HANDBOOK OF PLASTIC PROCESSES

CHARLES A. HARPER
Timonium, Maryland

WILEY-INTERSCIENCE
A JOHN WILEY & SONS, INC., PUBLICATION

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Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

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Library of Congress Cataloging-in-Publication Data:

Handbook of plastic processes / [edited by] Charles A. Harper.
p. cm.
Includes index.
ISBN-13: 978-0-471-66255-6 (cloth)
ISBN-10: 0-471-66255-0 (cloth)
1. Plastics—Handbooks, manuals, etc. 2. Plastics—Molding—Handbooks, manuals, etc.
I. Harper, Charles A.

TP1130.H355 2006
668.4—dc22

2005025148

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

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PREFACE

With the myriad of plastics, plastic compounds, and plastic types and forms, the list of end product applications is as limitless as the list of possible plastic parts is endless. We see plastic parts and assemblies in a never-ending stream of domestic and commercial or industrial applications, across every category of interior and exterior domestic application, and across every industry, from mechanical to electrical to heavy chemical to structures to art. Yet without proper processing, none of these plastic products would be possible. It suffices to say that with the breadth of plastic materials and products indicated above, processing is a major challenge. Fortunately, the strength, intelligence, and ingenuity of the army of specialists involved in all types of plastic processing has been equal to the task. To them we owe our gratitude, and to them we dedicate this book. The authors of the chapters in this book rank high among this group; and fortunately, they have achieved much through their cooperative efforts in the leading professional society in this field, *the Society of Plastics Engineers* (SPE), about which more will be said shortly. I am personally grateful to SPE for the great assistance of many of its staff and professional leaders, without whose advice and assistance I would not have been able to put together such an outstanding team of authors.

As can be seen from perusal of the subjects covered in this book, the book has been organized to fully cover each of the plastic processes that are used to convert plastic raw materials into finished product forms. The myriad of thermoplastic processes are each covered in an individual chapter, as are the thermosetting processes. The authors of each chapter detail its subject process and process variations and the equipment used in the process, discuss the plastic materials which can be utilized in that process, and review the advantages and limitations of that process. Also, since raw, molded, or fabricated parts often do not yet provide the desired end product, chapters are included on plastics joining, assembly, finishing, and decorating. Finally, and importantly, with the increasing impact of nanotechnology on plastics properties and processing, a chapter on nanotechnology is included.

As was mentioned above, success in achieving a book of this caliber can only result from having such an outstanding group of chapter authors as it has been my good fortune to obtain. Their willingness to impart their knowledge to the industry is indeed most commendable. Added to this is the fact that most of them are banded together for the advancement of the industry through their roles in the Society of Plastics Engineers. SPE has unselfishly advised me on the selection of many of the authors of this book. In addition to all of the chapter authors who are strong SPE representatives, I would like to offer special thanks to Roger M. Ferris, editor of the SPE *Plastics Engineering Journal;* Donna S. Davis, 2003–2004 SPE President; and Glenn L. Beall and John L. Hull, Distinguished Members of SPE.

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CHAPTER 1

Injection Molding

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1.1 INTRODUCTION

Injection molding is one of the most widely used processes for manufacturing plastics parts. It is a major processing technique for converting thermoplastics and thermoset materials into all types of products for different end uses: from automotive to electronics, medical to sports and recreation, and building and construction to consumer products. Injection molding is a relatively new method of producing parts. The first injection molding machines were manufactured and made available in the early 1930s, whereas other manufacturing methods that may be familiar date back more that 100 years.

According to the Injection Molding Division of the Society of Plastics Engineers, *injection molding* is defined as a method of producing parts with a heat-meltable plastics material [1]. This is done by the use of an injection molding machine. The shape that is produced is controlled by a confined chamber called a *mold*. The injection molding machine has two basic parts, the injection unit, the clamping unit. The *injection unit* melts the plastic and conveys or moves the material to the confined chamber or mold. The purpose of the *clamping unit* is to hold the mold in a closed position during injection to resist the pressures of the conveying or injection and forming of the material into a specific shape, and then opens after cooling to eject the part from the mold.

Rosato [2] describes the three basic operations that exist in injection molding. The first is raising the temperature of the plastic to a point where it will flow under pressure. This is done both by heating and by grinding down the granular solid until it forms a melt at an elevated temperature and uniform viscosity, a measurement of the resistance to flow. In most injection molding machines available today, this is done in the barrel of the machine, which is equipped with a reciprocating screw. The

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screw provides the vigorous working of the material along with the heating of the material. This part of the process is referred to as the *plasticating* of the material.

The second operation is to allow the molten plastic material to cool and solidify in the mold, which the machine keeps closed. The liquid, molten plastic from the injection molding machine barrel is transferred through various flow channels into the cavities of a mold, where it is formed into the desired object. What makes this apparently simple operation so complex is the limitations of the hydraulic circuitry used in the actuation of the injection plunger and the complex flow paths involved in filling the mold and the cooling action in the mold.

The third and last operation is the opening of the mold to eject the plastic after keeping the material confined under pressure as the heat, which is added to the material to liquefy it, is removed to solidify the plastic and freeze it permanently into the shaped desired for thermoplastics.

A variety of materials can be injection molded. Table 1.1 lists the thermoplastic materials that can be processed using injection molding.

