The advantage of the ram-assisted screw extruder is that highly filled, viscous materials are more easily processed. This type of device is commonly used when processing bulk molding compound (BMC)—a blend of thermosetting polyester, fillers, and glass. Here, the extruder mixes the fillers and glass with the polyester and then feeds the chamber of the ram extruder.

### 4.1.2 The Reciprocating Screw

As mentioned earlier, the reciprocating screw is the most commonly used plasticating unit. Because of the importance of this type of unit it will be described in detail. The most important components are the screw, nonreturn valve, barrel, nozzle, and screw drive. The components will be discussed next.

**The Plasticating Screw**

The main components of the plasticating unit are shown in Fig. 4.2. The most important component is the screw [1]. It is a long cylinder with one or more helical flights wrapped around it and a nonreturn valve at the end (see Fig. 4.3). Such a device is often referred to as an Archimedean screw, after Archimedes, who developed the
basic screw conveyor thousands of years ago. The screw determines the conveying, the heating, the mixing, and in some cases the degassing of the plastic. Degassing or devolatilization is performed on a vented system; these are machines with a vent opening in the barrel through which volatiles can escape. Venting requires a special screw geometry, the so-called two-stage screw.

The main requirements of a reciprocating screw are to deliver a homogeneous and high-quality melt to the end of the screw within a cycle and from cycle to cycle. Homogeneous refers to uniformity of melt temperature as well as consistency. Good melt homogeneity is best achieved by using a distributive mixing section at the end of the screw [2]. Mixing will be discussed in more detail in a later section.

Screw Design for Injection Molding

It is generally recognized that proper screw design is of critical importance in the extrusion of sheet, film, pipe, tubing, and profiles using conventional, nonreciprocating extruders. In injection molding, however, where the plasticating units are usually reciprocating extruders, it is often assumed that screw design is of little importance. This assumption is unfortunately often incorrect. Screw design technology for non-reciprocating extruders has advanced considerably over the years, as evidenced by steady improvements in output and quality and the large number of articles devoted to the subject. On the other hand, screw design for reciprocating extruders has progressed relatively little, despite the fact that injection molding machines have become more and more sophisticated in terms of process monitoring and control, mold design, and the like.

The basic functions performed in a nonreciprocating extruder are solids conveying, melting, melt conveying, mixing, and sometimes devolatilization. The very same functions are performed in a reciprocating system with the difference being the screw is moving backward while these functions are performed, and the nature of the process is cyclic instead of continuous. If consistency from cycle to cycle is to be achieved, however, the conveying, heating, and mixing process should be highly repeatable. Thus, improvements in screw design developed for nonreciprocating extruders are largely applicable to reciprocating extruders as well.

The Standard Injection Molding Screw

Injection molding screws often have similar characteristics to the extruder screw. A typical screw is shown in Fig. 4.3. The screw is single flighted with the flight pitch equal to the screw diameter and constant over the length of the screw. This is called a square pitch geometry, which is also frequently used in conventional extruders. The compression ratio usually varies from 2:1 for small machines to about 2.5:1 for large machines. The length of the feed section is about 50% of the total length, while the compression and metering section usually are 25%. This is different in a conventional extruder screw where the feed section is shorter and the compression and metering section longer. A typical screw for a regular extruder is shown in Fig. 4.4.

The width of the flight is about ten percent of the screw diameter. The channel depth in the feed section is deeper than in the metering section; the ratio of feed to
metering depth is called the compression ratio. The value of the compression ratio usually ranges from 2.5 to 3.0. In the modern extruder screw, mixing sections are used in most cases because the mixing capability of simple conveying screws is very limited.

Figure 4.5 shows some typical values of the channel depth in the metering section for reciprocating screws as described by Schwittay [3]. Within a diameter range of 30 to 120 mm, the channel depth increases approximately in a linear fashion with the diameter. Typical values of the compression ratio are shown in Fig. 4.6 [3].

