

# Contents

<b>Preface</b> . . . . .	vii
<b>Contributors</b> . . . . .	xix
<b>1 Introduction</b> . . . . .	1
<i>P. J. Gramann, T. A. Osswald</i>	
1.1 Historical Background . . . . .	1
1.2 The Reciprocating Screw Injection Molding Machine . . . . .	9
1.2.1 The Plasticating and Injection Unit . . . . .	9
1.2.2 The Clamping Unit . . . . .	10
1.2.3 The Mold Cavity . . . . .	11
1.3 The Injection Molding Cycle . . . . .	13
1.4 Related Injection Molding Processes . . . . .	17
References . . . . .	18
<b>2 Injection Molding Materials</b> . . . . .	19
<i>T. A. Osswald</i>	
2.1 Historical Background . . . . .	19
2.2 Macromolecular Structure of Polymers . . . . .	23
2.3 Molecular Weight . . . . .	27
2.4 Conformation and Configuration of Polymer Molecules . . . . .	30
2.5 Thermoplastic Polymers . . . . .	34
2.5.1 Amorphous Thermoplastics . . . . .	34
2.5.2 Semi-Crystalline Thermoplastics . . . . .	36
2.5.3 Examples of Common Thermoplastics . . . . .	43
2.6 Thermosetting Polymers . . . . .	46
2.6.1 Cross-Linking Reaction . . . . .	46
2.6.2 Examples of Common Thermosets . . . . .	48
2.7 Copolymers and Polymer Blends . . . . .	49
2.8 Elastomers . . . . .	51
<i>M. DeGreiff</i>	
2.9 Efficient Vulcanizing Systems . . . . .	52
2.10 Thermoplastic Elastomers . . . . .	53
<i>G. Holden</i>	
2.10.1 Service Temperatures . . . . .	54
2.10.2 Examples of Common Thermoplastic Elastomers . . . . .	55
References . . . . .	61

<b>3 Processing Fundamentals</b> . . . . .	63
<i>T. A. Osswald</i>	
3.1 Processing Data . . . . .	63
3.1.1 Temperature Settings . . . . .	64
3.1.2 Injection and Pack-Hold Pressure Settings . . . . .	64
3.1.3 Drying . . . . .	66
3.1.4 Processing Data for Thermoplastic Elastomers . . . . .	66
<i>G. Holden</i>	
3.1.5 Processing Data for Thermosets . . . . .	71
3.1.6 Processing Data for Elastomers . . . . .	72
3.2 Rheology of Polymer Melts . . . . .	72
3.2.1 Shear Thinning Behavior of Polymers . . . . .	73
3.2.2 Simplified Flows Common in Injection Molding . . . . .	75
3.2.3 Estimating Injection Pressure and Clamping Force (Stevenson Model) . . . . .	78
3.2.4 Nonisothermal Flows in Polymer Processing . . . . .	83
3.2.5 Normal Stresses in Shear Flow . . . . .	83
3.2.6 Deborah Number . . . . .	84
3.2.7 Rheology of Curing Thermosets . . . . .	85
3.2.8 Suspension Rheology . . . . .	87
3.3 Rheometry . . . . .	87
3.3.1 The Melt Flow Indexer . . . . .	88
3.3.2 The Capillary Viscometer . . . . .	88
3.3.3 Viscosity from the Capillary Viscometer . . . . .	89
3.4 Anisotropy Development During Processing . . . . .	91
3.4.1 Orientation in the Final Part . . . . .	91
3.4.2 Fiber Damage . . . . .	100
3.5 Solidification and Curing Processes . . . . .	102
3.5.1 Solidification of Thermoplastics . . . . .	103
3.5.2 Solidification of Thermosets . . . . .	112
3.5.3 Residual Stresses, Shrinkage, and Warpage . . . . .	117
References . . . . .	122
<b>4 Plasticating</b> . . . . .	125
<i>C. Rauwendaal, P. J. Gramann</i>	
4.1 The Plasticating Unit . . . . .	125
4.1.1 The Ram Extruder . . . . .	126
4.1.2 The Reciprocating Screw . . . . .	127
4.2 Functions of the Plasticating Unit . . . . .	140
4.2.1 Solids Conveying . . . . .	140
4.2.2 Melting or Plasticating . . . . .	144
4.2.3 Melt Conveying . . . . .	151
4.2.4 Degassing or Devolatilization . . . . .	157
4.2.5 Mixing . . . . .	158
4.3 Conclusion . . . . .	177
References . . . . .	178

