IMPORTANCE OF PROCESS DESIGN

The intention of this chapter is not merely to present the technology of polymer processing but to initiate the concepts required in the design of polymer processes. A knowledge of the types of polymers available today and the methods by which they are processed is certainly needed, but this is available in several sources such as *Modern Plastics Encyclopedia* (Green, 1992) and the *Plastics Engineering Handbook* (Frados, 1976). In this chapter we present primarily an overview of the major processes used in the processing of thermoplastics. In Section 1.1 we begin by classifying the various processes and point out where design is important. In Section 1.2 we present a case study concerned with film blowing to illustrate how the final physical properties are related all the way back to the melt flow of a polymer through the die. Finally, in Section 1.3 we summarize the principles on which polymer process design and analysis are based.

1.1 CLASSIFICATION OF POLYMER PROCESSES

The major processes for thermoplastics can be categorized as follows: extrusion, postdie processing, forming, and injection molding. We describe specific examples of some of the more common of these processes here.

The largest volume of thermoplastics is probably processed by means of extrusion. The extruder is the main device used to melt and pump thermoplastics through the shaping device called a die. There are basically two types of extruders: single and twin screws. The single-screw extruder is shown in Figure 1.1. The single-screw extruder basically consists of a screw (Fig. 1.2) that rotates within a metallic barrel. The length to diameter ratio (L/D) usually falls in the range of 20 to 24 with diameters falling in the range of 1.25 to 50 cm. The primary design factors are the screw pitch (or helix angle, \( \theta \)) and the channel depth profile. The main function of the plasticating extruder is to melt solid polymer and to deliver a homogeneous melt to the die at the end of the extruder. The extruder can also be used as a mixing device, a reactor, and a devolatilization tool (see Chapter 8).

There are an equal number of twin-screw extruders in use as single-screw extruders today. There are many different configurations available including corotating and counterrotating screws (see Fig. 1.3) and intermeshing and nonintermeshing screws. These extruders are primarily adapted to handling difficult to process materials and are used for compounding and mixing operations. The analysis and design of these devices is quite complicated and somewhat out of the range of the material level in this text. However, some of the basic design elements are discussed in Chapter 8.

The extruder feeds a shaping device called a die. The performance of the single-screw and corotating twin-screw extruders is affected by resistance to flow offered by the die. Hence, we cannot separate extruder design from the die design. Problems in die design include distributing the melt flow uniformly over the width of a die, obtaining a uniform thermal history, predicting the die dimensions that lead to the desired final shape, and the production of a smooth extrudate free of surface irregularities. Some of these design problems are accessible at this level of material while others are still research problems (see Chapter 6).

There are many types of extrusion die geometries including those for producing sheet and film, pipe and tubing, rods...
IMPORTANCE OF PROCESS DESIGN

FIGURE 1.1 Typical single-screw extruder. (Reprinted by permission of the author from Middleman, 1977.)

FIGURE 1.2 Two different extruder screw geometries along with the various geometric factors that describe the characteristics of the screw. (Reprinted by permission of the publisher from Middleman, 1977.)

FIGURE 1.3 Cross-sectional view of corotating and counterrotating twin-screw extruders.

As an example, a wire coating die is shown in Figure 1.4. Here metal wire is pulled through the center of the die with melt being pumped through the opening to encapsulate the wire. The design problems encountered here are concerned with providing melt flowing under laminar flow conditions at the highest extrusion rate possible and to give a coating of polymer of specified thickness and uniformity. At some critical condition polymers undergo a low Reynolds number flow instability, which is called melt fracture and which leads to a nonuniform coating. Furthermore, the melt expands on leaving the die leading to a coating that can be several times thicker than the die gap itself. (This is associated with the phenomenon of die swell.) The problems are quite similar for other types of extrusion processes even though the die geometry is different. The details associated with die design are presented in Chapter 7.

We next turn to postdie processing operations. Examples of these processes include fiber spinning (Fig. 1.5), film blowing (Fig. 1.6), and sheet forming (Fig. 1.7). These processes have a number of similarities. In particular, they are free surface processes in which the shape and thickness or diameter of the extrudate are determined by the rheological (flow) properties of the melt, the die dimensions, cooling conditions, and take-up speed relative to the extrusion rate. The physical and, in the case of film blowing and sheet forming, the
optical properties are determined by both the conditions of flow in the die as well as cooling rates and stretching conditions of the melt during the cooling process. Furthermore, slight changes in the rheological properties of the melt can have a significant effect on the final film or fiber properties. Design considerations must include predictions of conditions which provide not only the desired dimensions but the optical and physical properties of the film, fiber, or sheet.

