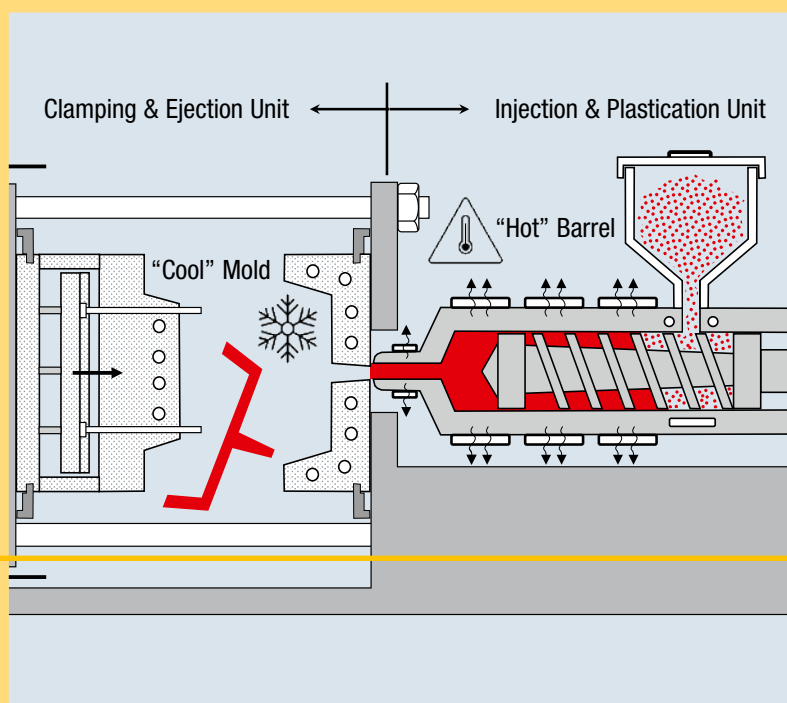


Robert A. Malloy

Plastic Injection Molding

A Practical Guide



HANSER

Accessibility disclaimer

Carl Hanser Verlag goes to great lengths to make its products accessible. This also includes making images or tables accessible for blind and visually impaired people. This is achieved through additional descriptive texts (alternative texts) that are integrated into the data. The alternative texts can be read aloud by assistive technologies (e.g. screen readers). An AI supports our teams of authors in the creation of these texts. Responsibility for the content remains with the editors and authors.

Malloy
Plastic Injection Molding

Robert A. Malloy

Plastic Injection Molding

A Practical Guide

HANSER



Print-ISBN: 978-1-56990-879-2

E-Book-ISBN: 978-1-56990-880-8

All information, procedures, and illustrations contained in this work have been compiled to the best of our knowledge and is believed to be true and accurate at the time of going to press. Nevertheless, errors and omissions are possible. Neither the authors, editors, nor publisher assume any responsibility for possible consequences of such errors or omissions. The information contained in this work is not associated with any obligation or guarantee of any kind. The authors, editors, and publisher accept no responsibility and do not assume any liability, consequential or otherwise, arising in any way from the use of this information – or any part thereof. Neither do the authors, editors, and publisher guarantee that the described processes, etc., are free of third party intellectual property rights. The reproduction of common names, trade names, product names, etc., in this work, even without special identification, does not justify the assumption that such names are to be considered free in the sense of trademark and brand protection legislation and may therefore be used by anyone.

The final determination of the suitability of any information for the use contemplated for a given application remains the sole responsibility of the user.

Bibliographic information of the German National Library:

The German National Library lists this publication in the German National Bibliography; detailed bibliographic data are available on the Internet at <http://dnb.d-nb.de>.

This work is protected by copyright.

All rights, including those of translation, reprint, and reproduction of the work, or parts thereof, are reserved. No part of this work may be reproduced in any form (photocopy, microfilm, or any other process) or processed, duplicated, transmitted, or distributed using electronic systems, even for the purpose of teaching – with the exception of the special cases mentioned in §§ 53, 54 UrhG (German Copyright Law) – without the written consent of the publisher.

No part of the work may be used for the purposes of text and data mining without the written consent of the publisher, in accordance with § 44b UrhG (German Copyright Law).

© 2026 Carl Hanser Verlag GmbH & Co. KG, Munich

Vilshofener Straße 10 | 81679 Munich | info@hanser.de

www.hanserpublications.com

www.hanser-fachbuch.de

Editor: Dr. Mark Smith

Production Management: Der Buchmacher, Arthur Lenner, Windach

Cover concept: Marc Müller-Bremer, www.rebranding.de, Munich

Cover design: Max Kostopoulos

Cover picture: © Robert A. Malloy

Typesetting: Eberl & Koesel Studio, Kempten

Printed and bound by: Elanders Waiblingen GmbH, Waiblingen

Printed in Germany

Dedicated to my friends and mentors Professor Stephen Driscoll and Professor Stephen Orroth, who have both shared their vast plastics engineering knowledge with so many, without ever seeking recognition for their efforts.



