

Contents

Foreword	VII
1 Injection Molding: Background	1
1.1 Plastic Materials and Properties	1
1.1.1 Plastics Classification.....	3
1.1.1.1 Molecular Structure	3
1.1.1.2 Processability	5
1.1.1.3 Method of Synthesis.....	5
1.1.1.4 Monomer(s) in Molecules	7
1.1.2 Structural Characteristics of Plastic	7
1.1.2.1 Molecular Weight and Distribution.....	8
1.1.2.2 Degrees of Crystallinity	10
1.1.2.3 Orientation	11
1.1.3 Basic Rheology Terminology	12
1.1.4 Non-Newtonian Flow: Phenomenon and Constitutive Equations....	15
1.1.4.1 Normal Stress Differences in Shear Flows.....	15
1.1.4.2 Viscoelastic Behavior	17
1.1.4.3 Viscoelastic Models	19
1.1.4.4 Extensional (Elongation) Flow.....	21
1.1.4.5 Polymer Melt Constitutive Equations for Viscous Flow ...	22
1.1.4.6 Power Law Constitutive Equation	23
1.1.4.7 Effects of Temperature and Pressure on Viscosity	26
1.1.4.8 Effect of Temperature on Viscosity.....	26
1.2 Plastics Processing Technologies.....	29
1.2.1 Extrusion	29
1.2.2 Blow Molding.....	31
1.2.3 Injection Molding Machine, Process, and Key Variables	32
1.2.3.1 Injection Molding Machine and Process	32
1.2.3.2 Injection Molding Key Process Variables.....	35
References.....	37

2	Feedback Control Algorithms Developed for Continuous Processes	39
2.1	Introduction of Feedback Control Background	39
2.2	Traditional Feedback Control: PID	41
2.3	Adaptive Control	44
2.3.1	Model Estimation	45
2.3.2	Pole-Placement Controller Design	46
2.3.3	Solving the Diophantine Equation	47
2.3.4	Injection Velocity Adaptive Control Result	48
2.3.4.1	Antiwindup Estimation	50
2.3.4.2	Adaptive Feed-Forward Control	52
2.3.4.3	Cycle-to-Cycle Adaptation	57
2.3.4.4	Adaptive Control Results with Different Conditions	58
2.4	Model Predictive Control	61
2.4.1	Basic Principle of MPC and GPC	61
2.4.2	Model Order Determination	64
2.4.3	Comparison with Pole-Placement Control	65
2.4.4	GPC Control with Different Conditions	68
2.5	Fuzzy Systems in Injection Molding Control	70
2.5.1	Fuzzy Inference System Background	70
2.5.2	Fuzzy V/P Switch-Over	71
2.5.3	Fuzzy V/P System Experimental Test	76
2.5.4	Further Improvement	76
	References	80
3	Learning Type Control for the Injection Molding Process	83
3.1	Learning Type Control Background	83
3.2	Basic Iterative Learning Control	85
3.2.1	PID-Type ILC	85
3.2.2	Time-Delay Consideration	86
3.2.3	P-Type ILC for Injection Velocity	87
3.2.4	P-Type ILC for Packing Pressure	88
3.3	Optimal Iterative Learning Control	90
3.3.1	Problem Formulation	91
3.3.2	Optimal Iterative Learning Controller	92
3.3.3	Robust and Convergence Analysis	94
3.3.4	Selection of the Weighting Matrices	96
3.3.5	Simulation Results	97
3.3.6	Experimental Results of Optimal ILC	101
	References	106