The third category of processing of thermoplastics is forming. Three examples of this type of process are blow molding (Fig. 1.8), thermoforming (Fig. 1.9), and compression molding (Fig. 1.10). Blow molding is primarily employed for making containers used to package a wide variety of fluids. Although polyolefins, such as high density polyethylene (HDPE), or polyethylene terephthalate (PET), both of which can be considered as commodity resins, are commonly used, interest is growing in using this technique for the processing of higher performance engineering thermoplastics.
Essentially a parison, which has been extruded or injection molded, is inflated by air until it fills the mold cavity. The inflated parison is held in contact with the cold mold walls until it is solidified. Considering the process of thermof orm ing, a sheet of polymer is heated by radiation (and sometimes cooled intermittently by forced convection) to a temperature above its glass transition temperature or in some cases above the crystalline melting temperature and then pressed into the bottom part of the mold (female part) either using mechanical force, pressure, or by pulling a vacuum. The key flow property is the extensional flow behavior of the melt, which controls the uniformity of the part thickness. Sometimes the deformation is applied at a temperature just below the onset of melting, in which case the process is referred to as solid phase forming. At other times the sheet is extruded directly to the forming unit and is formed before it cools down. (This is called scrapless or continuous thermforming.) Some of the key design considerations are the time required to heat the sheet, the final thickness of the part especially around sharp corners, and the cooling rate which controls the amount and type of crystallinity. In compression molding a slug of polymer is heated and then pressure is applied to squeeze the material into the remaining part of the mold. Some aspects of forming are discussed in Chapter 10.

The last general category is that of injection molding, which is shown in Figure 1.11. Polymer is melted and pumped forward just as in a screw extruder. The screw is then advanced forward by a hydraulic system that pushes the melt into the mold. Because of the high deformation and cooling rates, a considerable degree of structuring and molecular orientation occurs during mold filling. The physical properties of injection molded parts can be affected significantly by processing conditions. Design considerations include the required injection pressure to fill the mold cavity, the location of weld lines (places where two melt fronts come together), cooling rates, length of hold time in the mold, and distribution of molecular orientation. In conventional injection molding, parts may vary from a few grams to many kilograms (e.g., a car hood or trunk).

In the last 10 to 15 years one of the major variations in the injection molding process has been microinjection molding (μIM), which appears to be one of the most efficient processes for the large-scale production of thermoplastic polymer microparts (Giboz et al., 2007). These microparts can be as small as 0.6 mg and possess dimensions in the micron range along with dimensional tolerances in the range of microns. Examples of microparts are microelectromechanical systems, which is the name given to the combination of miniaturized mechanical and electronic structures in a system, and miniature gears and lenses. biomedical parts for insertion into the body such as heart stents and sensors are also produced by this method. Micromolding is still very much in its infancy as a new branch of injection molding. As will be discussed in Chapter 10 (Section 10.1.3), it is not just about scaling everything down, but it is a specialized technique in its own right, with a different set of challenges. Some of these factors are out of the realm of the material that can be covered by this book, but those aspects that are accessible are presented in Chapter 10.

Although the majority of the material in this book is concerned with the processing of thermoplastics, the processing of thermosetting systems should also be mentioned for the sake of completeness. We describe three types of processes involving reactive processing: reaction injection molding (RIM), compression molding, and pultrusion. RIM is a process in which two liquid intermediates are metered separately to a mixing head where they are combined by high pressure impingement mixing and subsequently flow into a mold where they are polymerized to form a molded part (see Fig. 1.12). A typical process consists of the reaction of diisocyanate and a polyol to form polyurethane. The important design factors are the degree of mixing and the appropriate heat transfer conditions to ensure uniform curing conditions in the mold. This process is discussed in more detail elsewhere (Becker, 1979).