Stephen A. Orroth



Stephen B. Driscoll

The Author



Robert Malloy is a Professor Emeritus of Plastics Engineering at the University of Massachusetts Lowell. He served as a faculty member at UMass Lowell for more than 30 years, the last 12 of which he was the department chair prior to his retirement from the university in 2016. He has also served as a faculty member at the Algerian Petroleum Institute Plastics Program in Annaba, Algeria before joining the faculty at Lowell. Over the years, he has taught hundreds of courses on the subjects of plastic materials, plastic processing, plastic part design, injection mold design, and engineering fundamentals. He has also served as advisor to many plastics engineering, manufacturing engineering, and biomedical engineering graduate students.

Professor Malloy is now an active researcher and engineering consultant in the areas of thermoplastic processing, plastic part design, and thermoplastic recycling. He is the author of many book chapters, patents, and publications including books on the subjects of “Plastic Part Design for Injection Molding” and “Injection Molding”. Over the years he has been active in a number of professional engineering societies. He is a past chairman of the Society of Plastics Engineers (SPE) Injection Molding Division, a recipient of SPE’s International Education Award, and a Fellow of the SPE. Professor Malloy is also a member of the Plastics Hall of Fame being inducted in 2012.

Preface

I have spent the majority of my professional engineering career as an educator and researcher in the areas of plastic materials, plastic part design and plastic processing. From the beginning, I have been fascinated by the injection molding process, due in large part to the versatility of this plastics manufacturing process. The injection molding process can be used to manufacture plastic parts that range from micro-size, complex geometry parts weighing only milligrams, to large automobile and truck body panels weighing many kilograms. Unfortunately, it is this incredible versatility that makes writing such a “how to do” book difficult, because there are few (if any) rules or guidelines that apply to all injection molding applications. Fortunately, there are many excellent books dedicated to injection molding technology. While this is true, I felt that it would be beneficial for me to share some of my experiences and the various plastics processing philosophies that I have developed over the years working with injection molding process. While plastic molding professionals with many years of experience may derive only limited benefit from this introductory text, it is hoped that those new to thermoplastic processing and injection molding will benefit more from reading or referencing the material in this book. For this reason, the text includes a large number of concept illustrations that should help the reader gain a better understanding of the topics being discussed.

The material presented in this book is limited to discussion of the thermoplastic injection molding process. Even with this limitation, there are literally thousands of commercial injection molding grades of thermoplastic available on the market today. Having an understanding of the processing requirements for these materials is a prerequisite to successful part production. For example, a molder with decades of experience molding an amorphous material, such as polystyrene, may encounter completely different processing issues when molding a semi-crystalline, glass fiber reinforced polypropylene. These materials can both be injection molded, but their processing characteristics are very different. As a result, the first chapter of this text is dedicated

to discussing the fundamental issues associated with thermoplastic materials and the additives they contain. It is my strong opinion that injection molding process technicians and engineers should have a very good understanding of the molding material properties before starting up a new injection molding process. Chapter 1 has been written in the hope that it will assist injection molding professionals with material supplier and customer communications.

The second chapter of the book is dedicated to the discussion of injection molding machinery and auxiliary equipment. Ideally, the molding machinery and auxiliary equipment used in manufacturing have been designed and purchased specifically for a specific molding application. While this is possible in some dedicated manufacturing operations, such as dedicated high-volume packaging applications, this is not always the case. Much of the injection molding industry is based on custom molding. A key with custom molding is to insure that all of the molding machinery used is closely matched to the application. Machinery considerations range from shot and clamp capacity to plasticating screw and nozzle geometry. The key variables associated with both molding and auxiliary machinery are given in this second chapter.

Chapter 3 of this book focusses on setting the process variables for the conventional injection molding process. The injection molding process is complex, and involves a large number of both sequential and concurrent process variables. Many different philosophies have been developed to assist molding professionals in setting these process variables, many of which exhibit complex interactions. These variable set points will influence both production rate and molded part quality. These two considerations are sometimes in conflict, making some set point decisions difficult. In this chapter, the effect that each primary process variable has on both production rate and part quality are discussed in an effort to provide some rationale or guidance on which process technicians or engineers can base their process set point decisions.

The fourth and last chapter provides a very basic overview of “other” non-standard injection molding processes. There are some molding applications where conventional injection molding is not the optimum process. For example, the low-pressure structural foam molding process may be a more appropriate process option when molding relatively thick, large thermoplastic parts. While this chapter does provide a basic description of these modified injection molding processes, the reader is directed to other sources if a more in-depth coverage of the specific modified molding process is required.

Lastly, I would like to sincerely thank the editorial staff at Hanser Publications, especially Rebecca Wehrmann and Mark Smith, for their encouragement and assistance with this project. I would also like to acknowledge and thank the following individuals from Wittmann USA, Inc. for their willingness to provide technical information that will hopefully benefit the injection molding industry in a broad way. Thanks to David Preusse, Steve Mussmann, Richard Heckbert, Chris Turnberg, and Crystal Bro-

cious for hosting my visit to the Wittmann USA facility in Torrington, CT. I also thank my colleagues at UMass Lowell for the many discussions that have helped me grow personally and professionally.