The purpose of this chapter is to break down the basic parts of the injection molding process as if you were actually taking a walking tour down the entire process. This tour is divided into four phases. The first phase is the *material feed phase* (Section 1.2). Here the focus is on material handling: how the material is dried and the preparation of the material to be injection molded. The second phase is the *melt-conveying phase* (Section 1.3). Our discussion is concentrated on the important aspects of how material goes from a solid pellet to a molten polymer. The emphasis here is on the screw, the barrel, and the nozzle. *The melt-directing phase* (Section 1.4) entails how the melt gets to its final destination, the mold cavity. In this section the sprue, runners, gates, and gate lands are reviewed as to what they do and how they

TABLE 1.1 Injection-Moldable Thermoplastic Materials

Acrylonitrile–Butadiene–Styrene (ABS)
ABS/nylon blends
ABS/TPU
Polyoxymethylene (POM) acetal
Polymethyl methacrylate (PMMA) acrylic
Ethylene vinyl acetate (EVA)
Nylon 6
Nylon 6,6
Nylon 12
Nylon 6,12
Polyetherimide (PEI)
Polycarbonate
Polycarbonate–ABS blends
Polycarbonate–PET blends
Polycarbonate–PBT blends
High-density polyethylene (HDPE)
Low-density polyethylene (LDPE)
Linear low-density polyethylene (LLDPE)
Polypropylene (PP)
Polyphenyl oxide (PPO)
Polystyrene
Syndiotactic polystryene (SPS)
Polysulfone
Polyether sulfone (PES)
Thermoplastic polyurethane (TPU)
Polybutylene terephthalate (PBT)
Polyethylene terephthalate (PET)
Liquid-crystal polymer (LCP)
Polyvinyl chloride (PVC)
Styrene–maleic anhydride (SMA)
Styrene–acrylonitrile (SAN)
Thermoplastic elastomer (TPE)
Thermoplastic polyolefin (TPO)

affect the molding process. The last stop is the *melt-forming phase* (section 1.5). Here we discuss how to design a tool or part for the injection molding process. Section 1.6 provides an overview on how to resolve injection molding issues and gives examples of troubleshooting commonly used plastic materials.

1.2 MATERIAL FEED PHASE

When a plastic material begins its journey through the injection molding process, the first thing that is considered is how the material is delivered and stored until it is used. The next step is to determine how the material will flow to the individual machines for molding, and finally, what process is needed to prepare the material so that it can be molded. Other side processes, such as color and additive feeding, also need to be considered if these apply. However, in this section, concentration is placed on the basic factors in getting the material to the hopper.

In this section we focus on the following issues for material feed. The first is that of drying the material, a process used in preparing most thermoplastic materials for injection molding. We then explain why materials need to be dried and what needs to be considered. Then the hopper and the concept of bulk density are reviewed, how this relates to sizing storage space for materials, the elements of material mass flow, and the time and conditions involved in drying the material.

1.2.1 Drying Material

One question that is asked by many molders in the injection molding industry has been: Why do some polymer materials need to be dried? This is best explained as follows.

The chemical structure of a particular polymer determines whether it will absorb moisture. Due to their nonpolar chemical structures, a number of polymers (e.g., polystyrene, polyethylene, and polypropylene) are nonhygroscopic and do not absorb moisture. However, due to their more complex chemistry, materials such as polycarbonate, polycarbonate blends, acrylonitrile–butadiene–styrene (ABS) terpolymers, polyesters, thermoplastic polyurethanes, and nylon are hygroscopic and absorb moisture. As shown in Figure 1.1, the moisture can either be external (surface of the pellet) or internal (inside the pellet). A problem arises when the polymer processing temperatures, which can exceed 400°F (204°C), boil off the water [at 212°F (100°C)] in the polymer.

The effect that water has on a molded part is that imperfections will appear on the surface because the bubbles generated from the boiling of the moisture get trapped in the polymer, cool, and solidify in the mold. This creates *splay marks* or *silver streaks*. In some cases, as in polycarbonate and nylon-based materials, polymer degradation can occur as the water reacts with the polymer to reduce its physical and mechanical properties. Another effect results in reversing the polymer-forming reaction in the polymer, leading to *chain scission* or *depolymerization*. These types of conditions can make a polymer difficult, if not impossible, to process.

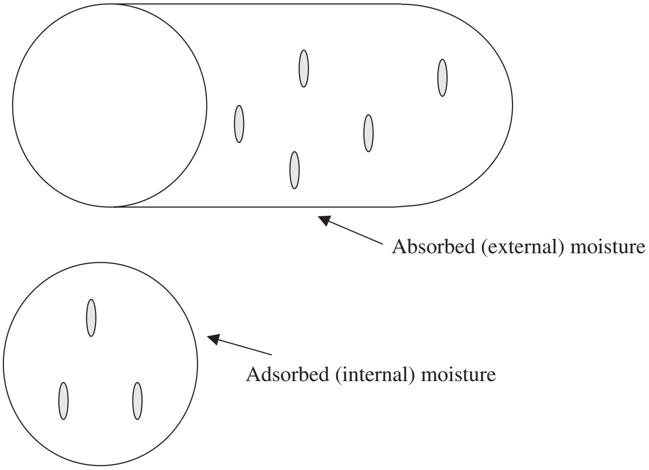

FIGURE 1.1 External and internal moisture.