Thermosetting composites can be processed by means of compression molding of uncured resin. Usually fiber reinforcement is used to provide additional strength and stiffness. The application of pressure pushes the resin into the fiber reinforcement and heat crosslinks the resin to form a solid material. The critical factors are the flow of the uncured resin into and around the reinforcement and the uniform and complete cure of the resin throughout the part. This technique is used primarily in the aerospace and automotive industries. Pultrusion is a process used for making continuous filament reinforced composite extruded profiles (see Fig. 1.13).
FILM BLOWING: CASE STUDY

Reinforcing filaments, such as glass fiber roving, are saturated with catalyzed resin and then pulled through an orifice similar to an extrusion die. As the two materials pass through the die, polymerization of the resin occurs to continuously form a rigid cured profile corresponding to the die orifice shape. The materials are pulled through the die rather than being pumped. Although the primary resins used are of the thermosetting type such as polyester, vinyl ester, and epoxy, thermoplastic resins can be utilized in the same process. The major design considerations for thermosetting systems consist of dispersion of the resin in the reinforcement and the conditions for complete cure of the resin. The processing of thermosetting systems is discussed elsewhere (Macosko, 1989).

The intention in Section 1.1 was more than just to review the technology of polymer processing, but to point out factors that must be considered in the design of polymer processes. However, since most students have little knowledge of the technology of processing of polymers, some general introduction is of value. Furthermore, a physical picture of the various processes is required to facilitate the discussion of the material presented in the next four chapters.

1.2 FILM BLOWING: CASE STUDY

The last section was merely concerned with describing the technology of polymer processing. This section is concerned with illustrating the role of processing in affecting the properties of polymeric systems. In particular, the properties of films of polybutylene (PB1) generated by means of film blowing are shown to be highly sensitive to processing conditions.

Most blown film is made from some form of polyethylene (PE), but polybutylene, PB1, has been considered because it is slightly cheaper to use in the production of film. However, it does not lead to the same physical properties without changing the processing conditions. Identification of the appropriate processing conditions is usually done either by a trial-and-error approach or through statistically designed experiments. If a model of film blowing was available, or if one could apply dimensional analysis concepts, then it might be possible to find the appropriate processing conditions without carrying out a lengthy set of costly experiments. The following example illustrates the many factors that affect the properties of blown PB1 film.
The film blowing process was shown in Figure 1.6. Polymer pellets are fed to the extruder in which melting, homogenization, and pumping occur. The melt then passes through the die, which is designed such that as it leaves the die, the melt has been subjected to both a uniform deformation as well as thermal history. Air is blown through the center of the die to expand the molten bubble to impart orientation of the molecules in the hoop direction. At the same time the bubble is being stretched as a result of the take-up velocity being greater than the average velocity of the melt leaving the die. The stretching imparted in the two directions controls the degree to which the molecules orient and hence affects the physical properties. Cooling air is blown along the bubble by an air ring, which is placed around the outside of the die. This serves to cause the film to solidify or crystallize and lock in the orientation imparted by the biaxial stretching process. The film is then taken up on a roller and either slit to make flat film or sealed and cut to make bags.

We now look at some of the factors that affect the physical properties of the blown film. The recommendations for the annular die gap opening for a desired film thickness are given in Table 1.1. It is probably clear as to why the die gap is larger than the desired film thickness as the film is to be drawn down to create molecular orientation. What is not clear is why it is recommended that the die land (the annular portion of the die) be shortened as the die gap increases. The physical properties based on the tear strength of the film are found to be significantly affected by the length of the die land as shown in Figure 1.14. Here the tear strength is plotted versus the blow up ratio, BUR, which is the ratio of the final film diameter to the die diameter (outer diameter). It is observed that there is on the order of a threefold difference in the tear strength for a 2.0 $\times$ $10^{-3}$ in. thick film when the die land is decreased from 1.5 in. to 1.0 in. One reason for this result is that more “die swell” (the expansion of a polymer melt on leaving a die) occurs for the die with the 1.0 in. land length, and hence a higher stretch ratio is required to draw the film down to 2.0 $\times$ $10^{-3}$ in. This leads to higher orientation of the molecules along the draw direction than in the case of the die with a 1.5 in. land length. Finally, the effect of the die gap on the tear strength measured both along the film length (this is called the machine direction, MD) and along the circumference of the film (this is called the transverse direction, TD) is shown in Figure 1.15. Here we see that the tear strength in the TD decreases significantly with an increase in die gap, while in the machine direction the effect is significant but nowhere near as large. Again it is not clear as to what would cause the loss of properties in both directions as the die gap increases other than the longer time available for molecular relaxation due to the increase in time required for cooling of the film. Factors other than orientation must be involved in controlling the properties. For example, the amount of crystallinity and the size of the spherulitic regions may play a significant role.