<b>5 Clamping Unit</b>	181
<i>R. Farrell</i>	
5.1 Metal Fatigue and Its Importance in Clamp Design	181
5.1.1 Importance in Clamp Design	181
5.1.2 A Brief History of Metal Fatigue	182
5.1.3 The Three Phases of Metal Fatigue	182
5.1.4 Determination of Design Stress for Metal Fatigue	183
5.1.5 Determination of Survival Factor (SF)	191
5.1.6 Conclusion of Discussion of Metal Fatigue	193
5.2 Functions of the Clamping System	193
5.3 The Three Types of Clamping Systems	194
5.3.1 Hydraulic	194
5.3.2 Hydromechanical	195
5.3.3 Mechanical	196
5.3.4 Types of Toggle Systems	198
5.4 Key Elements of a Clamp	200
5.4.1 Platens	200
5.4.2 Tie Rods and Nuts	213
5.4.3 Toggle Pins and Bushings	217
5.4.4 Tie-Rod Bushings	221
5.4.5 Moving Platen Support	222
5.4.6 Shut Height Adjustment	222
5.4.7 Ejector Systems	226
5.5 A Special Discussion of Tie-Rod Design	227
5.5.1 Why This Element Is So Important	227
5.5.2 Thread Load Distribution	227
5.5.3 Thread Bending Stress	230
5.5.4 Thread Axial Stress	232
5.5.5 Combined Stresses	232
5.5.6 Mitigating Factors	233
5.5.7 Ways to Improve the Design	234
5.6 Understanding Clamp Spring Rate (Stiffness)	236
5.6.1 How to Determine Clamp Spring Rate	237
5.6.2 The Importance of Clamp Spring Rate	238
5.7 Math Model for a Toggle Clamp	239
5.8 The Farrell Square Root Rule	243
5.8.1 Relationships That Follow from the Farrell Square Root Rule	244
5.8.2 The Whole Machine Can Follow the Square Root Rule	246
References	246
<b>6 Mold Design</b>	249
<i>J. Beaumont</i>	
6.1 Standard Mold Assembly	250
6.2 Cold Runner Molds	252
6.2.1 Two-Plate Cold Runner Mold	252
6.2.2 Three-Plate Cold Runner Mold	254
6.3 Hot Runner Molds	257
6.3.1 Externally Heated Manifold and Drops	259

6.3.2	Externally Heated Manifold with Internally Heated Drops . . . . .	259
6.3.3	Internally Heated Manifold and Internally Heated Drops . . . . .	261
6.3.4	Insulated Manifold and Drops . . . . .	262
6.3.5	Miscellaneous Hot Runner Systems Design . . . . .	263
6.3.6	Hot Sprues . . . . .	264
6.3.7	Hot Drops (Nozzles) . . . . .	265
6.3.8	Special Considerations in the Operation of Hot Runner Molds . . . . .	268
6.3.9	Stack Molds . . . . .	271
6.4	Runner Design . . . . .	272
6.4.1	Cold Runner Design . . . . .	274
6.4.2	Runner Balancing in Geometrically Balanced Runners (Cold and Hot Runners) . . . . .	276
6.4.3	Nongeometrically Balanced Runner Layouts . . . . .	284
6.5	Gate Design . . . . .	286
6.5.1	Gate Types . . . . .	286
6.5.2	Positioning Gates . . . . .	295
6.6	Structural Design of a Mold for Long Life and Rigidity . . . . .	296
6.6.1	Mold Material Selection . . . . .	296
6.6.2	Fatigue . . . . .	297
6.6.3	Deflection of Side Walls . . . . .	298
6.6.4	Core Deflection . . . . .	298
6.6.5	Deflection of Support Plates . . . . .	300
6.7	Mold Cooling . . . . .	302
6.7.1	Practical Considerations . . . . .	303
6.7.2	Thermal Expansion . . . . .	305
6.7.3	Parallel versus Series Cooling Circuits . . . . .	305
6.7.4	Baffles and Bubblers . . . . .	307
6.8	Mold Ejection Systems . . . . .	309
6.8.1	Basic Ejection Problems . . . . .	309
6.8.2	Means of Ejection . . . . .	312
6.8.3	Ejection Considerations . . . . .	315
6.8.4	Ejection Design . . . . .	316
6.9	Vent Design . . . . .	320
	References . . . . .	323

