

Sample Pages

David O. Kazmer

Injection Mold Design Engineering

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# Contents

<b>Preface to the 2<sup>nd</sup> Edition</b> .....	<b>V</b>
Preface to the 1 <sup>st</sup> Edition .....	VIII
<b>Nomenclature</b> .....	<b>XV</b>
<b>1 Introduction</b> .....	<b>1</b>
1.1 Overview of the Injection Molding Process .....	1
1.2 Mold Functions .....	4
1.3 Mold Structures .....	6
1.3.1 External View of Mold .....	6
1.3.2 View of Mold during Part Ejection .....	8
1.3.3 Mold Cross-Section and Function .....	9
1.4 Other Common Mold Types .....	11
1.4.1 Three-Plate, Multicavity Family Mold .....	12
1.4.2 Hot Runner, Multigated, Single Cavity Mold .....	14
1.4.3 Comparison .....	15
1.5 The Mold Development Process .....	16
1.6 Mold Standards .....	18
1.7 Chapter Review .....	20
1.8 References .....	20
<b>2 Plastic Part Design</b> .....	<b>21</b>
2.1 The Product Development Process .....	21
2.1.1 Product Definition .....	22
2.1.2 Product Design .....	23
2.1.3 Development .....	23
2.1.4 Scale-Up and Launch .....	24
2.1.5 Role of Mold Design .....	24

2.2	Design Requirements .....	25
2.2.1	Application Engineering Information .....	26
2.2.2	Production Planning .....	27
2.2.3	End-Use Requirements .....	28
2.2.4	Design for Manufacturing and Assembly .....	30
2.2.5	Plastic Material Properties .....	30
2.3	Design for Injection Molding .....	31
2.3.1	Uniform Wall Thickness .....	31
2.3.2	Rib Design .....	33
2.3.3	Boss Design .....	34
2.3.4	Corner Design .....	34
2.3.5	Surface Finish and Textures .....	36
2.3.6	Draft .....	38
2.3.7	Undercuts .....	39
2.4	Chapter Review .....	41
2.5	References .....	42
<b>3</b>	<b>Mold Cost Estimation .....</b>	<b>43</b>
3.1	The Mold Quoting Process .....	43
3.2	Cost Overview for Molded Parts .....	45
3.2.1	Mold Cost per Part .....	47
3.2.2	Material Cost per Part .....	48
3.2.3	Processing Cost per Part .....	49
3.2.4	Defect Cost per Part .....	52
3.3	Mold Cost Estimation .....	53
3.3.1	Mold Base Cost Estimation .....	54
3.3.2	Cavity Cost Estimation .....	55
3.3.2.1	Cavity Set Cost .....	56
3.3.2.2	Cavity Materials Cost .....	56
3.3.2.3	Cavity Machining Cost .....	58
3.3.2.4	Cavity Discount Factor .....	62
3.3.2.5	Cavity Finishing Cost .....	63
3.3.3	Mold Customization .....	64
3.4	Manufacturing Strategy .....	69
3.4.1	Breakeven Analysis .....	69
3.4.2	Prototyping Strategy .....	72
3.5	Chapter Review .....	76
3.6	References .....	77

<b>4</b>	<b>Mold Layout Design</b>	<b>79</b>
4.1	Parting Plane Design	79
4.1.1	Determine Mold Opening Direction	80
4.1.2	Determine Parting Line	83
4.1.3	Parting Plane	84
4.1.4	Shut-Offs	86
4.2	Cavity and Core Insert Creation	87
4.2.1	Height Dimension	87
4.2.2	Length and Width Dimensions	88
4.2.3	Adjustments	89
4.3	Mold Base Selection	91
4.3.1	Cavity Layouts	91
4.3.2	Mold Base Sizing	93
4.3.3	Molding Machine Compatibility	95
4.3.4	Mold Base Suppliers	97
4.4	Material Selection	98
4.4.1	Strength vs. Heat Transfer	100
4.4.2	Hardness vs. Machinability	101
4.4.3	Material Summary	102
4.4.4	Surface Treatments	103
4.5	Chapter Review	105
4.6	References	107
<b>5</b>	<b>Cavity Filling Analysis and Design</b>	<b>109</b>
5.1	Overview	109
5.2	Objectives in Cavity Filling	110
5.2.1	Complete Filling of Mold Cavities	110
5.2.2	Avoid Uneven Filling or Over-Packing	111
5.2.3	Control the Melt Flow	112
5.3	Viscous Flow	112
5.3.1	Shear Stress, Shear Rate, and Viscosity	112
5.3.2	Pressure Drop	113
5.3.3	Rheological Behavior	115
5.3.4	Newtonian Model	117
5.3.5	Power Law Model	119
5.4	Process Simulation	121
5.5	Cavity Filling Analyses and Designs	124
5.5.1	Estimating the Processing Conditions	124
5.5.2	Estimating the Filling Pressure and Minimum Wall Thickness	127

5.5.3	Estimating Clamp Tonnage .....	130
5.5.4	Predicting Filling Patterns .....	133
5.5.5	Designing Flow Leaders .....	135
5.6	Chapter Review .....	138
5.7	References .....	139
<b>6</b>	<b>Feed System Design .....</b>	<b>141</b>
6.1	Overview .....	141
6.2	Objectives in Feed System Design .....	141
6.2.1	Conveying the Polymer Melt from Machine to Cavities .....	141
6.2.2	Impose Minimal Pressure Drop .....	142
6.2.3	Consume Minimal Material .....	143
6.2.4	Control Flow Rates .....	145
6.3	Feed System Types .....	145
6.3.1	Two-Plate Mold .....	146
6.3.2	Three-Plate Mold .....	148
6.3.3	Hot Runner Molds .....	153
6.4	Feed System Analysis .....	156
6.4.1	Determine Type of Feed System .....	158
6.4.2	Determine Feed System Layout .....	159
6.4.3	Estimate Pressure Drops .....	163
6.4.4	Calculate Runner Volume .....	165
6.4.5	Optimize Runner Diameters .....	166
6.4.6	Balance Flow Rates .....	170
6.4.7	Estimate Runner Cooling Times .....	173
6.4.8	Estimate Residence Time .....	175
6.5	Practical Issues .....	176
6.5.1	Runner Cross-Sections .....	176
6.5.2	Sucker Pins .....	180
6.5.3	Runner Shut-Offs .....	182
6.5.4	Standard Runner Sizes .....	183
6.5.5	Steel Safe Designs .....	184
6.6	Advanced Feed Systems .....	185
6.6.1	Insulated Runner .....	185
6.6.2	Stack Molds .....	186
6.6.3	Branched Runners .....	188
6.6.4	Dynamic Melt Control .....	190
6.7	Chapter Review .....	192
6.8	References .....	194

<b>7 Gating Design</b> .....	<b>197</b>
7.1 Objectives of Gating Design .....	197
7.1.1 Connecting the Runner to the Mold Cavity .....	197
7.1.2 Provide Automatic De-gating .....	197
7.1.3 Maintain Part Aesthetics .....	198
7.1.4 Avoid Excessive Shear or Pressure Drop .....	198
7.1.5 Control Pack Times .....	199
7.2 Common Gate Designs .....	200
7.2.1 Sprue Gate .....	200
7.2.2 Pin-Point Gate .....	201
7.2.3 Edge Gate .....	202
7.2.4 Tab Gate .....	203
7.2.5 Fan Gate .....	204
7.2.6 Flash/Diaphragm Gate .....	205
7.2.7 Tunnel/Submarine Gate .....	206
7.2.8 Thermal Gate .....	209
7.2.9 Valve Gate .....	212
7.3 The Gating Design Process .....	213
7.3.1 Determine Gate Location(s) .....	213
7.3.2 Determine Type of Gate .....	215
7.3.3 Calculate Shear Rates .....	217
7.3.4 Calculate Pressure Drop .....	219
7.3.5 Calculate Gate Freeze Time .....	221
7.3.6 Adjust Dimensions .....	224
7.4 Chapter Review .....	225
7.5 References .....	226
<b>8 Venting</b> .....	<b>227</b>
8.1 Venting Design Objectives .....	227
8.1.1 Release Compressed Air .....	227
8.1.2 Contain Plastic Melt .....	228
8.1.3 Minimize Maintenance .....	228
8.2 Venting Analysis .....	228
8.2.1 Estimate Air Displacement and Rate .....	228
8.2.2 Identify Number and Location of Vents .....	229
8.2.3 Specify Vent Dimensions .....	232
8.3 Venting Designs .....	236
8.3.1 Vents on Parting Plane .....	236
8.3.2 Vents around Ejector Pins .....	238
8.3.3 Vents in Dead Pockets .....	239

8.4	Chapter Review .....	241
8.5	References .....	242
<b>9</b>	<b>Cooling System Design .....</b>	<b>243</b>
9.1	Objectives in Cooling System Design .....	243
9.1.1	Maximize Heat Transfer Rates .....	243
9.1.2	Maintain Uniform Wall Temperature .....	244
9.1.3	Minimize Mold Cost .....	244
9.1.4	Minimize Volume and Complexity .....	245
9.1.5	Maximize Reliability .....	245
9.1.6	Facilitate Mold Usage .....	245
9.2	The Cooling System Design Process .....	246
9.2.1	Calculate the Required Cooling Time .....	246
9.2.2	Evaluate Required Heat Transfer Rate .....	252
9.2.3	Assess Coolant Flow Rate .....	253
9.2.4	Assess Cooling Line Diameter .....	254
9.2.5	Select Cooling Line Depth .....	257
9.2.6	Select Cooling Line Pitch .....	260
9.2.7	Cooling Line Routing .....	262
9.3	Cooling System Designs .....	266
9.3.1	Cooling Line Networks .....	266
9.3.2	Cooling Inserts .....	269
9.3.3	Conformal Cooling .....	269
9.3.4	Highly Conductive Inserts .....	270
9.3.5	Cooling of Slender Cores .....	272
9.3.5.1	Cooling Insert .....	273
9.3.5.2	Baffles .....	274
9.3.5.3	Bubblers .....	275
9.3.5.4	Heat Pipes .....	275
9.3.5.5	Conductive Pin .....	276
9.3.5.6	Interlocking Core with Air Channel .....	277
9.3.6	One-Sided Heat Flow .....	278
9.4	Mold Wall Temperature Control .....	281
9.4.1	Pulsed Cooling .....	281
9.4.2	Conduction Heating .....	284
9.4.3	Induction Heating .....	285
9.4.4	Managed Heat Transfer .....	286
9.5	Chapter Review .....	288
9.6	References .....	289

<b>10 Shrinkage and Warpage</b> .....	<b>291</b>
10.1 The Shrinkage Analysis Process .....	293
10.1.1 Estimate Process Conditions .....	294
10.1.2 Model Compressibility Behavior .....	294
10.1.3 Assess Volumetric Shrinkage .....	297
10.1.4 Evaluate Isotropic Linear Shrinkage .....	300
10.1.5 Evaluate Anisotropic Shrinkage .....	301
10.1.6 Numerical Simulation .....	303
10.1.7 Shrinkage Analysis Validation .....	306
10.2 Shrinkage Design Practices .....	310
10.2.1 “Steel Safe” Mold Design .....	310
10.2.2 Processing Dependence .....	311
10.2.3 Semicrystalline Plastics .....	313
10.2.4 Effect of Fillers .....	314
10.2.5 Shrinkage Range Estimation .....	314
10.2.6 Final Shrinkage Recommendations .....	315
10.3 Warpage .....	317
10.3.1 Sources of Warpage .....	318
10.3.2 Warpage Avoidance Strategies .....	323
10.4 Chapter Review .....	324
10.5 References .....	324
<b>11 Ejection System Design</b> .....	<b>327</b>
11.1 Objectives in Ejection System Design .....	330
11.1.1 Allow Mold to Open .....	330
11.1.2 Transmit Ejection Forces to Moldings .....	330
11.1.3 Minimize Distortion of Moldings .....	331
11.1.4 Maximize Ejection Speed .....	331
11.1.5 Minimize Cooling Interference .....	332
11.1.6 Minimize Impact on Part Surfaces .....	332
11.1.7 Minimize Complexity and Cost .....	333
11.2 The Ejector System Design Process .....	333
11.2.1 Identify Mold Parting Surfaces .....	334
11.2.2 Estimate Ejection Forces .....	334
11.2.3 Determine Ejector Push Area and Perimeter .....	340
11.2.4 Specify Type, Number, and Size of Ejectors .....	343
11.2.5 Layout Ejectors .....	345
11.2.6 Detail Ejectors and Related Components .....	348
11.3 Ejector System Analyses and Designs .....	350
11.3.1 Ejector Pins .....	350



11.3.2	Ejector Blades .....	353
11.3.3	Ejector Sleeves .....	355
11.3.4	Stripper Plates .....	356
11.3.5	Elastic Deformation around Undercuts .....	359
11.3.6	Core Pulls .....	361
11.3.7	Slides .....	366
11.3.8	Early Ejector Return Systems .....	369
11.4	Advanced Ejection Systems .....	371
11.4.1	Split Cavity Molds .....	371
11.4.2	Collapsible Cores .....	373
11.4.3	Rotating Cores .....	375
11.4.4	Reverse Ejection .....	377
11.5	Chapter Review .....	378
11.6	References .....	380
<b>12</b>	<b>Structural System Design .....</b>	<b>381</b>
12.1	Objectives in Structural System Design .....	382
12.1.1	Minimize Stress .....	382
12.1.2	Minimize Mold Deflection .....	387
12.1.3	Minimize Mold Size .....	388
12.2	Analysis and Design of Plates .....	388
12.2.1	Plate Compression .....	389
12.2.2	Plate Bending .....	392
12.2.3	Support Pillars .....	395
12.2.4	Shear Stress in Side Walls .....	402
12.2.5	Interlocks .....	404
12.2.6	Stress Concentrations .....	407
12.3	Analysis and Design of Cores .....	410
12.3.1	Axial Compression .....	410
12.3.2	Compressive Hoop Stresses .....	412
12.3.3	Core Deflection .....	414
12.4	Fasteners .....	417
12.4.1	Fits .....	417
12.4.2	Socket Head Cap Screws .....	422
12.4.3	Dowels .....	424
12.5	Review .....	426
12.6	References .....	428

<b>13 Mold Technologies</b> .....	<b>429</b>
13.1 Introduction .....	429
13.2 Coinjection Molds .....	431
13.2.1 Coinjection Process .....	431
13.2.2 Coinjection Mold Design .....	433
13.3 Gas Assist/Water Assist Molding .....	434
13.4 Insert Molds .....	437
13.4.1 Low Pressure Compression Molding .....	437
13.4.2 Insert Mold with Wall Temperature Control .....	439
13.4.3 Lost Core Molding .....	441
13.5 Injection Blow Molds .....	443
13.5.1 Injection Blow Molding .....	443
13.5.2 Multilayer Injection Blow Molding .....	445
13.6 Multishot Molds .....	447
13.6.1 Overmolding .....	447
13.6.2 Core-Back Molding .....	449
13.6.3 Multi-station Mold .....	451
13.7 In-Mold Labeling .....	453
13.7.1 Statically Charged Film .....	454
13.7.2 Indexed Film .....	455
13.8 Review .....	456
13.9 References .....	457
<b>14 Mold Commissioning</b> .....	<b>459</b>
14.1 Mold Commissioning Objectives .....	459
14.1.1 Certify Mold Acceptability .....	459
14.1.2 Optimize Molding Process and Quality .....	461
14.1.3 Develop Mold Operation and Maintenance Plans .....	461
14.2 Commissioning Process .....	462
14.2.1 Mold Design Checklist .....	465
14.2.2 Component Verification .....	465
14.2.3 Mold Assembly .....	466
14.2.4 Mold Final Test .....	466
14.2.5 Preliminary Molding Recommendations .....	467
14.3 Molding Trials .....	470
14.3.1 Filling Stage .....	471
14.3.2 Packing Stage .....	473
14.3.3 Cooling Stage .....	475

14.4	Production Part Approval .....	476
14.4.1	Quality Assurance .....	476
14.4.2	Gauge and Process Repeatability & Reproducibility .....	477
14.4.3	Image-Based Dimensional Metrology .....	479
14.4.4	Process Capability Evaluation .....	481
14.5	Mold Maintenance .....	485
14.5.1	Pre-Molding Maintenance .....	487
14.5.2	Molding Observation and Mold Map .....	488
14.5.3	Post-Molding Maintenance .....	489
14.5.4	Scheduled Regular Maintenance .....	489
14.5.5	Mold Rebuilding .....	490
14.6	Summary .....	491
14.7	References .....	493
	<b>Appendix</b> .....	495
	Appendix A: Plastic Material Properties .....	497
	Appendix B: Mold Material Properties .....	502
	B.1 Nonferrous Metals .....	502
	B.2 Common Mold Steels .....	503
	B.3 Other Mold Steels .....	504
	Appendix C: Properties of Coolants .....	505
	Appendix D: Statistical Labor Data .....	506
	D.1 United States Occupational Labor Rates .....	506
	D.2 International Labor Rate Comparison .....	506
	Appendix E: Unit Conversions .....	508
	E.1 Length Conversions .....	508
	E.2 Mass/Force Conversions .....	509
	E.3 Pressure Conversions .....	509
	E.4 Flow Rate Conversions .....	509
	E.5 Viscosity Conversions .....	510
	E.6 Energy Conversions .....	510
	Appendix F: Estimation of Melt Velocity .....	511
	<b>The Author</b> .....	515
	<b>Index</b> .....	517

# Preface to the 2<sup>nd</sup> Edition

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Since the publication of the 1<sup>st</sup> edition, three major trends have continued with respect to plastic product and mold design:

- First, supply-chains are tightly integrated, with rapid flow of information between the product designers, molders, and mold designers. The landscape remains highly competitive, with firms differentiated by technical capability and efficiency.
- Second, advanced manufacturing is broadly recognized as a societal strategy for improving economic growth and human well-being. Of particular note is the broad interest in rapid prototyping processes (and 3D printing in particular) for supplying mold components and even low volume production of plastic parts.
- Third, the plastics industry is under increasing public pressure to minimize environmental impact. Designers of plastic products and their molds should strive to reduce, reuse, and recycle the resources that we are so fortunate to have.

