldflow	576
14.12.3	AC Technology/C-MOLD	580
14.12.4	Simcon	580
14.12.5	Sigma Engineering.....	580
14.12.6	Timon	581
14.12.7	Transvalor.....	581
14.12.8	CoreTech Systems.....	581
14.13	Simulation Science since 2000.....	582
14.14	Commercial Developments since 2000.....	584
14.14.1	Moldflow	584
14.14.2	Timon	585
14.14.3	Core Tech Systems	586
14.15	The Simulation Market Today.....	586

14.16	Conclusion	587
14.17	Appendix: 2.5D Analysis	587
14.17.1	Material Properties.....	588
14.17.2	Geometric Considerations.....	589
14.17.3	Simplification by Mathematical Analysis.....	590
14.18	Acknowledgments	592
	References.....	592
15	Three-Dimensional Injection Molding Simulation.....	599
	<i>Luisa Silva, Jean-Francois Agassant and Thierry Coupez</i>	
15.1	Introduction	599
15.1.1	Process Background.....	599
15.1.2	Historical Background on 3D Simulation	600
15.1.3	General Numerical Techniques for 3D Injection Molding Simulation.....	602
15.1.3.1	Constitutive Equations	602
15.1.3.2	Boundary Conditions	605
15.1.4	Numerical Issues in 3D Injection Molding	606
15.2	Temperature Independent Flows and Finite Element Techniques.....	607
15.2.1	Generalized Stokes Problem	607
15.2.1.1	Mixed Finite Elements for Newtonian Flows	607
15.2.1.2	More General Viscous Resolution	611
15.2.2	Extension to Weakly Isothermal Compressible Flows	612
15.2.3	Extension to Navier and Stokes Equations.....	614
15.2.4	Extension to Viscoelastic Flows	616
15.2.4.1	Viscoelasticity and Constitutive Models.....	617
15.2.4.2	Flow Determination for Viscoelastic Materials.....	618
15.3	Free Surface Determination.....	622
15.3.1	Techniques to Determine the Interface.....	622
15.3.2	The VOF (Volume of Fluid Method).....	623
15.3.2.1	Resolution of the Transport Equation.....	623
15.3.2.2	Advantages and Disadvantages of the VOF Method.....	625
15.3.3	The Level Set Method	627
15.3.3.1	Mathematical Considerations	627
15.3.3.2	Resolution of the Transport Equation.....	628
15.3.3.3	Advantages and Disadvantages of the Level Set Method	628
15.4	Thermomechanical Coupling	630
15.4.1	Material Properties Coupling	630
15.4.2	The Temperature Balance Equation.....	632
15.4.3	Numerical Solution	632
15.5	Advanced Computational Techniques	634
15.5.1	Meshing.....	634
15.5.1.1	Generation and Anisotropic Adaptation of Static Interfaces.....	634
15.5.1.2	Multidomain and Interface Capturing	636
15.5.2	Parallel Computing	637

15.5.3	Application to Filling Simulation with Mold Coupling	639
15.6	Application to a 3D Part.....	641
15.7	Conclusion.....	644
	Acknowledgements	645
	Appendixes.....	645
	Appendix 15.1: Viscosity Equations.....	645
	Appendix 15.2: Tait Equation Parameters	646
	Notations	647
	References.....	650
16	Viscoelastic Instabilities in Injection Molding	653
	<i>G. W. M. Peters, A. C. B. Bogaerts</i>	
16.1	Introduction.....	653
16.2	Background, Literature Review.....	654
16.3	Experimental Motivation	656
16.4	Analysis.....	658
16.5	Numerical Modelling: Governing Equations.....	660
16.6	Numerical Modelling: Finite Element Analysis	662
16.7	Domain Perturbation Technique	668
16.8	Results	672
16.8.1	Steady State Results	673
16.8.2	Stability Results.....	677
16.9	Discussion	678
	Symbols and Notation.....	680
	References.....	682
Part V:	Microstructure Development, Characterization, and Prediction	685
17	Evolution of Structural Hierarchy in Injection Molded Semicrystalline Polymers	687
	<i>M. Cakmak and B. Yalcin</i>	
17.1	Introduction.....	687
17.2	Fundamentals of the Injection Molding Process	688
17.2.1	Experiences of Polymer Chains in a Typical Injection Molding Machine ..	688
17.2.2	Flow Behavior into Injection Molding Cavities	689
17.3	Structure Development in Injection Molded Fast Crystallizing Polymers....	693
17.3.1	Polyethylene (PE)	693
17.3.2	Polypropylene (PP)	694
17.3.3	Polyoxymethylene (POM) and Other Fast Crystallizing Polymers	696
17.3.4	Injection Molded PVDF and its Blends with PMMA	696
17.3.5	Polyamides (PA)	702
17.3.6	Effect of Platelet Type Nanoparticles in Injection Molding	703
17.3.7	Influence of Nano Clay on the Crystallization and Orientation – Summary ..	708
17.3.8	Structure Development in Thermotropic Liquid Crystalline Polymers	708