July 2025

Robert Malloy

Contents

The Author	VII
Preface	IX
Contents	XIII
1 Injection Molding: Thermoplastic Material Considerations ...	1
1.1 Basic Injection Molding Process Overview	1
1.2 Material Considerations for the Injection Molding Process	4
1.3 Thermoplastic Material Nomenclature	6
1.4 The Four Plastic Material Pillars	9
1.4.1 Plastic Material Pillar #1: Average Polymer Chain Length	10
1.4.1.1 Melt Flow Rate (MFR)	12
1.4.1.2 Molecular Weight Distribution	15
1.4.2 Plastic Material Pillar #2: Repeating Unit Chemical Structure	17
1.4.2.1 Polymer Structure Nomenclature	17
1.4.2.2 Polarity and Hygroscopicity	19
1.4.2.3 Hydrolytic Degradation for Condensation Polymers	21
1.4.3 Plastic Material Pillar #3: Morphology or Chain Arrangements ...	24
1.4.3.1 Amorphous Morphology	25
1.4.3.2 Semi-Crystalline Morphology	26
1.4.3.3 Post-molding Dimension Changes	30
1.4.4 Plastic Material Pillar #4: Additives	31
1.4.4.1 Additives: Method of Incorporation	32

1.4.4.2	Additives: Negative Side Effects	34
1.4.4.3	Additives: Short and Long Fiber Reinforced Plastics.....	36
1.4.4.4	Additives: Other Polymers	39
1.5	Physical Forms of Plastic Raw Material.....	42
1.5.1	Housekeeping Considerations for Thermoplastic Pellets.....	44
1.6	Commercial Plastic Designations	45
1.6.1	IUPAC Chemical Nomenclature	45
1.6.2	Trademarked Thermoplastic Nomenclature.....	45
1.6.3	ASTM D4000 Nomenclature Standard	46
1.7	Re-use of Manufacturing Scrap or “Regrind”.....	47
1.7.1	Source of the Regrind	48
1.7.2	Material Considerations for Regrind	50
1.7.3	Processing Considerations for Thermoplastic Regrind	50
1.8	Thermal Transitions.....	52
1.8.1	Thermal Transitions for Amorphous Thermoplastics	52
1.8.2	Thermal Transitions for Semi-crystalline Thermoplastics	54
1.8.3	Other Thermal Properties: DTUL and Vicat Softening Temperature	56
1.8.3.1	Deflection Temperature Under Load (DTUL).....	56
1.8.3.2	Vicat Softening Temperature.....	57
1.8.3.3	Correlation With Glass Transition Temperature	58
1.9	Injection Molded Part Cooling Time Estimation	59
1.10	Thermoplastic Material Flow Behavior	62
1.11	Generic Identification and Marking Codes for Thermoplastic Parts	65
1.11.1	The SPI (now PLASTICS) Resin Identification Coding System.....	65
1.11.2	Other Injection-Molded Plastic Part Marking Protocols.....	66
1.12	Get to Know Your Plastic Material	67
1.12.1	Plastic Material Data Sheets and Injection Molding Process Guides.....	68
2	Injection Molding Machinery and Auxiliary Equipment	75
2.1	Injection Molding Process Evolution	75
2.1.1	Compression Molding Process	75
2.1.2	Early Injection Molding Processes.....	78
2.1.3	Improving Plasticating Capacity and Shot Size	81
2.1.3.1	Plunger Injection Molding Machines.....	81
2.1.3.2	Reciprocating Screw Injection Molding Machines.....	83
2.1.3.3	Reciprocating Screw Equipped with a Non-Return Valve ..	84

2.2	Major Components of a Reciprocating Screw Injection Molding Machine.	86
2.2.1	Injection Molding Machine Controller	88
2.2.1.1	Basic Injection Molding Process Steps.	89
2.2.2	Injection and Plasticating Unit	91
2.2.2.1	Feed Material Handling Equipment.	94
2.2.2.2	Injection Molding Machine Barrel and Barrel Heaters.	103
2.2.2.3	Reciprocating Screws	106
2.2.2.4	Non-Return (Check) Valves.	119
2.2.2.5	Injecting Molding Nozzles	123
2.2.3	Injection Molding Machine Clamping Unit	133
2.2.3.1	Directly Acting Hydraulic Clamp Unit.	134
2.2.3.2	Estimating Clamp Force Requirements.	139
2.2.3.3	Toggle Mold Clamping Units	143
2.2.3.4	Tie-Bar-Less Mold Clamping Units.	145
2.2.3.5	Injection Mold Lifting Hardware	146
2.2.3.6	Injection Mold Mounting Clamps.	150
2.2.3.7	Mold Insulation Sheets	155
2.2.3.8	Single Minute Exchange of Die (SMED) Carts	156
2.3	Injection Molds	158
2.3.1	Injection Mold Functions.	158
2.3.2	Cold Runner Injection Molds	159
2.3.2.1	Cold Runner Geometry	161
2.3.2.2	Injection Mold Vents	166
2.3.2.3	Injection Mold Cooling	169
2.3.3	Conventional Hot Runner Injection Molds	170
2.3.4	Valve-Gated Hot Runner Injection Molds.	172
2.3.5	In-Mold Pressure Sensors	174
3	Injection Molding Process Variables and Their Effect on Part Quality	179
3.1	Pre-Production Process Planning	179
3.1.1	Customer Communications and Molded Part Target Specifications.	181
3.1.2	Material Supplier Molding Process Recommendations	182
3.1.3	Molding Machinery Selection for Captive Injection Molding	183
3.1.4	Molding Machinery Selection for Custom Injection Molding	184

