

Contents

Preface	V
Preface to the Third Edition	VII
Preface to the Second Edition	IX
Preface to the First Edition	XI
1 Introduction	1
1.1 Reference of Chapter 1	7
2 Properties of Polymeric Melts	9
2.1 Rheological Behavior	9
2.1.1 Viscous Properties of Melts	10
2.1.1.1 Viscosity and Flow Functions	10
2.1.1.2 Mathematical Description of the Pseudoplastic Behavior of Melts	12
2.1.1.3 Influence of Temperature and Pressure on the Flow Behavior	19
2.1.2 Determination of Viscous Flow Behavior	26
2.1.3 Viscoelastic Properties of Melts	32
2.2 Thermodynamic Behavior	38
2.2.1 Density	39
2.2.2 Thermal Conductivity	41
2.2.3 Specific Heat Capacity	42
2.2.4 Thermal Diffusivity	43
2.2.5 Specific Enthalpy	43
2.3 References of Chapter 2	46

3	Fundamental Equations for Simple Flows	49
3.1	Flow through a Pipe	50
3.2	Flow through a Slit	56
3.3	Flow through an Annular Gap	60
3.4	Summary of Simple Equations for Dies	64
3.5	Phenomenon of Wall Slip	74
3.5.1	Model Considering the Wall Slip	74
3.5.2	Instability in the Flow Function - Melt Fracture	79
3.5	References of Chapter 3	82
4	Computation of Velocity and Temperature Distributions in Extrusion Dies	85
4.1	Conservation Equations	85
4.1.1	Continuity Equation	86
4.1.2	Momentum Equations	87
4.1.3	Energy Equation	88
4.2	Restrictive Assumptions and Boundary Conditions	92
4.3	Analytical Formulas for Solution of the Conservation Equations	94
4.4	Numerical Solution of Conservation Equations	100
4.4.1	Finite Difference Method	101
4.4.2	Finite Element Method	104
4.4.3	Comparison of FDM and FEM	109
4.4.4	Examples of Computations of Extrusion Dies	112
4.5	Consideration of the Viscoelastic Behavior of the Material	126
4.6	Computation of the Extrudate Swelling	130
4.7	Methods for Designing and Optimizing Extrusion Dies	136
4.7.1	Industrial Practice for the Design of Extrusion Dies	137
4.7.2	Optimization Parameters	140
4.7.2.1	Practical Optimization Objectives	140
4.7.2.2	Practical Boundary Conditions and Constraints When Designing Flow Channels	141
4.7.2.3	Independent Parameters during Die Optimization	142
4.7.2.4	Dependent Parameters during Die Optimization and Their Modeling	142
4.7.3	Optimization Methods	144
4.7.3.1	Gradient-Free Optimization Methods	146
4.7.3.2	Gradient-Based Optimization Methods	149
4.7.3.3	Stochastic Optimization Methods	150

4.7.3.4	Evolutionary Methods	150
4.7.3.5	Treatment of Boundary Conditions	152
4.7.4	Practical Applications of Optimization Strategies for the Design of Extrusion Dies	154
4.7.4.1	Optimization of a Convergent Channel Geometry	154
4.7.4.2	Optimization of Profile Dies	156
4.8	References of Chapter 4	162
5	Monoextrusion Dies for Thermoplastics	167
5.1	Dies with Circular Exit Cross Section	167
5.1.1	Designs and Applications	167
5.1.2	Design	175
5.2	Dies with Slit Exit Cross Section	180
5.2.1	Designs and Applications	180
5.2.2	Design	187
5.2.2.1	T-Manifold	190
5.2.2.2	Fishtail Manifold	190
5.2.2.3	Coathanger Manifold	192
5.2.2.4	Numerical Procedures	203
5.2.2.5	Considerations for Clam Shelling	205
5.2.2.6	Unconventional Manifolds	206
5.2.2.7	Operating Performance of Wide Slit Dies	209
5.3	Dies with Annular Exit Cross Section	212
5.3.1	Types	213
5.3.1.1	Center-Fed Mandrel Support Dies	213
5.3.1.2	Screen Pack Dies	217
5.3.1.3	Side-Fed Mandrel Dies	218
5.3.1.4	Spiral Mandrel Dies	219
5.3.2	Applications	222
5.3.2.1	Pipe Dies	222
5.3.2.2	Blown Film Dies	223
5.3.2.3	Dies for the Extrusion of Parisons for Blow Molding	225
5.3.2.4	Coating Dies	232
5.3.3	Design	235
5.3.3.1	Center-Fed Mandrel Dies and Screen Pack Dies	235
5.3.3.2	Side-Fed Mandrel Dies	239
5.3.3.3	Spiral Mandrel Dies	242
5.3.3.4	Coating Dies	246
5.4	Formulas for the Computation of the Pressure Loss in Flow Channel Geometries other than Pipe or Slit	250