For most thermoplastics the compression ratio increases from about 2:1 at small screw diameters to 2.5:1 for large screw diameters (100 mm or 4 inches). For rigid PVC, however, much lower values of the compression ratio are used, because PVC is quite susceptible to degradation, so using a lower compression ratio will deter this from happening. The radial flight clearance for reciprocating screws [3] is considerably larger than it is for regular screws [4], as shown in Fig. 4.7; the difference is a factor of about 2 to 3. This is mainly due to the fact that the reciprocating screw not only has an angular movement, but an axial movement. This action will wear the top of a flight quickly if it is not properly designed.

Figure 4.4 Typical screw for a regular extruder.

Figure 4.5 Typical values of channel depth in the metering section [3].

Figure 4.6 Typical values of the compression ratio.
The first is to support the mold and traverse it between the open and closed positions. This function requires only enough force to accelerate the moving mass and to overcome friction. Guidance of the moving mold half is important to prevent excessive wear in the mold leader pins.

- Hold mold closed during part formation

The second is to hold the mold closed during the injection of melt into the cavities. This may require considerable clamping force as the melt pressure within the mold is often very high.

- Provide means of ejecting parts

Once the parts have cured (cooled) and the mold has opened, a means must be provided to eject the parts. The force required for this is relatively small compared with the clamping force.

5.3 The Three Types of Clamping Systems

Clamping mechanisms for injection molding usually fall into three categories: hydraulic (or pneumatic), hydromechanical, and mechanical.

5.3.1 Hydraulic

Hydraulic (or pneumatic) clamps are distinguished from the other types by the following:

- The load path passes through the fluid (oil or air) used to pressurize the clamping cylinder(s) (Fig. 5.7)
- The length of the column of fluid being pressurized is equal to or greater than the stroke of the clamp. This fact separates this class of clamps from hydromechanical clamps.
- The clamping force is in direct proportion to the pressure applied to the clamping cylinder.
- Available clamp stroke is a function of maximum open daylight and the shut height of the mold.

An example of a hydraulic clamp is shown in Fig. 5.8. These clamps are often favored for their simplicity and ease of setup.
5.3.2 Hydromechanical

Hydromechanical clamps are distinguished from the other types by the following:

- The load path passes through the fluid (oil or air) used to pressurize the clamping cylinder(s) (Fig. 5.9).
The length of the column of fluid being pressurized is independent of and much less than the stroke of the clamp. Typically the height of the oil column is less than 2cm (3/4 in). This fact separates this class of clamps from hydraulic clamps.

The clamping force is in direct proportion to the pressure applied to the clamping cylinder.

Available clamp stroke is a function of the traversing actuator stroke with provisions for varying mold shut heights typically being through tie rod nut adjustments on the rear platen.

An example of a hydromechanical clamp is shown in Fig. 5.10. A wide variety of novel approaches have been used in the design of this class of clamps.

### 5.3.3 Mechanical

Mechanical clamps are typically referred to as toggle clamps and are distinguished from the other types by the following:

- The load path does not pass through the hydraulic/pneumatic cylinder(s) or electrically driven actuator(s) (Fig. 5.11).
- The clamp force is not in direct proportion to the force of the actuator. Instead, it is a complex relationship between the available actuating force during toggle-up and the stiffness of the clamp. This will be discussed later.
- Available clamp stroke is a function of the linkage system with provisions for varying mold shut heights typically being through tie rod nut adjustments on the rear platen. The pin-to-pin center line length of the rear link is the dominant factor in determining clamp stroke. An example of a mechanical clamp is shown in Fig. 5.12.
6.6.5 Deflection of Support Plates

The support plate on the ejector half of the mold must resist the high forces developed from clamping and from the injection pressures. The support plate is particularly susceptible to deflection because it is suspended over the open space of the ejector housing. This deflection will result in flashing and irregularities in the finished molding. It is important that the plate must be sufficiently thick and rigidly supported by support columns to resist deflection.