The critical factor in drying plastics materials is to remove moisture not only from the pellet's exterior surface but from the pellet's interior as well. Pellets reach a moisture balance point with the surrounding environment. This is determined by the resin type, the ambient relative humidity, and time. For some resins (e.g., ABS) this is usually 0.3%, whereas for nylons this is typically 0.15%. Moisture can be driven out of the pellets under four essential conditions: (1) heat, (2) airflow, (3) dry air, and (4) time for drying effects to take place. Heat drives the moisture to the surface of the pellet. The dry air acts as a recipient or "sponge" to receive the moisture from the pellet surface. The dry airflow supplies the transportation to remove the moist air, which goes to the desiccant dryer for collection and reconditioning. All of these steps are important in drying plastic materials properly.

The delivery of air to the hopper must be such that it can absorb water from the moist pellets. The drier the air, the more effective it will be in extracting moisture from the resin. The term *dew point* is used to describe the actual amount of water in the air. The dew point temperature is defined as the temperature at which moisture will just begin to condense at a given temperature and pressure. It is a measure of the actual water in the air: the higher the dew point, the more saturated the air.

The delivery air to the hopper must be dry. Only a dew point meter can determine this. Some drying units have an onboard dew point meter, which quickly becomes unreliable due to vibration, oxidation on sensor plates, and contamination from plant air (oils, dust, etc.). After some time, an onboard unit may read −40°F (−40°C) continuously even though the actual dew point is much higher. Handheld dew point meters are suggested as an alternative because they are not exposed to continuous use and are typically stored in a dry, clean environment. Sensor plates, which are critical to the function of a dew point meter, remain clean, allowing for accurate and reliable results.

When using a handheld unit, some precautions must be taken because the unit draws a sample from the delivery air (which should be hot and dry). The air filter must be in place to avoid plugging or contaminating the sensor plates. The handheld unit draws in a sample at a very slow rate. Operation of the dryer needs to be considered because desiccant beds do swing or index at predetermined times; one bed may be acceptable while the other is faulty. Enough time should be given to measure dew point temperature to monitor all beds inside the system, which normally consists of two or three beds.

The typical life expectancy for replacement of desiccant beds is two to three years. Also, the desiccant beds must be inspected for contamination by fines, dust, and the chemical by-products of dried resins, such as lubricants and plasticizers. Desiccant beds must be properly sealed, and clean filters must always be in place to avoid the loss of drying capacity.

An insufficient dew point does not always point to bad desiccant beds. The rate of moisture pickup from the air intake may simply overwhelm the capacity of the dryer unit. This can occur for several reasons, such as inaccurate sizing of the dryer or an air leak in the return system. For air leaks it is strongly recommended that hoppers operate with the secured hopper lids and that hoses be checked for pinhole leaks because these problems can draw moist plant air into the dryer and create inefficient drying.

Hygroscopic materials can absorb more moisture from the air than can other plastic resins. This puts some demands on the molder to keep the material dry before and during molding. High-dew-point temperatures above 15°F (−9°C) are not adequate to dry most hygroscopic materials properly because the air is already saturated with moisture before contacting the resin to be dried. It is recommended that dew point temperatures of −20° to −40°F be used to dry hygroscopic materials such as nylons, polyesters, polycarbonate, and polycarbonate blends.

Table 1.2 lists recommended drying temperatures for a number of thermoplastic materials. Table 1.3 is a checklist for determining the efficiency of the dryer system and areas in the drying equipment that should be monitored.

1.2.2 The Hopper

The hopper is the section of the injection molding machine that stores material just before it enters the barrel of an injection molding machine. The hopper also has a holding area for the material as it is fed from its bulk storage (gaylords, railcars, etc.) and awaits any preconditioning of the material that may be needed, such as drying. Hopper size is a critical element in determining how to make the injection molding process efficient. The two concepts discussed here, material mass flow and bulk density, provide information on how to choose the correct-size hopper and what requirements are needed to store material prior its being sent to the hopper.

1.2.2.1 Bulk Density

Bulk density is an important material property as it relates to the injection molding process. According to Rosato [2], *bulk density* is defined as the weight per unit volume of a bulk material, including the air voids. *Material density* is defined as the weight of the unit volume of the plastic, excluding air voids.

TABLE 1.2 Typical Drying Conditions for Thermoplastic Materials

	Drying Conditions		
Material	Time (hr)	Temperature [°F (°C)]	
ABS	2–4	180–200	(82–93)
ABS/nylon	1–3	175–190	(79–88)
ABS/TPU	3–4	170	(77)
Acetal	1–4	185	(85)
Acrylic	2–3	180	(185)
Nylon 6	2–4	180–185	(82–85)
Nylon 6,6	2–4	175–185	(79–85)
PEI	4–6	270–300	(132–149)
Polycarbonate	4	250	(121)
PC–ABS	3–4	175–200	(79–93)
PC–PBT	3–4	240	(116)
PC–PET	3–4	240	(116)
Polyethylene	1–2[a]	120–140	(49–60)
PPS	2–3	300–350	(149–177)
Polypropylene	1–2	120–140	(49–60)
PPO	2–4	200–250	(93–121)
Polystyrene	1–2[a]	150–175	(66–79)
Polysulfone	4	250–275	(121)
PBT	2–4	250–280	(121–138)
PET	2–4	275	(135)
Liquid crystal Polymer	2–4	140–150	(60–66)
PVC	2[a]	170–180	(77–82)
SMA	2	180–200	(82–93)
TPE	1–2	212	(100)
TPO	1–2[a]	120–140	(49–60)

[a] Drying typically not needed.