The second edition has been extensively revised while reflecting on these trends. The intent has remained to provide a practical yet reasoned engineering approach. I continue to hope that *Injection Mold Design Engineering* is accessible and useful to all who read it. I welcome your ongoing feedback and future cooperation.

Best wishes,

*David Kazmer*, P.E., Ph. D.

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Department of Plastics Engineering  
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March 2016

## ■ Preface to the 1<sup>st</sup> Edition

Mold design has been more of a technical trade than an engineering process. Traditionally, practitioners have shared standard practices and learned tricks of the trade to develop sophisticated molds that often exceed customer expectations.

However, the lack of fundamental engineering analysis during mold design frequently results in molds that may fail and require extensive rework, produce moldings of inferior quality, or are less cost effective than may have been possible. Indeed, it has been estimated that on average 49 out of 50 molds require some modifications during the mold start-up process. Many times, mold designers and end-users may not know how much money was “left on the table.”

The word “engineering” in the title of this book implies a methodical and analytical approach to mold design. The engineer who understands the causality between design decisions and mold performance has the ability to make better and more informed decisions on an application by application basis. Such decision making competence is a competitive enabler by supporting the development of custom mold designs that outperform molds developed according to standard practices. The proficient engineer also avoids the cost and time needed to delegate decision to other parties, who are not necessarily more competent.

The book has been written as a teaching text, but is geared towards professionals working in a tightly integrated supply chain including product designers, mold designers, and injection molders. Compared to most handbooks, this textbook provides worked examples with rigorous analysis and detailed discussion of vital mold engineering concepts. It should be understood that this textbook purposefully investigates the prevalent and fundamental aspects of injection mold engineering.

I hope that *Injection Mold Design Engineering* is accessible and useful to all who read it. I welcome your feedback and partnership for future improvements.

Best wishes,

*David Kazmer, P.E., Ph. D.*

Lowell, Massachusetts

June 1, 2007

# 1

## Introduction

Injection molding is a common method for mass production and is often preferred over other processes, given its capability to economically make complex parts to tight tolerances. Before any parts can be molded, however, a suitable injection mold must be designed, manufactured, and commissioned.

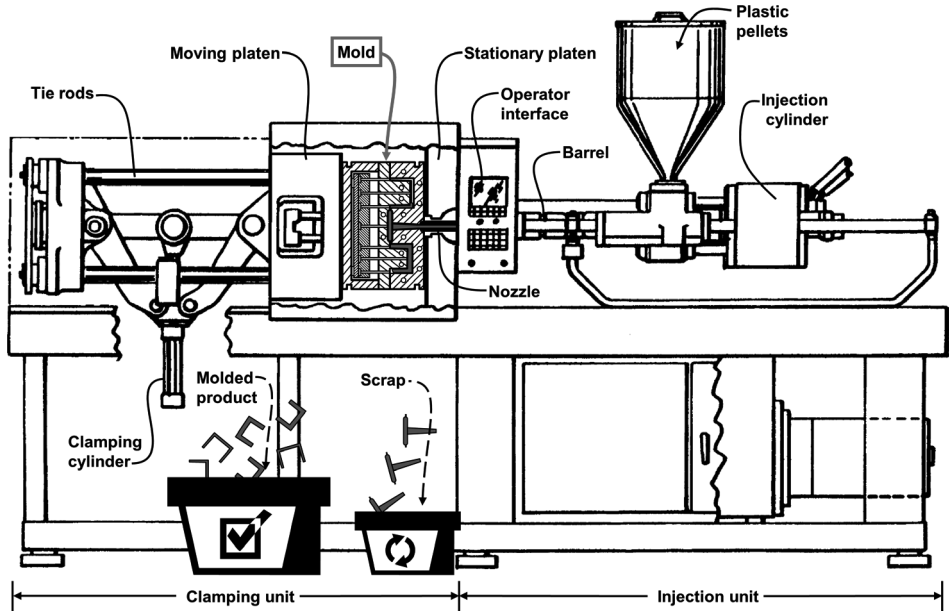
The mold design directly determines the molded part quality and molding productivity. The injection mold is itself a complex system comprised of multiple components that are subjected to many cycles of temperature and stress. There are often trade-offs in mold design, with lower-cost molds sometimes resulting in lower product quality or inefficient molding processes. Engineers should strive to design injection molds that are “fit for purpose”, which means that the mold should produce parts of acceptable quality with minimal life cycle cost while taking a minimum amount of time, money, and risk to develop.

This book is directed to assist novice and expert designers of both products and molds. In this chapter, an overview of the injection molding process and various types of molds is provided so that the mold design engineer can understand the basic operation of injection molds. Next, the layout and components in three of the more common mold designs are presented. The suggested methodology for mold engineering design is then presented, which provides the structure for the remainder of this book.

### ■ 1.1 Overview of the Injection Molding Process

Injection molding is sometimes referred to as a “net shape” manufacturing process because the molded parts emerge from the molding process in their final form with no or minimal post-processing required to further shape the product. An operating injection molding machine is depicted in Fig. 1.1. The mold is inserted and clamped between a stationary and moving platen. The mold typically is con-

nected to and moves with the machine platens, so that the molded parts are formed within a closed mold, after which the mold is opened so that the molded parts can be removed.



**Figure 1.1** Depiction of an injection molding machine and mold, adapted from [1]

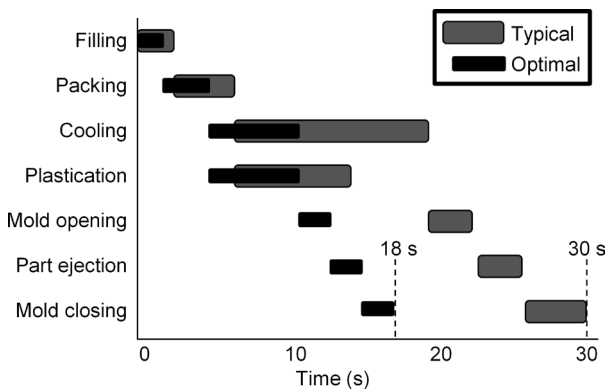
The mold cavity is the “heart” of the mold where the polymer is injected and solidified to produce the molded part(s) with each molding cycle. While molding processes can differ substantially in design and operation, most injection molding processes generally include plastication, injection, packing, cooling, and ejection stages. During the plastication stage, a screw within the barrel rotates to convey plastic pellets and form a “shot” of polymer melt. The polymer melt is plasticized from solid granules or pellets through the combined effect of heat conduction from the heated barrel as well as the internal viscous heating caused by molecular deformation as the polymer is forced along the screw flights. Afterwards, during the filling stage, the plasticated shot of polymer melt is forced from the barrel of the molding machine through the nozzle and into the mold. The molten resin travels down a feed system, through one or more gates, and throughout one or more mold cavities where it forms the molded product(s).

After the mold cavity is filled with the polymer melt, the packing stage provides additional material into the mold cavity as the molten plastic melt cools and contracts. The plastic’s volumetric shrinkage varies with the material properties and application requirements, but the molding machine typically forces 1 to 10% addi-

tional melt into the mold cavity during the packing stage. After the polymer melt ceases to flow, the cooling stage provides additional time for the resin in the cavity to solidify and become sufficiently rigid for ejection. Then, the molding machine actuates the moving platen and the attached moving side of the mold to provide access to the mold cavities. The mold typically contains an ejection system with moving slides and pins that are then actuated to remove the molded part(s) prior to mold closure and the start of the next molding cycle.

A chart plotting the timing of each stage of the molding process is shown in Fig. 1.2 for a molded part approximately 2 mm thick having a cycle time of 30 s. The filling time is a small part of the cycle and so is often selected to minimize the injection pressure and molded-in stresses. The packing time is of moderate duration, and is often minimized through a shot weight stability study to end with freeze-off of the polymer melt in the gate. In general, the cooling stage of the molding process dominates the cycle time since the rate of heat flow from the polymer melt to the cooler mold is limited by the low thermal diffusivity of the plastic melt. However, the plastication time may exceed the cooling time for very large shot volumes with low plastication rates. The mold reset time is also very important to minimize since it provides negligible added value to the molded product.

To minimize the molding cycle time and costs, molders strive to operate fully automatic processes with minimum mold opening and ejector strokes. The operation of fully automatic molding processes requires careful mold design, making, and commissioning. Not only must the mold operate without any hang-ups, but the quality of the molded parts must consistently meet specification.



**Figure 1.2** Injection molding process timings

Figure 1.2 also shows the possible cycle timings for a more advanced mold design using additional investment in technology. Hot runner feed systems, for example, allow the use of less plastic material while also reducing injection and pack times.



Conformal cooling and highly conductive mold inserts can significantly reduce cooling times. Molds and molding processes can also be optimized to minimize mold opening, part ejection, and mold closing times. The net result of additional engineering is a reduction in the cycle time from 30 to 18 s. While some cycle time improvements are often possible just through careful engineering design, many productivity improvements require additional upfront investment in mold materials, components, or processing.

There are also many variants of the injection molding process (such as gas assist molding, water assist molding, insert molding, two shot molding, coinjection molding, injection compression molding, and others discussed later) that can be used to provide significant product differentiation or cost advantages. These more advanced processes can greatly increase the quality of the molded parts but at the same time can increase the complexity and risk of the mold design and molding processes while also limiting the number of qualified suppliers. As such, the product design and mold design should be conducted concurrently while explicitly addressing manufacturing strategy and supply chain considerations. The cost of advanced mold designs must be justified either by net cost savings or increases in the customer's willingness to pay for advanced product designs. Cost estimation thus serves an important role in developing appropriate manufacturing strategies and mold designs.

## ■ 1.2 Mold Functions

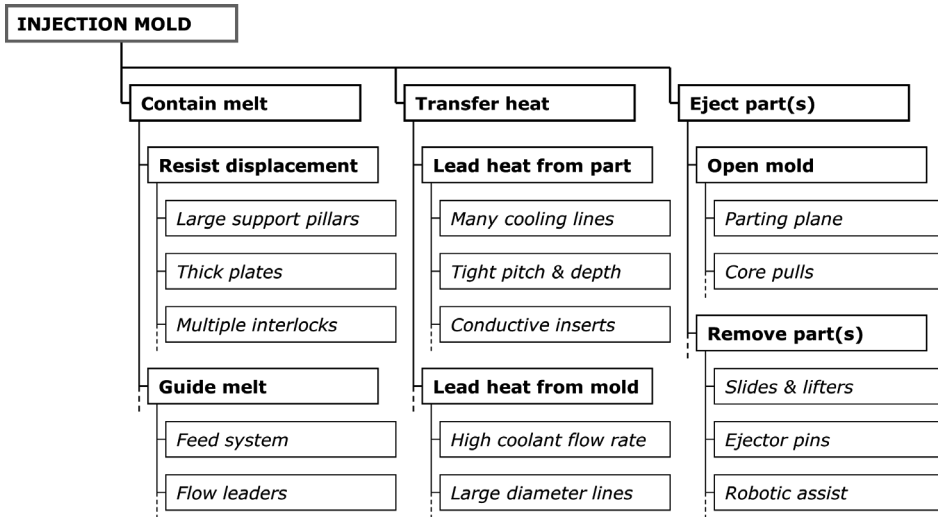
The injection mold is a complex system that must simultaneously meet many demands imposed by the injection molding process. The primary function of the mold is to contain the polymer melt within the mold cavity so that the mold cavity can be completely filled to form a plastic component whose shape replicates the mold cavity. A second primary function of the mold is to efficiently transfer heat from the hot polymer melt to the coolant flowing through the mold, such that injection molded products may be produced as uniformly and rapidly as possible. A third primary function of the mold is to eject the part from the mold in an efficient and consistent manner without imparting excessive stress to the moldings.

These three primary functions—contain the melt, transfer the heat, and eject the molded part(s)—also place secondary requirements on the injection mold. Figure 1.3 provides a partial hierarchy of the functions of an injection mold. For example, the function of containing the melt within the mold requires that the mold:

- *resist displacement* under the enormous forces that will tend to cause the mold to open or deflect. Excessive displacement can directly affect the dimensions of the

moldings or allow the formation of flash around the parting line of the moldings. This function is typically achieved through the use of rigid plates, support pillars, and interlocking components.

- *guide the polymer melt* from the nozzle of the molding machine to one or more cavities in the mold where the product is formed. This function is typically fulfilled through the use of a feed system and flow leaders within the cavity itself to ensure laminar and balanced flow.



**Figure 1.3** Function hierarchy for injection molds

It should be understood that Fig. 1.3 does not provide a comprehensive list of all functions of an injection mold, but just some of the essential primary and secondary functions that must be considered during the engineering design of injection molds. Even so, a skilled designer might recognize that conflicting requirements are placed on the mold design by various functions. For instance, the desire for efficient cooling may be satisfied by the use of multiple tightly spaced cooling lines that conform to the mold cavity. However, the need for part removal may require the use of multiple ejector pins at locations that conflict with the desired cooling line placement. It is up to the mold designer to consider the relative importance of the conflicting requirements and ultimately deliver a mold design that is satisfactory.

There are significant compromises and potential risks associated with mold design. In general, smaller and simpler molds may be preferred since they use less material and are easier to operate and maintain. Conversely, it is possible to under-design molds such that they may deflect under load, wear or fail prematurely, or require extended cycle times to operate. Because the potential costs of failure are

often greater than the added cost to ensure a robust design, there is a tendency to over-design with the use of conservative estimates and safety factors when in doubt. Excessive over-designing should be avoided since it can lead to large, costly, and inefficient molds.

## ■ 1.3 Mold Structures

An injection mold has many structures to accomplish the functions required by the injection molding process. Since there are many different types of molds, the structure of a simple “two-plate” mold is first discussed. It is important for the mold designer to know the names and functions of the mold components, since later chapters will assume this knowledge.