The practice in industry is to overdesign the structure of the mold using excessive plate thickness and support. This is an accepted practice because the cost for the thicker mold plates, support columns, and related machining is relatively small. A structural analysis would ideally be performed, although it is rarely done. The following is a simplified method that can be used to help determine the required thickness of the support plate. It uses standard beam equations. Judgment must be made as to whether the ends of the support plate should be treated as fully supported or freely supported. This example assumes a fully supported plate because the ends of the plates are reasonably fixed when the machines clamp is closed.

Example 6.1

The objective is to determine how thick the support plate needs to be to resist deflection in excess of 0.005 mm. The assumption is that there are no support pillars, that the two sides of the plate are fully constrained, and that there is a distributed load [cavities are well distributed across the plate (see Fig. 6.53)] of 200 metric tons (200,000 kg.). The 200 tons is based on the machines' rated clamp. The clamp should be the maximum load acting to deflect the plates. Modulus of the support plate steel is 206,897 MPa (2,109,770 kg/cm²)

Given the loading case shown, the plate deflection \((y)\) can be determined as follows.

\[
y = \frac{FL^3}{384EI}
\]  
(6.2)

\[
I = \frac{bd^3}{12}
\]  
(6.3)

\[
y = \frac{FL^3}{384E(bd^3)}
\]  
(6.4)

where \(d\) = plate thickness
\(b\) = plate width (see Fig. 6.54)
\(l\) = plate length
From Eq. 6.4, the required plate thickness can be found by manipulating the equation to solve for \(d\) (plate thickness).

\[
d = \sqrt[3]{\frac{FL^2}{384Eby}}
\]

\[
d = \sqrt[3]{\frac{(200,000 \text{ kg})(36 \text{ cm})^3(12)}{(384)(2,109.770 \text{ kg/cm}^2)(60 \text{ cm})(5.0 \times 10^4 \text{ cm})}}
\]

\[
d = 16.64 \text{ cm} \text{ plate thickness required to maintain a deflection of 0.005mm.}
\]

- To reduce this plate thickness, support pillars can be placed along the plate’s centerline. This effectively reduces the unsupported area to less than one half. If 3.8-cm diameter pillars are spaced every 5.0 cm, the unsupported length of the support plate is reduced to approximately 16.1 cm. Solving for thickness \((d)\), given a length \((l)\) of 16.1 cm, gives a plate thickness of only 5.91 cm.
- The required plate thickness can also be affected by modulus of the support plates.

It is also important to check that the design stresses of the steel are not exceeded. The stress developed in the plates during loading for the preceding example are found as follows. Again, this is based on simple-beam equations using the previous assumptions.

\[
\sigma = \frac{Fl}{12Z} \quad Z = \frac{I}{d/2} = \frac{bd^2}{6}
\]

\[
Z = \frac{(60 \text{ cm})(5.91 \text{ cm})^2}{6} = 349.3 \text{ cm}^3
\]

\[
\sigma = \frac{(100.00 \text{ kg})(16.1 \text{ cm})}{12(349.3 \text{ cm})^3}
\]

\[
\sigma = 384.1 \frac{\text{kg}}{\text{cm}^2} = 37.7 \text{ MPa}
\]
9.5 In-Mold Decoration and In-Mold Lamination

In-mold decoration (IMD) comprises insertion of a film or foil into the cavity, followed by injection of polymer melts on the inner side of the insert to produce a part with the final finish defined by the decorative film/foil. On the other hand, the in-mold lamination process resembles IMD except that a multilayered textile laminate is used. These two processes provide a cost-effective way to enhance and/or modify the appearance of product for marking, coding, product differentiation, and model change without costly retooling. The laminated component can have desirable attributes (e.g., fabric or plastic skin finish with soft-touch) or properties (e.g., electromagnetic interference, EMI, or radiofrequency interference, RFI, shielding).

