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