

# Contents

|                                                                                     |            |
|-------------------------------------------------------------------------------------|------------|
| <b>Preface to the Second Edition</b> .....                                          | <b>VII</b> |
| <b>Preface to First Edition</b> .....                                               | <b>IX</b>  |
| <b>1 Introduction to Scientific Processing</b> .....                                | <b>1</b>   |
| 1.1 The Evolution and Progress of Injection Molding .....                           | 1          |
| 1.2 The Molding Process .....                                                       | 2          |
| 1.3 The Three Types of Consistencies Required in Injection Molding .....            | 2          |
| 1.4 Scientific Processing .....                                                     | 6          |
| 1.5 The Five Critical Factors of Molding .....                                      | 7          |
| 1.5.1 Part Design .....                                                             | 8          |
| 1.5.2 Material Selection .....                                                      | 8          |
| 1.5.3 Mold Design and Construction .....                                            | 9          |
| 1.5.4 Machine Selection .....                                                       | 9          |
| 1.5.5 Molding Process .....                                                         | 9          |
| 1.6 Concurrent Engineering .....                                                    | 10         |
| 1.7 Variation .....                                                                 | 10         |
| <b>2 Properties of Polymers and Plastics That Influence Injection Molding</b> ..... | <b>13</b>  |
| 2.1 Polymers .....                                                                  | 13         |
| 2.2 Molecular Weight and Molecular Weight Distribution .....                        | 15         |
| 2.3 Polymer Morphology (Crystalline and Amorphous Polymers) .....                   | 17         |
| 2.4 Role of Morphology in Injection Molding .....                                   | 22         |
| 2.4.1 Differences in Shrinkage between Amorphous and Crystalline Materials .....    | 22         |
| 2.4.2 Melt Processing Range .....                                                   | 22         |
| 2.4.3 Mold Filling Speed .....                                                      | 23         |

|          |                                                                                                 |           |
|----------|-------------------------------------------------------------------------------------------------|-----------|
| 2.4.4    | Mold Temperatures .....                                                                         | 24        |
| 2.4.5    | Barrel Heat Profile .....                                                                       | 24        |
| 2.4.6    | Screw Recovery Speeds .....                                                                     | 25        |
| 2.4.7    | Nozzle Temperature Control .....                                                                | 25        |
| 2.4.8    | Cooling Times .....                                                                             | 26        |
| 2.4.9    | Mechanical Properties .....                                                                     | 26        |
| 2.4.10   | Optical Clarity .....                                                                           | 26        |
| 2.5      | Exceptions of Morphology Rules to Polyolefins .....                                             | 27        |
| 2.6      | Thermal Transitions in Polymers .....                                                           | 28        |
| 2.6.1    | Relationship between the Glass Transition Temperature<br>and Post Mold Shrinkage .....          | 32        |
| 2.7      | Shrinkage of Polymers in Injection Molding .....                                                | 36        |
| 2.8      | The Plastic Pressure–Volume–Temperature (PVT) Relationship .....                                | 39        |
| 2.8.1    | Importance of Plastic Density in Injection Molding .....                                        | 40        |
| 2.8.2    | Residence Time and Maximum Residence Time of a Plastic ...                                      | 41        |
| 2.8.3    | Plastic Datasheets .....                                                                        | 43        |
| 2.9      | References .....                                                                                | 45        |
| <b>3</b> | <b>Polymer Rheology .....</b>                                                                   | <b>47</b> |
| 3.1      | Viscosity .....                                                                                 | 47        |
| 3.2      | Newtonian and Non-Newtonian Materials .....                                                     | 49        |
| 3.3      | Viscosity in Polymer Melts .....                                                                | 50        |
| 3.4      | Effect of Temperature on Viscosity .....                                                        | 54        |
| 3.5      | Velocity and Shear Rate Profiles .....                                                          | 55        |
| 3.6      | Application to Injection Molding .....                                                          | 56        |
| 3.6.1    | Flow Imbalance in an 8-Cavity Mold .....                                                        | 57        |
| 3.6.2    | Racetrack Effect in a Part with Constant Thickness .....                                        | 59        |
| 3.6.3    | Stress Build-Up in Molded Parts .....                                                           | 59        |
| 3.6.4    | Warpage Difference between Cavities .....                                                       | 60        |
| 3.7      | Solving Flow Imbalances Using Melt Rotation Techniques .....                                    | 60        |
| 3.8      | Fountain Flow .....                                                                             | 62        |
| 3.9      | Effect of Fountain Flow on Crystallinity, Molecular Orientation,<br>and Fiber Orientation ..... | 65        |
| 3.10     | Characterization of Polymer Viscosity .....                                                     | 66        |
| 3.11     | References .....                                                                                | 67        |