**7 Material Handling and Auxiliary Equipment . . . . . 325**

*S. Collins*

7.1	Bulk Material Handling . . . . .	325
7.2	Pneumatic Conveying Systems. . . . .	326
7.3	Receivers and Loaders . . . . .	329
7.3.1	Self-Contained Loaders . . . . .	331
7.4	Material Handling Controls . . . . .	332
7.5	Feeders and Blenders . . . . .	333
7.6	Dryers . . . . .	336
7.7	Inntegrated Drying and Conditioning System . . . . .	338
7.8	Mold and Process Temperature Control . . . . .	339
7.9	Automation . . . . .	341
7.10	Granulators . . . . .	344

<b>8</b>	<b>Statistical Process Control</b>	<b>347</b>
	<i>C. Rauwendaal</i>	
8.1	Statistical Process Control	347
8.1.1	Implementing Statistical Process Control	347
8.1.2	Basic Statistical Concepts	350
8.2	Control Charts	357
8.2.1	Introduction	357
8.2.2	Control Charts for Variables Data	357
8.2.3	Control Charts for Attributes Data	364
8.3	Process Capability and Special SPC Tools for Molding	365
8.3.1	Introduction	365
8.3.2	Capability Indexes	366
8.3.3	Use of Computers	369
8.3.4	Special SPC Techniques for Injection Molding	370
	References	374
<b>9</b>	<b>Special Injection Molding Processes</b>	<b>375</b>
	<i>L.-S. Turng</i>	
9.1	Coinjection (Sandwich) Molding	376
9.1.1	Process Description	378
9.1.2	Process Advantages	380
9.1.3	Process Disadvantages	383
9.1.4	Applicable Materials	383
9.1.5	Typical Applications	383
9.2	Fusible (Lost, Soluble) Core Injection Molding	385
9.2.1	Process Description	385
9.2.2	Process Advantages	388
9.2.3	Process Disadvantages	388
9.2.4	Applicable Materials	388
9.2.5	Typical Applications	389
9.3	Gas-Assisted Injection Molding	389
9.3.1	Process Description	390
9.3.2	Process Advantages	393
9.3.3	Process Disadvantages	395
9.3.4	Applicable Materials	395
9.3.5	Typical Applications	395
9.4	Injection-Compression Molding	398
9.4.1	Process Description	398
9.4.2	Process Advantages	399
9.4.3	Process Disadvantages	400
9.4.4	Applicable Materials	400
9.4.5	Typical Applications	401
9.4.6	Computer Simulation for Injection-Compression Molding	401
9.5	In-Mold Decoration and In-Mold Lamination	402
9.5.1	Process Description	402
9.5.2	Process Advantages	404
9.5.3	Process Disadvantages	404
9.5.4	Mold Design and Processing Considerations	405