5.5	Dies with Irregular Outlet Geometry (Profile Dies)	255
5.5.1	Designs and Applications	255
5.5.2	Design	264
5.6	Dies for Foamed Semifinished Products	272
5.6.1	Dies for Foamed Films	274
5.6.2	Dies for Foamed Profiles	274
5.7	Special Dies	276
5.7.1	Dies for Coating of Profiles of Arbitrary Cross Section	276
5.7.2	Dies for the Production of Profiles with Reinforcing Inserts	277
5.7.3	Dies for the Production of Nets	278
5.7.4	Slit Die with Driven Screw for the Production of Slabs	279
5.8	References of Chapter 5	282
6	Coextrusion Dies for Thermoplastics	289
6.1	Designs	290
6.1.1	Externally Combining Coextrusion Dies	290
6.1.2	Adapter (Feedblock) Dies	291
6.1.3	Multimanifold Dies	294
6.1.4	Layer Multiplication Dies	294
6.2	Applications	296
6.2.1	Film and Sheet Dies	296
6.2.2	Blown Film Dies	298
6.2.3	Dies for the Extrusion of Parisons for Blow Molding	299
6.3	Computations of Flow and Design	300
6.3.1	Computation of Simple Multilayer Flow with Constant Viscosity	303
6.3.2	Computation of Coextrusion Flow by the Explicit Finite Difference Method	308
6.3.3	Computation of Velocity and Temperature Fields by the Finite Difference Method	311
6.3.4	Computation of Velocity Fields in Coextrusion Flows by FEM ...	314
6.4	Instabilities in Multilayer Flow	316
6.5	References of Chapter 6	323
7	Extrusion Dies for Elastomers	325
7.1	Design of Dies for the Extrusion of Elastomers	325
7.2	Fundamentals of Design of Extrusion Dies for Elastomers	327
7.2.1	Thermodynamic Material Data	327
7.2.2	Rheological Material Data	328

7.2.3	Computation of Viscous Pressure Losses	331
7.2.3.1	Formulas for Isothermal	331
7.2.3.2	Approaches to Nonisothermal Computations	334
7.2.4	Estimation of the Peak Temperatures	335
7.2.5	Consideration of the Elastic Behavior of the Material	336
7.3	Design of Distributor Dies for Elastomers	337
7.4	Design of Slotted Disks for Extrusion Dies for Elastomers	339
7.4.1	Computation of Pressure Losses	339
7.4.2	Extrudate Swelling (Die Swell)	342
7.4.3	Simplified Estimations for the Design of a Slotted Disk	346
7.5	References of Chapter 7	354
8	Heating of Extrusion Dies	357
8.1	Types and Applications	358
8.1.1	Heating of Extrusion Dies with Fluids	358
8.1.2	Electrically Heated Extrusion Dies	359
8.1.3	Temperature Control of Extrusion Dies	360
8.2	Thermal Design	362
8.2.1	Criteria and Degrees of Freedom for Thermal Design	362
8.2.2	Heat Balance of the Extrusion Die	364
8.2.3	Restrictive Assumptions in the Modeling	369
8.2.4	Simulation Methods for Thermal Design	369
8.3	References of Chapter 8	378
9	Mechanical Design of Extrusion Dies	381
9.1	Mechanical Design of a Breaker Plate	382
9.2	Mechanical Design of a Die with Axially Symmetrical Flow Channels ..	387
9.3	Mechanical Design of a Slit Die	397
9.4	General Design Rules	401
9.5	Materials for Extrusion Dies	402
9.6	References of Chapter 9	409
10	Handling, Cleaning, and Maintaining Extrusion Dies	411
10.1	References of Chapter 10	414

11 Calibration of Pipes and Profiles	415
11.1 Types and Applications	418
11.1.1 Friction Calibration	418
11.1.2 External Calibration with Compressed Air	419
11.1.3 External Calibration with Vacuum	420
11.1.4 Internal Calibration	424
11.1.5 Precision Extrusion Pullforming (the Technoform Process)	425
11.1.6 Special Process with Movable Calibrators	426
11.2 Thermal Design of Calibration Lines	426
11.2.1 Analytical Computational Model	428
11.2.2 Numerical Computational Model	432
11.2.3 Analogy Model	437
11.2.4 Thermal Boundary Conditions and Material Data	440
11.3 Effect of Cooling on the Quality of the Extrudate	441
11.4 Mechanical Design of Calibration Lines	442
11.5 Cooling Dies, Process for Production of Solid Bars	442
11.6 References of Chapter 11	446
Index	449