|          |                                                                 |           |
|----------|-----------------------------------------------------------------|-----------|
| <b>4</b> | <b>Plastic Drying</b>                                           | <b>69</b> |
| 4.1      | Problems in Melt Processing Related to the Presence of Moisture | 71        |
| 4.1.1    | Degradation of Plastic                                          | 71        |
| 4.1.2    | Presence of Surface Defects                                     | 71        |
| 4.2      | Hygroscopic Polymers                                            | 75        |
| 4.3      | Drying of Plastics                                              | 77        |
| 4.3.1    | Drying Temperatures and Times                                   | 77        |
| 4.3.2    | Relative Humidity and Dew Point                                 | 79        |
| 4.3.3    | Air Flow Rate                                                   | 80        |
| 4.4      | Equipment for Drying Plastics                                   | 80        |
| 4.4.1    | Oven Dryers                                                     | 80        |
| 4.4.2    | Hot Air Dryers                                                  | 81        |
| 4.4.3    | Desiccant Dryers                                                | 81        |
| 4.4.4    | Classifications Based on the Location of the Dryer              | 81        |
| 4.5      | Determination of the Amount of Moisture                         | 82        |
| 4.5.1    | The Glass Slide Technique (TVI Test)                            | 82        |
| 4.5.2    | The Karl-Fischer Titration Method                               | 83        |
| 4.5.3    | Electronic Moisture Analyzer                                    | 83        |
| 4.5.4    | Measurement of the Dew Point                                    | 84        |
| 4.6      | 'Overdrying' or Overexposure to Drying Temperatures             | 85        |
| 4.7      | Cautions                                                        | 92        |
| 4.8      | Prevention of Overexposure to Longer Drying Times               | 92        |
| 4.9      | Overdrying Controller                                           | 93        |
| 4.10     | References                                                      | 94        |
| <b>5</b> | <b>Common Plastic Materials and Additives</b>                   | <b>95</b> |
| 5.1      | Classification of Polymers                                      | 95        |
| 5.2      | Commercially Important Plastics                                 | 97        |
| 5.2.1    | Polyolefins                                                     | 97        |
| 5.2.2    | Polymers from Acrylonitrile, Butadiene, Styrene, and Acrylate   | 98        |
| 5.2.3    | Polyamides (PA)                                                 | 99        |
| 5.2.4    | Polystyrenes (PS)                                               | 100       |
| 5.2.5    | Acrylics                                                        | 101       |
| 5.2.6    | Polycarbonates (PC)                                             | 101       |
| 5.2.7    | Polyesters                                                      | 101       |
| 5.2.8    | Polyvinyl Chloride (PVC)                                        | 101       |
| 5.2.9    | Polyoxymethylene (POM or Acetal)                                | 102       |
| 5.2.10   | Fluoropolymers                                                  | 103       |