9.5.1 Process Description

IMD

In the IMD process, a predecorated carrier laminated onto film stock from the roll is pulled through the mold and positioned precisely between the mold halves. The film stock may be decorated by printing methods (e.g., silk-screen or hot stamping) prior to molding [48]. During the molding stage, the polymer melt contacts the film and fuses with it so that the decoration can be lifted off from the carrier film and strongly attach to the surface of the molding. An injection molding machine with a typical IMD set up is shown in Fig. 9.19.

In one of the IMD techniques, the so-called paintless film molding (PFM) or laminate painting process, a three-layer coextrusion film with pigment incorporated into

Figure 9.19 In-mold decorating setup with a foil-feeding device built into the injection molding machine [49]. (From Injection Molding—An Introduction, Pötsch, G. and Michaeli, W. (1995), Hanser, Munich, p. 175, Fig. 8.6.)
layers of clear-coat cap layers and core layer is first thermoformed into the shape of the finished part and then inserted into the cavity and overmolded with thermoplastics to produce a final part [50]. With this technique, it is possible to obtain a high-quality, extremely smooth paint finish on thermoplastic exterior body claddings and moldings ready for assembly without subsequent spray painting or finishing. Unlike in-mold coating and mold-in-color, this process provides high-gloss metallic and non-metallic finishes. It provides unique patterns and designs that are not feasible with paint. The paint laminate finish provides superior weatherability, acid etch resistance, and a safe worker environment because it is virtually pollution-free.

In addition to injection molding, IMD can be used with a variety of other processes, such as structural foam injection molding, ICM, compression molding, blow molding, thermoforming, resin transfer molding, and rotational molding [25].

In-Mold Lamination Process

Instead of using a thin film/foil as does IMD, the in-mold lamination process employs a multilayered textile laminate positioned in the parting plane to be overmolded by the polymer melt on the inner side. The decorative laminate can be placed in the mold as a cut sheet, pulled from the roll with needle gripper, or, by means of a clamping frame method. By means of a thermoforming operation, the clamping frame method allows defined predeformation of the decorative laminate during the mold-closing operation. In-mold lamination is also known as “laminate insert molding” [51] or “fabric molding” [52] for manufacturing automotive instrument panels and interior panels, respectively.

For in-mold lamination, the outer, visible layer of the decorative laminate can be made of polyester, PA, PP, polyvinyl chloride (PVC), or acrylonitrile-butadiene-styrene (ABS) film, cotton textile (woven, knitted, tufted, or looped fabrics), or leather. This outer layer typically comes with a variety of features to create an appearance or feel. In general, low surface texture is preferred because the ironing effect typically occurs with high pile or fiber loops. To provide the product with a soft-touch effect, there is typically an intermediate layer of polyurethane (PU), PP, PVC, or polyethersulfone (PES) foam between the top layer and the liner layer. Underneath the foam layer is the liner layer, which is used to stabilize the visible layer against shear and displacement, prevent the penetration of polymer melt into the intermediate layer, and provide thermal insulation against the polymer melt. This liner layer can be woven, knitted, or a nonwoven fabric. The typical structure of the in-mold laminated parts is shown in Table 9.6.

To avoid damage or undesirable folding of the laminate during molding, low injection pressure and low temperature are desirable. This makes low-pressure injection molding (see Sec. 9.8), ICM (see Sec. 9.4), compression molding, and cascade injection molding with sequential valve-gate opening and closing suitable candidates for in-mold lamination. Note that the latter process also eliminates the common problem associated with the weld lines, which are more evident with the IMD process.
9.5.2 Process Advantages

When compared with conventional surface decoration methods, such as painting, metallizing, hot stamping, PVC film laminating, and various painting methods, IMD and in-mold lamination offer a wide range of advantages, such as [55]:

- The process is a cost-effective way of surface decoration that replaces the traditional multistaged lamination process with a single molding cycle. The potential savings can amount up to 15 to 25%.
- The process is environmentally friendly with no volatile solvents released during adhesive lamination, and no posttreatment is needed.
- The decoration exhibits strong adhesion with the molding, as well as high surface-wear resistance and good chemical resistance.
- Use of the regrind is possible if permitted by the application and requirements.
- Three-dimensional decoration is possible within the limitations of the deformability of the film/foil and laminate.