A rough estimate of bulk density, measured in pounds per cubic foot, can be made using the following equation:

$$\mathrm{BD} = (42)\,\frac{\rho}{1.13} \qquad (1.1)$$

where BD is the bulk density (lb/ft^3) and ρ is the specific gravity (g/cm^3). Table 1.4 lists the bulk densities for a number of thermoplastics based on Eq. (1.1).

Rosato [2] provides some guidelines in the interpretation of bulk density data. If the bulk density is greater than 50% of the actual density of the material, the bulk material will be reasonably easy to convey through the injection molding screw. However, if the bulk density of the material is less than 50% of the actual density, solids-conveying

TABLE 1.3 Dryer Operation Checklist

Issue	Area to Check
Drying temperature	Check operating temperature of dryer using a temperature probe at the hopper inlet. Check length of delivery hose. Set hose length so that there is minimal or no change in inlet temperature from set temperature.
Air drying	Use a handheld dew point meter to assure that the dew point is between −20° and −40 °F (−29° to −40 °C) range. Do not depend on dew point monitors that come with drying units. Check for plugged air filters that will prohibit air from entering the system. Inspect operation of desiccant beds to assure that they regenerate properly. Visually inspect desiccant beds for any contamination, such as fines, dust particles, and certain chemical additives that are by-products of some materials. Check for proper material mass flow. Inspect hose for pinhole leaks that can cause moist air to enter the system. Cover all hoppers with lids and make sure that the hopper system is sealed from plant air. If needed, apply a nitrogen blanket to keep hygroscopic materials dry in the hopper and seal the hopper.
Air delivery	Check airflow of the drying unit. Inspect for dirty or blocked filters due to fines and pellets. Inspect delivery lines for twists or kinks. Check material mass flow.
Mechanical/ electrical problems	Check for faulty timers for swinging desiccant beds. Inspect for possible disconnections of internal hoses. Check for faulty limit switches at the top of the hopper. Assure that material mass flow still matches part and production requirements. Insulate hoppers and hoses to improve drying efficiency.

problems can occur. When bulk density is less than 30%, a conventional plasticator usually will not handle the bulk material. Separate devices, such as crammers and force feeders, would be needed to feed the material.

1.2.2.2 Hopper Sizing for Drying and Material Mass Flow

Proper sizing of the hopper is critical and depends on the mass flow of the material. Inside the hopper, plastic material pellets move downward due to gravity, while drying air moves upward, assuming plug flow conditions. Mass flow is determined by

TABLE 1.4 Bulk Density Data for Thermoplastics

Material	Bulk Density (lb/ft^3)
ABS	42
Acrylic	42
Acetal	40
Ionomer	44
Nylon 6	41
Nylon 6,6	41
25% glass-filled nylon 6,6	49
35% glass-filled nylon 6,7	52
45% glass-filled nylon 6,8	56
PEI	52
Polycarbonate	41
PC–ABS	41
PC–PBT	42
PC–PET	42
Polyethylene	34
PPS	50
Polypropylene	34
20% talc-filled PP	40
PPO	49
Polystyrene	40
Polysulfone	50
PBT	48
PET	52
Liquid crystal polymer	50
PVC (rigid)	52
PVC (flexible)	48
SAN	40
SMA	38
TPE	48
TPO	34

three factors: (1) the shot size of the part, (2) the cycle time to manufacture the part, and (3) the number of machines supplied by the drying equipment. Figure 1.2 illustrates how to calculate material mass flow for a given material, in this case for the material ABS. The variables used are as follows:

w_p = part weight (lb)

t_c = cycle time for manufacturing the part (min)

Q_t = machine throughput (lb/hr)

M_t = mass flow (lb)

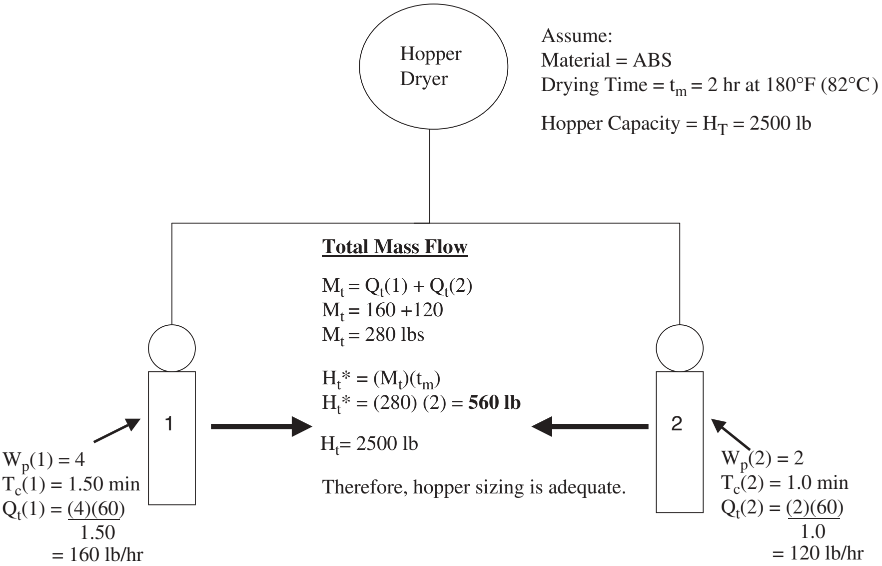

FIGURE 1.2 Determination of material mass flow.

t_m = drying time (hr)

H_T = hopper dryer capacity (lb)

$H_T{}^*$ = hopper dryer capacity needed

To determine material mass flow for an individual injection molding machine, the following equation is used:

$$Q_t(x) = \frac{w_p}{T}\,(60) \tag{1.2}$$

where $x = 1, 2, 3, \ldots$. When several machines are used, the total material mass flow, M_t, is determined by adding the material mass flow for machine 1 [Q_t (1)] together with that for machine 2 [Q_t (2)] as follows:

$$M_t = Q_t\,(1) + Q_t(2) + Q_t(3) + \cdots \tag{1.3}$$

The hopper dryer capacity needed, $H_T{}^*$, is determined with the following equation:

$$H_T{}^* = M_T\,t_m \tag{1.4}$$

The following condition determines if the hopper sizing is sufficient. If $H_T > H_T{}^*$, the hopper sizing is adequate to provide enough drying in the system for the material.