- 3.2 Molding Material Preparation 188
 - 3.2.1 Hygroscopic Material Pre-Drying 188
 - 3.2.2 Vented Barrel Processing..... 190
 - 3.2.3 Moisture Re-absorption 190
 - 3.2.4 Multi-Material Feed Streams..... 191
- 3.3 Injection Mold Temperature Considerations 192
 - 3.3.1 Mold Temperature Range 192
 - 3.3.2 Skin Layer Development 194
 - 3.3.3 Frozen-in Molecular Orientation..... 196
 - 3.3.4 Degree of Crystallinity 198
 - 3.3.5 Mold Temperature Controllers..... 199
 - 3.3.6 Mold Cooling Water Flow Rate 202
 - 3.3.6.1 Turbulent Coolant Flow 203
 - 3.3.6.2 Cooling Channel Scaling 205
 - 3.3.7 Rapid Heat Cycle Molding Processes..... 206
 - 3.3.8 Post Mold Annealing..... 209
- 3.4 Barrel, Nozzle and Melt Temperature Considerations..... 210
- 3.5 Evaluation of Melt Quality and Melt Temperature..... 214
 - 3.5.1 Safety Considerations When Purging 214
 - 3.5.2 Visual Observations When Purging 215
 - 3.5.3 Measuring Bulk Melt Temperature..... 218
- 3.6 Phases of the Injection Molding Process 221
- 3.7 Injection Unit Carriage Position Options..... 226
 - 3.7.1 Operation Without Sprue Break 226
 - 3.7.2 Operation With Sprue Break..... 227
- 3.8 Shot Size (Dose) 228
- 3.9 Mold Filling Injection Velocity 230
 - 3.9.1 Open Loop Injection Units..... 230
 - 3.9.2 Closed Loop Velocity Controlled Injection Units 232
 - 3.9.2.1 Setting Injection Velocity 233
 - 3.9.2.2 Considerations Associated with Fast Mold Filling Rates.... 234
 - 3.9.2.3 Mold Venting Considerations..... 237
 - 3.9.2.4 Experimental Injection Velocity Study 239
 - 3.9.2.5 Multi-stage Injection Velocity Profiling..... 240
 - 3.9.3 Low Injection Velocity Constant Pressure Molding..... 243

3.10	Packing Pressure and Packing Time.	244
3.10.1	Pack Pressure: Final Mold Filling Considerations	246
3.10.2	Pack Pressure: Compression Phase Considerations	249
3.11	Holding Pressure and Holding Time	252
3.11.1	Effect of Holding Pressure Magnitude	253
3.11.2	Effect of Holding Pressure Time.	255
3.11.3	Experimental Gate Seal Study	257
3.11.4	Limitations Associated with Constant Holding Pressure	259
3.11.5	Multi-stage Holding Pressure Profiling	262
3.12	Plastication Delay Time	264
3.13	Decompress Before Screw Rotation	267
3.14	Screw Rotational Speed and Back Pressure	268
3.14.1	Screw Rotational Speed	269
3.14.2	Back Pressure	270
3.15	Decompress After Screw Rotation.	272
3.16	Additional Cooling Time	274
3.17	Part Ejection Parameters.	278
3.18	Part Dimensional Qualification.	279
3.18.1	Measurement Errors.	279
3.18.2	Dimensional Stabilization Time.	280
3.19	Molding Process Shut-Down Procedures.	282
3.19.1	Short Term Shut-Down Procedures.	283
3.19.2	Longer-Term Mold Storage Considerations.	284
4	Other Injection Molding Processes	291
4.1	Introduction	291
4.2	Small Part and Micro Injection Molding	292
4.3	Structural Foam Injection Molding.	295
4.3.1	Structural Foam Material Considerations	296
4.3.2	Low-Pressure Structural Foam Injection Molding Process	297
4.3.3	Gas Counter Pressure Structural Foam Injection Molding Process . .	301
4.4	Gas Assist Injection Molding Process	303
4.4.1	Contained Channel Gas Assist Injection Molding Process	303
4.4.2	Open Channel Gas Assist Injection Molding Process.	307
4.4.3	External Gas Assist Injection Molding Process.	310

4.5	Co-injection Molding Process.....	311
4.6	Multi-shot Injection Molding Process.....	314
4.7	Insert Injection Molding Process.....	320
4.8	Injection – Compression Molding Process.....	322
4.9	Metal (and Ceramic) Injection Molding Processes	324
	Index.....	329

1

Injection Molding: Thermoplastic Material Considerations

1.1 Basic Injection Molding Process Overview

Injection molding is one of many plastic manufacturing processes that can be used to produce thermoplastic parts. The injection molding process has many variants but almost all of these injection molding processes have a number of commonalities. Fundamentally, the injection molding process involves a number of sequential process steps beginning with the melting or softening of a thermoplastic material formulation as shown in Figure 1.1. The charge or shot of plastic melt is then injected into a relatively cool closed mold, through the mold's flow passages (runners) and into the mold cavity(ies) where the molded plastic part shape is formed and cooled. The relatively cool mold will cause the runners and plastic part(s) to cool and solidify to a point where the mold can be opened, and the parts can be "ejected" or de-molded using a mechanical ejector system. The mold then closes and the process repeats itself over and over again for the length of the production run. Once ejected from the mold, the plastic parts will continue to cool and shrink until they reach the ambient temperature. The injection molding process description given above is overly simplistic. The thermoplastic injection molding process and the molding process machinery will be examined in more detail in subsequent sections of this text.