|          |                                                                                                |            |
|----------|------------------------------------------------------------------------------------------------|------------|
| 5.3      | Additives .....                                                                                | 103        |
| 5.3.1    | Fillers .....                                                                                  | 104        |
| 5.3.2    | Plasticizers .....                                                                             | 104        |
| 5.3.3    | Flame Retardants .....                                                                         | 104        |
| 5.3.4    | Anti-aging Additives, UV Stabilizers .....                                                     | 105        |
| 5.3.5    | Nucleating Agents .....                                                                        | 105        |
| 5.3.6    | Lubricants .....                                                                               | 106        |
| 5.3.7    | Processing Aids .....                                                                          | 106        |
| 5.3.8    | Colorants .....                                                                                | 106        |
| 5.3.9    | Blowing Agents .....                                                                           | 106        |
| 5.3.10   | Other Polymers .....                                                                           | 107        |
| 5.4      | Closing Remarks .....                                                                          | 108        |
| 5.5      | Reference .....                                                                                | 108        |
| <b>6</b> | <b>Injection Molding and Molding Machines .....</b>                                            | <b>109</b> |
| 6.1      | The History of Injection Molding .....                                                         | 109        |
| 6.2      | Injection Molding Machines and Their Classifications .....                                     | 110        |
| 6.3      | Machine Specifications .....                                                                   | 112        |
| 6.3.1    | Clamp Force (Tonnage) .....                                                                    | 113        |
| 6.3.2    | Shot Size .....                                                                                | 113        |
| 6.3.3    | Screw Diameter and L/D Ratio .....                                                             | 113        |
| 6.3.4    | Plasticating Capacity .....                                                                    | 114        |
| 6.3.5    | Maximum Plastic Pressure .....                                                                 | 114        |
| 6.4      | The Injection Molding Screw .....                                                              | 114        |
| 6.5      | Screw Designs .....                                                                            | 117        |
| 6.6      | The Check Ring Assembly .....                                                                  | 118        |
| 6.7      | Intensification Ratio (IR) .....                                                               | 119        |
| 6.8      | Obtaining Intensification Ratios .....                                                         | 121        |
| 6.9      | Selecting the Right Machine for the Mold .....                                                 | 122        |
| 6.9.1    | Physical Size of the Mold .....                                                                | 122        |
| 6.9.2    | Calculating the Required Machine Tonnage for a Mold .....                                      | 124        |
| 6.10     | The Rule of Thumb for Tonnage Is Only an Estimate .....                                        | 126        |
| 6.10.1   | Percentage Shot Size Used and Number of Shots in the Barrel .....                              | 127        |
| 6.10.2   | Residence Time of the Material in the Barrel .....                                             | 130        |
| 6.10.3   | Practical Methods to Find Percentage Shot Size, Shots in<br>a Barrel, and Residence Time ..... | 130        |
| 6.10.4   | Residence Time Distribution .....                                                              | 131        |

|          |                                                                                      |            |
|----------|--------------------------------------------------------------------------------------|------------|
| <b>7</b> | <b>Scientific Processing, Scientific Molding, and Molding Parameters</b>             | <b>133</b> |
| 7.1      | Introduction                                                                         | 133        |
| 7.1.1    | Process Robustness                                                                   | 135        |
| 7.1.2    | Process Consistency                                                                  | 135        |
| 7.2      | The 11 + 2 Plastic Injection Molding Machine Parameters                              | 138        |
| 7.3      | Process Outputs                                                                      | 141        |
| 7.4      | What Scientific Molding and Scientific Processing Are Not                            | 142        |
| 7.5      | The Injection Molding Cycle                                                          | 143        |
| 7.5.1    | Injection, Pack, and Hold                                                            | 143        |
| 7.5.2    | Speed and Pressure                                                                   | 145        |
| 7.5.3    | Pressure Limited Process                                                             | 146        |
| 7.5.4    | Decoupled Molding <sup>SM</sup>                                                      | 146        |
| 7.5.5    | Intensification Ratio (IR)                                                           | 147        |
| 7.5.6    | Screw Speed                                                                          | 148        |
| 7.5.7    | Back Pressure                                                                        | 150        |
| 7.5.8    | Cycle Time                                                                           | 151        |
| 7.6      | References                                                                           | 152        |
| <b>8</b> | <b>Process Development Part 1: the 6-Step Study – Exploring the Cosmetic Process</b> | <b>153</b> |
| 8.1      | Introduction                                                                         | 153        |
| 8.2      | Introduction to Process Development                                                  | 153        |
| 8.3      | Premolding Setup                                                                     | 156        |
| 8.4      | Storage and Drying of Resin                                                          | 156        |
| 8.4.1    | Plastic Drying                                                                       | 157        |
| 8.5      | Machine Selection                                                                    | 159        |
| 8.6      | Importance of Adding Charge Delay Time                                               | 160        |
| 8.7      | Filling in Injection: Weight or Volume?                                              | 161        |
| 8.8      | Setting of the Melt Temperatures                                                     | 162        |
| 8.9      | Setting Mold Temperatures                                                            | 165        |
| 8.10     | Process Optimization – the 6-Step Study                                              | 165        |
| 8.10.1   | Step 1: Optimization of the Injection Phase–Rheology Study                           | 165        |
| 8.10.2   | Procedure to Determine the Viscosity Curve at the Molding Machine                    | 169        |
| 8.10.3   | How to Use this Information                                                          | 171        |
| 8.10.4   | Cautions and Exceptions                                                              | 173        |
| 8.10.5   | Profiling of Injection Speeds                                                        | 173        |

