

# Contents

<b>Acknowledgments</b> .....	<b>V</b>
<b>Preface</b> .....	<b>VII</b>
<b>About the Author</b> .....	<b>XI</b>
List of Contributors .....	XII
<b>PART 1 Polymer Materials and Process Micro Technology</b> .....	<b>1</b>
<b>1 Micro Injection Molding Machines Technology</b> .....	<b>3</b>
1.1 Introduction .....	3
1.2 Patent Analysis .....	3
1.3 Architectures and Solutions for Micro Injection Molding Machines ....	9
1.3.1 Introduction to Functional-Based Modelling .....	9
1.3.2 Method .....	12
1.3.3 Functional Analysis .....	13
1.4 Appendix .....	25
References .....	28
<b>2 Micro Molding Process Monitoring and Control</b> .....	<b>31</b>
2.1 The Need for Process Monitoring in Micro Molding .....	31
2.2 Micro Molding Sensor Technologies .....	32
2.2.1 Volumetric Flow Rate .....	32
2.2.2 Temperature Sensors .....	34
2.2.3 Pressure Sensors .....	35
2.2.4 Ultrasonic Sensors .....	37
2.3 Visualization Systems .....	38
2.3.1 Tool Design for Visualization .....	38

2.3.2	High-Speed Imaging .....	39
2.3.3	Thermal Imaging Methods .....	42
2.4	Data Acquisition and Archiving Systems .....	42
2.4.1	Data Acquisition Hardware .....	42
2.4.2	Synchronization of DAQ Systems .....	44
2.4.3	Communication and Storage Strategies .....	44
2.5	Applications for Process Monitoring Systems .....	45
2.5.1	Qualification of Machine Performance .....	45
2.5.2	Material Quality Assessment .....	47
2.5.3	Process Window Evaluation .....	48
2.5.4	Simulation Boundary Conditions and Validation of Results .....	50
2.5.5	Sensor Development and Validation .....	51
2.5.6	Intelligent Process Control .....	53
	References .....	54
<b>3</b>	<b>Polymer Materials Structure and Properties in Micro Injection Molding Parts .....</b>	<b>57</b>
3.1	Introduction .....	57
3.2	Specific Properties of Polymers for Micro Injection Molding Applications .....	58
3.3	Materials Scaling Effects in Micro Injection Molding .....	59
3.3.1	Rheology in the Micro and Nano Dimensional Ranges, at Low, High, and Ultra-High Shear Rates .....	60
3.3.2	Polymer pvT Properties at the Micro Scale .....	63
3.3.3	Thermal Properties of Polymers at the Micro Scale .....	65
3.3.4	Mechanical Properties of Micro Molded Components (Micro Tensile Test and Nano Indentation) .....	67
3.4	Molecular Orientation and Crystallinity in Micro Molded Parts .....	70
3.4.1	Amorphous Polymers .....	71
3.4.2	Semi-Crystalline Polymers .....	73
3.5	Micro/Nano Composites in Micro Injection Molding .....	76
	References .....	79
<b>4</b>	<b>Surface Replication in Micro Injection Molding .....</b>	<b>83</b>
4.1	Replication of Micro and Nano Structures .....	83
4.2	Engineering of Micro- and Nanostructured Surfaces .....	86
4.2.1	Lithographic Techniques .....	87
4.2.2	Non-Lithographic Electrochemical-Based Techniques .....	88

4.3	Replication Assessment of Polymer Surfaces at the Sub-Micrometer Scale .....	91
4.3.1	Dimensional Evaluation of Replication Fidelity .....	92
4.3.2	Applications of Profile Measurements .....	93
4.3.3	Applications of Amplitude and Slope Replication of Polymer Surfaces .....	94
4.3.4	Applications of Areal Parameters .....	97
4.3.5	Application of Angular Intensity Distribution Measurements ...	99
4.4	Influence of Tooling and Process Parameters on Replication of Microstructures .....	101
4.4.1	Replication and Optimization of Deterministic Structures .....	101
4.4.2	Replication Quality of Large Area Nano-Structured Surfaces .....	104
4.4.3	Influence of Process Parameters on Surface Replication .....	106
	References .....	109
<b>PART 2 Tooling Technologies for Micro Mold Making.....</b>		<b>113</b>
<b>5</b>	<b>Micro Machining Technologies for Micro Injection Mold Making .....</b>	<b>115</b>
5.1	Introduction .....	115
5.2	Process Chains for Micro Mold Making .....	117
5.3	Micro Mechanical Material Removal .....	121
5.3.1	Size Effects .....	122
5.3.2	Cutting Forces and Tool Deflection .....	124
5.3.3	Machine Tools .....	124
5.4	Micro Milling .....	125
5.4.1	Cutting Tools .....	125
5.5	Micro Turning .....	127
5.6	Micro Drilling .....	128
5.7	Thermal Material Removal Processes .....	128
5.8	Micro Electrical Discharge Machining .....	129
5.8.1	Micro EDM Sinking .....	132
5.8.2	Micro Wire EDM .....	132
5.8.3	Micro EDM Drilling .....	133
5.8.4	Wire Electrical Discharge Grinding .....	133
5.8.5	Micro EDM Milling .....	133
5.9	Application Examples of Machining Technologies for Micro Mold Making .....	135
5.9.1	Micro Mold Produced by Direct Tooling .....	135