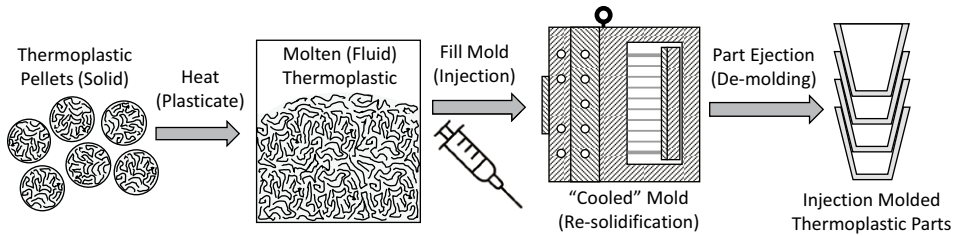


Figure 1.1 Fundamentally, the injection molding process involves a number of sequential steps, beginning with the melting or softening of a thermoplastic material, and ending with the ejection or de-molding of the cooled and solidified parts.

Figure 1.2 shows a simplified cross-sectional schematic of a typical reciprocating screw injection molding machine. Injection molding machines are typically described as having two main sections, the “injection unit” and the “clamping unit”. Each unit must carry out a number of thermal and mechanical actions or functions. The injection unit is responsible for (i) melting and mixing the thermoplastic material, (ii) building up a charge of molten material (the shot), (iii) injecting the plastic melt into the mold, and (iv) applying pressure as the melt solidifies. The molding machine’s clamping unit (i) holds the mold halves in place, (ii) opens and closes the mold, (iii) generates clamp force (to counteract the applied melt pressure), and (iv) energizes the mold’s mechanical ejector system to eject the solidified parts at the end of the injection molding cycle. It is very important to note that the injection molding process can be a dangerous process since it involves high temperatures, high pressures and mechanical actions. As a result, injection molding machines incorporate a variety of safety features and guards designed to minimize the potential for injury. A safety first mindset is essential when injection molding plastic parts.

Molding machines also have very sophisticated control systems that regulate the injection molding process variables, of which there are many. The molding machine’s mechanical functions can be driven either by hydraulic systems or directly by electronic servomotors or in some cases by both (in the case of hybrid injection molding machines). Injection molding processes also involve the use of various types of auxiliary equipment. This auxiliary equipment can include material pre-dryers, gravimetric feeders, mold temperature circulators, automation robots, granulators and the like.

Injection molding machines come in a very wide variety of shapes and sizes, which is one of the main reasons why this widely utilized process is difficult to describe in a universal way. Large molded plastic parts, such as automobile bumpers or facia, require very large injection molding machines featuring injection units with large shot capacities, and large, high force clamp units. The injection molding process is also used to produce tiny plastic parts, also known as micro molded plastic parts. Some plastic parts are so small that a single plastic pellet can produce multiple plastic parts.

The technical issues a molder may face with an auto bumper are very different than those for micro-molded parts. Most injection molded parts have a physical size that is somewhere between these two extremes.

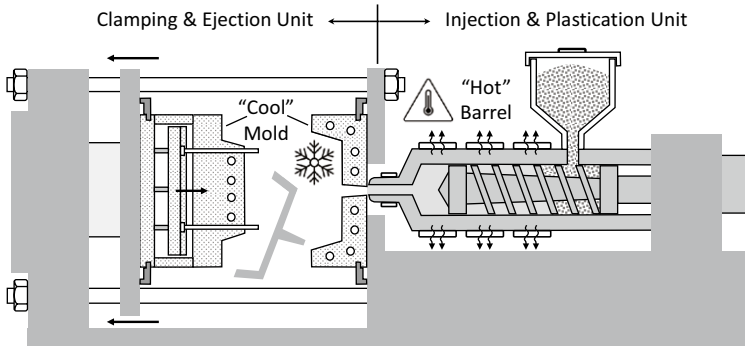


Figure 1.2 Injection molding machines are typically described as having an injection unit and a clamping unit, along with machine controls and auxiliary equipment. Each unit carries out a number of different functions. This simplified schematic shows a reciprocating screw injection molding machine at the point in the process where the solidified part is being ejected from the injection mold.

The injection molding process is commonly used for the production of plastic parts because it offers a large number of advantages and very few limitations. Some of the key advantages of the injection molding process are listed below.

- Most thermoplastics are available as injection moldable grades.
- The injection molding process can produce parts with a very complex geometry.
- Injection molded parts can have extremely tight dimensional tolerances.
- The process is economical, particularly for high production applications.

The most significant “barrier to entry” for the injection molding process is the injection mold or tool cost, which is why injection molding is generally limited to higher production applications. The tool cost must be amortized based on the number of parts that the mold will produce. The molding machinery itself is more cost effective because the injection molding machinery can be used for multiple injection molds and multiple materials. While some injection molding operations, particularly high-volume applications, utilize dedicated injection molding machinery, there are also many “custom” injection molding manufacturing businesses. Using custom molders for part production eliminates the lead times and costs of establishing a dedicated in-house injection molding facility. Whether molding is “dedicated” or “custom”, the tool cost is associated only with the part to be molded. There are ways to reduce the cost of an injection mold for applications where part production volumes are rela-

tively low and the tooling budget is limited. However, tooling short-cuts will generally lead to trade-offs with respect to the tool's durability or ability to maintain tight dimensional tolerances (for these low production applications). Note that while tool design is not the main focus of this text, the reader is directed to a number of helpful texts on the subject of injection mold design [1–4]. Certain aspects of injection mold tool design are discussed here, particularly where they involve mold features that have a significant influence on injection molding process variables.