1.3 MELT-CONVEYING PHASE

When the word *conveying* comes to mind, a number of different methods are visualized. For example, a moving belt moving articles from one location to another is an example of conveying. Another example is the use of an auger, a screwlike device that moves grain, powder, or even objects like rocks through a cylinder opened on both ends. The auger acts as the conveyor where the material is transferred within the flights of the auger in channels that have the same depth throughout the length of the auger. The open-ended cylinder acts as a guide to the conveying of material by keeping the material moving linearly. The auger–cylinder example can be used to explain melt conveying in the injection molding process.

In injection molding, an open-ended cylinder, referred to as a *barrel*, acts as a guide for the pellets and moves the pellets and melt from the hopper to the mold where the part is made. The auger, referred to as a *screw*, conveys material down through the barrel from the barrel to the mold. However, what is different in the screw and barrel from the auger and cylinder example discussed earlier is that the channels of the screw do not have a constant depth. The screw at the hopper end of the barrel will be deep, and moving forward toward the mold end of the screw, the depth of the channel becomes shallow. As all this is taking place, the inside opening of the barrel stays at a constant diameter. So, in terms of conveying, material is fed at the deep channels and conveyed into shallower channels, which cause the material to compress and pack together. This compression process increases the friction of the material against the inside wall of the barrel, providing frictional heat. In addition to this, heaters are spaced on the outside diameter of the entire length of the barrel, providing additional heat. Therefore, the frictional heat of the material in the screw plus the heat applied on the outside of the barrel together provide enough heat to convert material in pellet form at the hopper end of the screw and barrel to material in a melt form midway down the length of the barrel to the end of the barrel and screw. This simplified example provides background on the melt-conveying section.

Next, we go into more detail regarding this process by examining the barrel, screw, external heating mechanisms, venting, and nozzle sections of the melt-conveying phase.

1.3.1 The Barrel

The barrel is defined here as an open-ended cylinder that controls the linear direction of the melt-conveying process, from the hopper to the mold. This also provides a frictional surface for the plastic material, to assist in the melting of the plastic from pellet form to molten form and results in moving the material in a basically linear direction from the hopper to the mold.

One of the most important properties of the barrel is the material from which the barrel is made. The typical material is steel with a bimetallic liner. This liner is made from a steel alloy, typically a 4140 alloy. Most injection molding machine barrels are made to withstand burst strengths of approximately 22,000 lb/in^2. In special applications, barrels are made to withstand between 45,000 and 50,000 lb/in^2, especially for thin-wall injection molding [$<$0.0625 in. (1.6 mm)].

There are several types of barrel liners that are used for various types of materials. An abrasion-resistant liner is used for most unfilled materials or materials that contain low levels of reinforcing fillers, such as glass, talc, and mineral fillers. Another type of barrel liner is a corrosion-resistant barrel, used for materials where volatiles that can evolve from certain plastic materials will not corrode or pit the surface of the barrel. Two examples of these plastic materials are polyvinyl chloride (PVC) and polyoxymethylene, or acetal. Finally, highly abrasion resistant liners are used when a plastic material has very high loadings, percentages, or combinations of reinforcing fillers, such as glass fiber, talc, mineral filler, mineral fiber, mica, or carbon fiber.

Barrel wear is one of the problems that can be encountered in the injection molding process. There are several signs of barrel wear. During the injection phase of the molding cycle, a shot size setting used for a period of time may all suddenly provide incompletely filled parts, or *short shots*. In this case, material is back-flowing inside the barrel through a worn area of the barrel and goes back down the screw in the direction of the hopper, away from the mold. To resolve this, a repair can be made to the barrel by adding a metallic sleeve in that section of the liner to “fill in” the worn section of the barrel. Another sign of a worn barrel occurs when the screw is retracting back after injecting material into the mold. The screw should retract smoothly and evenly until it retracts to its set location. However, with a worn barrel, the screw will hesitate once or a number of times, slowing down screw retraction time and eventually slowing down the overall injection cycle. In this case, the material is flowing over the check ring and as a result, does not develop enough pressure to retract the screw. In this particular situation, complete replacement of the barrel may be required.

1.3.2 Heater Bands

Several types of heater bands are used for heating a barrel. These include tubular heaters, cartridge heaters, band heaters, and natural gas heaters.

Tubular heaters are made by suspending a coiled resistance heating element made of nichrome in a metal tube or sheath. Tubular heaters are placed on the barrel by bending and forcing them into machined grooves on the barrel surface. These heaters are held in place by peening the grooves into the grooves. Economically, use of the heaters can be expensive, due to the machining of the grooves into the hardened outside diameter of the barrel. However, the tubular heater has been known to last as long as the life of the barrel. Tubular heaters are cast in aluminum shaped to the exterior diameter of the barrel. They are effective heaters and do not require much maintenance.