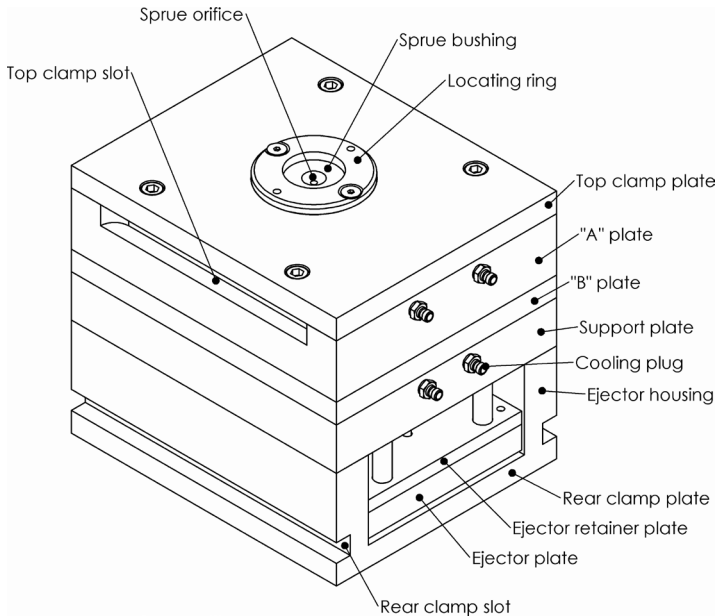
The design of these components and more complex molds will be analyzed and designed in subsequent chapters.

### 1.3.1 External View of Mold

An isometric view of a two-plate mold is provided in Fig. 1.4. From this view, it is observed that a mold is constructed of a number of plates bolted together with socket head cap screws. These plates commonly include the top clamp plate, the cavity insert retainer plate or “A” plate, the core insert retainer plate or “B” plate, a support plate, and a rear clamp plate or ejector housing. Some mold components are referred to with multiple names. For instance, the “A” plate is sometimes referred to as the cavity insert retainer plate, since this plate retains the cavity inserts. As another example, the ejector housing is also sometimes referred to as the rear clamp plate, since it clamps to the moving platen located towards the rear of the molding machine. In some mold designs, the ejector housing is replaced with a separable rear clamp plate of uniform thickness and two parallel ejector “rails” that replace the side walls of the integral “U”-shaped ejector housing. This alternative rear clamp plate design requires more components and mold-making steps, but can provide material cost savings as well as mold design flexibility.

The mold depicted in Fig. 1.4 is referred to as a “two-plate mold” since it uses only two plates to contain the polymer melt. Mold designs may vary significantly while performing the same functions. For example, some mold designs integrate the “B” plate and the support plate into one extra-thick plate, while other mold designs may integrate the “A” plate and the top clamp plate. As previously mentioned, some mold designs may split up the ejector housing, which has a “U”-shaped profile to house the ejection mechanism and clamping slots, into a rear clamp plate and tall

rails (also known as risers). The use of an integrated ejector housing as shown in Fig. 1.4 provides for a compact mold design, while the use of separate rear clamp plate and rails provides for greater design flexibility.



**Figure 1.4** View of a closed two-plate mold

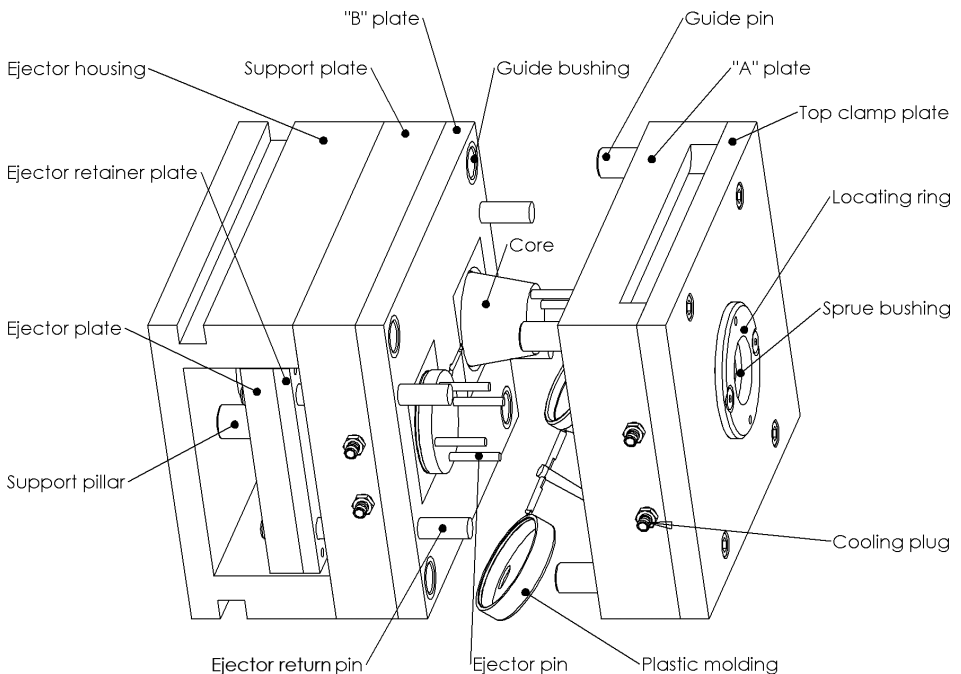
To hold the mold in the injection molding machine, toe clamps are inserted in slots adjacent to the top and rear clamp plates and subsequently bolted to the stationary and moving platens of the molding machine. A locating ring, usually found at the center of the mold, closely mates with an opening in the molding machine's stationary platen to align the inlet of the mold to the molding machine's nozzle. The opening in the molding machine's stationary platen can be viewed in Fig. 1.1 around the molding machine's nozzle. The use of the locating ring is necessary for at least two reasons. First, the inlet of the melt to the mold at the mold's sprue bushing must mate with the outlet of the melt from the nozzle of the molding machine. Second, the ejector knockout bar(s) actuated from behind the moving platen of the molding machine must mate with the ejector system of the mold. Molding machine and mold suppliers have developed standard locating ring specifications to facilitate mold-to-machine compatibility, with the most common locating ring diameter being 100 mm (4 in).

When the molding machine's moving platen is actuated, all plates attached to the rear clamp plates will be similarly actuated and cause the mold to separate at the parting plane. When the mold is closed, guide pins and bushings are used to

closely locate the “A” and the “B” plates on separate sides of the parting plane, which is crucial to the primary mold function of containing the melt. Improper design or construction of the mold components may cause misalignment of the “A” and “B” plates, poor quality of the molded parts, and accelerated wear of the injection mold.

### 1.3.2 View of Mold during Part Ejection

Another isometric view of the mold is shown in Fig. 1.5, oriented horizontally for operation with a horizontal injection molding machine. In this depiction, the plastic melt has been injected and cooled in the mold, such that the moldings are now ready for ejection. To perform ejection, the mold is opened by at least the height of the moldings. Then, the ejector plate and associated pins are moved forward to push the moldings off the core. From this view, many of the mold components are observed, including the “B” or core insert retainer plate, two different core inserts, feed system, ejector pins, and guide pins and bushings.



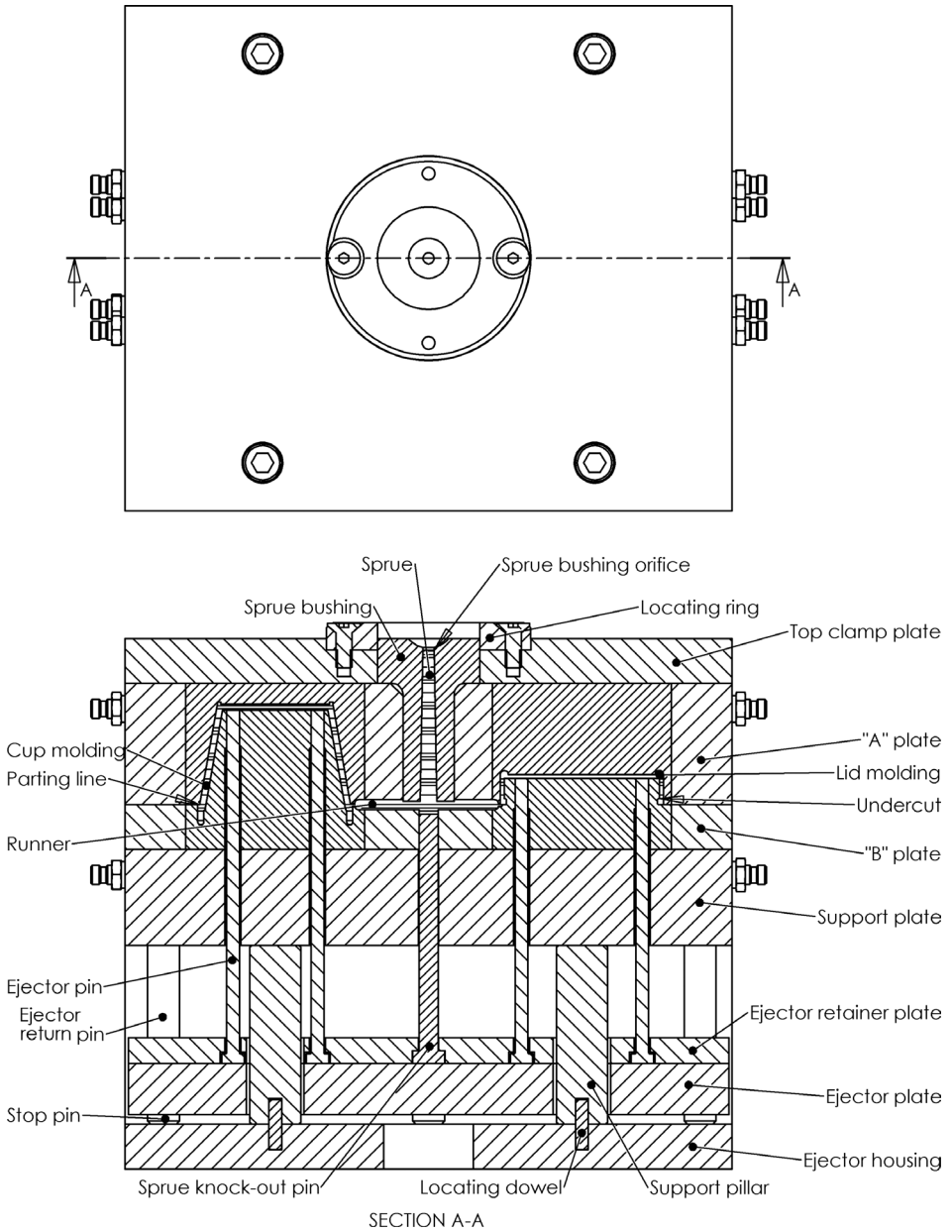
**Figure 1.5** View of molding ejected from injection mold

Figure 1.5 indicates that the plastic molding consists of two different molded parts (like a cup and a lid) attached to a feed system. This mold is called a two-plate, cold-runner, or two-cavity family mold. The term “family mold” refers to a mold in which multiple components of varying shapes and/or sizes are produced at the same time, most commonly to be used in a product assembly. The term “two-cavity” refers to the fact that the mold has two cavities to produce two moldings in each molding cycle. Such multicavity molds are used to rapidly and economically produce high quantities of molded products. Molds with eight or more cavities are common. The number of mold cavities is a critical design decision that impacts the technology, cost, size, and complexity of the mold; a cost estimation method is provided in Chapter 3 to provide design guidance.

In a multicavity mold, the cavities are placed across the parting plane to provide room between the mold cavities for the feed system, cooling lines, and other components. It is generally desired to place the mold cavities as close together as possible without sacrificing other functions such as cooling, ejection, etc. This usually results in a smaller mold that is not only less expensive, but is also easier for the molder to handle while being usable in more molding machines. The number of mold cavities in a mold can be significantly increased by not only using a larger mold, but also by using different types of molds such as a hot runner mold, three-plate mold, or stack mold as later discussed with respect to mold layout design in Chapter 4.

### 1.3.3 Mold Cross-Section and Function

Figure 1.6 shows the top view of the mold, along with the view that would result if the mold was physically cut along the section line A-A and viewed in the direction of the arrows. Various hatch patterns have been applied to different components to facilitate identification of the components. It is very important to understand each of these mold components and how they interact with each other and the molding process.



**Figure 1.6** Top and cross-section views of a two-plate mold

Consider now the stages of the molding process relative to the mold components. During the filling stage, the polymer melt flows from the nozzle of the molding machine through the orifice of the sprue bushing. The melt flows down the length of the sprue bushing and into the runners located on the parting plane. The flow then traverses across the parting plane and enters the mold cavities through small

gates. The melt flow continues until all mold cavities are completely filled. Chapters 5, 6, and 7 provide analysis and design guidelines for flow in the mold cavity, feed system, and gates. As the polymer melt fills the cavity, the displaced air must be vented from the mold. Some analysis and design guidelines are provided in Chapter 8.

After the polymer melt flows to the end of the cavity, additional material is packed into the cavity at high pressure to compensate for volumetric shrinkage of the plastic as it cools. The estimation of shrinkage and guidelines for steel-safe design are described in Chapter 9. Typically, the injection molding pressure, temperature, and timing are adjusted to achieve the desired part dimensions. The duration of the packing phase is typically controlled by the size and freeze-off of the gate between the runner and the cavity. During the packing and cooling stages, heat from the hot polymer melt is transferred to the coolant circulating in the cooling lines. The heat transfer properties of the mold components, together with the size and placement of the cooling lines, determines the rate of heat transfer and the cooling time required to solidify the plastic. At the same time, the mold components must be designed to resist deflection and stress when subjected to high melt pressures. Chapters 10 and 11 describe the analysis and design of the mold's cooling and structural systems.

After the part has cooled, the molding machine's moving platen is actuated and the moving half of the mold (consisting of the "B" plate, the core inserts, the support plate, the ejector housing, and related components) moves away from the stationary half (consisting of the top clamp plate, the "A" plate, the cavity inserts, and other components). Typically, the moldings stay with the moving half since they have shrunk onto the core. This shrinkage results in tensile stresses, like a rubber band stretched around a cylinder or box, that will tend to keep the moldings on the core.

After the mold opens, the ejector plate is pushed forward by the molding machine. The ejector pins are driven forward and push the moldings off the core. The moldings may then drop out of the mold or be picked up by an operator or robot. Afterwards, the ejector plate is retracted and the mold closes to receive the melt during the next molding cycle. The ejector system design is analyzed in Chapter 12.

## ■ 1.4 Other Common Mold Types

A simple two-plate mold has been used to introduce the basic components and functions of an injection mold. About half of all molds closely follow this design, since the mold is simple to design and economical to produce. However, the two-plate mold has many limitations, including:



# 3

## Mold Cost Estimation

### ■ 3.1 The Mold Quoting Process

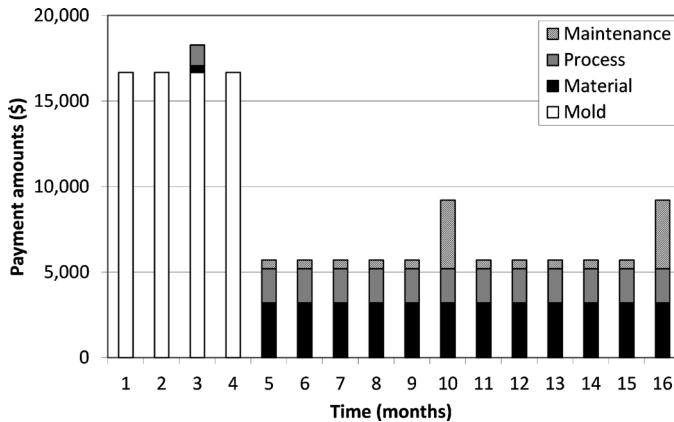
The quoting process for plastic parts can be difficult for both the mold customer and supplier. Consider the view of the mold customer. The procurement specialist for the product development team sends out requests for quotes (RFQs) to several mold makers. After waiting days or weeks, the quotes come back and the customer discovers that the development time and cost of the mold may vary by a factor of three or more. In such a case, prospective mold purchasers should ask about the details of the provided quotes and check if the costs can be reduced through product redesign. To reduce uncertainty related to pricing and capability, many prospective customers maintain a list of qualified suppliers who have been found to provide satisfactory lead times, quality, and pricing across multiple projects. Long-term trust-based partnerships can provide for rapid application and mold development by avoiding the quoting process altogether and invoicing on a labor cost plus materials cost (referred to as “cost plus”) basis.

Now consider the view of the mold supplier. The mold designer may need to invest significant time developing a quote that may have a relatively small chance of being accepted. Sometimes, the mold designer may have to redesign the product and perform extensive analysis to provide the quote. While the quote may seem high to the prospective customer, the design may correspond to a mold of higher-quality materials and workmanship that can provide a higher production rate and longer working life than some other, lower-cost mold. This more expensive mold may quickly recoup its added costs during production.