1.2 Material Considerations for the Injection Molding Process

The focus of this text is on the injection molding process, beginning with raw material selection and ending with the production of an in-specification injection molded part. The overall concept associated with establishing a new injection molding process is depicted in Figure 1.3. New consumer products that incorporate plastic components are being developed every day. Many of these products are assemblies made up of multiple components, some of which may be injection molded plastic parts. The development process for new plastic parts can be a very complex task; it was discussed in an earlier text entitled “Plastics Part Design for Injection Molding” [5]. This plastic part development process involves defining the part's end use requirements, engineering design, material selection, prototyping, tool design and construction, and ultimately injection molding (i. e., manufacturing).

The methodology of new product development can be managed in a variety of ways, including the “*over the wall*” approach to development or by “*concurrent engineering*”. While the silo-like *over the wall* method of development is known to be inefficient, it is still relatively common. *Concurrent engineering* will generally reduce development time, and lead to higher quality products because all groups within the product development team have an opportunity to weigh-in on important design decisions. Consulting with the injection molder is considered to be a very good practice when developing a new plastic part that will ultimately be produced using the injection molding process. The molder can provide a perspective on molding issues that could lead to part performance or cost concerns that may be overlooked by the part designer.

Regardless of which methodology is used for the development of a new plastic part, part production by injection molding will begin at some point. Process engineers will need to develop an economical injection molding process that is capable of producing the required quantity of high-quality plastic parts. Various aspects of this process engineering task are discussed in this text. It is assumed that at this point of the new part development process that the process engineer has a number of fixed and variable

inputs. The fixed inputs are (i) the injection mold that has been built, (ii) the plastic material formulation that has been selected, and (iii) the molded part specifications (e.g., dimensional requirements), which have all been defined.

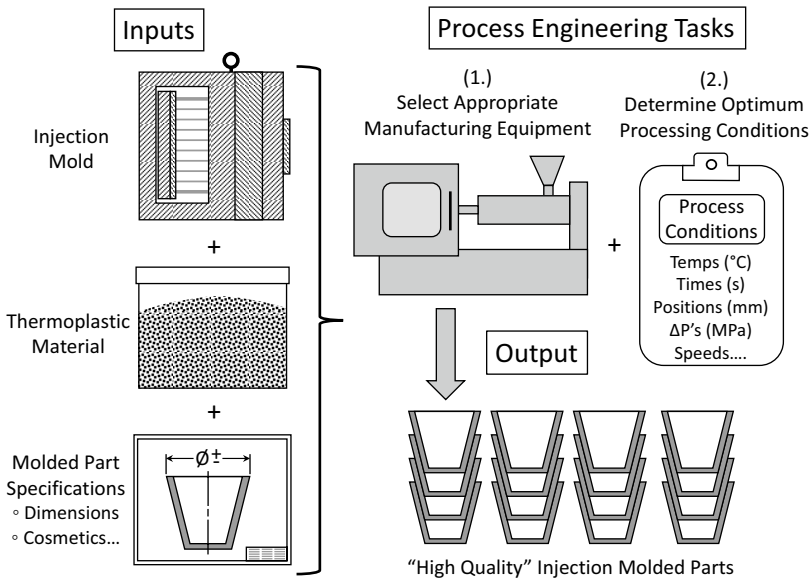


Figure 1.3 Process engineers are routinely given the task establishing a production injection molding process for a new material and new mold. They must first determine what type of molding machinery is most suitable for the new application and then develop a set of molding process parameters that will result in injection molded parts of acceptable quality.

Given these fixed inputs, the process engineer must then:

- Determine what type of injection molding machinery and auxiliary equipment is most suitable for production with the specific material formulation and injection mold to be used. Injection molding machinery is the focus of Chapter 2.
- The process engineer must then procure, acquire or locate suitable production machinery and schedule time for qualification trials and eventual production runs. Ideally, new, perfectly matched injection molding equipment would be specified and purchased for every new molding application. However, in most cases, process engineers must select from existing and available injection molding machinery. The key here is to select molding machinery that is the most appropriate for this new application. Some amount of machinery modification is typically required when new materials and injection molds are put into production (e.g., molding machine nozzle tips, end of arm tooling)

- The process engineer must also establish a production process for the new application. Every injection molding process parameter must be established. The goal is to establish process conditions that result in the production of high-quality molded parts (i. e., parts that meet the end use specifications) while keeping the molding cycle time as short as possible. The methods and concepts used to determine molding process parameters are discussed in Chapter 3 of this text.

There are many factors to consider when the process engineer is given the task outlined above. It is my opinion that learning as much as possible about the plastic material to be molded is the logical starting point. There are so many things about the plastic to be molded that will influence both the machinery selection and the injection molding process parameter settings. For example, if the plastic material is hygroscopic, it will need to be pre-dried. If the plastic material formulation contains abrasive or corrosive additives, appropriate injection molding machine metallurgy will be required. Different types of plastic may require different plasticizing screw geometries or nozzle tip designs. The list of possible material-machine interactions goes on and on. The sections that follow in this chapter are all plastic material related; they have been included because they all have the potential to influence some aspects of the injection molding process or molding equipment requirements. Having a complete understanding of a plastic's processing characteristics and material behavior will help guide a process engineer with decisions when establishing a new injection molding process.