5.9.2	Micro Mold Produced by Indirect Tooling .....	136
	References .....	138
<b>6</b>	<b>Ultra-Precision Machining Technologies for Micro Injection Mold Making .....</b>	<b>141</b>
6.1	General Aspects of Ultra-Precision Machining .....	143
6.2	Diamond Machining .....	144
6.2.1	Diamond Turning .....	144
6.2.2	Diamond Milling .....	147
6.2.3	Shaping .....	150
6.3	Abrasive Machining .....	152
6.3.1	Process Chains .....	152
6.3.2	Ultra-Precision Grinding .....	153
6.3.3	Polishing .....	157
6.4	Applications of Ultra-Precision Machining .....	159
6.4.1	Fresnel Lens .....	160
6.4.2	Micro Beam Splitter .....	160
6.4.3	Diffractive Optical Elements .....	161
6.4.4	Retroreflectors .....	162
	References .....	164
<b>7</b>	<b>Surface Treatment of Mold Tools in Micro Injection Molding ..</b>	<b>169</b>
7.1	Introduction .....	169
7.2	Investigation of DLC Surface Treatment Effects in Micro Injection Molding .....	170
7.2.1	Surface Treatment for Improved Demolding .....	170
7.2.2	An Experimental Case Study for Improving Part Demolding Using Surface Treatment .....	171
7.2.3	Validation, Verification, and Results .....	172
7.3	Temperature Effects on DLC-Coated Micro Molds .....	173
7.3.1	DLC Coatings Used on Micro Molds .....	173
7.3.2	An Experimental Case Study for Identifying the Temperature Effects on DLC-Coated Micro Molds .....	175
7.3.3	Validation, Verification, and Results .....	176
7.3.3.1	Linear and Superficial Thermal Expansion During Processing .....	176
7.3.3.2	Finite Element Analysis Results .....	177
7.3.4	Main Findings .....	180

7.4	A Novel Surface Treatment Texturing of Micro Injection Molding Tools	180
7.4.1	Mold Tool Texturing and Demolding Force	180
7.4.2	An Experimental Case Study for Tool Texturing	181
7.4.3	Validation, Verification, and Results	184
7.4.3.1	Nano-Structured Surfaces Replication and Demolding Forces	184
7.4.3.2	Main Findings	186
7.5	Conclusions	186
	References	187
<b>PART 3 Micro Molding Key-Enabling Technologies</b>		<b>191</b>
<b>8</b>	<b>Vacuum-Assisted Micro Injection Molding</b>	<b>193</b>
8.1	Introduction	193
8.1.1	Air Evacuation in Injection Molding	193
8.1.2	Vacuum-Assisted Micro Injection Molding	194
8.1.3	Cavity Air Flow in Micro Injection Molding	195
8.2	Advantages and Limitations	195
8.3	Equipment and Design Solutions	197
8.3.1	Active Venting	197
8.3.2	Mold Design for Vacuum-Assisted Micro Injection Molding	198
8.3.3	Cavity Sealing	201
8.3.4	Vacuum Control	201
8.4	Effects on Replication	202
8.4.1	Height of Replicated Features	202
8.4.2	Feature Definition	203
8.4.3	Part Morphology	205
8.5	Venting Optimization	206
8.5.1	Effect of Micro Injection Molding Process Parameters	206
8.5.2	Effect of Polymer Selection	208
8.6	Concluding Remarks	210
	References	210
<b>9</b>	<b>Modeling and Simulation of Micro Injection Molding</b>	<b>213</b>
9.1	Introduction	213
9.1.1	The Micro Injection Molding Process	213
9.1.2	Why Simulate the Injection Molding Process?	214