From time to time, mold makers and molders will adjust their quote based on whether or not they want the business. If the supplier is extremely busy or idle, then the estimated number of hours and/or hourly rate may be adjusted to either discourage or encourage the potential customer from accepting the quote. Such adjustments should be avoided since the provided quote does not represent the true costs of the supplier, which would become the basis for future engagements between the mold supplier and the customer. Thus, the development of a long-term and mutually beneficial partnership will begin with justifiable project quotes.

The provided mold purchase contract typically states payment and delivery terms for the mold(s) and perhaps even the molded part(s). A typical mold purchase agreement may specify that the cost of a mold is paid in three installments:

- the first third: on acceptance of the quote (after which the mold base and key materials are typically purchased);
- the second third: halfway through the mold making project (often when cavity inserts have been machined); and
- the final third: upon acceptance of the quality of the molded parts.



**Figure 3.1** Schedule of mold and molding expenses

After the mold is purchased, molds are typically shipped to the specified molder or the customer's facility where the parts are molded and marginal costs are incurred on a per-part basis. The cash outlays for a typical project are plotted in Fig. 3.1 on a monthly basis. The material and processing costs in month 3 are related to molding trials by which the mold design is validated and improved; a batch of pre-production parts are sampled at this time for marketing and testing purposes. Later, monthly processing and material costs are incurred during production. Maintenance costs may appear intermittently throughout production to maintain the quality of the mold and moldings.

There has been a trend in the industry towards large vertically integrated molders with tightly integrated supply chains that can supply molded parts and even complete product assemblies. As such, the structure of the quote can vary substantially with the structure of the project and business requirements. With a vertically integrated supplier, there is typically an upfront fee for the costs associated with the development of the mold, followed by a fee for each molded part. To protect the supplier, contracts are typically developed that specify minimum production quantities with discounts and/or fees related to changes in the production schedule.

Some prospective mold customers may purposefully choose to disintegrate their supply chains in order to minimize the “leakage” of intellectual property. In this model, they may have one firm perform analysis or simulation of one component in the design, a second firm develop a mold for the same component, a third firm develop other designs and molds for other components in the design, yet other firms for molding different components, and then perform the assembly internally. Such a disintegrated supply chain can raise significant issues with respect to scheduling and product qualification.

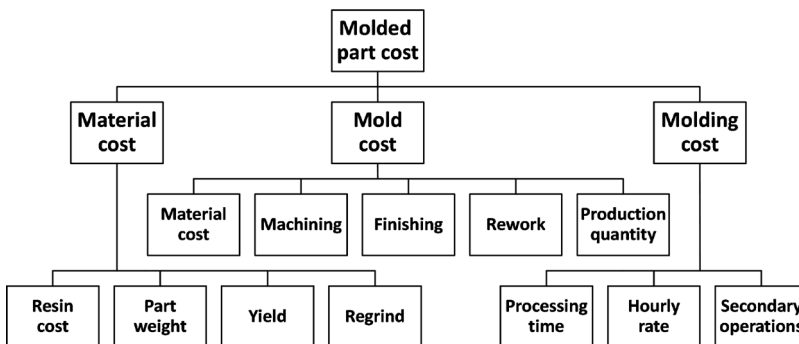
Since the structure and magnitude of quotes will vary substantially with the supply chain strategy and supplier(s), a prospective buyer of plastic parts should solicit quotes from multiple vendors and select the quote from the supplier that provides the most preferable combination of design capability, molded part quality, and payment/delivery terms.

## ■ 3.2 Cost Overview for Molded Parts

There are three main cost drivers for molded products:

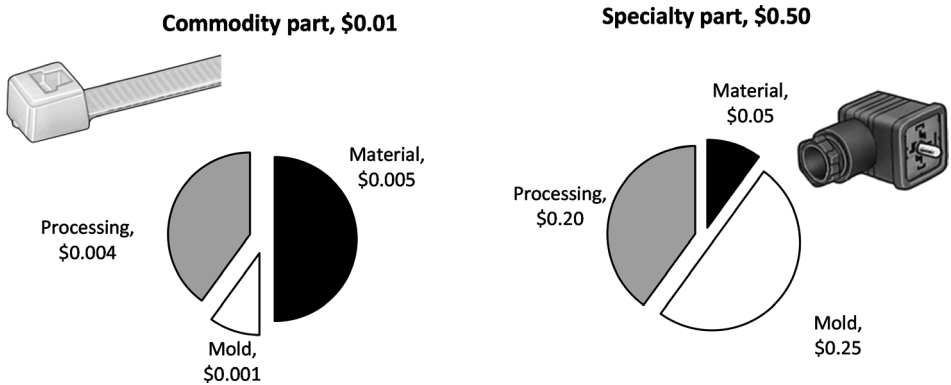
1. the cost of the mold and its maintenance,
2. the materials cost, and
3. the processing cost.

Figure 3.2 provides a breakdown of these primary cost drivers and their underlying components. It is important to note that these costs do not include indirect costs such as facilities, administrative overhead, fringe benefits, or profits. However, such indirect costs may be accounted for through the adjustment of hourly rates or application of indirect cost rates.



**Figure 3.2** Cost drivers for injection molded products

Even though most molded products have the same cost drivers, the proportion of costs varies widely by application. Figure 3.3 shows the cost breakdown for a commodity application (such as a cable tie with a production volume of 10 million pieces) and a specialty application (such as a custom electrical connector with a production volume of 100,000 pieces). While these two products are approximately the same weight, it is observed that the magnitude and proportion of costs are vastly different. The commodity part will tend to have lower costs due to economies of scale that allow (1) amortization of the mold cost across vast production quantities, (2) optimization of the molding process for lower molding costs, and (3) lower material costs associated with bulk purchases of resin. As Fig. 3.3 suggests, the material costs represent the majority of the total molded part cost in commodity applications whereas the mold/tooling costs can dominate for custom moldings with low production quantities.

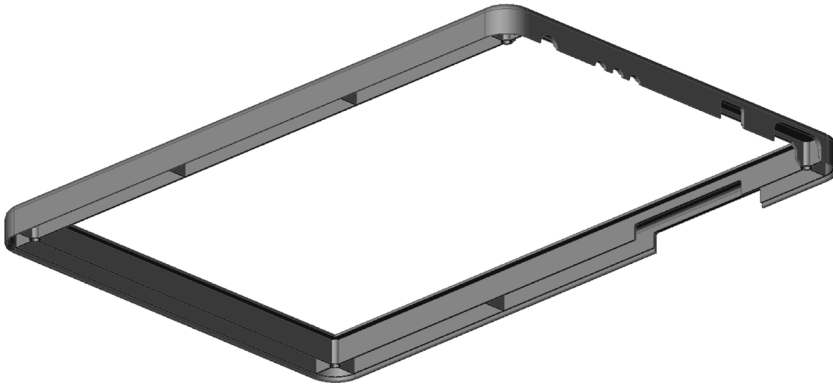


**Figure 3.3** Cost comparisons for a commodity and specialty part

For analysis, the total part cost of a molded product,  $C_{\text{part}}$ , can be estimated as

$$C_{\text{part}} = \frac{C_{\text{mold/part}} + C_{\text{material/part}} + C_{\text{process/part}}}{\text{yield}} \quad (3.1)$$

where  $C_{\text{mold/part}}$  is the amortized cost of the mold and maintenance per part,  $C_{\text{material/part}}$  is the material cost per part,  $C_{\text{process/part}}$  is the processing cost per part, and  $\text{yield}$  is the fraction of molded parts that are acceptable. Each of these terms will be subsequently estimated. To demonstrate the cost estimation method, each of these cost drivers is analyzed for the laptop bezel shown in Fig. 3.4. The example analysis assumes that 1,000,000 parts are to be molded of ABS from a single-cavity hot runner mold. Some relevant application data required to perform the cost estimation is provided in Table 3.1.



**Figure 3.4** Isometric view of laptop bezel

**Table 3.1** Laptop Design Data

Parameter	Laptop bezel
Material	ABS
Production quantity	1,000,000
$L_{\text{part}}$	240 mm
$W_{\text{part}}$	160 mm
$H_{\text{part}}$	10 mm
$A_{\text{part\_surface}}$	45,700 mm <sup>2</sup>
$V_{\text{part}}$	27,500 mm <sup>3</sup>
$H_{\text{wall}}$	1.5 mm

### 3.2.1 Mold Cost per Part

The cost of the mold for a given application is estimated in Section 3.3. Given the estimate or a quote for the mold cost,  $C_{\text{total\_mold}}$ , the cost of the mold per part can be assessed as

$$C_{\text{mold/part}} = \frac{C_{\text{total\_mold}}}{n_{\text{total}}} \times f_{\text{maintenance}} \quad (3.2)$$

where  $n_{\text{total}}$  is the total production quantity of parts to be molded, and  $f_{\text{maintenance}}$  is a factor associated with maintaining the mold. Most molders perform several levels of maintenance, including:

- preventive maintenance after every molding run,
- inspections and minor repairs on an intermittent basis,
- scheduled general mold maintenance on a quarterly or semiannual basis, and
- mold rebuilding as necessary.

The need for mold maintenance and repair is related to the number of molding cycles performed, the properties of the plastic and mold materials, the processing conditions, and the quality of the mold. As a general rule, annual maintenance costs can be estimated as 10% of the mold purchase cost [1], but will vary with the design, materials, and processing conditions in application. As the resin becomes more abrasive relative to the hardness of the mold, the wear of the mold accelerates and more maintenance is required. Conversely, a well-designed, hardened mold should exhibit lower maintenance costs when used with an unfilled low-viscosity plastic. Table 3.2 provides some maintenance estimates.

**Table 3.2** Mold Maintenance Coefficient,  $f_{\text{maintenance}}$ , per Million Cycles

	Unfilled, low viscosity plastic	High viscosity or particulate filled plastic	High viscosity and fiber filled plastic
Soft mold material, such as aluminum or mild steel	4	16	64
Standard mold steel, such as P20	2	4	16
Hardened surface or tool steel, such as H13	1	2	4



**Example:**

Estimate the amortized cost of the mold base per molded laptop bezel.

ABS is a moderate viscosity, unfilled material. If the mold inserts are made from D2 tool steel with a hardened surface, then a mold maintenance coefficient of 2 is estimated. Given that the mold has a single cavity, one million cycles are required. The amortized cost of the mold per molded laptop bezel (including the initial purchase cost and maintenance costs) is then estimated as:

$$C_{\text{mold/part}} = \frac{\$75,900}{1,000,000 \text{ parts}} \cdot 2 = \$0.152/\text{part}$$

### 3.2.2 Material Cost per Part

The cost of the material per part can be estimated as:

$$C_{\text{material/part}} = V_{\text{part}} \cdot \rho_{\text{polymer}} \cdot \kappa_{\text{polymer}} \cdot f_{\text{scrap}} \quad (3.3)$$

where  $V_{\text{part}}$  is the volume of the molded part,  $\rho_{\text{polymer}}$  is the density of the molded polymer at room temperature,  $\kappa_{\text{polymer}}$  is the cost of the molded polymer per unit weight, and  $f_{\text{scrap}}$  is the total proportion of material consumed including startup, defects, and scrap associated with the feed system.

Table 3.3 provides estimates of the total material consumption for various types of feed systems. A cold runner is simple and low-cost but results in molded plastic that must be either discarded or recycled. Utilizing the recycled plastic as regrind reduces the waste but incurs some cost related to the labor and energy of recycling. As later described, hot runners have the potential to significantly reduce material costs but consume significant material during start-up and so are less effective in short runs.

**Table 3.3** Material Waste Coefficient

Type of feed design	Feed system waste factor, $f_{\text{feed\_waste}}$
Cold runner	1.25
Cold runner, fully utilizing regrind	1.08
Hot runner with short runs	1.05
Hot runner with long runs	1.02



**Example:**

Estimate the cost of the plastic material per molded laptop bezel.

Since a hot runner system is used and the production quantity is one million parts, large production runs are assumed with a feed waste factor of 1.02. Using the cost and density from Appendix A, the cost of the plastic material per molded part is estimated as

$$C_{\text{material/part}} = 27.5 \text{ cm}^3 \cdot \left( \frac{0.01 \text{ m}}{\text{cm}} \right)^3 \cdot 1044 \frac{\text{kg}}{\text{m}^3} \cdot 2.80 \frac{\$}{\text{kg}} \cdot 1.02 = \$0.082/\text{part}$$

The cost of the plastic material per part is quite low since the part has a very low thickness (1.5 mm) and low part weight (28.7 g).

### 3.2.3 Processing Cost per Part

The processing cost per part is a function of the number of mold cavities, the cycle time,  $t_{\text{cycle}}$ , and the hourly rate of the machinery and labor,  $R_{\text{molding}}$ :

$$C_{\text{process/part}} = \frac{t_{\text{cycle}}}{n_{\text{cavities}}} \times \frac{R_{\text{molding}}}{3600 \text{ s/h}} \quad (3.4)$$

The cycle time is effected primarily by the thickness of the part,  $h_{\text{wall}}$ , and, to a lesser extent, by the size of the part and the type of feed system. While the cycle time will be more accurately estimated during the cooling system design, a reasonable estimate is provided by

$$t_{\text{cycle}} = 4 \left[ \frac{s}{\text{mm}^2} \right] (h_{\text{wall}} [\text{mm}])^2 \times f_{\text{cycle\_efficiency}} \quad (3.5)$$

where the cycle efficiency,  $f_{\text{cycle\_efficiency}}$ , is a function of the type of feed system and process that is being operated according to Table 3.4. While it is desirable to operate a fully automatic molding cell with a hot runner, many molders continue to use cold runner molds operating in semiautomatic mode.

**Table 3.4** Cycle efficiency coefficient

Type of feed system and mold operation	Cycle efficiency factor, $f_{\text{cycle\_efficiency}}$ , cold runner	Cycle efficiency factor, $f_{\text{cycle\_efficiency}}$ , hot runner
Semiautomatic molding with operator removal of molded parts	2.25	2.0
Semiautomatic molding with gravity drop or high speed robotic take-out	1.5	1.25
Fully automatic molding	1.25	1.0

The hourly rate for the molding machine is primarily a function of the clamp tonnage, which drives the size and cost of the machine. The following model was developed relating the clamp tonnage and capability to the machine hourly rate:

$$R_{\text{molding}} = (43.3 + 0.095 \cdot F_{\text{clamp}}) \cdot f_{\text{machine}} \quad (3.6)$$

where  $F_{\text{clamp}}$  is the clamp tonnage in metric tons (mTon), and  $f_{\text{machine}}$  is a factor relating to the capability of the machine and the associated labor. This equation was derived using published U.S. national hourly rate data [2] for twelve different sized molding machines ranging from 20 to 3500 metric tons; the described model has a coefficient of determination,  $R^2$ , equal to 0.979.

The hourly rate data is also a function of the geographic region, machine and molder costs, and other factors. To account for these variances, the machine capability factor,  $f_{\text{machine}}$ , is estimated according to Table 3.5. In general, molding machines with advanced capabilities and higher clamp tonnage cost more to purchase and operate, and so command a price premium. Machines with specialized capability (such as multiple injection units or very high injection pressures/velocities) are more expensive to purchase and so likewise command a price premium per hour of operation. The cost of all auxiliaries should be added to the appropriate machine coefficient. While advanced technology can increase the hourly rate of the molding process, it should provide a net savings by improving quality and reducing the processing and materials costs. Variances due to geographic locale may be accounted by scaling the machine factor by the labor rate data provided in Appendix D relative to the U.S. cost data.



**Table 3.5** Molding Machine Capability

Type of molding machine and labor required	Machine factor, $f_{\text{machine}}$
Old hydraulic machine (purchased before 1985) without operator or profit	0.8
Standard hydraulic machine or older electric machine (before 1998) operator or profit	1.0
Modern electric machine without operator or profit	1.1
Molder profit	Add 0.1
Take-out robot and conveyor	Add 0.05
Hot runner temperature control	Add 0.05
Gas assist control	Add 0.1
Injection-compression control	Add 0.1
Dedicated operator/assembler	Add 0.3
Foaming or induction heating unit	Add 0.3
Two-shot molding machine	Add 0.6
Three-shot molding machine	Add 0.9

The clamp tonnage required for molding will be analyzed during the filling system design. However, the clamp tonnage can be conservatively estimated assuming an average melt pressure of 80 MPa (11,600 psi) applied to the projected area,  $A_{\text{projected}}$ , of the mold cavities. If the projected area is unknown, it can be estimated as the product of the part length and width. The clamp force in metric tons,  $t = 9800 \text{ N}$ , is then

$$F_{\text{clamp}} = 80 \cdot 10^6 [\text{Pa}] \cdot \left( n_{\text{cavities}} \cdot \frac{A_{\text{projected}}}{L_{\text{part}} \cdot W_{\text{part}}} [\text{m}^2] \right) \cdot \frac{[t]}{9800 [\text{N}]} \quad (3.7)$$

**Example:**

Estimate the processing cost per molded laptop bezel.

