

Contents

Preface to the Fourth Edition	vii
Preface to the First Edition	ix
1 Introduction	
1.1 Basic Process	
1.2 Scope of the Book	2
1.3 General Literature Survey	2
1.4 History of Polymer Extrusion	4
References	6
Part I Extrusion Machinery	
2 Different Types of Extruders	11
2.1 The Single Screw Extruder	11
2.1.1 Basic Operation	12
2.1.2 Vented Extruders	13
2.1.3 Rubber Extruders	14
2.2 The Multiscrew Extruder	18
2.2.1 The Twin Screw Extruder	18
2.2.2 The Multiscrew Extruder with More Than Two Screws	19
2.2.3 The Gear Pump Extruder	20
2.3 Disk Extruders	21
2.3.1 Viscous Drag Disk Extruders	21
2.3.2 The Elastic Melt Extruder	26
2.3.3 Overview of Disk Extruders	27
2.4 Ram Extruders	12
2.4.1 Single Ram Extruders	28
2.4.2 Multi Ram Extruder	31
Appendix 2.1	32
References	33
3 Extruder Hardware	36
3.1 Extruder Drive	36
3.1.1 AC Motor Drive System	36
3.1.2 DC Motor Drive System	36
3.1.3 Hydraulic Drive System	41
3.1.4 Comparison of Various Drive Systems	43
3.1.5 Reducer	44
3.1.6 Constant Torque Characteristics	45
3.2 Thrust Bearing Assembly	46
3.3 Barrel and Feed Throat	48
3.4 Feed Hopper	52
3.5 Extruder Screw	53
3.6 Die Assembly	54
3.6.1 Screens and Screen Changers	55

3.7	Heating and Cooling Systems . . .	57
3.7.1	Electric Heating	58
3.7.2	Fluid Heating	59
3.7.3	Extruder Cooling	59
3.7.4	Screw Heating and Cooling	62
	References	63
4	Instrumentation and Control	65
4.1	Instrumentation Requirements	65
4.1.1	Most Important Parameters	66
4.2	Pressure Measurement	66
4.2.1	The Importance of Melt Pressure	66
4.2.2	Different Types of Pressure Transducers	67
4.2.3	Mechanical Considerations	70
4.2.4	Specifications	72
4.2.5	Comparisons of Different Transducers	74
4.3	Temperature Measurement	75
4.3.1	Methods of Temperature Measurement	75
4.3.2	Barrel Temperature Measurement	78
4.3.3	Stock Temperature Measurement	80
4.4	Other Measurements	84
4.4.1	Power Measurement	84
4.4.2	Rotational Speed	85
4.4.3	Extrudate Thickness	86
4.4.4	Extrudate Surface Conditions	89
4.5	Temperature Control	91
4.5.1	On-Off Control	91
4.5.2	Proportional Control	92
4.5.3	Controllers	99
4.5.4	Time-Temperature Characteristics	101
4.5.5	Tuning of the Controller Parameters	107
4.6	Total Process Control	112
4.6.1	True Total Extrusion Process Control	113
	References	114

Part II Process Analysis

5	Fundamental Principles	119
5.1	Balance Equations	119
5.1.1	The Mass Balance Equation	119
5.1.2	The Momentum Balance Equation	120
5.1.3	The Energy Balance Equation	121
5.2	Basic Thermodynamics	122
5.2.1	Rubber Elasticity	126
5.2.2	Strain Induced Crystallization	128
5.3	Heat Transfer	128
5.3.1	Conductive Heat Transfer	129
5.3.2	Convective Heat Transfer	129
5.3.3	Dimensionless Numbers	129