|          |                                                                                 |            |
|----------|---------------------------------------------------------------------------------|------------|
| 8.10.6   | When a Short Shot Sticks .....                                                  | 174        |
| 8.10.7   | Selecting Melt Temperature for Viscosity Graphs .....                           | 176        |
| 8.10.8   | Step 2: Determining the Cavity Balance –<br>Cavity Balance Study .....          | 177        |
| 8.11     | Reasons for Cavity Imbalance .....                                              | 180        |
| 8.11.1   | Determining the Cause of Cavity Imbalances .....                                | 184        |
| 8.11.2   | Calculating Cavity Imbalance .....                                              | 184        |
| 8.11.3   | Acceptable Level of Cavity Imbalance .....                                      | 185        |
| 8.11.4   | Step 3: Determining the Pressure Drop –<br>Pressure Drop Studies .....          | 187        |
| 8.12     | Effect of Pressure Drop on the Pack and Hold Phase .....                        | 194        |
| 8.12.1   | Step 4: Determining the Cosmetic Process Window –<br>Process Window Study ..... | 195        |
| 8.13     | Relationship between Cavity Balance and Process Windows .....                   | 202        |
| 8.14     | The Pack and Hold Pressure Rule Not to Be Used .....                            | 202        |
| 8.14.1   | Step 5: Determining the Gate Seal Time – Gate Seal Study ....                   | 203        |
| 8.15     | Differentiating between the Pack and the Hold Phase .....                       | 206        |
| 8.16     | Hot Runner and Valve Gated Molds .....                                          | 210        |
| 8.16.1   | Step 6: Determining the Cooling Time – Cooling Time Study ..                    | 210        |
| 8.16.2   | Optimization of Screw Rotation Speed .....                                      | 213        |
| 8.16.3   | Why to Not Use the Rule of Thumb .....                                          | 214        |
| 8.17     | Optimization of Back Pressures .....                                            | 215        |
| 8.18     | The Cosmetic Scientific Process .....                                           | 216        |
| 8.18.1   | Post Mold Shrinkage Studies .....                                               | 216        |
| 8.18.2   | Procedure to Measure Shrinkage .....                                            | 219        |
| 8.19     | Recommended Mold Function Qualification Procedure .....                         | 220        |
| 8.20     | Recommended Adjustments to Maintain Process Consistency<br>and Robustness ..... | 221        |
| 8.21     | Process Documentation .....                                                     | 222        |
| 8.22     | References .....                                                                | 223        |
| <b>9</b> | <b>Process Development Part 2:</b>                                              |            |
|          | <b>Exploring the Dimensional Process via the DOE .....</b>                      | <b>225</b> |
| 9.1      | Parameters in Injection Molding .....                                           | 226        |
| 9.1.1    | Design of Experiments: Definition .....                                         | 228        |
| 9.2      | Terminology .....                                                               | 230        |
| 9.2.1    | Factor .....                                                                    | 230        |
| 9.2.2    | Response .....                                                                  | 231        |