The analysis assumes that a hot runner system is used with a take-out robot to fully automate the molding process. The corresponding cycle efficiency factor is 1.5. The cycle time is then estimated as

$$t_{\text{cycle}} = 4 \left[ \frac{\text{s}}{\text{mm}^2} \right] (1.5 [\text{mm}])^2 \cdot 1.5 = 13.5 \text{ s}$$

If a modern electric machine is used with a take-out robot/conveyor, and a hot runner controller, then, allowing for molder profit, the machine technology factor is

$$f_{\text{machine}} = 1.1 + 0.05 + 0.05 + 0.1 = 1.3$$

The clamp tonnage is estimated as

$$F_{\text{clamp}} = 75 \cdot 10^6 [\text{Pa}] \cdot (1 \cdot 0.24 \text{ m} \cdot 0.16 \text{ m} [\text{m}^2]) \cdot \frac{[\text{mTon}]}{9800 [\text{N}]} = 294 \text{ mTon}$$

It should be noted that the true required clamp tonnage is likely less than 294 metric tons since the laptop bezel has a large window in it. The analysis, however, is conservative.

The molding machine rate is then estimated as

$$R_{\text{molding\_machine}} = (43.3 + 0.095 \cdot 294) \cdot 1.3 = \$92.60/\text{hr}$$

The processing cost of the molded part can then be estimated by Eq. (3.4) as

$$C_{\text{process/part}} = \frac{13.5 \text{ s/cycle}}{1 \text{ part/cycle}} \times \frac{\$92.60/\text{hr}}{3600 \text{ s/hr}} = \$0.347/\text{part}$$

### 3.2.4 Defect Cost per Part

There are many reasons that molded parts are rejected. Some common defects include short shot, flash, contamination, improper color match, surface striations due to splay or blush, warpage and other dimensional issues, burn marks, poor gloss, and others. Since customers demand high quality levels on the molded parts they purchase, molders often internally inspect and remove any defective parts that are molded before shipment to the customer.

The cost of these defects can be incorporated into the part cost by estimating the yield. Typical yields vary from 50 to 60% at start-up for a difficult application with many quality requirements to virtually 100% for a fully matured commodity product. Table 3.6 provides yield estimates according to the number of molding cycles and quality requirements.

**Table 3.6** Yield Estimates

Total number of molding cycles	Low quality requirements	High quality requirements
~ 10,000	0.95	0.90
~ 100,000	0.98	0.95
~ 1,000,000	0.99	0.98

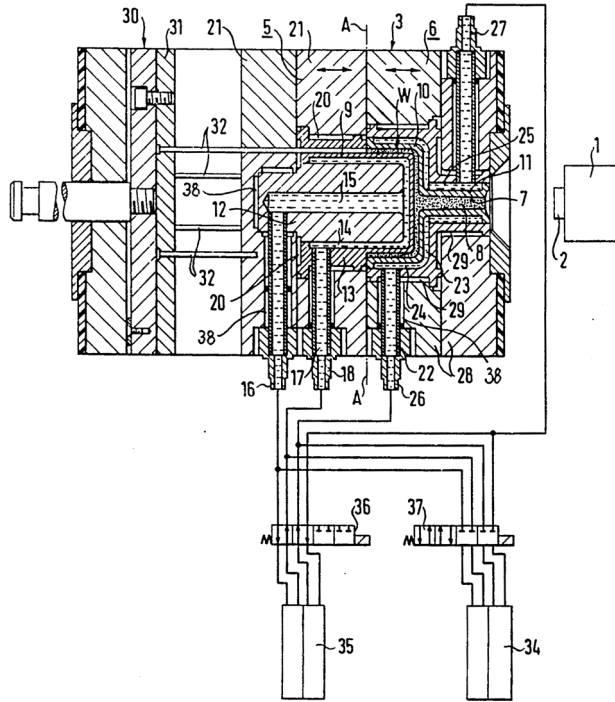
## ■ 9.4 Mold Wall Temperature Control

The analyses and designs presented for mold cooling are adequate for most injection molding applications. However, there are some applications in which the use of conventional cooling designs is unacceptable. Normally, the development of a solidified skin occurs when the hot polymer melt contacts the cold mold wall [23]. In some molding applications, the solidified skin may lead to premature freeze-off of the melt in the cavity, excessive birefringence in the molded part, or inadequate levels of gloss or surface replication. In other applications, mold wall temperature fluctuations across the surface of the mold cavity may lead to a lack of dimensional control. As such, some molding applications involving lenses, airplane cockpit canopies, optical storage media, and fiber reinforced materials may seek to improve the quality of the moldings through dynamic control of the mold wall temperature. Several different strategies are next discussed.

### 9.4.1 Pulsed Cooling

One approach to controlling the mold wall temperature is to use one or more sets of cooling channels to actively heat and then actively cool the mold. One such mold design is shown in Fig. 9.28; this was developed to provide tight tolerances when molding highly sensitive plastic materials or very thin walled moldings [24]. In this pulsed cooling design, a mold cavity 7 is formed by a cavity insert 10 and a core insert 9. The core insert is purposefully designed to be as thin as possible, and surrounds an internal core 12 so as to provide a channel 14 for circulation for temperature controlled fluids. The cavity insert 10 is similarly designed to mate with the cavity plate 28 and the outer insert 29 to form channels 24 and 25.

In operation, two fluids are separately temperature-controlled with a heating device 35 and a cooling device 34; two separate fluids are recommended to reduce the cost and time associated with sequentially heating and cooling a single fluid. Prior to the injection of the polymer melt, the control valves 36 and 37 will direct the heated fluid to the inlet 18 and through the mold core via channels 14 and 15 before returning via the outlet 16; a similar heating circuit is formed for the mold cavity via elements 26, 22, 25, and 27. Once the inserts 9 and 10 are at a temperature above the freezing point of the plastic melt, the plastic melt is injected into the cavity 7. The control valves can then be actuated to direct the cooling fluids from the cooling device 34 through the same channels previously used for heating.



**Figure 9.28** Mold design for pulsed cooling

The success of this mold design is highly dependent on minimizing the mass of the mold steel and coolant required to form and cool the walls of the mold cavity. It is clearly desirable to minimize the thickness of the mold inserts, the length of the cooling channels and lines, and the heat transfer to adjacent mold components. In this design, air gaps 20, 29, and 38 are used to reduce the amount of heat transfer and so improve the thermal efficiency and dynamic performance of the mold; insulating sheets (not numbered) are also provided adjacent the top and rear clamp plate to minimize heat transfer to the platens. Unfortunately, the size of the cavity and the structural requirements on the mold components necessitates the use of fairly large mold components that need to be heated and subsequently cooled. The dynamic thermal response is limited.

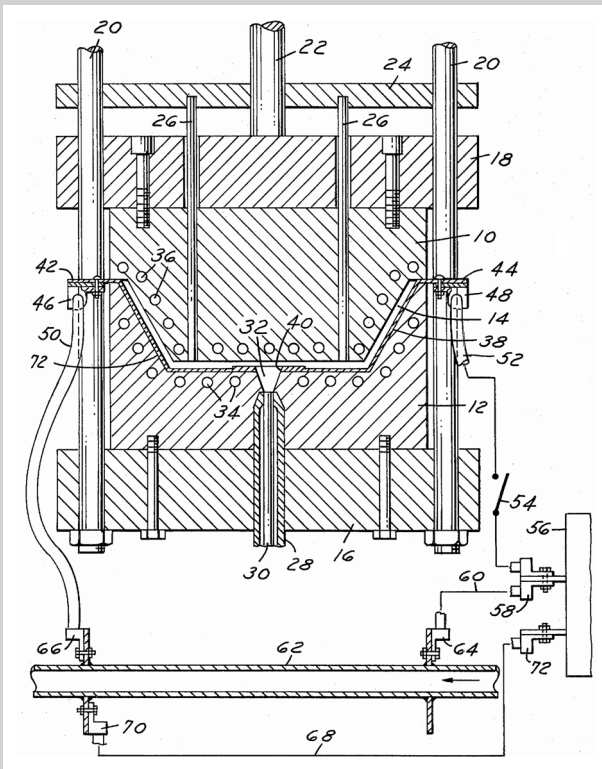
**Example:**

Estimate the energy required to heat the mold core and cavity inserts depicted in Fig. 9.29 for a pulsed cooling process.

For the purpose of estimating thermal energy, the core and cavity inserts can be modeled together as a block of steel with a width and length of 100 mm and a depth of 200 mm. Given a density of steel of  $8000 \text{ kg/m}^3$ , the mass of the inserts estimated as 16 kg. The amount of heat,  $E$ , required for a temperature change,  $\Delta T$ , of  $100^\circ\text{C}$  is:

$$E = mC_p\Delta T = 16 \text{ kg} \cdot 500 \text{ J/kg}^\circ\text{C} \cdot 100^\circ\text{C} = 800,000 \text{ J}$$

At a cost of \$0.14 per kW h, the energy cost for heating alone is on the order of \$0.03 per molding cycle. This cost does not include the energy cost required for cooling, the extended molding cycle time required for heating and cooling the mold inserts, or the added cost of the mold and auxiliary systems required for implementation. For these reasons, pulsed cooling is not commonly used except in very demanding applications.



**Figure 9.29** Mold design with conduction heating

### 9.4.2 Conduction Heating

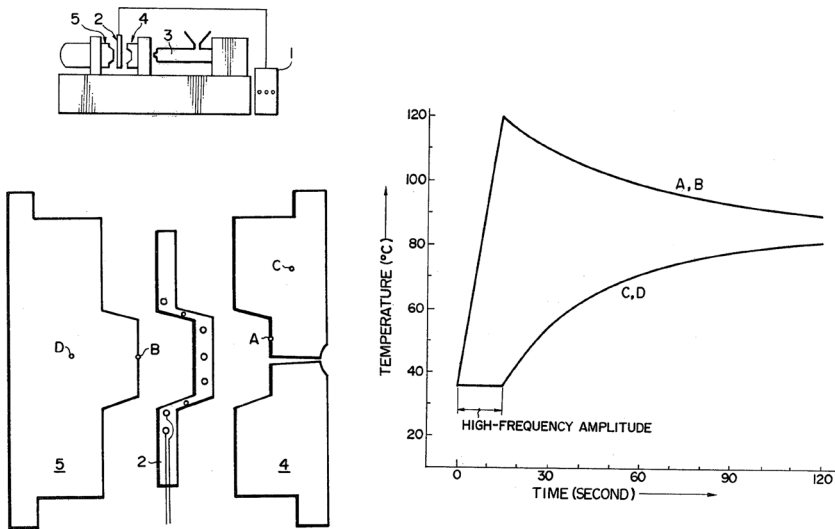
Given the large thermal mass of the mold and the cooling system, another strategy to control the mold wall is to use conduction heaters at or near the surface of the mold. One design is shown in Fig. 9.29; this was developed to provide a smooth surface finish to one side of a foamed plastic product [25]. The mold consists of a cavity insert 12 and a core insert 10, both including a network of cooling lines 34 and 36 as per conventional mold design. A thin metallic sheet 38 conforms to the surface of the mold cavity 12, with a thin insulating layer of oxide deposited between the sheet and the cavity insert. The thin metallic sheet 38 includes an opening 40 to deliver the plastic melt from the sprue 32 to the mold cavity 14. Electrical cable attachments 46 and 48 attach the sheet 38 to low voltage, high current electric cables 50 and 52.

Just prior to mold closure, the switch 54 is closed to pass a high current through the sheet 38. In this design, a 0.2 cm thick steel plate was used with a length and width of 30 cm and 10 cm, respectively. To analyze the heating requirements, consider a typical molded part with a heat capacity of 2000 J/kg°C, a 3 mm thickness, a melt temperature of 240°C, an ejection temperature of 100°C, and a cycle time of 30 s. In this case, the heat load imposed on the mold by the ABS melt is 28 kW/m<sup>2</sup>; given that the cooling lines are placed on two sides of the mold, the cooling power is approximately 1.4 W/cm<sup>2</sup>. As such, a 30 cm by 10 cm heating plate must deliver at least 420 W simply to overcome the heat transfer to the cooling lines before the temperature of the heating plate begins to increase significantly.

It is noted that conduction heaters are widely available with power densities exceeding 250 W/cm<sup>2</sup>. Such a heater, if placed on the surface of a mold cavity, could increase a 0.2 cm by 30 cm by 10 cm steel plate's surface temperature by 200°C in 6 s. Attempts have been made to incorporate higher power, thin film heaters directly into the mold surface [26]. However, such efforts to incorporate conduction heaters into molds have not been widely successful for at least three reasons. First, the large, cyclic pressure imposed on the heater(s) by the polymer melt tends to fatigue the heaters. Second, it is difficult to configure the heater(s), mold cavity, and cooling channels to provide the uniform wall temperature required to deliver aesthetic surfaces with tight dimensional controls. Third, the heaters are located between the mold cavity and the cooling channels, tend to reduce the rate of heat transfer during cooling, and so extend the cooling time.

### 9.4.3 Induction Heating

Induction heating is another approach to increasing the mold wall temperature prior to mold filling, and is seeing increased application for micromolding [27], gloss [28], and strength [29]. One design is shown in Figure 9.30 [30]; this was developed to injection mold reinforced thermoplastic composites with superior surface gloss and substantially no surface defects. To reduce energy consumption and heating time, only a small portion of the mold's surface is selectively heated by high-frequency induction heating. As shown in Fig. 9.30, a conventional injection molding machine 3 delivers polymer melt to a mold consisting of a stationary mold half 4 and a movable mold half 5.



**Figure 9.30** Mold design with induction heating

Prior to mold closure and filling, a high-frequency oscillator 1 drives alternating current through an inductance coil (inductor) 2 temporarily placed near the surface(s) of the mold. When a high-frequency alternating current is passed through the inductor 2, an electromagnetic field is developed around the inductor, which subsequently generates eddy currents within the metal. The resistance of the mold metal subsequently leads to internal Joule heating of the mold surface. Traces A and B in Fig. 9.30 demonstrate the increased mold surface temperature at locations A and B caused by induction heating; traces C and D show no initial effect at location C and D away from the induction heating but later increase with the heat transfer from the injected polymer melt into the mold cavity.

As with all the previously described approaches for mold wall temperature control, molders wish to elevate the surface temperature of the mold as quickly as possible. The heating power through a high-frequency induction heating is proportional to the square of the alternating frequency, the square of the current, and the square of the coil density, among other factors. As such, the inductors must be carefully designed to locally heat the mold surface in a controlled manner to avoid an undesirable temperature distribution. For example, an inductor was made from copper tube of 5 mm diameter and wound as a spiral with a pitch of 5 mm. The distance between the surface of the metal mold and the inductor was set to 1 cm. Experiments indicated that a driving frequency of 400 kHz yielded a heating power at the mold surface on the order of 1000 W/cm<sup>2</sup>, which required approximately 10 s to increase the surface of the mold by 50°C.

