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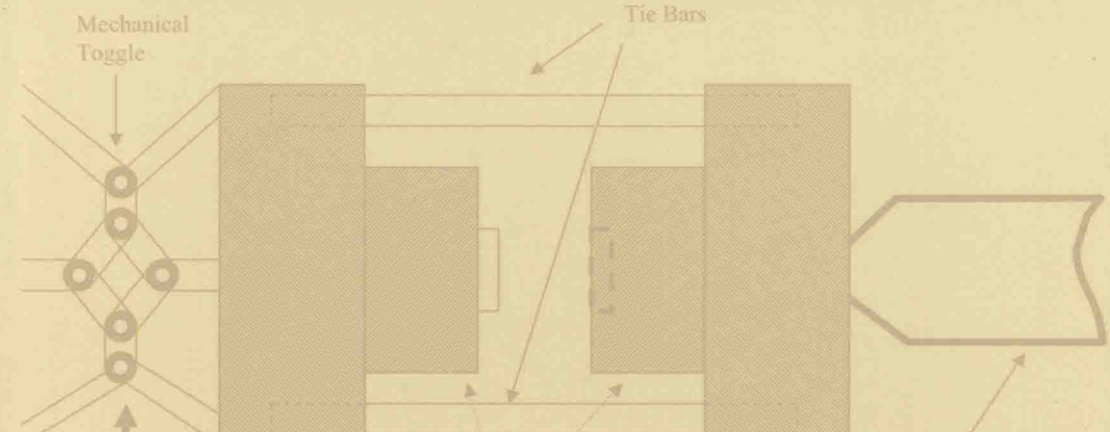
Handbook of Plastic Processes

Edited by Charles A. Harper



HANDBOOK OF PLASTIC PROCESSES

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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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CONTENTS

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)

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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.

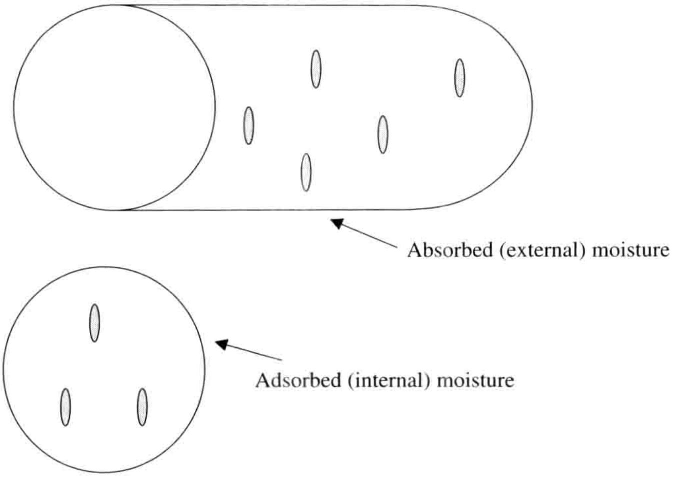

FIGURE 1.1 External and internal moisture.

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:

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

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)

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