5.3.4	Viscous Heat Generation	136
5.3.5	Radiative Heat Transport	136
5.4	Basics of Devolatilization	141
5.4.1	Devolatilization of Particular Polymer	146
5.4.2	Devolatilization of Polymer Melts	147
Appendix 5.1	151
References	153
6	Important Polymer Properties	155
6.1	Properties of Bulk Materials	155
6.1.1	Bulk Density	155
6.1.2	Coefficient of Friction	157
6.1.3	Particle Size and Shape	162
6.1.4	Other Properties	164
6.2	Melt Flow Properties	164
6.2.1	Basic Definitions	164
6.2.2	Power Law Fluid	170
6.2.3	Other Fluid Models	174
6.2.4	Effect of Temperature and Pressure	175
6.2.5	Viscoelastic Behavior	179
6.2.6	Measurement of Flow Properties	180
6.3	Thermal Properties	192
6.3.1	Thermal Conductivity	192
6.3.2	Specific Volume and Morphology	194
6.3.3	Specific Heat and Heat of Fusion	198
6.3.4	Specific Enthalpy	199
6.3.5	Thermal Diffusivity	200
6.3.6	Melting Point	202
6.3.7	Induction Time	202
6.3.8	Thermal Characterization	204
6.4	Polymer Property Summary	205
References	207
	Functional Process Analysis	210
7.1	Basic Screw Geometry	210
7.2	Solids Conveying	213
7.2.1	Gravity Induced Solids Conveying	213
7.2.2	Drag Induced Solids Conveying	222
7.3	Plasticating	253
7.3.1	Theoretical Model of Contiguous Solids Melting	254
7.3.2	Other Melting Models	272
7.3.3	Power Consumption in the Melting Zone	276
7.3.4	Computer Simulation	278
7.3.5	Dispersed Solids Melting	279
7.4	Melt Conveying	285
7.4.1	Newtonian Fluids	287
7.4.2	Power Law Fluids	299
7.4.3	Non-Isothermal Analysis	310
7.5	Die Forming	344
7.5.1	Velocity and Temperature Profiles	345

7.5.2 Extrudate Swell	352
7.5.3 Die Flow Instabilities	354
7.6 Devolatilization	358
7.7 Mixing	362
7.7.1 Mixing in Screw Extruders	363
7.7.2 Static Mixing Devices	376
7.7.3 Dispersive Mixing	386
7.7.4 Backmixing	398
Appendix 7.1	405
Appendix 7.2	407
Appendix 7.3	407
References	414

Part III Practical Applications

8 Extruder Screw Design	425
8.1 Mechanical Considerations	425
8.1.1 Torsional Strength of the Screw Root	425
8.1.2 Strength of the Screw Flight	427
8.1.3 Lateral Deflection of the Screw	429
8.2 Optimization for Output	434
8.2.1 Optimizing for Melt Conveying	434
8.2.2 Optimizing for Plasticating	444
8.2.3 Optimizing for Solids Conveying	450
8.3 Optimizing for Power Consumption	452
8.3.1 Optimum Helix Angle	453
8.3.2 Effect of Flight Clearance	455
8.3.3 Effect of Flight Width	456
8.4 Single Flighted Extruder Screws	460
8.4.1 The Standard Extruder Screw	460
8.4.2 Modifications of the Standard Extruder Screw	461
8.5 Devolatilizing Extruder Screws	463
8.5.1 Functional Design Considerations	464
8.5.2 Various Vented Extruder Screw Designs	467
8.5.3 Vent Port Configuration	474
8.6 Multi-Flighted Extruder Screws	476
8.6.1 The Conventional Multi-Flighted Extruder Screws	476
8.6.2 Barrier Flight Extruder Screws	477
8.7 Mixing Screws	491
8.7.1 Dispersive Mixing Elements	491
8.7.2 Distributive Mixing Elements	521
8.8 Scale-Up	525
8.8.1 Common Scale-Up Factors	526
8.8.2 Scale-Up for Heat Transfer	528
8.8.3 Scale-Up for Mixing	529
8.8.4 Comparison of Various Scale-Up Methods	531
8.9 Rebuilding Worn Screws and Barrels	532
8.9.1 Application of Hardfacing Materials	533
8.9.2 Rebuilding of Extruder Barrels	536
References	526