9.5.5	Applicable Materials	406
9.5.6	Typical Applications	407
9.6	Insert and Outsert Molding	409
9.6.1	Insert Molding Process Description	409
9.6.2	Outsert Molding Process Description	410
9.7	Lamellar (Microlayer) Injection Molding	412
9.7.1	Process Description	412
9.7.2	Process Advantages	412
9.7.3	Process Disadvantages	415
9.7.4	Applicable Materials	415
9.7.5	Typical Applications	416
9.8	Low-Pressure Injection Molding	416
9.8.1	Process Description	416
9.8.2	Process Advantages	420
9.8.3	Process Disadvantages	420
9.8.4	Applicable Materials	420
9.8.5	Typical Applications	420
9.9	Microinjection Molding	421
9.9.1	Process Description	421
9.9.2	Process Advantages	426
9.9.3	Process Disadvantages	426
9.9.4	Applicable Materials	427
9.9.5	Typical Applications	427
9.10	Microcellular Molding	427
9.10.1	Process Description	427
9.10.2	Process Advantages	430
9.10.3	Process Disadvantages	431
9.10.4	Applicable Materials	431
9.10.5	Typical Applications	431
9.11	Multicomponent Injection Molding (Overmolding)	431
9.11.1	Process Description	432
9.11.2	Process Advantages	433
9.11.3	Process Disadvantages	434
9.11.4	Applicable Materials	434
9.11.5	Typical Applications	435
9.12	Multiple Live-Feed Injection Molding	436
9.12.1	Process Description	436
9.12.2	Process Advantages	438
9.12.3	Process Disadvantages	440
9.12.4	Applicable Materials	441
9.12.5	Typical Applications	441
9.13	Push-Pull Injection Molding	441
9.13.1	Process Description	441
9.13.2	Process Advantages and Disadvantages	442
9.13.3	Applicable Materials	442
9.13.4	Typical Applications	444
9.14	Powder Injection Molding	444
9.14.1	Process Description	445
9.14.2	Process Advantages	447

9.14.3	Process Disadvantages	447
9.14.4	Typical Applications	448
9.15	Reaction Injection Molding	448
9.15.1	Process Description	448
9.15.2	Process Advantages	450
9.15.3	Process Disadvantages	450
9.15.4	Applicable Materials	450
9.15.5	Typical Applications	451
9.16	Resin Transfer Molding and Structural RIM	451
9.16.1	Process Description	451
9.16.2	Process Advantages	453
9.16.3	Process Disadvantages	453
9.16.4	Applicable Materials	453
9.16.5	Typical Applications	453
9.17	Rheomolding	454
9.17.1	Process Description	455
9.17.2	Process Advantages	456
9.17.3	Process Disadvantages	457
9.18	Structural Foam Injection Molding	457
9.18.1	Process Description	457
9.18.2	Process Advantages	460
9.18.3	Process Disadvantages	461
9.18.4	Applicable Materials	461
9.18.5	Typical Applications	464
9.19	Thin-Wall Molding	464
9.19.1	Process Description	464
9.19.2	Process Advantages	466
9.19.3	Process Disadvantages	466
9.19.4	Applicable Materials	468
9.19.5	Typical Applications	468
9.20	Vibration Gas Injection Molding	468
9.20.1	Process Description	468
9.21	Water Assisted Injection Molding	469
9.21.1	Process Description	469
9.21.2	Process Advantages	470
9.21.3	Process Disadvantages	471
9.21.4	Applicable Materials	471
9.22	Rubber Injection	471
	<i>M. DeGreiff, N. Castaño</i>	
9.22.1	Rubber Molding Processes	471
9.22.2	Curing Systems in Rubber Injection Process	474
9.23	Injection Molding of Liquid Silicone Rubber	476
	Acknowledgement	478
	References	479