1.3 Thermoplastic Material Nomenclature

Historically, the term “plastic” was used only as an adjective. The term is derived from the Greek word “plastikos” meaning *something (a material) that is capable of being shaped or molded*. As an adjective, the term plastic is essentially the opposite of elastic in the context of material behavior. Elastic deformation is described as being fully and instantly recoverable when an applied stress is removed from a deformed object, while plastic deformation is NOT recoverable. It was not until 1927 that the term plastic first appeared as a noun in that year's version of the *Century Dictionary and Cyclopedia*. In that reference, plastic, as a noun, was defined as “*A natural or synthetic (normally) organic polymer that can be formed into a desired shape when heated and then set into a solid or a more rigid state.*”

Plastic: This noun was and is still used to describe these versatile materials that are very widely used to manufacture all kinds of consumer products that we use in our daily lives. Plastics have been described as the most versatile materials on earth. They can be flexible or rigid. They can be opaque, translucent or transparent. Most plastics have excellent electrical insulating properties complementing the electrical conductivity of metals for the manufacture of electronic devices (that require both electri-

cally conductive and insulating components). Plastics are available in a variety of forms including liquids for coatings, paints and adhesives, or as solids for the injection molded products that are the focus of this text. This text also focuses on the injection molding of thermoplastics, which are materials that soften when heated and solidify upon cooling. This text does not focus on the molding of thermosetting plastics (or thermosets), such as a phenolic. Thermosetting plastics are based on polymers that solidify as a result of an irreversible crosslinking chemical reaction. Most thermoplastics are available as grades that can be processed by injection molding. Some thermosetting plastics can be injection molded, but most thermosetting materials are processed using other manufacturing processes, such as compression molding or transfer molding.

The thermoplastics that are used in the injection molding industry are sometimes sub-categorized as being either:

- Commodity thermoplastics
- Engineering thermoplastics
- High-performance thermoplastics

Commodity thermoplastics, such as polystyrene (PS), are high volume, lower cost materials with general purpose properties. Engineering thermoplastics, like polycarbonate (PC), are medium volume, higher cost materials that exhibit improved mechanical performance and temperature capabilities compared to commodity thermoplastics. High performance thermoplastics, such as polyether imide (PEI), are lower volume, higher cost special-purpose materials that offer even better performance. High performance thermoplastics are sometimes referred to as “super engineering thermoplastics”.

While the term “plastic” is very widely used in general materials engineering practice, there are a number of other material descriptors, phrases or terms that are sometimes used instead. These terms may have different meanings to different people, but they are listed and described here based on my interpretation and understanding of these terms.

Plastic material: The more descriptive term “plastic material” is also commonly used as synonym for the noun plastic.

Plastics: It is common to see an “s” added to the noun plastic. Some consider the terms plastic and plastics to be completely interchangeable. Dictionaries state that the term plastics is the plural of the noun plastic. ABS is a plastic (noun), while ABS and HDPE are both plastics (plural noun).

Polymer: The term polymer is also very common in material science. A polymer (or high polymer) is a large, usually chain-like molecule made up of many (poly) parts (mers). Fundamentally, all plastics are polymers, but not all polymers are plastics. For example, DNA, proteins, (unmodified) natural rubber, and cellulose are all polymers,

but are not considered to be “plastics” since they *canNOT be formed into a desired shape when heated and then set into a solid or a more rigid state*. Polyethylene is both a polymer and a plastic. Polyethylene is a polymer because it is a long chain-like molecule. Polyethylene is considered to be a plastic (noun) since it can be melted, molded and resolidified. The phrase “polymeric material” is synonymous with “polymer”.

Natural polymers: Polymers that exist as a naturally occurring materials are typically described as natural polymers. For example, cellulose (from cotton) is a natural polymer, but it is not moldable and is therefore not considered to be a plastic or plastic material. However, this natural polymer can be “chemically modified” and fortified with additives to produce a moldable plastic material formulation, such as plasticized cellulose nitrate (*celluloid*) or cellulose acetate. Celluloid is cellulose nitrate (i. e., a chemically modified cellulose) that contains camphor as a plasticizing additive. Such chemically modified natural polymers are sometimes described as “semi-synthetic” plastics.

Fully synthetic polymers: The vast majority of commercial plastic materials are “fully synthetic” polymers. The first commercially successful fully synthetic plastic, phenol formaldehyde, was commercialized in 1908. Most of these polymers do not exist in nature and are synthesized by chemically reacting low molecular weight raw materials, known as monomers or co-monomers. The monomers themselves, such as the ethylene glycol co-monomer used to produce PET, can be derived from petrochemicals or from more renewable resources, such as agricultural products. While there are only so many naturally occurring polymers, there are no limits as to the number of fully synthetic polymer structures that can be produced. In some cases, synthetic versions of naturally occurring polymers are produced to increase the material supply, as in the case of synthetic rubber, since the natural supply is limited.