17.4	Structure Development in Injection Molded Slowly Crystallizing Polymers .	709
17.4.1	General Characteristics of Structure Development in Slow Crystallizing Polymers.....	710
17.4.2	Poly(Phenylene Sulfide) (PPS)	710
17.4.3	Effect of Molecular Weight.....	713
17.4.4	Poly(Ether Ether Ketone) PEEK.....	716
17.4.5	Syndiotactic Polystyrene (s-PS)	719
17.4.6	Polyethylene Naphthalate (PEN)	721
17.4.7	Structure Characteristics of Injection Molded Slowly Crystallizing Polymers – Summary	722
17.5	Simulation of the Structure Development During Injection Molding Process.....	722
17.6	General Summary	725
	Abbreviations.....	726
	References.....	727
18	Modeling Aspects of Post-Filling Steps in Injection Molding	731
	<i>Roberto Pantani and Giuseppe Titomanlio</i>	
18.1	Introduction.....	731
18.1.1	The Post-Filling Stages	732
18.1.2	State of the Art on Post-Filling Modeling.....	732
18.1.3	Outline	735
18.2	Understanding Pressure Evolution.....	736
18.2.1	The Evolution of Pressure Curves During Injection Molding.....	736
18.2.1.1	The Filling Stage.....	736
18.2.1.2	The Packing-Holding Stage.....	737
18.2.1.3	The Cooling Stage	740
18.2.2	Pressure Curves Inside the Runners During Cooling.....	744
18.3	A Suitable Modeling of the Process	744
18.3.1	Modeling the Packing – Holding Stage.....	746
18.3.2	Modeling the Cooling Stage.....	747
18.3.3	Time-Depending Heat Transfer Coefficient	747
18.4	Relevant Aspects of Rheological Behavior.....	751
18.4.1	The Effect of Pressure on Viscosity	751
18.5	Mold Deformation	753
18.5.1	Effect of Mold Deformation on the Packing Stage.....	754
18.5.2	Effect of Mold Deformation on the Cooling Stage.....	754
18.5.3	Effect of Mold Deformation on Pressure Evolution and on Gate Sealing Time.....	755
18.6	Molecular Orientation.....	756
18.6.1	Experimental Evidences	757
18.6.2	Modeling the Evolution of Orientation.....	760
18.6.2.1	Leonov Model	761
18.6.2.2	Non-Linear Maxwell Model.....	761

18.6.3	Results of Modeling for Amorphous Materials.....	762
18.7	Semi-Crystalline Polymers.....	766
18.7.1	Effect of Crystallinity on Material Properties	767
18.7.1.1	Effect of Crystallinity on Rheology	767
18.7.1.2	Effect of Crystallinity on Specific Volume	769
18.8	Morphology Evolution During the Post-Filling Stages.....	770
18.9	Concluding Remarks.....	773
	Nomenclature	774
	References.....	776
19	Volumetric and Anisotropic Shrinkage in Injection Moldings of Thermoplastics	779
	<i>A. I. Isayev and Keehae Kwon</i>	
19.1	Introduction.....	779
19.2	Theoretical Analysis.....	780
19.2.1	Volumetric Shrinkage	780
19.2.2	Anisotropic Shrinkage.....	782
19.3	Comparison Between Simulations and Experiments	789
19.3.1	Volumetric Shrinkage	789
19.3.2	Anisotropic Shrinkage.....	793
19.4	Conclusions	804
19.5	Acknowledgement	805
	Nomenclature	805
	References.....	807
20	Three-Dimensional Simulation of Gas-Assisted and Co-Injection Molding Processes	809
	<i>Jean-François Hétu, Florin Ilinca</i>	
20.1	Introduction.....	809
20.2	Background	811
20.3	Mathematical Modeling and Formulations	812
20.3.1	Conservation of Mass and Momentum.....	813
20.3.2	Conservation of Energy	814
20.3.3	Boundary and Initial Conditions	814
20.3.4	The Compressibility Effects.....	815
20.4	Front Capturing Methods for Co-Injection Molding	815
20.4.1	The VOF and phase field methods.....	816
20.4.2	The Level-Set Method.....	817
20.4.3	Use of Level-Set in Co-Injection Molding	818
20.5	Numerical Implementation	818
20.5.1	A Finite Element Method.....	818
20.5.1.1	Momentum-Continuity Equations	819
20.5.1.2	Energy Equation.....	819
20.5.1.3	Level-Set Equation	821

20.5.2	Solution Algorithm	822
20.6	Validation Cases and Applications.....	823
20.6.1	Gas-Assisted Injection Molding	824
20.6.1.1	Gas-Assisted Injection of a Plate with a Flow Channel.....	824
20.6.1.2	Secondary Penetration in Gas-Assisted Injection	828
20.6.1.3	Gas-Assisted Injection of a Thick Part	829
20.6.2	Co-Injection Molding	830
20.6.2.1	Co-Injection of a Side Gated Rectangular Plate	830
20.6.2.2	Co-Injection of a Center-Gated Rectangular Plate	833
20.6.2.3	Co-Injection of a C-Shaped Plate.....	837
20.6.3	Simulation of Breakthrough in Co-Injection Molding.....	838
20.7	Conclusions	845
	List of Symbols and Abbreviations.....	846
	References.....	848
21	Co-Injection Molding of Polymers	851
	<i>A. I. Isayev and Nam Hyung Kim</i>	
21.1	Introduction.....	851
21.2	Technology.....	853
21.3	Experimental Studies.....	860
21.3.1	Effect of Process Parameters on Skin-Core Structure.....	860
21.3.2	Breakthrough Phenomenon.....	867
21.3.3	Interfacial Instability	874
21.3.4	Mechanical Properties.....	875
21.3.5	Microstructure	881
21.3.6	Biomedical Applications.....	884
21.4	Modeling of the Co-Injection Molding Process	884
21.4.1	Simulation Approaches.....	884
21.4.2	Comparison between Simulation and Experiment	898
21.5	Conclusions	909
	Nomenclature	909
	References.....	912
	Subject Index	917