9.5.3 Process Disadvantages

The disadvantages of IMD and in-mold lamination processes are additional equipment cost as well as extra steps for handling, die-cutting, performing, and placement of the decorative film/foil and laminate into the mold. Although conventional injection molding machines can be used with nonsensitive decorative materials, special machine equipment specifically made for these processes produces the best results and savings. Other disadvantages include longer cycle time (due to the insulating
effect of the decorative layer), part warpage that results from unbalanced cooling, part rejection associated with damage, creasing, folding, shade changes, overstretching, and weld-line marks of the decorative layer.

9.5.4 Mold Design and Processing Considerations

To ensure the quality of the molded parts with decorative laminate, special considerations on designs of part and mold, selection of coating and base (carrier) materials, and set up of process conditions have to be taken into account, as we will discuss in the following sections.

Mold Design Considerations

Although the existing tools can often be adopted for IMD and in-mold lamination, it is generally recommended to design the tool specifically for these processes. In addition to the conventional design rules, such as appropriate radii and taper angle, the following design considerations have to be taken into account:

- For IMD, the film/foil must be carried into the mold between well-separated dowel pins, and run close against (but without rubbing) the mold surface.
- The design of the mold and the way the decorative laminate is fixed in the mold should ensure that the material is not overstretched during mold closing.
- Complex surfaces may result in problems caused by air entrapment or stretching of the film and laminate.
- The weld lines and sink marks associated with ribs become more evident, especially with thin films and textiles due to accumulation of decoration material at weld lines.
- The injection of polymer melt must be carried out in such a way that it will not adversely displace or deform the decorative laminate, resulting in creasing of the decoration, or damaging the surface structure of the film/foil or the three-dimensional structure of the textile.
- Because the decorative laminate typically sits on the moving platen, the part must be ejected from the sprue side to avoid leaving ejector pin mark on the decorated side, which faces the moving half of the mold.
- For IMD, the film/foil must be wide enough to cover all the cavities if a multicavity system is used.
- When decoration is three-dimensional, the extensibility of the IMD carrier film must not be exceeded.
- Venting should be provided between the film/foil and the moving mold half to prevent entrapped air and thus burning during the molding.
- Care must be taken to ensure that no melt reaches the display side of the decorative laminate, either through it or around the edges of the blank.
- The construction of the mold should allow automatic insertion of the decorative laminate and removal of the overmolded part.
Processing Considerations

The process conditions have to be changed slightly when running with IMD or in-mold lamination. For example, to avoid undesirable displacement of the decorative laminate, especially as melt first contacts the insert, the initial injection speed should be low. In addition, the injection rate should be set in such a way that the required injection pressure is at minimum. Note that for injection molding, if the injection pressure required to fill a cavity is plotted against the fill time, a U-shape curve typically results, with the minimum value of the required injection pressure occurring at an intermediate fill time. The curve is U-shaped because, on the one hand, a short fill time involves a high melt velocity and thus requires a higher injection pressure to fill the cavity. On the other hand, the injected polymer cools more with a prolonged fill time. This leads to a higher melt viscosity and thus requires a higher injection pressure to fill the mold. The curve shape of injection pressure versus fill time strongly depends on the material used, as well as on the cavity geometry and mold design. If the required pressure exceeds what can be tolerated by the decoration due to the flow-length/wall thickness ratios, special molding processes that permit low-pressure molding should be considered, as mentioned earlier [56].