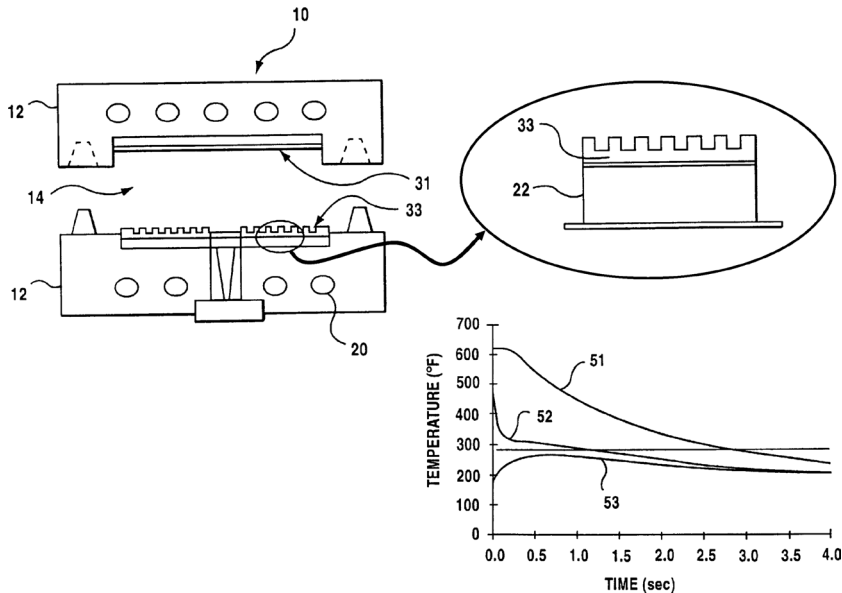
Compared to pulsed cooling and conduction heating, induction heating provides for increased heating rates with little added mold complexity. The primary issue in implementation is the design of the inductor, and in particular the spacing of its coil windings and their relation to the mold surfaces. If the design is improper, then the heating may be limited to low power levels. Experiments [30] indicated that a heating power less than 100 W/cm<sup>2</sup> did not significantly increase the mold surface temperature and eventually caused the overload breaker to actuate. On the other hand, when the power output exceeded 10,000 W/cm<sup>2</sup>, the rate of the surface temperature increase became too steep to control such that uniform heating was no longer possible; defects such as gloss irregularities, sink marks, etc. were observed with temperature differences of more than 50°C across the surface of the mold.

#### 9.4.4 Managed Heat Transfer

Given the difficulties associated with active mold wall temperature control, a “passive” cooling design has been developed; the term “passive” is used to imply that the mold does not utilize any external power to control the mold wall temperature. The design shown in Fig. 9.31 was specifically developed to control the mold wall temperature during the molding of optical media [31]. The mold includes two halves 12 to form a mold cavity 14. Cooling lines 20 are provided per conventional design to remove the heat from the polymer melt. However, a thermal insulating member 22 is placed between the mold halves 12 and the stampers 31 and 33. The thermal insulating member 22 is made from a low thermally conductive material, preferably a high temperature polymer, such as polyimides, polyamideimides, polyamides, polysulfone, polyethersulfone, polytetrafluoroethylene, and polyetherketone. The insulating polymer is typically spin coated in an uncured form to provide a layer with a thickness on the order of 0.25 mm and subsequently heat cured. The



stamper 33 is typically fabricated from nickel, and provides the surface details for replication while also protecting and providing the insulator with a uniform, highly polished surface during molding.



**Figure 9.31** Mold design with managed heat transfer

During molding, the insulating layer 22 behind the stamper 33 slows the initial cooling of the resin during the molding operation. Because of this insulation, the stamper's temperature increases and so the skin layer retains heat longer during the mold filling stage, thereby avoiding the surface irregularities created by rapid surface cooling. The temperature of the stamper:melt interface can be controlled by specification of the process conditions as well as the layers' thicknesses and material properties; one-dimensional cooling analysis can be used to understand the physics and assist in the design optimization. In this example, it was found that the centerline temperature 51 of the disc dictates the minimum cooling time for the part to cool below the glass transition temperature of the polymer melt. The temperature 52 at the stamper:melt interface impacts the thermal stress and pit replication on the disc's surface and is measured. The temperature 53 in the mold behind the insulator suggests that the mold acts as a heat sink and is maintained at a substantially constant temperature.

The mold designer and process engineer should intuitively understand that the addition of an insulating layer will tend to reduce the rate of heat transfer from the melt to the mold, and therefore require extended cooling times. To alleviate this issue, the cooling lines can be operated at a lower temperature to provide for higher

rates of heat transfer after the initial heating of the stamper. Accordingly, this design strategy provides a reasonable level of mold wall temperature control without any additional energy consumption or control systems. However, the level of temperature control is limited compared to the other active heating designs. In addition, this approach may be difficult to apply to complex three-dimensional geometries.

## ■ 9.5 Chapter Review

Cooling system design is often not leveraged in injection mold design even though relatively little additional investment can reap significant increases in molder productivity. The cooling system design process includes the estimation of the cooling time, required heat transfer rate, and coolant flow rate to subsequently determine the cooling line diameter, depth, and pitch. Once these specifications are determined, a suitable cooling line layout can be developed that provides high and uniform rates of heat transfer while not interfering with other mold components. The cooling system design must also specify the flow of the coolant through the cooling line network as well as the design of conductive inserts and other mold elements for achieving uniform temperatures across the molded parts.

After reading this chapter, you should understand:

- The cooling system design process, and the flow of decisions needed to rationally engineer a cooling system;
- How to estimate the cooling time and potential errors in this estimation;
- How to estimate the required rate of heat transfer and check this value with the specifications of mold temperature controllers;
- How to calculate the required coolant flow rate and check this value with the specifications of mold temperature controllers;
- How to estimate the minimum and maximum size of a cooling line, and select a final cooling line diameter;
- How to estimate the depth and pitch of the cooling lines for a specific molding application;
- How to layout an effective cooling line design that does not interfere with other mold components, or redesign the mold to provide for more effective cooling;
- How to identify and remedy cooling-related issues in molding applications, such as sharp corners and deep cores.
- Potential approaches for controlling the mold wall temperature within a molding cycle.

In the next chapter, the shrinkage and warpage behavior of the solidified molding is examined. Afterwards, an ejection system design process is presented. As will be made clear, the shrinkage and ejection of the molded parts are closely linked to the cooling process.

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# 14

## Mold Commissioning

Injection molding is a preferred manufacturing process given its ability to quickly and efficiently make complex products to high quality. However, it is quite common for problems to be encountered during mold commissioning given the challenge of delivering stringent yet diverse key product characteristics (KPCs) while also managing significant uncertainty related to material properties and start-up processing conditions. When problems occur, it is important to assess the root cause and associated corrective remedy. Typically there issues will arise from one of four sources: 1) material properties, 2) processing conditions, 3) product design, or 4) mold design.

Multiple tuning loops are often required to develop a mold design and molding process that provide acceptable quality levels. A significant issue with mold commissioning is that the root cause(s) and potential remedies can be subject to debate. Different decision makers may strongly advocate different remedies based on their prior experiences and financial interests. Fortunately, most companies are self-interested in long-term financial stability and so will work cooperatively as partners to resolve issues and develop more strategic partnerships. While each application is governed by the specifics of the negotiated mold purchase agreement, there are some well-known customs set forth by the Society of the Plastics Industry and other industry organizations. This chapter provides an overview of some of the most important concepts with some practical guidance.

### ■ 14.1 Mold Commissioning Objectives

#### 14.1.1 Certify Mold Acceptability

As described in Section 2.2, it is common for the mold purchase cost to not be fully paid until the mold has been found acceptable and the customer signs off on the mold acceptance. The mold designer and mold maker appreciate prompt payment

for any balance due, so the molder and end-user of the molded products should strive to certify mold acceptance within 30 days after the mold has been delivered. Longer delays can cause financial distress with the mold maker. Furthermore, very long delays can impede corrective remedies as the mold designer and mold maker will move on to other applications and may, eventually, forget or discard details related to the mold's development such as sketches, drawings, CNC programs, patterns, and cutting tools. For this reason, molders should plan to trial received molds within a week of their arrival.

Given the potential for conflict during mold commissioning, parties in the molded product supply chain need to be reasonable with respect to mold acceptance and the implementation of corrective remedies as needed. The molder often serves as an intermediary between the mold designer/maker and the end-user of the molded parts. As such, the molder will try to balance the interests of all parties and seek the most cost- and time-effective solutions. Molders will often try to resolve molding issues first through process changes, then material changes, and finally mold design changes. Since molders routinely maintain their inventoried molds, many molders are able to quickly perform many of the changes to the mold design. However, the molder should contact the mold designer and mold maker prior to making these changes, since modification of the mold without permission can constitute acceptance of the mold by contract.

In a best case scenario, the mold will be found acceptable as shipped. In most cases where significant mold rework is required, the mold is typically shipped back to the mold maker. The cost of the mold rework can be significant and is dependent on the needed remedy as well as the expertise of the mold designer and mold maker. The owner of the mold should budget approximately 50% or more of the initial purchase price of the mold for mold rework and maintenance. Indeed, some companies employ a mold procurement strategy of purchasing multiple copies of the cheapest molds possible, then budgeting an amount for rework equal to the full purchase cost of the molds.

In a worst case scenario, the molds are not found acceptable and the cooperating parties dispute the best course of action. In some cases, the contractual obligations may not be clear or reparations cannot be made. Then, the final payment to the mold maker is never made and the molder/end-user will seek out a third party to implement corrective remedies. The original parties may simply let the matter drop or seek legal remedy regarding financial remuneration and property ownership.

### 14.1.2 Optimize Molding Process and Quality

Once a mold has been found acceptable, the mold commissioning process turns to optimizing the molding process and the quality of the molded products. This optimization process is typically performed by the molder with the support and approval of the end-user. The molder is motivated to maximize their profit by maximizing the yield of acceptable products while also minimizing material consumption and cycle time. Meanwhile, the end-user of the molded parts is motivated to ensure the product quality and so needs to provide strict guidance as to acceptable quality levels during mold commissioning.

Often, purchase agreements for molded products assume annual productivity gains in injection molding. The end-user should assume that the molder will attempt to continue to improve their molding processes. Accordingly, such process optimization is best conducted in early production runs, before reference process settings and quality levels are established. Minor mold design changes are often made to facilitate process optimization. The mold designer and mold maker may or may not be involved and, if so, may charge for their services on a “cost plus” basis that accounts for their time and related expenses.

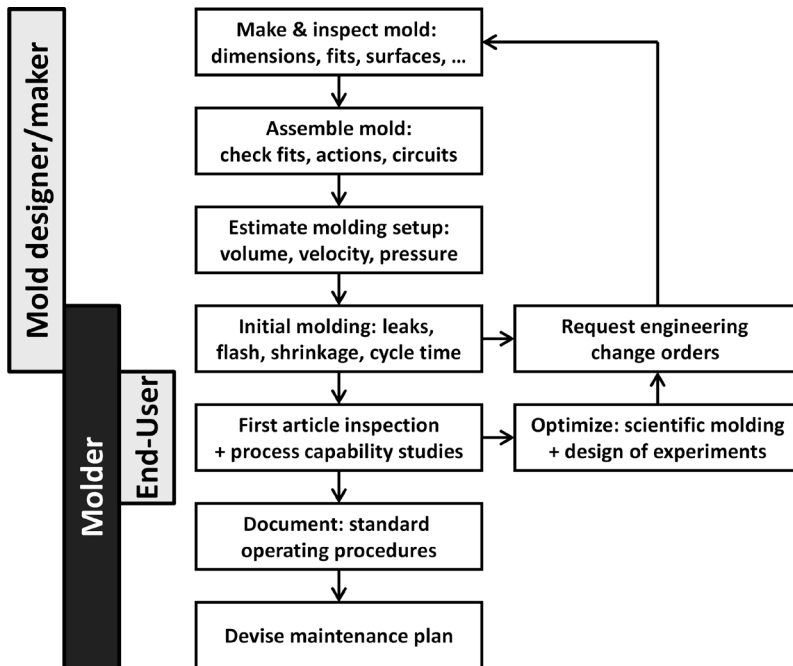
### 14.1.3 Develop Mold Operation and Maintenance Plans

Molders will typically work with many end-users to develop mold operation and maintenance plans. During initial mold commissioning, these “plans” can be fairly rough with significant uncertainty that needs to be resolved on an application-specific basis. The reason is that each molding application has its own molding behavior with a unique set of requirements that must be fulfilled. Indeed, each mold should be considered a custom-designed machine with distinct components, operation, and maintenance requirements.

Hundreds or thousands of parts will typically be molded during the mold commissioning process, leading to valuable experience with the operation of the mold. The molder should strive to leverage these molding trials to validate and customize the acceptance and maintenance plans. Subsequently, the mold designer and mold maker are rarely involved unless replacement parts or mold rebuilding is planned on an intermittent basis. In such cases, it may be advantageous to purchase replacement parts (e.g. pins, spare cavities/cores) with the mold. Similarly, it is standard practice to order standard mold components (for example, ejector pins, cooling plugs, nozzle heaters, etc.) that may shut-down production if damaged.

## ■ 14.2 Commissioning Process

Figure 14.1 provides a flow chart of the mold commissioning process, where the parties that are typically involved are shown on the left. The mold designer and mold maker are usually responsible for an internal inspection and test before they ship the mold to the molder. The mold designer and molder should work together to determine the molding process conditions such as temperature, pressures, and timings; many of these process conditions should have been estimated early in the mold specification and design. Both these parties usually work together during the initial molding trial where the mold operation is verified. Any significant defects in the mold design or workmanship are often revealed at this time, and engineering change orders (ECOs) are issued to the mold designer/maker as needed.



**Figure 14.1** Mold commissioning process

Once the initial mold verification is complete, the mold designer and mold maker have fulfilled their obligations and should be paid though they are still liable for warranty costs according to the mold purchase agreement. The molder will perform a first article inspection to fully characterize the quality of the moldings. Process capability studies are often performed to optimize the molding process, perhaps with the use of scientific molding techniques and design of experiments [1]. Engineering change orders for the mold may be requested to remedy defects in the mold design or workmanship, increase the molded product quality, or otherwise improve molding productivity. The cost of these ECOs should be paid by the party responsible for the root cause:

- Mold design change due to product design change: end-user (original equipment manufacturer, OEM)
- Mold design change due to change in the mold specification: end-user or molder
- Mold design change due to defect in mold design or making: mold designer or maker

Once the mold is fully qualified with acceptable operation and molded product quality, the standard operating procedures should be recorded with a maintenance plan. Each of these foregoing steps is described in greater detail in subsequent sections.

### 14.2.1 Mold Design Checklist

Figure 14.2 provides a checklist for the completed mold design. At the top of the list is a set of design documents that the mold designer should provide to the molder/owner. The mold designer might begin by reviewing the mold purchase agreement and mold specification to verify that all requirements are fulfilled in the implemented mold design. The design documentation is typically specified relative to the bill of materials (BOM). Every mold component should be listed in the bill of materials along with that component's supplier and drawing number if custom. A full set of drawings should be delivered, including completed title blocks with material, tolerances, and finishes.

The design documentation should include a mold design report or manual describing the rationale for the mold design including analysis and simulation. Layout drawings for the feed system, water lines, and ejector systems should be provided. This mold manual should also provide layout drawings of the assembled mold from every slide and views from the parting plane; these drawings can be helpful with respect to mold maintenance. The mold manual should also provide a basic process setup sheet with the estimates used for mold design. Drawings of the molded parts, both isometric and orthogonal views, should be provided with critical to quality



attributes indicated. If the mold includes a hot runner system, then the hot runner drawings and instructions should also be provided with the mold manual. All this information should be provided in native electronic CAD format unless otherwise agreed to.

### 14.2.2 Component Verification

Mold designers/makers often take pride in their work and will typically fully assemble the mold prior to inspection by the molder/owner. Molders are often tempted to immediately take the fully assembled mold and begin molding trials. However, if the mold is to be used for long-term production, then a thorough inspection of the mold components and their assembly is warranted. The component verification items identified in Fig. 14.2 can be performed at the mold maker prior to assembly, or at the molder/owner's location after the mold has been disassembled. Each component in the mold's bill of materials (BOM) should be verified with respect to its materials, finishes, treatments, and quantity. For complex molds, it is standard practice to number cores, cavities, ejector pins, etc. according to the mold drawings to facilitate assembly and maintenance of the mold. The core and cavity inserts should be carefully inspected with respect to finish, texture, and critical dimensions against the design drawings.

During mold assembly, the molder should verify that the mold is fully marked to their satisfaction. Each plate can be marked at its top corner with a "0" or the plate number (from 1 to the number of plates in the stack) to facilitate mold reassembly. Each mold plate should have its external edges chamfered, and eyebolt holes centered on its side(s). Each water line circuit should be labeled, with water line connectors per the molder specification. To interface with the molder's machinery, the molder should verify the appropriateness of the mold's locating ring, sprue bushing, and ejector rod knock-out pattern.