The melt extrusion temperature is also observed (Fig. 1.16) to have a significant effect on the physical properties as the tear strength in both directions increases with increasing melt temperature. This is probably due to lower levels of orientation as the result of lower stress levels in the melt and shorter relaxation times allowing a rapid relaxation of molecular orientation.

Table 1.1: Die Recommendations for the Blowing of PB1 with a Blow Up Ratio of 2.4–2.8 at a Melt Temperature of 370–390 °F

<table>
<thead>
<tr>
<th>Film Thickness ($\times$ 10^-3 in.)</th>
<th>Die Gap (inches)</th>
<th>Land Length (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5–1</td>
<td>0.015</td>
<td>1.5–2</td>
</tr>
<tr>
<td>1–2</td>
<td>0.018–0.023</td>
<td>1.2</td>
</tr>
<tr>
<td>2–7</td>
<td>0.028–0.032</td>
<td>1</td>
</tr>
<tr>
<td>8–15</td>
<td>0.040–0.050</td>
<td>1</td>
</tr>
<tr>
<td>15–40</td>
<td>0.050–0.060</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 1.14: Effect of the annular die land length on the film tear strength of polybutylene extruded at the rate of 10 m/min for two different film thicknesses.

Figure 1.15: Effect of die gap on the film tear strength of polybutylene extruded at the rate of 10 m/min. The film thickness is 0.002 in. and the blow up ratio is 2.8.
The line speed, given in feet per minute (fpm), as shown in Table 1.2, has a very significant effect on the properties. For example, as the line speed increases from 14 fpm, the breaking strength in the MD increases from 4800 g/mil to 6600 g/mil but decreases in the TD from 5000 g/mil to 2300 g/mil (mil here means 0.001 in.). This is mostly associated with the degree of molecular orientation. The more the molecules are oriented along the MD the stronger the films are, but the poorer the tear strength in this direction. The other properties given here can be explained by similar arguments.

The blow up ratio, BUR, can be used to obtain a better balance of properties as shown in Figure 1.17. As BUR increases the tear properties become more uniform in both directions. Biaxial orientation (i.e., orientation of molecules in two directions) is generated in the blowing process, which leads to more uniform properties.

As one can imagine the film blowing process is very difficult to model and, hence, very little quantitative design work has been done. Although the complete modeling of this process is beyond the level of the material in this book (or even an advanced book for that matter), the example serves to illustrate that the properties of a polymeric material are highly dependent on the processing conditions and some of the problems faced by the engineer. In designing a polymer process one must be concerned with not only how much material per unit time can be produced but with the properties of the material. In the next section we look at the fundamental principles on which the design and analysis of polymer processes is based.

### Table 1.2 Line Speed Versus Properties for PB1

<table>
<thead>
<tr>
<th>Line Speed (fpm)</th>
<th>Break Strength (g/mil) MD</th>
<th>TD</th>
<th>Yield Strength (g/mil) MD</th>
<th>TD</th>
<th>Ultimate Elongation (g/mil)</th>
<th>Dart Drop (g/mil)</th>
<th>Tear Strength (g/mil) MD</th>
<th>TD</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>4800</td>
<td>5000</td>
<td>2000</td>
<td>2000</td>
<td>220</td>
<td>260</td>
<td>350</td>
<td>1700 550</td>
</tr>
<tr>
<td>20</td>
<td>4600</td>
<td>3700</td>
<td>2100</td>
<td>2000</td>
<td>160</td>
<td>230</td>
<td>280</td>
<td>1510 550</td>
</tr>
<tr>
<td>30</td>
<td>5500</td>
<td>2800</td>
<td>2500</td>
<td>1900</td>
<td>110</td>
<td>170</td>
<td>190</td>
<td>680 390</td>
</tr>
<tr>
<td>40</td>
<td>6600</td>
<td>2300</td>
<td>3000</td>
<td>1900</td>
<td>80</td>
<td>150</td>
<td>90</td>
<td>80 270</td>
</tr>
</tbody>
</table>
8 IMPORTANCE OF PROCESS DESIGN

4. Principles of mixing
5. Chemical reactions

In the first five chapters of this book we deal with the fundamental principles required in the design of polymer processes. The last six chapters are concerned with the details of specific types of processes and the reprocessing of polymers and the processing of renewable polymers.

REFERENCES

Richardson, P. N. 1974. Introduction to Extrusion (Society of Plastics Engineers, Inc., Greenwich, CT).