9 Die Design	539
9.1 Basic Considerations	539
9.1.1 Balancing the Die by Adjusting the Land Length	540
9.1.2 Balancing by Channel Height	544
9.1.3 Other Methods of Die Balancing	546
9.2 Film and Sheet Dies	547
9.2.1 Flow Adjustment in Sheet and Film Dies	549
9.2.2 The Horseshoe Die	550
9.3 Pipe and Tubing Dies	552
9.3.1 Tooling Design for Tubing	555
9.4 Blown Film Dies	559
9.4.1 The Spiral Mandrel Geometry	561
9.4.2 Effect of Die Geometry on Flow Distribution	562
9.4.3 Summary Spiral Mandrel Die Design Variables	565
9.5 Profile Extrusion Dies	566
9.6 Coextrusion	567
9.6.1 Interface Distortion	570
9.7 Calibrators	572
References	574
10 Twin Screw Extruders	576
10.1 Introduction	576
10.2 Twin versus Single Screw Extruder	577
10.3 Intermeshing Co-Rotating Extruders	579
10.3.1 Closely Intermeshing Extruders	579
10.3.2 Self-Wiping Extruders	581
10.4 Intermeshing Counter-Rotating Extruders	596
10.5 Non-Intermeshing Twin Screw Extruders	605
10.6 Coaxial Twin Screw Extruder	617
10.7 Devolatilization in Twin Screw Extruders	618
10.8 Commercial Twin Screw Extruders	623
10.8.1 Screw Design Issues for Co-Rotating Twin Screw Extruders	626
10.8.2 Scale-Up in Co-Rotating Twin Screw Extruders	628
10.9 Overview Twin Screw Extruders	630
References	632
11 Troubleshooting Extruders	634
11.1 Requirements for Efficient Troubleshooting	634
11.1.1 Instrumentation	634
11.1.2 Understanding of the Extrusion Process	635
11.1.3 Collect and Analyze Historical Data (Timeline)	635
11.1.4 Team Building	636
11.1.5 Condition of the Equipment	636
11.1.6 Information on the Feed Stock	637
11.2 Tools for Troubleshooting	638
11.2.1 Temperature Measurement Devices	638
11.2.2 Data Acquisition Systems (DAS)	639
11.2.3 Light Microscopy	641
11.2.4 Thermochromic Materials	642
11.2.5 Thermal Analysis	643
11.2.6 Miscellaneous Tools	644

11.3	Systematic Troubleshooting	644
11.3.1	Upsets versus Development Problems	644
11.3.2	Machine Related Problems	644
11.3.3	Polymer Degradation	666
11.3.4	Extrusion Instabilities	681
11.3.5	Air Entrapment	691
11.3.6	Gel Problems	693
11.3.7	Die Flow Problems	696
	References	701
12	Modeling and Simulation of the Extrusion Process	706
	<i>Paul J. Gramann, Bruce A. Davis, and Tim A. Osswald</i>	
12.1	Introduction	706
12.2	Background	707
12.2.1	Analytical Techniques	707
12.2.2	Numerical Methods	708
12.2.3	Remeshing Techniques in Moving Boundary Problems	711
12.2.4	Rheology	713
12.3	Simulating 3-D Flows with 2-D Models	714
12.3.1	Simulating Flows in Internal Batch Mixers with 2-D Models	714
12.3.2	Simulating Flows in Extrusion with 2-D Models	717
12.3.3	Simulating Flows in Extrusion Dies with 2-D Models	722
12.4	Three-Dimensional Simulation	725
12.4.1	Simulating Flows in the Banbury Mixer with 3-Dimensional Models	725
12.4.2	Simulating Flows in Extrusion Dies with 3-Dimensional Models	726
12.4.3	Simulating Flows in Extrusion with 3-Dimensional Models	731
12.4.4	Static Mixers	746
12.5	Conclusions	749
	References	749
	Index	755