4	Two-Dimensional Control Algorithms	109
4.1	Two-Dimensional Control Background	109
4.2	Two-Dimensional Generalized Predictive Iterative Learning Control	112
4.2.1	2D-GPILC Control Algorithm	112
4.2.2	Injection Velocity Control with 2D-GPILC	116
4.3	Two-Dimensional Dynamic Matrix Control	121
4.3.1	Problem Formulation	121
4.3.2	Controller Design	122
4.3.2.1	2D Equivalent Model with Repetitive Nature	123
4.3.2.2	2D Prediction Model	123
4.3.2.3	Cost Function and Control Law	125
4.3.2.4	Analysis of Convergence and Robustness	127
4.3.2.4.1	Model of the Closed-Loop Control System	128
4.3.2.4.2	Tracking Error and Convergence Conditions	130
4.3.2.4.3	Robustness Analysis	133
4.3.3	Simulation Illustration	136
4.3.3.1	Case 1: Convergence Test	138
4.3.3.2	Case 2: Repetitive Disturbances	140
4.3.3.3	Case 3: Nonrepetitive Disturbances	142
4.3.4	Experimental Test of 2D-DMC	144
	References	148
5	Statistical Process Monitoring (SPM) of Injection Molding: Basics	149
5.1	Process Monitoring	149
5.2	Statistical Process Monitoring (SPM)	150
5.2.1	Data Collection and Preprocessing	154
5.2.2	Construction of Nominal Statistical Model	155
5.2.3	Application of Statistical Models	157
5.3	Multivariate Statistical Analysis Methods for SPM	158
5.3.1	Principal Component Analysis and Partial Least Squares	158
5.3.2	PCA/PLS-Based Statistical Process Monitoring	160
5.3.3	Multiway PCA/PLS	162
5.3.4	Multiway PCA/PLS-Based Batch Process Monitoring	165
5.4	Challenges in Monitoring Injection Molding Process	166
5.4.1	Multiple Operation Phases	166
5.4.2	Within-Batch and Batch-to-Batch Dynamics	168
5.4.3	Unequal Batch Length	169
	References	170

6	Phase-Based SPM Strategies	173
6.1	Introduction	173
6.2	Phase-Division-Based Sub-PCA Modeling and Monitoring	175
6.2.1	Overview	175
6.2.2	Data Normalization	176
6.2.3	Phase Recognition and Division	177
6.2.4	Phase PCA Modeling	180
6.2.5	Statistics and Control Limits	181
6.2.6	Online Process Monitoring	182
6.2.7	Summary	183
6.3	Application of Phase-Based SPM to Injection Molding	184
6.3.1	Experimental Setup	184
6.3.2	Result Analysis of Phase Division and Modeling	185
6.3.3	Result Analysis of Process Monitoring and Fault Diagnosis	187
6.4	Improved Phase-Based SPM for Unequal-Length Batch Processes	193
6.4.1	Overview	193
6.4.2	Data Normalization	194
6.4.3	Phase Recognition and Division	196
6.4.4	Sub-PCA Modeling Procedure	198
6.4.5	Process Monitoring Procedure	199
6.4.6	Summary	200
6.5	Application of Improved Phase-Based SPM to Injection Molding	202
6.5.1	Experimental Setup	202
6.5.2	Result Analysis of Phase Division and Modeling	203
6.5.3	Result Analysis of Process Monitoring and Fault Diagnosis	205
	6.5.3.1 Monitoring of a Normal Batch	205
	6.5.3.2 Monitoring of Faulty Batches	207
	References	211
7	Phase-Based Quality Improvement Strategies	213
7.1	Introduction	213
7.2	Phase-Based Process Analysis and End-Product Quality Prediction (Method A)	214
7.2.1	Phase-Based PLS Modeling	214
7.2.2	Phase-Based Quality-Related Process Analysis	217
7.2.3	Online Quality Prediction	219
7.3	Application of Phase PLS Model (Method A) to Injection Molding	220
7.3.1	Experimental Setup	220
7.3.2	Illustration of Phase-Based Process Analysis	222
	7.3.2.1 Phase Division	222
	7.3.2.2 Process Analysis in the Critical-to-Surface Phase	224