9.2	Mathematical Background .....	215
9.2.1	Viscosity of Plastics .....	215
9.2.2	Thermodynamics .....	217
9.2.3	Flow of Plastics .....	218
9.3	State-Of-The-Art and Challenges of Micro Injection Molding Simulations .....	220
9.4	Best Practice Strategies for Micro Molded Component Simulations .....	222
9.4.1	Modeling .....	222
9.4.2	Meshing .....	225
9.4.3	Material Data .....	226
9.4.4	Validation and Verification .....	228
9.5	Examples of Simulation-Aided Design and Simulated Phenomena .....	231
9.5.1	Gate Design Optimization .....	232
9.5.2	Hesitation Effect .....	235
9.6	Conclusions .....	236
	References .....	237
<b>10</b>	<b>Metrological Quality Assurance in Micro Injection Molding ...</b>	<b>241</b>
10.1	Introduction .....	241
10.2	Quality of the Measurement Process: Calibration and Traceability .....	242
10.2.1	Accuracy and Precision .....	244
10.2.1.1	Repeatability and Reproducibility .....	245
10.3	Metrology for Micro Injection Molding .....	246
10.3.1	Dimensional Metrology .....	246
10.3.2	Surface Metrology .....	250
10.3.2.1	Areal Topography Measurements .....	252
10.4	Instrumentation for Micro Injection Molded Parts and Micro Injection Molding Tools .....	257
10.4.1	Optical Instruments .....	270
10.5	Uncertainty of Dimensional and Surface Topography Measurements of Micro Molded Parts and Micro Tools .....	277
10.5.1	Assessment of the Uncertainty for Micro Injection Molding Applications .....	282
	References .....	284

<b>11 Additive Manufacturing for Micro Tooling and Micro Part Rapid Prototyping</b> .....	<b>289</b>
11.1 Additive Manufacturing Process Technologies and Materials .....	289
11.1.1 Additive Manufacturing Methods for Polymer Materials .....	293
11.1.2 Additive Manufacturing Methods for Metal Materials .....	295
11.2 Additive Manufacturing Technologies for Micro Tooling .....	297
11.2.1 AM Technologies for Micro Injection Molding Hard Tooling Applications .....	298
11.2.2 AM Technologies for Micro Injection Molding Soft Tooling Applications .....	299
11.2.3 Indirect Methods for Micro Tooling Production .....	303
11.3 Additive Manufacturing for the Direct Manufacturing of Micro Products .....	306
References .....	310
 <b>PART 4 Multimaterial Micro Processing</b> .....	 <b>315</b>
<b>12 Micro Powder Injection Molding</b> .....	<b>317</b>
12.1 Introduction .....	317
12.2 Process Description .....	319
12.2.1 Feedstocks for Powder Injection Molding .....	319
12.2.1.1 Binder .....	319
12.2.1.2 Powder Particle Properties .....	320
12.2.1.3 Feedstock Preparation and Rheological Properties .....	321
12.2.2 Debinding .....	321
12.2.3 Sintering .....	322
12.3 Powder Injection Molding of Micro Components (MicroPIM) .....	322
12.3.1 Dissimilarities between Powder and Plastics Injection Molding ..	323
12.3.2 Dissimilarities between Macro- and MicroPIM .....	324
12.4 2C Powder Injection Molding .....	328
12.5 Simulation of MicroPIM .....	330
12.5.1 MicroPIM Simulation by Use of Commercial Programs .....	330
12.5.2 MicroPIM Simulation Using Modified or Newly Developed Software Programs .....	331
12.6 Summary and Outlook .....	333
References .....	334

<b>13 Multimaterial Micro Injection Molding</b> .....	<b>339</b>
13.1 Introduction .....	339
13.2 Multimaterial Molding and Multimaterial Micro Molding .....	340
13.2.1 Introduction and Applications .....	340
13.2.2 Application Areas .....	343
13.2.3 Advantages and Disadvantages .....	344
13.2.4 Variants of Multimaterial Molding .....	345
13.3 Two-Component Micro Molding .....	346
13.3.1 Polymer-Polymer Bonding .....	347
13.3.1.1 Hypotheses on Adhesion of 2K Molded Polymers .....	349
13.3.1.2 Experimental Investigations and Results .....	351
13.3.1.3 Other Factors Affecting Bonding between Polymers .....	358
13.3.1.4 Effects of Surface Roughness on the Bonding of Two Polymers .....	359
13.3.1.5 Effects of Environmental Factors .....	361
13.3.2 Polymer-Polymer Interface .....	364
13.3.2.1 Challenges for 2K Injection Molding: Bonding and Interface Dilemma .....	365
13.3.2.2 Special Considerations for the Polymer-Polymer Interface of Micro Parts .....	369
13.4 Adhesion Modification for Multicomponent Molding .....	370
13.5 Other Quality Issues for Multicomponent Micro Molding .....	372
13.6 Conclusion .....	373
References .....	375
<b>Index</b> .....	<b>378</b>