<b>10 Part Design</b>	483
<i>J. Beaumont</i>	
10.1 The Design Process	483
10.2 The Four Building Blocks of Plastics Part Design	487
10.2.1 Material	487
10.2.2 Product Design	497
10.2.3 Mold Design and Machining	499
10.2.4 Process	501
10.3 Part Design Guidelines for Injection Molded Plastic Parts	514
10.3.1 Designing the Primary Wall	516
10.3.2 Ribs, Gussets, and Bosses	519
10.3.3 Bosses	522
10.3.4 Corners, Fillets, and Radii	525
10.3.5 Taper and Draft Angles	526
10.3.6 Undercuts and Holes	526
10.3.7 Gating and Process Considerations	529
10.3.8 Cores	530
10.3.9 Avoid Picture Frame Features	531
10.3.10 Integral Hinges	531
10.4 Sample Part Design	533
10.5 Estimating Part Costs	536
References	539
<b>11 Simulation in Injection Molding</b>	541
<i>B. A. Davis, A. C. Rios, V. Yang</i>	
11.1 Introduction	541
11.2 History	542
11.3 Governing Equations	545
11.3.1 Flow Models	545
11.3.2 Orientation Models	548
11.3.3 Heat Transfer Models	549
11.3.4 Constitutive Equations	551
11.4 Numerical Methods	553
11.4.1 Finite Difference Method	554
11.4.2 Finite Element Method	554
11.4.3 Boundary Element Method	555
11.4.4 Finite Volume Method	556
11.5 Simplified Calculations	557
11.5.1 Finite Difference Based Calculations	557
11.5.2 Midplane Model-Based Calculations	558
11.5.3 Solid Model-Based Calculations	559
11.5.4 True 3-D Calculations	563
11.6 Advanced Calculations	564
11.6.1 Commercial Software	565
11.6.2 Specialty Calculations	570
11.7 Injection-Compression Molding	574
11.7.1 IC Molding of Thermoplastic Materials	576
11.7.2 IC Molding of Thermoset Materials	577



11.8	Molding Process Optimization . . . . .	578
11.8.1	Optimal Gating . . . . .	578
11.8.2	Active Process Control . . . . .	578
11.9	Conclusions . . . . .	579
	Acknowledgements . . . . .	580
	References . . . . .	580
<b>12</b>	<b>Process Troubleshooting . . . . .</b>	<b>581</b>
12.1	Introduction to Troubleshooting . . . . .	581
	<i>J. Wickman, T. Springett, and R. Vadlamudi</i>	
12.2	Troubleshooting Guide . . . . .	586
12.2.1	Troubleshooting Table . . . . .	586
	<i>J. Bozzelli</i>	
12.2.2	Troubleshooting on Injection Molding of Rubber . . . . .	627
	<i>M. DeGreiff</i>	
12.2.3	Important Troubleshooting Considerations . . . . .	631
	<i>T. Osswald</i>	
12.3	Technology and Process Troubleshooting . . . . .	632
	<i>J. Wickman, T. Springett, and R. Vadlamudi</i>	
12.3.1	Technology Implications . . . . .	633
12.3.2	Injection Molding Process and Sensors . . . . .	634
12.3.3	Pressure Sensors . . . . .	636
12.3.4	Temperature Sensors . . . . .	638
12.3.5	Process Monitoring . . . . .	638
12.3.6	Automatic Troubleshooting . . . . .	638
12.3.7	Design of Experiments . . . . .	639
12.3.8	Factorial Design of Experiments . . . . .	640
12.4	Conclusions . . . . .	642
	<i>J. Wickman, T. Springett, and R. Vadlamudi</i>	
	References . . . . .	642
<b>13</b>	<b>Materials Troubleshooting . . . . .</b>	<b>645</b>
	<i>M. Sepe</i>	
13.1	Composition Problems . . . . .	646
13.1.1	Diagnostic Tools for the Polymer . . . . .	647
13.1.2	Diagnostic Tools for Fillers and Reinforcements . . . . .	668
13.1.3	Diagnostic Tools for Additives . . . . .	675
13.2	Molecular Weight Problems . . . . .	682
13.3	Performance Problems . . . . .	708
13.3.1	Material Selection Process . . . . .	708
13.3.2	Use of Fillers . . . . .	715
13.3.3	Deflection Temperature Under Load . . . . .	717
13.3.4	Impact Properties . . . . .	720
13.4	A Brief Discussion of Viscoelasticity . . . . .	725
13.5	Conclusion . . . . .	754
	References . . . . .	754
	<b>Index . . . . .</b>	<b>755</b>