7.3.2.3	Process Analysis in Critical-to-Dimension Phases	225
7.3.3	Illustration of Phase-Based Quality Prediction	228
7.4	Phase-Based Process Analysis and End-Product Quality Prediction (Method B)	232
7.4.1	Critical Phase Identification	232
7.4.2	Key Variable Selection Based on Variable-Wise Unfolding.	235
7.4.3	Phase-Based PLS Modeling Algorithm	239
7.4.4	Online Quality Prediction.	241
7.5	Application of Phase PLS Model (Method B) to Injection Molding.	242
7.5.1	Illustration of Correlation Analysis.	242
7.5.2	Results of Quality Prediction	246
	References.	250
8	In-Mold Capacitive Transducer for Injection Molding Process.	251
8.1	Fundamentals of Capacitive Transducers.	252
8.2	Dielectric Properties of Polymers	255
8.3	Principle and Preliminary Tests of Capacitive Transducer in Injection Mold	257
8.4	Design of In-Mold Capacitive Transducer.	260
8.4.1	Mold Base Design	260
8.4.2	Mold Insert Design	263
8.4.3	Capacitance Measurement.	264
8.5	Applications in Melt Flow Detection during Filling Stage	266
8.5.1	Detection of Filling Start	266
8.5.2	Detection of V/P Transfer.	267
8.5.3	Detection of melt flow during filling.	269
8.6	Applications for the Packing and Cooling Stages	279
8.6.1	Guide to Packing Pressure Setting	279
8.6.2	Detection of Gate Freezing-Off Time.	282
8.6.3	Solidification Rate Monitoring.	284
8.7	Online Part Weight Prediction Using the Capacitive Transducer	287
	References.	292
9	Profile Setting of Injection Velocity.	295
9.1	Constant Melt-Front-Velocity Strategy	295
9.2	Scheme Based on Average-flow-length	301
9.3	Neural Network Model of Average-flow-length	302
9.3.1	Inputs and Output of the Neural Network Model	302
9.3.2	Architecture of the Neural Network Model	303
9.3.3	Training Algorithm.	305
9.3.4	Data Collection of Training and Validation Samples.	306

9.3.5	Model Performance.....	308
9.4	Profiling Strategy via Optimization.....	317
9.5	Parabolic Velocity Profile.....	319
9.6	Piece-Wise Ramp Velocity Profile.....	323
9.7	Conclusions.....	325
	References.....	326
10	Profile Setting of Packing Pressure.....	329
10.1	Online Autodetection of Gate Freezing-Off Point.....	329
10.1.1	Gate Freezing-Off Detection.....	330
10.1.2	Development of Autodetection System.....	333
10.1.3	Tests of Constant Packing Pressure Cases.....	337
10.1.4	Tests of Varying Packing Pressure Profile Cases.....	342
10.1.4.1	Online Detection Results of Step Pressure Profile.....	342
10.1.4.2	Online Detection Results of Ramp Pressure Profile.....	343
10.2	Influence of Packing Profile on Part Quality.....	346
10.2.1	Constant Packing Profile.....	348
10.2.2	Ramp Packing Profile.....	351
10.2.3	Step-Change Packing Profile.....	359
10.2.4	Summary.....	363
10.3	Profiling of Packing Pressure.....	364
10.3.1	Profiling Rules.....	364
10.3.2	Online Profiling of Constant Packing Pressure.....	365
10.3.3	Ramp Profile for Specific Thickness Distribution.....	368
10.4	Conclusions.....	370
	References.....	370
11	Parameter Setting for the Plastication Stage.....	371
11.1	Visual Barrel System Development.....	372
11.2	Plastication Behavior.....	373
11.2.1	Melting Behavior.....	373
11.2.2	Processing Condition Effects.....	380
11.3	Neural Network Modeling of Melt Temperature.....	384
11.4	Optimal Parameter Setting for the Plastication Stage.....	385
	References.....	389
	Subject Index.....	391