Another type of heater, the *cartridge heater*, is made with nichrome wire wound on forms with a magnesium oxide type of cement. Iron–nickel chromium metal has allowed for increased heating capability. These heaters, in the shape of a pencil barrel, are placed inside a hole and supply heat to the area surrounding the hole. They are used in barrel heating but are used extensively in controlling mold temperature. Cartridge heaters require low maintenance to other types of barrel heaters. The only disadvantage with cartridge heaters is that in some applications, these heaters can cause heat to concentrate in a small area.

Band heaters are the heaters most widely used in heating barrels in the injection molding process. These heaters are made of nichrome wire wound on a form and are insulated. Mica and ceramic are used as the insulating materials in band heaters. These heaters produce a high amount of heat capacity, between 30 and 40 W/in^2, in comparison to tubular heaters (20 to 40 W/in^2) and cartridge heaters (40 W/in^2). Special heat-resistant metal alloys are used instead of copper wires for band heaters since these resist oxidation as occurs with copper wiring. The key to maximum efficiency of the band heater is the contact surface of the heater. If a band heater is not in full contact with the barrel surface, air caught inside the band heater will act as an insulator and prevent the drawing off of heat from the metal of the heater. Another problem known to cause band heater failure is plastic material coming in contact with the band heater. This can get inside the heater, shorting out the nichrome heater.

A novel method of barrel heating was developed in 2003 by the University of Duisberg–Essen in Germany using natural gas as a means to heat the barrel. *Natural gas heaters* provide heating capacities similar to those of electrical heating but with reduced energy costs. Heating of the barrel takes place by using a radial burner placed around the barrel, producing heat by convection and radiation. Work is still under way to further prove the feasibility of this novel method of barrel heating.

1.3.3 Measuring Barrel Heat: The Thermocouple

A thermocouple is used to measure and control the amount of heat being applied to the barrel by the heaters. The basic concept behind the thermocouple is that electrical energy is converted from heat energy when metals that are dissimilar are bonded or welded together. The amount of energy converted is dependent on the metals selected and the temperature. Iron and constantin, an alloy of copper and nickel, are most widely used for thermocouple materials. Two types of thermocouple are used, the J and K types. The J type is most widely used in the injection molding industry.

1.3.4 The Screw

Earlier, the analogy of the auger and cylinder was used to describe how the melt is conveyed in the injection molding process. The cylinder was just reviewed; now, it is time to discuss the auger part of the process.

The screw can be considered to be the “heart and soul” of the injection molding process, and can also be considered as the most complicated and complex section to understand. The screw is what forces the pellet, then the melt material, forward out of the nozzle into the mold. The key factor is that the material must adhere to the inside wall of the barrel. Otherwise, the screw will rotate in one spot without any forward movement.

Traditionally, the screw is divided into three parts: (1) the feed section, (2) the transition section, and (3) the metering section. In the feed section, the material in pellet form moves from the hopper section of the injection molding barrel toward the nozzle and mold section. The pellets here are still in solid form, but there has been some initial softening. The channels of the screw are deep in this area to allow the pellets to convey down the barrel. Temperature settings of the barrel are the lowest in this section, to avoid premature melting of the pellets, which can cause degradation or interfere with material feed into the barrel.

In the transition section the pellet material begins to melt and mix with unmelted pellets. In this section the channel depth of the screw becomes shallow, and this degree of shallowness increasing down the transition section. This increasing shallowness causes the melt–pellet mix to compress against the inside of the barrel wall. Frictional heat builds up, and in combination with the heat generated by the barrel heater, creates more melt to be formed within the screw flight channels. The melt pool formed as you go down the transition section increases. As the pellets reach the section where compression takes place, the volume of material inside the screw flight channel decreases until the metering section is reached.

The metering section of the screw of the standard injection molding screw acts as the pumping mechanism for the melt, forcing molten material forward accurately and completing the melting process. As the material goes forward to the front of the screw, force is generated to push the screw back in the direction of the hopper to the original, set position of the shot size. As the screw rotates and pumps the molten material through the nonreturn valve, the molten material that is accumulating in front of the valve is pushing and reciprocating the screw.

1.3.4.1 Screw Types

Over the past 50 years, a number of screw types have been developed for injection molding. In this chapter the focus is placed on three screws commonly used in the industry today: (1) the conventional screw, (2) the barrier screw, and (3) the ET screw.[1] The *conventional screw* is the screw most commonly used in injection molding machines, due to wide availability and low cost. As shown in Figure 1.3*a*, a conventional screw is recognized by its deep channels in the feed section and gradually decreasing channel depth going toward the transition and metering section. This screw design works well for most thermoplastics. However, the conventional screw is limited in performance and does not provide good melt quality or mix, in particular for color mixing. Improvements in color mixing can be achieved with the addition of a mixing head or "motionless mixer" placed at the front of the barrel beyond the metering section of the screw.

More modern screw designs utilize a *barrier flight* (Figure 1.3*b*). As the melt film is wiped off the barrel surface by the main flight, the melt is deposited into a separate melt channel. A barrier flight divides the solid and melt channels such that the clearance over the barrier flight will only allow melt to enter this channel. The main

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[1] Barr ET is a registered trademark of Barr, Inc.