Organic vs. inorganic plastics: Almost all commercial plastics are organic materials, having a carbon-based polymer backbone and other elements that determine the material’s chemical structure and performance properties. Organic plastics may also contain elements that include; hydrogen, nitrogen, oxygen, sulfur, chlorine, bromine and fluorine. Plastics that do not have a carbon-based backbone, such as silicone-based plastic, are inorganic plastics.

Resin: The term resin is often used as a synonym for the noun plastic. For example, the phrase “resin supplier” would be synonymous with “plastic material supplier” in the context of the plastics industry. Dictionaries generally define resins as “*natural organic substances that are usually transparent or translucent and yellowish to brown, that are formed especially in plant secretions*” (which is not a definition of plastic material). In some respects, the term resin as a synonym for plastic seems to be an older (perhaps outdated) term that may trace its roots back to the invention of liquid phenolics or other liquid plastics or plastic precursors, such as epoxy resins or unsaturated polyester resins. That said, the term resin is still very widely used as a synonym for the noun plastic.

Rubbers and Elastomers: Rubbers and elastomers (or plastomers) are polymers that exhibit good flexibility, extensibility and recovery. They can be naturally occurring or, more commonly, fully synthetic. They can be thermosetting, as with vulcanized natural rubber, or thermoplastic, as in the case of a thermoplastic elastomer (TPE). There seems to be general agreement that all rubbers and elastomers are flexible polymers. These materials are considered by some to be flexible plastics, while others consider that rubbers or elastomers are a separate category of polymers (i. e., they are thermoplastic or thermosetting elastomers, not plastics).

Composites: Dictionary definitions state that a composite material is a “*combination of two materials with different physical and chemical properties.*” This is a very generic term that can be used for many material combinations. In the plastics industry, the term composite is commonly used to describe a material that consists of a polymer or plastic matrix material strengthened by fibrous or fabric reinforcements. Composites that are produced using a thermosetting plastics matrix material are often described as advanced composites. Injection moldable composites, that are produced using a thermoplastic matrix material and a reinforcement, such as glass fiber-reinforced nylon 66, are more appropriately described as either short fiber, or long fiber-reinforced thermoplastic composites.

1.4 The Four Plastic Material Pillars

The idea of using “Four Pillars” to describe the underlying dynamics of a subject area or discipline has been seen in many instances. There are the *Four Pillars of Life*, the *Four Pillars of Happiness*, the *Four Pillars of Sustainability*. This list goes on and on. This four-pillar model also provides for a convenient and systematic method of describing four key attributes that are associated with every plastic material in existence. The four underlying pillars that are associated with all thermoplastic materials are:

- Average chain length (i. e., average weight and molecular weight distribution).
- Repeating unit or chain link chemical structure.
- Morphology or chain arrangements.
- Additives that are incorporated into the thermoplastic matrix material.

Once a plastic material has been selected for a particular application, such as for an injection molded plastic part, it is important that process engineers and molding technicians gain a thorough and fundamental understanding of how each of these pillars affects the properties and processability of the plastic material formulation to be molded. Each of these four pillars will have a significant effect on both the processability and performance of the plastic material. The recommendation here is to re-

search or learn as much as you possibly can about the selected plastic material prior to injection molding, especially if the engineers and technicians do not have previous experience of molding the plastic material. This type of information is available from a variety of sources, including plastic material textbooks [6-8], but it is typically the material supplier that can provide the most valuable plastic material information. The four underlying pillars that influence the properties and processability of thermoplastic materials are discussed in more detail in the following sections.

1.4.1 Plastic Material Pillar #1: Average Polymer Chain Length

All thermoplastics are chain-like molecules having a far higher molecular weight than non-polymeric materials. Most thermoplastics have linear, chain-like structures, although some do have a branched structure with side chains that are distributed over the length of the main backbone chain. The average length of these polymeric chains is one of the four variables that will influence the polymer's flow and physical properties. While it can be difficult to generalize when discussing plastics, it is generally true that higher molecular weight thermoplastics exhibit superior performance (in terms of, say, mechanical properties or chemical resistance) than their lower molecular weight counterparts (all other factors being equal).

Higher molecular weight materials exhibit improved performance for at least two main reasons. First, longer molecular chain molecules have a tendency to exhibit a greater degree of "entanglement". A material having more entanglement tends to offer greater resistance to an applied stress. Secondly, the intermolecular forces (the forces between the chains) will also dictate a plastic's performance. These electrostatic interactions, known as secondary chemical bonds (e.g., Van der Waals forces) ensure resistance to applied stresses. The sum of these forces will be greater when the polymer chains are longer, also helping to improve the material's performance.

As an example, consider the linear polyethylene thermoplastic material depicted in Figure 1.4. Material suppliers that produce polyethylene can create different polyethylene grades that have different chain lengths and branching types by controlling the polymerization process variables and catalysts used to make the polyethylene. It should also be noted here that, while material suppliers have a target chain length (or molecular weight) for each material grade they produce, the result of any polymerization process will be a thermoplastic having a statistical distribution of different chain lengths. This is why it is common to describe a material's molecular weight as a weight average molecular weight or number average molecular weight value.

Figure 1.4 shows some examples of polyethylene applications for polyethylene grades with different molecular weights. The candle is produced from a very short chain, low molecular weight polyethylene. The candle material can be melted and cooled and could be injection molded, but candle "wax", as it is called, has very limited me-