For IMD or in-mold lamination, mold-wall temperature control is very important, because the decorative laminate is sensitive to the temperature. The melt temperature would normally exceed the maximum temperature that the decorative laminate can withstand. That is the reason why an additional backing layer is needed, which provides the insulation against the melt while reducing the possibility of melt breakthrough and folding. Meanwhile, because of the insulating effect of the decorative laminate, the mold-wall temperature on the decorated side should be set lower than the other side to promote balanced cooling and avoid part warpage.

9.5.5 Applicable Materials

As far as the base material is concerned, the processes are feasible with virtually all thermoplastics [57]. The largest volume resin used in in-mold lamination is PP, mostly for automotive applications. A wide range of other materials, including ABS, ABS/PC blends, PS, modified PPO, polyesters, PBT, PA 6, PA 66, and PE, have also been used successfully.

On the other hand, decorative laminate must have good thermal stability and resilience due to their exposure to high injection temperature and pressure. Color change that occurs at the outer surface of the decoration typically results from thermal damage. In addition, the extensibility (stretching ability) of the decoration laminate is crucial for its applicability. Poor extensibility leads to tearing of the decoration laminate, whereas excessive extensibility results in overstretching that causes difference in surface brightness or show-through of the base material. Finally, compatibility and adhesion of the laminate with the base (carrier) resin are important considerations. The adhesion of the laminate to the part can be done through using
a heat-activated adhesive layer or by melt penetration into a fabric backing to form a mechanical bond.

Because the recyclability of the laminated composite is becoming an important issue, the use of a single polyolefin-based system for the decorative, intermediate, and base layers seems to be a viable and cost-effective approach [58]. Moreover, due to the special characteristics of the processes, use of regrind as the base material is feasible. For example, recycled PP has been in favor by the automotive industry. It should be pointed out, however, that the presence of the metallic film in the laminate makes the recycling of decorated components more difficult.

9.5.6 Typical Applications

The IMD and in-mold lamination processes are suitable for many situations by providing integrated, single-step surface decoration and greater design freedom. For example, in-mold decoration has been used to produce rooftops, bumper fascia, and exterior mirror housings, as well as automotive lenses (cf. Fig. 9.20) and body-side molding with mold-in colors to help automakers eliminate costs and environmental concerns associated with painting. On the other hand, in-mold lamination has been used widely for automotive interior panels and other application areas. For example, Figs. 9.21 and 9.22 show the automotive interior panels and a shell chair featuring textile surfaces, respectively. These parts were made using a low-pressure in-mold lamination technique [35]. Finally, Table 9.7 lists some of the typical applications for

Figure 9.20 Automotive lenses with transparent film made by low-pressure in-mold decoration process. (Courtesy of Hettinga Technologies, Inc., Des Moines, Iowa, USA.)
Table 9.7  Typical Applications for In-Mold Decoration and In-Mold Lamination

<table>
<thead>
<tr>
<th>Application area</th>
<th>Molded parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automotive industry</td>
<td>Column cladding panels, consoles, door panels, headliners, heater/air conditioning controls, pillars, seat back panel, ventilation grilles, wheel covers, glove boxes, horn knobs, scale for tachometers, emblems</td>
</tr>
<tr>
<td>Household appliances</td>
<td>Appliance control panels (e.g., washing machine cover plates, front of microwave oven, toaster housing, etc.)</td>
</tr>
<tr>
<td>Telecommunication devices</td>
<td>Key pads and membrane switches for cellular phones</td>
</tr>
<tr>
<td>Radio industry</td>
<td>Cassette packs, covers for cassette players, video front plates</td>
</tr>
<tr>
<td>Sport equipment</td>
<td>Hockey sticks, water skis</td>
</tr>
<tr>
<td>Cosmetic industry</td>
<td>Caps for containers, powder-compact lids</td>
</tr>
</tbody>
</table>