# Index

## A

acceptable quality levels 461, 476, 481  
acceptance sampling 476  
actuation 466  
actuation force 363  
additional draft 38  
aesthetic defect 111  
aesthetics 29, 439  
aesthetic surface 377  
air channel 277  
allowance 89  
aluminum 261  
aluminum 6061-T6 386  
aluminum tooling 72  
amorphous 313  
amortized cost 46  
angle pins 366, 371, 489  
anisotropic shrinkage 301  
anisotropy 314  
annealing 103  
anodizing 104  
A plate 6, 94, 149  
apparent shear rate 119  
AQLs, *See* acceptable quality levels  
artificial balancing 159  
automatic de-gating 13, 197, 209  
automatic molding 374  
Automotive Industry Action Group (AIAG)  
476  
auxiliaries 50  
auxiliary equipment 14  
auxiliary systems 72  
avoid uneven filling 111  
axial compression  
– of cores 410  
axial mold opening direction 82

## B

baffles 274  
banana gate 209  
barrel temperature 312  
beam bending 394  
bending 397  
BHN, *See* Brinell Hardness Number  
bill of materials 463, 464  
blush 52  
bolt strength  
– ultimate stress 422  
BOM, *See* bill of materials  
bore diameter 365  
boss 34, 355  
boss design 34  
B plate 6, 94  
branched runners 188  
breakeven analysis 69  
Brinell Hardness Number 20, 101  
bronze gib 366  
bubbler 275, 373  
buckling 320, 323, 350  
buckling constraint 352  
bulk temperature 123  
burn marks 52, 125, 135, 227  
business development 23

## C

CAD, computer aided design 18  
cam 372, 374  
carbon black 314  
carburizing 104  
case hardening 103  
cashew gate 209  
cavities  
– shutting off during molding 486  
cavity complexity 59  
cavity cost estimation 55

- cavity discount factor 62
- cavity filling analysis 109
- cavity finishing cost 63
- cavity insert 79, 80, 87
- cavity insert retainer plate 6
- cavity layout 91
- cavity machining cost 58
- cavity materials cost 56
- cavity retainer plate 372
- cavity set cost 56
- chamfer 348
- chamfers 35
- changeover, *See* switchover
- change-over times 14
- checklist
  - for mold design inspection 463
  - for mold layout design 106
- cheek 88, 372, 402
- circular layout 92
- clamp force 186
- clamp tonnage 50, 79, 97, 110, 130
- class 72
- Class 101 mold 19, 99
- Class 103 mold 20
- clearance 356
- closed loop control 190
- coefficient of friction (COF) 104
- coefficient of linear thermal expansion 296
- coefficient of thermal expansion 291, 314
- coefficient of volumetric thermal expansion 295
- coinjection 431
- coinjection mold design 433
- coinjection molding 431
- cold runner 49, 50, 142, 144, 180, 185
- collapsible cores 373
- color change 14, 71, 175, 211
- color matching 29
- color streaking 211
- common defects 52
- complexity factor 58
- compressibility 291, 294, 296
- compression 397
- compression molding 437
- compression spring 368
- compressive stress 340, 389, 421
  - on cores 411
- computed tomography system 481
- computer aided design 18
- computer simulation 317, 322, 472
- concurrent engineering 17
- conduction heating 284
- conductive inserts 270
- conductive pin 276
- conformal cooling 269
- constraints 426
- contamination 52
- continuous improvement 493
- contoured ejector pins 347
- convective boundary 251
- coolant 11
- coolant flow rate 253
- coolant manifolds 266
- coolant temperature 311
- cooling 297
  - air channel 277
  - baffle 274
  - complexity 245
  - conductive pin 276
  - cooling line depth 257
  - cooling line pitch 260
  - cooling line routing 262
  - cooling power 252
  - cooling time estimate 250
  - heat pipe 275
  - heat transfer 243
  - heat transfer coefficient 250
  - insulating layer 280
  - internal manifold 267
  - minimum time 248
  - mold-making cost 244
  - parallel setup 267
  - post-mold 292
  - reliability 245
  - required coolant flow rate 253
  - series setup 266
  - shrinkage 292
  - system design 243, 246, 266
  - temperature distribution 265
  - temperature gradient 271
  - turbulent flow 255
  - wall temperature 244
- cooling circuit 266
- cooling insert 269, 273
- cooling line 11, 87
  - layout 91
  - maintenance 490
  - networks 266
- cooling plugs 256
- cooling stage 3
- cooling system 49, 65, 243
- cooling system cost 66
- cooling time 3, 11, 173, 243, 251, 284, 311, 447, 475
  - estimate 246

- copper 261
  - core 11, 410
    - minimum wall thickness 412
    - slender 414
  - core back 447
  - core-back molding 449
  - core bending 414
  - core deflection 414
  - core height 415
  - core insert 79, 80, 87
  - core insert retainer plate 6
  - core inserts
    - with stripper plate 357
  - core pull 330, 361
    - actuators 330
  - corner design 34
  - corrosion
    - in cooling lines 490
  - cost drivers 45
  - cost estimates 22
  - cost plus 43, 461
  - $C_p$ , *See* process capability index
  - $C_{pk}$ , *See* process capability index
  - cracks 385, 408
    - in molds 491
  - critical milestones 27
  - critical stress 116
  - Cross-WLF model 115
  - CTE, *See* coefficient of thermal expansion
  - Cu 940 270
  - cycle efficiency 50
  - cycle efficiency factor 50, 51
  - cycle time 3, 16, 27, 49, 243, 284, 446, 450
    - reduction 473, 475
  - cycle time estimate 251
  - cyclic stresses 385
- D**
- daylight 13, 96, 153
  - dead pockets 231, 239
  - deep cores 273, 410
  - defect
    - race-tracking 135
  - defect cost per part 52
  - defects
    - burn marks 125
    - flash 125
    - hesitation 111
    - jetting 111
    - short shot 111, 138
    - warpage 111
  - defects per million opportunities 481, 482
  - deflection 372, 389, 394
    - side walls 403
  - deflection temperature under load 248
  - degradation 97
  - delivery terms 44
  - density 246, 314
  - design changes 323
  - design for assembly 23, 30
  - design for injection molding 31
  - design for manufacturing 23, 30
  - design for manufacturing and assembly 291
  - design iterations 17
  - design of experiments 306, 484
  - design requirements 25
  - design standards 28
  - detailed design 23
  - development time 16
  - diaphragm 205
  - diaphragm gate 206
  - dieseling 227
  - die set for mold stack height 466
  - differential shrinkage 31, 243, 265, 318
  - dimensional adjustments 89
  - dimensional metrology 479
    - computer tomography (CT) 480
    - coordinate measurement machines 480
    - optical image recognition 480
  - dimensions 28
  - direct metal laser sintering 269
  - discount factor 56
  - dispute
    - during mold commissioning 460
  - DMLS, *See* direct metal laser sintering
  - documentation
    - of mold design 463
  - DOE, *See* design of experiments
  - double domain 294
  - dowels 417, 424
  - DPMO, *See* defects per million opportunities
  - draft angle 38
  - drawings
    - layout of subsystems 463
    - of mold design 463
  - drive-interference fit 419
  - drops 153
  - dry cycle 466, 470, 487
  - DTUL, *See* deflection temperature under load
  - dynamic melt control 190
- E**
- early ejector return 369
  - ECOs, *See* engineering change orders

- edge gate 202
  - EDM, *See* electric discharge machining
  - effective area 336, 337
  - efficiency 50
  - ejection 38, 292
    - coefficient of friction 335
    - internal stresses 334
    - molding machine setup 330
    - normal force 334
    - part removal system 331
    - surface roughness 335
  - ejection force 334, 345
    - hoop stress 337
    - pin-to-pin variations 352
    - undercuts 359
  - ejection forces
    - unbalanced 360
  - ejection stage 330
  - ejection system 327, 371
    - cooling interference 332
    - cost 333
    - ejection forces 330
    - mold opening 330
    - part aesthetics 332
    - part distortion 331
    - positive return 371
    - speed 331
  - ejection temperature 248, 336
  - ejector
    - layout 345
  - ejector assembly 327
  - ejector blade 353
    - buckling 354
  - ejector housing 6, 95, 377
  - ejector knock-out rod 328, 369, 396
  - ejector locations 110
  - ejector pad 346
  - ejector pin 181, 230, 238, 327, 350, 396
    - clearance 238
    - contoured 39
    - stepped 352
  - ejector plate 11, 146, 327, 369, 377
  - ejector retainer plate 327, 349
  - ejectors
    - alignment 349
    - buckling 351
    - clearance 349
    - compressive stresses 341
    - detailing 348
    - interference 347
    - number 343
    - placement 345
    - push area 341
      - push pin 342
      - shear stress 342
      - size 343
      - sliding bearing 348
      - stripper plate 356
      - total required perimeter 342
  - ejector sleeve 346, 355
  - ejector system 65
    - design process 333
    - design strategies 343
  - ejector system cost 66
  - ejector travel 94, 95
  - elastic deformation 359
  - elastic limit 359
  - elastic modulus 383
  - electrical connectors 466
  - electric discharge machining 407
  - encapsulated 437
  - endurance limit 100
  - endurance stress 258, 385, 505
  - energy efficiency 20
  - engineering change orders 463, 467, 484
  - ethylene glycol 257
  - excessive deflection 426
  - external undercuts 371
- ## F
- factor of safety 384
  - family mold 9, 248
  - fan gate 204
  - fasteners 417
  - fatal flaws 17
  - fatigue 100, 385, 413, 426
    - in cores 413
  - FDM, *See* fused deposition modeling
  - feed system 48, 141, 185
    - artificially balanced 145, 170
    - branched layout 160
    - comparison 15
    - cooling time 173
    - cost 66
    - cross-sections 176
    - custom layout 162
    - diaphragm 160
    - dynamic feed control 191
    - fill times 172
    - hybrid layout 161
    - imbalances in naturally balanced 188
    - insulated runner 185
    - layouts 159
    - maximum pressure drop 143
    - maximum volume 143

- naturally balanced 160, 170
  - number of turns 175
  - objectives 156
  - optimization 166
  - pressure drop specification 167
  - primary runners 147
  - radial layout 160
  - residence time 175
  - secondary runners 147
  - self-regulating valves 192
  - stack mold 186
  - standard runner diameters 183
  - steel safe design 184
  - sub-runners 216
  - tertiary runners 147
  - volume 165
  - waste factor 49
- fidelity
- of quality measurements 479
- fillers
- carbon black 314
  - glass bead 314
  - glass fiber 314
  - mica 314
  - rubber 314
- fillet 35
- filling 297
- complete cavity 110
- filling patterns 133
- filling pressure 128
- filling profile
- of injection velocity 122, 467, 472
- filling stage 2, 10
- filling time 3, 109, 125, 469
- finger 435
- finishing method 36
- finishing rates 63
- finishing time 63
- first article inspection 17, 463, 476
- fit 417
- fit for purpose 1
- fits 417
- apparent diameter 418
  - clearance 417
  - insertion force 420
  - interference 418
  - locational-clearance 425
  - locational-interference 425
  - locational-transitional 425
  - retention force 419
  - unilateral hole basis 418
  - using dowels 424
- fixed core pin 355

- flash 52, 83, 125, 228, 475
- flash gate 205
- flashing 387
- flow channel 127, 436
- flow leaders 135, 138, 416
- flow length 213
- flow rate 142
- fluid assist 431
- fluid assisted molding 434
- foam 432
- freeze-off 11
- fully automatic 50, 182
- fully automatic molding 13, *See also* injection molding
- fused deposition modeling 72, 269

## G

- gantry robots 331
- gas assist 431
- gas assist molding 434
- gas trap 134, 145
- gas traps 229, 239
- gate 11, 146, 197
- ring 416
- gate freeze time 221, 223, 469, 473
- gate types 216
- gate well 201
- gating
- automatic de-gating 197
  - comparison 216
  - design recommendations 218
  - diaphragm gate 205
  - direct sprue 200
  - edge gate 202
  - fan gate 204
  - film gate 205
  - fine-tuning 224
  - flash gate 205
  - freeze time 222
  - gating location 213
  - no-flow temperature 222
  - objectives 197
  - pack time 199
  - pin-point gate 201
  - pressure drops 219
  - shear rates 198, 217
  - submarine gate 209
  - tab gate 203
  - thermal gate 209
  - thermal sprue gate 211
  - tunnel gate 206
  - vestige 198

gating design 197, 213  
 gating flexibility 12, 14, 16  
 gating location 109, 127  
 gauge repeatability and reproducibility 309, 477, 478  
 gauge R & R, *See* gauge repeatability and reproducibility  
 geometric complexity 58  
 geometric distortion 31  
 gibs 371  
 glass bead 314  
 glass fiber 314  
 glass filled 301  
 gloss 281, 285, 286  
 gloss level 29  
 grid layout 92  
 guides  
 – for ejector blades 354  
 gusset 34

## H

H13 steel 102  
 Hagen-Poiseuille 163, 257  
 hardness 101  
 HDT 248  
 hear stresses 114  
 heat conduction 246  
 heat content  
 – of moldings 252  
 heat deflection or distortion temperature 248  
 heater resistance 466  
 heat flux 260  
 heating element 439  
 heat load 284  
 heat pipes 275  
 heat transfer 11  
 – insulating layer 287  
 heat transfer coefficient 250  
 heel block 368  
 height allowance 88  
 height dimension 87  
 helix 375  
 hesitation 111  
 hoop stress  
 – in cores 412  
 hot runner 14, 46, 64, 142, 153, 185, 209  
 – color change 144  
 – maintenance 489, 490  
 – residence time 144  
 – turn-over 144  
 hot runner mold 14, 16

hot runner system  
 – configurations 155  
 – H manifold 155  
 – stacked manifolds 155  
 – straight-bar 155  
 – X manifold 155  
 hot spots 270  
 hot sprue bushing 14, 153  
 hourly rate 49  
 hourly wage 62  
 hybrid layout 93  
 hydraulic actuators 364  
 hydraulic diameter 177

## I

improper color match 52  
 increased molding productivity 14  
 indexing head 445  
 indirect costs 45  
 induction heating 285  
 initial investment 16  
 injection blow molding 443  
 injection blow molds 443  
 injection compression 373, 432, 435  
 injection decompression 435  
 injection mold 4, 6  
 injection molding  
 – cooling stage 475  
 – filling stage 471  
 – fully automatic molding 487  
 – packing stage 472  
 – process capability 481  
 – semiautomatic mode 487  
 injection molding process 1, 2, 16  
 injection molding process timings 3  
 injection pressure 97  
 – maximum 110, 471  
 injection velocity 471  
 injection velocity profiling 471  
 ink  
 – after mold rebuilding 491  
 – to check fits 466  
 in-mold film  
 – indexed 455  
 – statically charged 454  
 in-mold labeling 453  
 in-mold sensors 306  
 insert creation 87  
 insertion force 417  
 insert mold 437, 439  
 insert sizing guidelines 87  
 inspections 47

insulated runner 185  
 intellectual property 45  
 interlock 362  
 interlocking 415  
 interlocking core 277  
 interlocking features 85  
 internal corners 271  
 internal thread 41  
 internal threads 374  
 internal voids 33  
 isothermal boundary 249  
 isotropic 300  
 iterative mold development 16

## J

jetting 125, 199, 468

## K

Kentucky windage 322, 323  
 key product characteristics 459, 476  
 keyway 362  
 knit-line 145  
 knit-line location 439  
 KPCs, *See* key product characteristics

## L

laminar flow 163  
 laser sintering 72  
 lay flat 110, 129, 133  
 layout design  
 – conflict 93  
 lean manufacturing 72, 267  
 length dimension 88  
 liability  
 – mold designer/maker 463  
 – molder 486  
 lifter 40  
 limit stress 100, 384, 386  
 limit switches 366  
 linear flow velocity 119  
 linear melt flow 204  
 linear melt velocity 157  
 linear shrinkage 300  
 linear velocity 112  
 locating dowel 357  
 locating pins 417  
 locating ring 7  
 locational-interference fit 419  
 lofted surfaces 85  
 lost core molding 41, 441