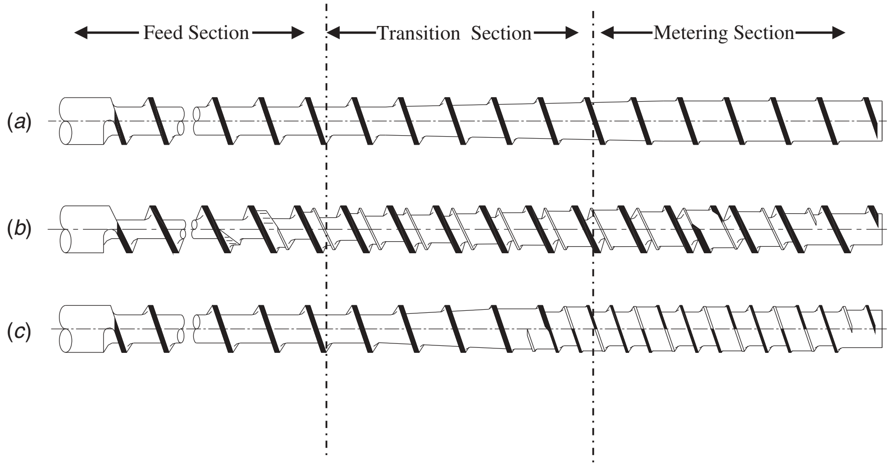

FIGURE 1.3 (*a*) Conventional, (*b*) barrier, and (*c*) ET screw designs. (Courtesy of Barr, Inc.)

function of a barrier flight is to separate the melted polymer from the solid bed and keep the solid bed from becoming unstable and breaking up prematurely. By removing the melt film continuously over the barrier flight, the solid bed surface remains intact. This allows for a greater solid bed surface area on the barrel wall to keep the viscous energy dissipation via shearing as high as possible. In addition, since the melt film thickness over the barrier flight is small, the shear energy is also high. It is believed that this type of phase separation will increase the melting rates over those of nonbarrier screws. However, since approximately 90% of the polymer is melted by the high shear in the barrier section, the melt temperatures are correspondingly higher, which is undesirable in many applications. The limitations of the barrier screw are that it is prone to high shear and higher melt temperatures than those of the conventional screw design, and is susceptible to solid pellet wedging at the start of the barrier section.

Recognizing the inherent problems and limitations of barrier screws, a solid–melt mixing screw known as the *ET screw* was developed. This principle differs from that of barrier designs in that the metering section is divided into two equal subchannels by a secondary flight. The solid bed is broken up intentionally at the end of the melting section to allow some solids to enter the mixing section. The clearance of the secondary flight is much greater than the clearance of the barrier flight on a barrier screw, allowing unmelted pellets to pass through. The depth of one subchannel decreases, while the depth of the other increases, forcing the melt to flow over the secondary flight at relatively low shear rates. Solid bed fragments mixed in the melt are broken into individual pellets by passing over the secondary flight. The pellets are mixed with the melt continually, promoting heat transfer by conduction from the melt to the pellets. Since the viscous energy dissipation via shearing in solid–melt mixing screws is low and the primary melting mechanism is by conduction, the melt temperature is reduced.

The barrier screw (Figure 1.3*b)* is characterized by the double channels found primarily in the transition section of the screw. As the pellets are conveyed in this screw design, the material is separated into the two channels: one for solid, unmelted pellets and the other for molten material. The barrier flight is undercut below the primary flight, allowing melt to flow over it. This screw design provides a higher melting rate than that of conventional screw design and gives slightly better mixing. No mixing head is needed with a barrier screw.

The ET screw (Figure 1.3*c*) has a configuration in the feed section similar to that of a conventional screw, but as the pellets enter the transition zone, the channel depth is less than that of a conventional screw. In addition, the metering section of the ET screw takes on a double-channel design. This design provides increased melting efficiency and utilizes less energy for melting the material. In addition, improved mixing and melt uniformity, as well as increased output rate and lower melt temperatures, provide the flexibility to injection mold a wide range of polymers. Its limitation is that this design is higher in cost that either the conventional or barrier screws because it is more difficult to manufacture.

Table 1.5 provides a comparison of the conventional, barrier, and ET screw designs.

TABLE 1.5 Conventional, Barrier and ET Screw Designs: Advantages and Disadvantages

Screw Type	Advantages	Disadvantages
Conventional	Cost	Performance, melt quality, poor mixing especially with colors Mixing head may be needed to improve color mixing
Barrier	Increased melting rate Slightly better mixing in comparison to the conventional screw	High shear Higher melt temperatures Prone to solid wedging Not as forgiving as a conventional screw
ET	Increased melting efficiency Increased energy utilization Increased mixing and melt uniformity Increased output rate Lower melt temperatures needed to melt material Works well for a wide range of polymers	Higher cost, due to increased difficulty in manufacturing and design of the screw

Source: Barr, Inc.

1.3.4.2 **L/D** *Ratio*

The *L/D* (length/diameter) ratio is an important concept for determining the sizing of an injection unit. The *L/D* ratio is determined by the following equation:

$$\frac{L}{D} = \frac{L_s}{D_s} \tag{1.5}$$

where L_s is the overall flight length of the screw and D_s is the nominal diameter of the screw. In the injection molding process, screws with *L/D* ratios of 18 : 1 and 20 : 1 are typically used. However, *L/D* ratios of 16 : 1, 22 : 1, 24 : 1, and 26 : 1 are also used.

1.3.4.3 Compression Ratio

Compression ratio is a term used to give an idea of how much the screw compresses and squeezes the melt–molten material mix in the screw. The intent of this concept is to divide the volume of a flight in the feed section by that of the flights in the metering section. However, the depth of the screw channel is used to calculate the compression ratio.