|           |                                                                                        |            |
|-----------|----------------------------------------------------------------------------------------|------------|
| 9.2.3     | Level .....                                                                            | 231        |
| 9.2.4     | Designed Experiment .....                                                              | 231        |
| 9.3       | Relationships between the Number of Factors, Levels,<br>and Experiments .....          | 232        |
| 9.4       | Balanced Arrays .....                                                                  | 234        |
| 9.5       | Interactions .....                                                                     | 235        |
| 9.6       | Confounding or Aliasing .....                                                          | 238        |
| 9.7       | Randomization .....                                                                    | 240        |
| 9.8       | Factorial Experiments .....                                                            | 241        |
| 9.9       | Data Analysis .....                                                                    | 241        |
| 9.9.1     | Tornado Charts .....                                                                   | 243        |
| 9.9.2     | Contour Plots .....                                                                    | 244        |
| 9.9.3     | Prediction Equation .....                                                              | 245        |
| 9.9.4     | Process Sensitivity Charts .....                                                       | 246        |
| 9.10      | Using the Results from DOE .....                                                       | 247        |
| 9.10.1    | Process Selection .....                                                                | 247        |
| 9.10.2    | Cavity Steel Adjustment .....                                                          | 248        |
| 9.10.3    | Process Adjustment Tool .....                                                          | 249        |
| 9.10.4    | Setting Process Change Tolerances .....                                                | 249        |
| 9.10.5    | Reducing Inspection .....                                                              | 249        |
| 9.11      | The Dimensional Process Window (DPW) .....                                             | 250        |
| 9.12      | Selections of Factors for DOEs .....                                                   | 252        |
| 9.13      | Analysis of Variance (ANOVA) .....                                                     | 257        |
| 9.14      | Collecting Shots for a Quality Check .....                                             | 258        |
| 9.15      | Choosing the Highs and Lows for DOEs from the Process Window ....                      | 259        |
| 9.16      | DOE Application to Optimize Pack and Hold Times .....                                  | 260        |
| 9.17      | Setting Acceptable Machine Tolerances and Alarms during<br>Production .....            | 265        |
| 9.18      | Summary .....                                                                          | 266        |
| <b>10</b> | <b>Mold Qualification Flowchart, Production Release,<br/>and Troubleshooting .....</b> | <b>269</b> |
| 10.1      | Mold Qualification Flowchart .....                                                     | 269        |
| 10.1.1    | Mold Function Qualification Procedure .....                                            | 271        |
| 10.1.2    | Mold and Part Quality Qualification Procedure .....                                    | 271        |
| 10.2      | Mold Qualification Checklist .....                                                     | 271        |

|           |                                                                                    |            |
|-----------|------------------------------------------------------------------------------------|------------|
| 10.3      | Process Documentation .....                                                        | 272        |
| 10.3.1    | Process Sheet .....                                                                | 272        |
| 10.3.2    | Waterline Diagrams .....                                                           | 273        |
| 10.3.3    | Mold Temperature Maps .....                                                        | 274        |
| 10.3.4    | Setup Instructions .....                                                           | 275        |
| 10.3.5    | Operator Instructions .....                                                        | 275        |
| 10.4      | Documentation Books .....                                                          | 276        |
| 10.5      | Qualification Production Runs .....                                                | 277        |
| 10.6      | Mold Specific Troubleshooting Guide .....                                          | 277        |
| 10.7      | Molding Startup and Shutdown .....                                                 | 278        |
| 10.7.1    | Purging .....                                                                      | 278        |
| 10.7.2    | Startup of a Molding Machine .....                                                 | 279        |
| 10.7.3    | Shutdown of a Molding Machine .....                                                | 280        |
| 10.8      | Troubleshooting .....                                                              | 280        |
| 10.9      | Important Equipment and Tools for Qualifications and<br>Troubleshooting .....      | 283        |
| 10.10     | Common Defects, Their Causes, and Prevention .....                                 | 284        |
| 10.10.1   | Splay: What is it? How to get rid of it? .....                                     | 285        |
| 10.10.2   | Defects in Molding .....                                                           | 287        |
| <b>11</b> | <b>Role of Mold Cooling, Venting, and Regrind in Process<br/>Development .....</b> | <b>293</b> |
| 11.1      | Mold Cooling .....                                                                 | 293        |
| 11.1.1    | Number of Cooling Channels .....                                                   | 294        |
| 11.1.2    | Reynolds Number of the Coolant Flow .....                                          | 294        |
| 11.1.3    | Type of Coolant .....                                                              | 295        |
| 11.1.4    | Series and Parallel Cooling .....                                                  | 296        |
| 11.2      | Venting .....                                                                      | 297        |
| 11.2.1    | Dimensions of the Vent .....                                                       | 298        |
| 11.2.2    | Primary Vent Depths .....                                                          | 299        |
| 11.2.3    | Location of Vents .....                                                            | 302        |
| 11.2.4    | Forced Venting or Vacuum Venting .....                                             | 304        |
| 11.3      | Regrind .....                                                                      | 305        |
| 11.3.1    | Effect of the Molding Process on the Part Properties .....                         | 305        |
| 11.3.2    | Using Regrind .....                                                                | 307        |
| 11.3.3    | Batch and Continuous Processes of Incorporating Regrind ....                       | 307        |
| 11.3.4    | Estimating the Amount of Regrind from<br>Different Generations .....               | 308        |