LPL, *See* processing limits  
 LSL, *See* specification limits  
 lubricity 104

## M

machine capability factor 50  
 machining and wear performance 101  
 machining efficiency factor 61  
 machining factor 58  
 machining labor rate 58  
 machining rate 101  
 machining time 58  
 maintenance 44, 228  
 – venting 228  
 maintenance cost 16, 48  
 maintenance plan 461  
 managed heat transfer 286  
 manifold 153, 187, 443  
 – cooling 267  
 manufacturing strategies 72  
 manufacturing strategy  
 – for purchasing molds 460  
 marginal cost 69  
 material consumption 16  
 material cost per part 46, 48  
 material removal rate 59  
 materials cost 45  
 material supplier 316  
 material waste 49  
 maximum cavity pressure 110  
 maximum deflection 398  
 maximum diameter 255  
 maximum shear stress 402  
 maximum stroke 353  
 mechanisms 466, 489  
 melt flipper 160, 189  
 melt flow  
 – pressure drop 121  
 – velocity profile 120  
 melt front advancement 110  
 melt front velocity 468  
 melt pressure 109, 142  
 – injection limit 143  
 – maximum, due to endurance stress 258  
 melt temperature 294  
 metrology 476  
 MFI, melt flow index 115  
 mica 314  
 microfinish 36  
 minimum cooling line diameter 255  
 minimum draft angle 38  
 minimum wall thickness 129



- mirror finish 36
- modulus 336
- mold acceptance 459
- mold base 17, 18, 53, 79, 93, 97
- mold base cost estimation 54
- mold base selection 91
- mold base sizing 93
- mold base suppliers 97
- mold cavity 2, 80
- mold commissioning 17, 29, 459
  - component verification 464
  - general process 462
  - mold assembly 466
  - mold map 488
  - mold verification 463
  - process 462
  - recommissioning 491
  - saving the last molding 489
- mold cost estimation 53
- mold cost per part 47
- mold customer 43
- mold customization 64
- mold defect codes 488
- mold design 16, 21, 24
- mold development process 17, 25
- mold dimensions 54
- molded-in stresses 292
- Moldex3D 303
- mold filling simulation 121, 317
  - lay-flat analysis 128
- mold filling simulations 110
- Moldflow Plastics Insight 122, 303
- mold functions 4
- molding cycle 297
- molding machine 50
- molding machine capability 51
- molding machine compatibility 95
- molding processes
  - strategic advantages 429
- molding process instabilities 469
- molding process setup sheet 468
- molding productivity 15
- molding trial methodology 470
- molding trials 17, 44, 470
- mold insert 361
- mold inspection checklist 465
- mold interlocks 404
- mold layout design 54, 79
- mold log and maintenance checklist 486
- mold maintenance 37, 97, 485
  - post-molding 485, 489
  - pre-molding 485, 487
  - rebuilding 485
  - regular preventive 485, 489
- mold manual 463
- mold map 488
- mold materials
  - A2 100, 102
  - aluminum 6061-T6 99
  - aluminum 7075-T6 99
  - aluminum QC10 98, 99
  - C-18200 100
  - D2 100
  - digital ABS 102
  - grain structure 103
  - H13 100
  - SS420 99
  - Ultem (PEI) 102
- mold material selection 98, 107
- mold opening direction 79, 80
- mold opening distance 150
- mold opening height 13
- mold operating log 488
- mold prototyping 73
- mold purchase agreement 44
- mold quoting 24, 43
- mold rebuilding 47, 490
- mold reset time 3
- mold setup time 267
- mold structures 6
- mold supplier 43
- mold technology 429
- mold technology selection 430
- mold temperature controllers 253
- mold texturing 37
- mold wall temperature control 281
  - conduction heating 284
  - induction heating 285
  - insert mold 439
  - managed heat transfer 286
  - passive heating 286
  - pulsed cooling 281
- moment of inertia 351, 354, 394, 414
- moving cavity inserts 371
- moving core 330, 362
- moving half 11, 404
- moving platen 11, 96
- moving side 332
- multicavity molds 9, 91
- multigated 14
- multilayer injection blow molding 445
- multishot molding 280
- multishot molds 447
- multi-station 447

multi-station mold 451  
 multivariate optimization 166

## N

naturally balanced 154, 162  
 naturally balanced feed system 92  
 net shape manufacturing 1  
 Newtonian 219  
 Newtonian limit 116  
 Newtonian model 117, 163  
 nitriding 104  
 nominal dimensions 311  
 nominal shrinkage rate 312  
 nonuniform shrinkage 475  
 normal probability 478  
 nozzles 153

## O

oil, for cooling 257  
 one-sided heat flow 278, 447  
 opening time 153  
 open loop control 191  
 operating cost 15  
 orientation 112  
 orifice diameter 95  
 original design manufacturer 30  
 original equipment manufacturer 30  
 over-filling 145  
 overmolding 280, 447  
 over-packing 111, 315, 469  
 overpressure 413, 426

## P

P20 steel 98, 100, 102, 383  
 packing 297  
 packing pressure 294, 469, 473  
 packing stage 2  
 – gate freeze time 222  
 packing stage profiling 473  
 packing time 3, 199, 311, 473  
 pack pressure profiling 312, 323, 473  
 parison 444, 446  
 part cost 46  
 part dimensions 473  
 parting line 83, 84, 86  
 parting plane 9, 79, 80, 84, 93, 146, 228, 236, 404  
 parting surfaces 334  
 part interior 231  
 payment terms 27

peak clamp tonnage 131  
 physical vapor deposition 104  
 pilot production 24  
 pin length 352  
 pin-point gate 201  
 planetary gears 376  
 plastication 297  
 plastication stage 2  
 plastication time 3  
 plastic part design 21  
 plate bending 382, 392  
 plate compression 389  
 platen deflection 387  
 platens  
 – bending 381  
 plating 104, 491  
 polyjet printing 73, 269  
 polymer  
 – amorphous 295  
 – compressibility 296  
 – semicrystalline 295  
 poor gloss 52  
 positive return 369  
 power-law 163, 167, 219  
 power law index 116, 119, 120  
 power law model 119  
 power law regime 116  
 PPAP, *See* production part approval process  
 preliminary quote 16  
 preloading 400  
 pressure difference 414  
 pressure drop 110, 113, 142, 163, 219, 255  
 – annulus 179  
 – channel flow 119  
 – gates 198  
 – in vents 234  
 – tube flow 163  
 pressure test  
 – of water lines and feed system 466  
 pressure transmission 14  
 pressure-volume-temperature 309  
 preventive maintenance 47  
 process capability, *See* injection molding  
 process capability index 479  
 – rolled-up 483  
 processing conditions 124  
 – robust 484  
 processing cost 44  
 processing cost per part 46, 49  
 processing limits 483  
 process optimization  
 – of injection molding 461

process simulation 121, *See also* simulation  
 process window 483  
 process window development 483  
 product definition 22  
 product design 16, 23  
 product development process 21, 24  
 production data 27  
 production flexibility 72  
 production part approval process 476, 482  
 production planning 23, 27  
 projected area 51  
 projections 449  
 prototype mold 316  
 prototype molding 29  
 pulsed cooling 281  
 purchase agreement  
   – for injection molds 459, 463  
   – warranties for injection molds 463  
 purchase agreements  
   – for molded products 461  
 purchase cost 15  
 purge 175  
 purging 14  
 push area 340  
 push-pin 331, 342  
   – defect 475  
 PVT, pressure-volume-temperature behavior  
   294

## Q

QC7 aluminum 383  
 QC10 aluminum 270  
 quality assurance 476  
 quality assurance methodology 477  
 quick ship 98  
 quoting process 43, 158

## R

race-tracking 134, 135  
 radial flow 204  
 radial mold opening direction 81  
 rails 6, 327  
 rear clamp plate 6, 327, 395  
 recommended melt velocity 125, 127  
 reduced material consumption 14  
 reduce setup times 72  
 regulatory agencies 25  
 replacement parts 461  
 requests for quotes 43  
 required heat transfer rate 252  
 residence time 175

residual stress 111, 292  
 retainer plate 88, 366  
 return pins 327  
 reverse ejection 333, 377  
 rework  
   – cost of 460  
 Reynolds number 163, 255  
 RFQs, request for quote 43  
 rheology 115  
 rib design 33  
 root cause analysis 459  
 rotating cores 375  
 rubber 314  
 rule of thumb 251  
 runner 10, 142, 146, 149, *See also* feed system  
   – annulus 179  
   – efficiency 178  
   – full round 176  
   – half-round 176  
   – hydraulic diameter 177  
   – round-bottom 176  
   – shut-offs 182  
   – standard sizes 183  
   – trapezoidal 176  
 runner volume 165

## S

safety margin 109  
 scientific molding 123, 463, 470  
 selective laser sintering 269  
 self-regulating valve 191  
 self-threading screws 34  
 semiautomatic 50  
 semiautomatic mode, *See* injection molding  
 semicrystalline 313  
 sensor  
   – cavity pressure 306  
   – cavity temperature 306  
 sensor stack 306  
 series layout 91, 159  
 setup sheet  
   – for molding 467  
 sharp corners 34  
 shear heating 468  
 shear rate 112, 115, 217  
 shear rates  
   – maximum 217  
 shear stress 112, 340, 372, 392, 405, 455  
 shear thinning 120  
 shims 466  
 short shot 52, 111, 125, 142, 199  
 short shot studies 471

- shot size 97, 471
- shot volume 97
- shot weight stability studies 3
- shrinkage 11, 112, 291, 292, 432
  - anisotropic 302
  - contractual obligation 317
  - in-mold 310, 475
  - isotropic 303
  - linear 292, 300
  - lower limit 314
  - negative 315
  - nonuniform 304
  - pack pressure profiling 312
  - post-mold 310
  - post-molding 475
  - processing dependence 311
  - recommendations 315
  - uncertainty 316
  - uniformity 323
  - upper limit 315
  - validation 306
  - volumetric 300
- shrinkage analysis 293
- shrinkage behavior 29
- shrinkage data 316
- shrinkage range 314
- shut-offs 86
- shut-off surface 230
- side action 361
- side wall
  - deflection 402
- side walls 372
  - bending due to shear 402
- Sigmasoft 303
- simulation
  - Moldex3D 122
  - mold filling 121
  - Moldflow 122
  - shrinkage 303
  - Sigmasoft 122
  - Simpoe 122
- single cavity 14
- single cavity mold 91
- sink 33, 203
- sink marks 286
- sintered vent 240
- slender 415
- slender core 272, 278
- slides 366
- slideways 371
- sliding cores 366
- sliding fit 362, 432
- SLS, selective laser sintering 269
- snap beam 39
- snap finger 39
- S-N, stress-number fatigue curve 385, 505
- Society of the Plastics Industry 19, 36
- socket head cap screws 6, 417, 422
- solidification temperature 336
- solidified plug 209
- solidified skin 281
- solvent 448
- specification limits 479
- specific heat 246
- specific volume 313
  - relation to shrinkage 298
- SPI *See* Society of the Plastics Industry
- SPI finish 36
- splay 52, 199, 468
- split cavity 443, 446
- split cavity design 82
- split cavity mold 82, 334, 371
- sprue 95, 142
- sprue break 148
- sprue bushing 10, 146, 149
- sprue gate 200
- sprue knock-out pin 147
- sprue pickers 331
- sprue pullers 12, 150, 180
- SS420 steel 102
- stack height 94, 96, 153, 187, 388
- stack molds 186, 452
- staged deployment 311
- stagnant material 210
- standards 19
- start-up times 16
- stationary half 11, 404
- statistical process control 476
- steady flow 113
- steel safe 143, 218, 310, 316, 347
- steel safe designs 184
- stereolithography 72, 269
- stop pins 327
- strain 359, 383, 389
- strength 100
- stress 383
  - during ejection 359
- stress concentrations
  - due to cooling lines 257
  - ejector holes 407
  - water lines 407
- stress-strain behavior 383
- stripper bolt 12, 150
- stripper plate 12, 149, 356
- structural and thermal performance 100

structural design 67, 381  
   – minimize stress 382  
   – mold deflection 387  
   – mold size 388  
   – safety factor 384  
 structural integrity 245  
 structural system design 381  
   – cost 67  
 structured development 21  
 submarine gate 209  
 sub-runners 216  
 sucker pins 150, 180, 209  
 superposition 397  
 supply chain 19, 23, 44, 158  
 support pillars 388, 395  
 support plate 6, 94, 327, 372, 395  
 surface area 59  
 surface area removal rate 505  
 surface finish 36  
 surface refinishing 491  
 surface roughness 36, 38  
 surface striations 52  
 surface texture 36, 37  
 surface treatments 103  
 switchover 486  
   – dynamics of velocity and pressure 474  
   – position 472, 475  
   – surge forward 475  
 switchover condition 472

## T

tab gate 203  
 Tait equation 294  
 technical feasibility 27  
 temperature differences 286  
 temperature differential 266  
 temperature fluctuations 281  
 temperature gradient 243, 260, 265  
 temperature variation 262  
 tensile stress 336  
 test mold 316  
 thermal conductivity 243, 246  
 thermal contact resistance 264, 332  
 thermal contraction 291  
 thermal diffusivity 246  
 thermal expansion 291, 296  
 thermal gate 14, 209  
 thermal sprue gate 211  
 thermal strain 336  
 thermocouple 466  
 thermoplastic elastomer 280  
 thermoreactive diffusion 104

thickness 49  
 thin wall 125, 143, 281, 409  
 three-dimensional printing 72  
 three-plate 142, 148, 153, 180  
 three-plate mold 12, 13, 16, 185  
 thrust pads 154  
 tie bar 95  
   – tension 381  
 tie bar spacing 95  
 tight tolerance 29, 281, 305, 313, 323,  
   387, 389  
 tight tolerances 293  
 tolerance 28, 311  
   – stack-up 347, 348  
 tolerance limit 419  
 tolerances  
   – tight 293  
   – typical 293  
 tolerance specifications 29  
 tolerance stack-up 356  
 toll-gate process 21  
 top clamp plate 6  
 torpedo 209  
 total cost 68  
 TPE, thermoplastic elastomer 280  
 tuning loops 459  
 tunnel gate 206  
 turbulent flow 255  
 turret drives 452  
 two cavity 9  
 two-plate 142, 146, 153  
 two-plate mold 7, 11, 16  
 two-shot molding 280  
 type of gate 110  
 typical tolerance 29

## U

ultimate stress 100, 383  
 undercut 39, 208, 359, 361, 449  
   – horizontal boss 39  
   – internal thread 41  
   – overhang 39  
   – side window 39  
   – snap finger 39  
 undercuts 334  
 undercutting 373  
 uniformly distributed 345  
 uniform wall thickness 31  
 unsupported spans 393  
 UPL, *See* processing limits  
 USL, *See* specification limits

## V

valve gate 187, 212  
 valve pin 179, 212  
 velocity to pressure switchover 474  
 vent channel 236  
 venting 227, 348  
 - analysis 228  
 - dead pockets 239  
 - defects 227  
 - design 229, 236  
 - dimensions 232  
 - ejector pins 238  
 - flashing 228  
 - locations 110, 229  
 - maintenance 228  
 - pressure drop 234  
 - relief 236  
 - thickness  
 - maximum 235  
 - minimum 233  
 vertically integrated molders 44  
 viscosity 112, 115  
 - Arrhenius temperature dependence 116  
 - Cross-WLF model 115  
 - Newtonian model 118  
 - Newtonian plateau 117  
 - no-flow temperature 222  
 - power law model 119  
 - power law regime 116  
 - WLF temperature dependence 116  
 viscous flow 112  
 volumetric flow rate 118, 120, 171  
 volumetric removal rate 505  
 volumetric shrinkage 33, 297, 473  
 von Mises stress 382, 407  
 V/P, *See* switchover condition

## W

wall thickness 32, 109  
 - minimum 127  
 warpage 52, 111, 243, 291, 317  
 - avoidance strategies 323  
 - differential shrinkage 318  
 - Kentucky windage 322  
 - out of plane deflection 318  
 - pressure gradient 319  
 - radius of curvature 318  
 - sources 318  
 - temperature gradient 318  
 water assist 431  
 water assist molding 434  
 water lines 487  
 - maintenance 489  
 wear  
 - maintenance of 490  
 wear plates 372  
 weld line 134  
 width dimension 88  
 windage 322  
 window 86  
 witness line 83, 86, 333, 358, 375  
 witness mark 198, 332, 377, 446  
 worst case scenario 384, 423

## Y

yield 46, 53, 481  
 yield estimates 52  
 yield stress 100, 383

## Z

zero shear viscosity 116, 118