The equation to determine the compression ratio is

$$\mathrm{CR} = \frac{D_f}{D_m} \tag{1.6}$$

where D_f is the depth of the channels in the feed section and D_m is the depth of the channels in the metering section. Table 1.6 shows typical values of the compression ratio for various thermoplastic materials. Typical compression ration values range from 1.2 to 4.0 for most thermoplastics.

1.3.4.4 Screw and Barrel Wear

Screw and barrel wear is an area that can affect the performance and processing of thermoplastic materials. A number of factors affect how a barrel and screw wear:

- Misalignment of the screw, barrel, and drive alignment.
- Straightness of the screw and barrel. This can be especially true for a high-*L/D*=ratio screw (22 : 1).
- Screw design. High-compression-ratio screws wear faster.
- Barrel heating uniformity. Sections of the barrel run at low process temperatures, especially at the rear near the hopper, will show higher wear.
- Material being processed. The higher the material hardness, the greater the wear.
- Abrasive fillers, such as glass fiber, talc, mineral fillers, mineral fibers, mica, and carbon-fiber-filled materials.
- Screw surface and liner materials. Different alloy combinations will wear more.
- Insufficient support of the barrel can cause sections of the barrel to contact the screw, and as the screw rotates, wear to the barrel can occur.
- Corrosion from volatiles given off by some plastics materials.
- Excessive back pressure can cause increased wear.

TABLE 1.6 Compression Ratios for Various Thermoplastic Materials

Compression Ratio Range	Low Compression Ratio 1.2–1.9	Medium Compression Ratio 2.0–2.8	High Compression Ratio 3.0–4.5
Thermoplastic material	Polymethylmethacrylate (PMMA)	Polyoxymethylene (POM)-acetal	Polytetrafluoroethylene
	Acrylonitrile butadiene styrene (ABS) terpolymers	Cellulose acetate	Polyamides (nylon)-high melt index
	Styrene acrylonitrile (SAN) copolymers	Cellulose propionate	Polyethylene (high melt index)
	Polyvinyl chloride (PVC), rigid	Polyamides (nylon)-low melt index	Polypropylene (high melt index)
		Polyphenylene oxide (PPO)	
		Polyethylene (low–medium melt index)	
		Polypropylene (low–medium melt index) polystryene	
		Polyvinyl chloride (PVC), plasticized	
		Thermoplastic polyolefin (TPO)	
		Thermoplastic polyurethane (TPU)	
		Polyethylene terephthalate (PET)	
		Polybutylene terephthalate (PBT)	
		Polycarbonate	
		Polycarbonate/ABS blends (PC/ABS)	
		Polycarbonate/PBT blends (PC/PBT)	
		Polycarbonate/PET blends (PC/PET)	
		Acrylic styrene acrylonitrile (ASA) blends	
		Polyetherimide (PEI)	

Source: Multiple industry sources.

All of the factors mentioned can lead to wear issues for screws and barrels. Wear can be classified into three types: (1) abrasive, (2) adhesive, and (3) corrosive. *Abrasive wear* is caused by damage from fillers such as glass fibers, talc, mineral fillers, mineral fibers, mica, and carbon fibers. These materials will scrape metal off the screw and barrel over a period of time. Glass fibers are one of the worst offenders since these can abrade the root of the screw at the leading edge, usually in the transition and compression sections of the screw, where the fibers have been exposed by some melting and unmelted pellets that are squeezed against the screw and barrel. Hard surfacing materials can be applied to both the screw and barrel to reduce this wear.

Adhesive wear is gauging caused by metal-to-metal contact. In this case, certain types of metals can adhere to each other when high levels of frictional heating take place, pulling apart on further rotation of the screw. Proper clearance and alignment of the screw and barrel, compatible metallic materials, and proper hardness can reduce this type of wear.

Corrosive wear is caused by chemical attack on the barrel and screw when the plastic material is overheated and a corrosive chemical is released. The origin of this chemical can be from the material itself, such as PVC and acetal, or from additives in a particular material. The best way to prevent wear in this case is simply not to overheat the material or let material sit in the barrel for long periods of time. Corrosion-resistant coatings can be used to reduce the chance of this occurring.

1.3.5 Barrel-to-Shot Ratio

When molding a plastic part, selecting a machine with the correct barrel size is critical. Using too much of the material in the barrel can cause unmelted material to show up on a plastic part, which can affect part structural integrity. Also, using too small an amount of material in the barrel can cause material to be exposed for too long at an elevated process temperature, referred to as *residence time*, causing material to degrade and produce parts of poor structural quality. One method used in determining how much material is in the barrel related to the size of the part being molded is called the *barrel-to-shot ratio* (BSR). This ratio is calculated as

$$\mathrm{BSR} = \frac{W_{\mathrm{r+p}}}{\mathrm{SC}_m}\left(\frac{\rho_m}{\rho_{\mathrm{ps}}}\right) \tag{1.7}$$

where $W_{\mathrm{r+p}}$ is the weight of the part plus runner system, SC_m the shot capacity of the machine (ounces), ρ_m the density of the plastic material to be molded, and ρ_{ps} the density of polystyrene. Typically, the optimum BSR values for most thermoplastic materials range from 30 to 65%.

1.3.6 Check Rings

When the screw comes forward to inject the material forward into the mold, molten material can flow back over the screw flights. To prevent this backflow from occurring, a check ring is used. A number of different types of check rings are used in