|                   |                                                                               |            |
|-------------------|-------------------------------------------------------------------------------|------------|
| 11.3.5            | Effect of Regrind on Processing .....                                         | 311        |
| 11.3.6            | Closing Remarks .....                                                         | 311        |
| <b>12</b>         | <b>Related Technologies and Topics .....</b>                                  | <b>313</b> |
| 12.1              | Cavity Pressure Sensing Technology .....                                      | 313        |
| 12.1.1            | Sensors and Output graphs .....                                               | 314        |
| 12.1.2            | Types and Classification of Pressure Sensors .....                            | 315        |
| 12.1.3            | Use of Information from the Pressure Graphs .....                             | 317        |
| 12.1.4            | Controlling the Process with Cavity Pressure Sensors .....                    | 319        |
| 12.1.5            | Sensor Locations .....                                                        | 321        |
| 12.2              | Building a Knowledge Base .....                                               | 322        |
| 12.3              | Concurrent Engineering in Injection Molding .....                             | 324        |
| 12.3.1            | The Product Designer .....                                                    | 326        |
| 12.3.2            | The Tooling Engineer .....                                                    | 326        |
| 12.3.3            | The Mold Designer and Mold Maker .....                                        | 327        |
| 12.3.4            | The Material Supplier .....                                                   | 327        |
| 12.3.5            | The Process Engineer .....                                                    | 328        |
| 12.3.6            | The Quality Engineer .....                                                    | 329        |
| 12.3.7            | The Sales Team at the Molder .....                                            | 329        |
| 12.3.8            | Mandatory for All Departments .....                                           | 330        |
| 12.3.9            | Implementing Concurrent Engineering .....                                     | 330        |
| <b>13</b>         | <b>Quality Concepts .....</b>                                                 | <b>333</b> |
| 13.1              | Basic Concepts .....                                                          | 333        |
| 13.2              | Histogram .....                                                               | 334        |
| 13.3              | Normal Distribution .....                                                     | 335        |
| 13.4              | Standard Deviation .....                                                      | 336        |
| 13.5              | Specification Limits and Standard Deviation .....                             | 337        |
| 13.6              | Capability Index .....                                                        | 339        |
| 13.7              | Process Capability .....                                                      | 340        |
| 13.8              | Statistical Quality Control (SQC) and Statistical Process Control (SPC) ..... | 342        |
| 13.9              | References .....                                                              | 342        |
| <b>Appendix A</b> | <b>Materials Data Sheet .....</b>                                             | <b>343</b> |
| <b>Appendix B</b> | <b>Conversion Tables for Commonly Used<br/>Process Parameters .....</b>       | <b>349</b> |

|                   |                                                                       |            |
|-------------------|-----------------------------------------------------------------------|------------|
| <b>Appendix C</b> | <b>Water Flow Tables .....</b>                                        | <b>351</b> |
| <b>Appendix D</b> | <b>Part Design Checklist .....</b>                                    | <b>353</b> |
| <b>Appendix E</b> | <b>Mold Design Checklist .....</b>                                    | <b>355</b> |
| <b>Appendix F</b> | <b>Mold Qualification Checklist .....</b>                             | <b>357</b> |
| <b>Appendix G</b> | <b>Regrind Tables – Percentage of Regrind<br/>in Total Shot .....</b> | <b>359</b> |
| <b>Index</b>      | <b>.....</b>                                                          | <b>361</b> |