

SELECTING THE MATERIAL AND THE PROCESS

The term “plastics” can be likened to the term “metals.” The plastics family embraces a broad spectrum of synthetic materials that can be molded or shaped by applying and then removing heat and pressure.

Thermoplastic materials are fully reacted or polymerized products that soften when subjected to sufficient heat. Pressure makes them flow and assume new forms, at which point they are cooled to form a useful shape. Scrap or defective shapes can be remelted and reprocessed. The easy formability and economic recovery of recyclable material make thermoplastics the material of choice for many packaging applications.

Thermoset plastics are polymers that have not fully completed their polymerization reaction, but do so when activated, usually by heat. The resulting product is cross-linked. It will not be softened again by heat and cannot be reprocessed or reshaped. Thermosets such as phenol, urea and melamine formaldehyde are used for specialty closures occasionally, but the use of thermosets for dimensional parts in packaging is negligible. This discussion of plastic forming is limited to methods that shape thermoplastic materials.

The proper balance of product protection, containment and appearance qualities, relative to affordable cost, can be obtained by referring to the mechanical and chemical properties of the various polymers. Once a material is selected, the process or method for converting the polymer resin into a useful form must be determined.

One of the most important considerations when thinking of producing a plastic dimensional part is tooling cost—the cost of molds and other devices that are needed to shape the plastic into the desired form. The cost of tooling is directly related to the forces required to create the form.

- Profile extrusion to make continuous solid profiles or tube simply requires a shaped aperture through which to push the plastic. Tooling cost is low.
- Thermoforming is done with open molds using vacuum and compressed air at moderate levels. Tooling cost is low to moderate depending on the complexity of the form to be made.

- Extrusion blow molding of bottle forms requires a water-cooled mold consisting of two matched halves. Tooling costs are moderate. Almost any company with a reasonable market share can afford to produce a custom-designed bottle.
- Injection blow molding tooling cost is higher than extrusion blow molding in that two molds are necessary. Process savings from not having any secondary trimming and regrind steps offset the higher mold costs somewhat.
- Injection molding requires massive molds capable of withstanding molding forces calculated in hundreds of tons. A 32-cavity stack mold to make margarine tubs can cost \$500,000 or more. It is common for companies that make injection-molded closures and dairy tubs to have stock molds, which means the high mold costs are borne by several customers.

Other factors that need to be considered are:

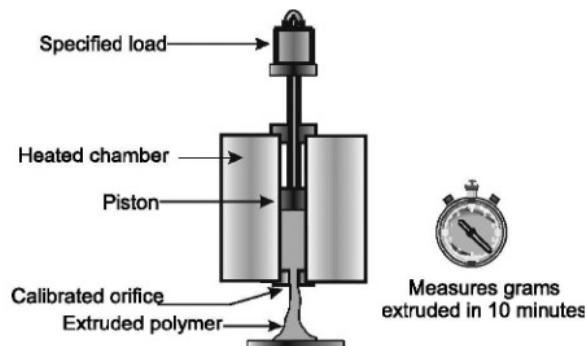
- Resin type.
- Geometry of the finished part.
- Number of units required.
- Dimensional tolerance requirements.
- Container wall thickness needed to meet structural and economic requisites.

To relate these factors, the principal manufacturing methods must be understood. The most common thermoplastic forming methods for packaging purposes are discussed in this chapter:

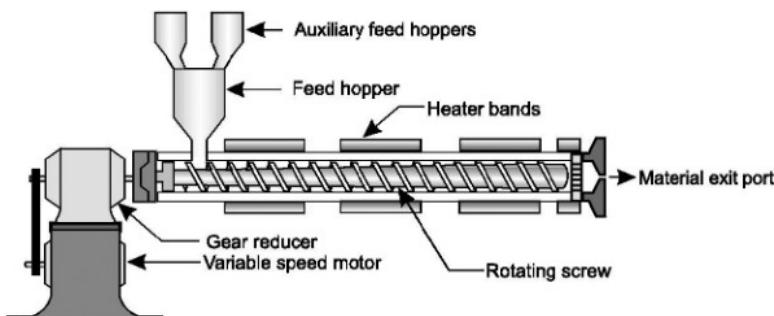
- Extrusion (including profile extrusion, extrusion cast film and sheet, blown-film extrusion and coextrusion).
- Thermoforming (a secondary forming process using extruded sheet).
- Injection molding.
- Extrusion blow molding.
- Injection blow molding (including injection-stretch blow molding).
- Rotational and compression molding.

All shaping methods require heating the thermoplastic to a point where the material has plasticity or fluidity appropriate to the intended molding method. A key attribute of any plastic material is its behavior at elevated temperatures.

Melt flow rate (reference test method ASTM D1238) is a method of quantifying this behavior. (See Figure 11.1) Briefly, a charge of the polymer is heated to the test temperature in a chamber. A specified load is then placed on a piston, which forces the polymer melt through a calibrated orifice. The weight of polymer extruded in 10 minutes is reported as the melt flow rate (sometimes referred to as the melt index). For a given polymer, the flow rate decreases as molecular weight increases, so melt flow rate can be regarded as a crude indicator of molecular weight.

**Figure 11.1**

A polymer's flow characteristics at elevated temperatures are measured with an extrusion plastometer. Different test temperatures are used for different polymers.

**Figure 11.2**

A plasticating extruder. Most plastics are colored by adding color concentrates along with polymer resin at the feed hopper. Auxiliary hoppers are used to meter in colorants, antistatic agents and other additives.

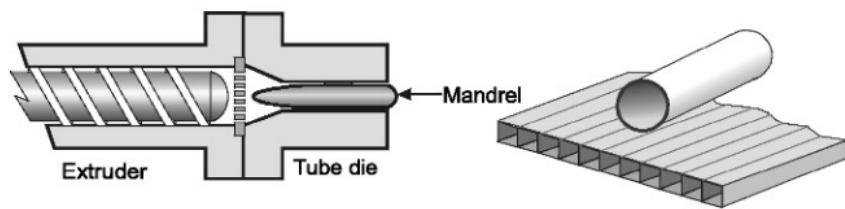
PLASTICATING EXTRUDERS

Polymer resins are received at a molding plant in the form of small granules or pellets, similar in appearance to rice. Regardless of the forming process, the first task is to heat and melt the pellets into a flowable form. The plasticating extruder is a heavy barrel in which a screw rotates, driving pellets from the feed hopper at one end to the exit port at the other end. (See Figure 11.2) The work of driving polymer melt down the barrel provides most of the heat required to melt the polymer. Heater bands help maintain precise melt temperatures, and a cooling jacket keeps the feed hopper area cool.

Extruder sizes are described as the barrel diameter to screw length ratio. For example, a 20:1 extruder will have a screw length 20 times the barrel diameter. Length-to-diameter (LD) ratios and screw geometry vary widely depending on the material and the nature of the molding process.

PROFILE EXTRUSION

A shape of constant cross-section (a profile) can be extruded by forcing polymer melt through a shaped orifice in a die placed at the exit port. At its simplest, the die may be a metal plate with a round hole, in which case, the extrusion is a round rod of approximately the same diameter as the hole. Tooling costs are low since the process takes place at relatively low pressures, and neither the extruder nor the die needs to be substantial. Placing a suitable torpedo-shaped mandrel in the die exit permits extrusion of a hollow pipe or tube. (See Figure 11.3)

**Figure 11.3**

A profile extruder. Placing a torpedo-shaped mandrel in the die exit creates a tube. With other die and mandrel configurations, shapes resembling corrugated board are produced from the extruder.

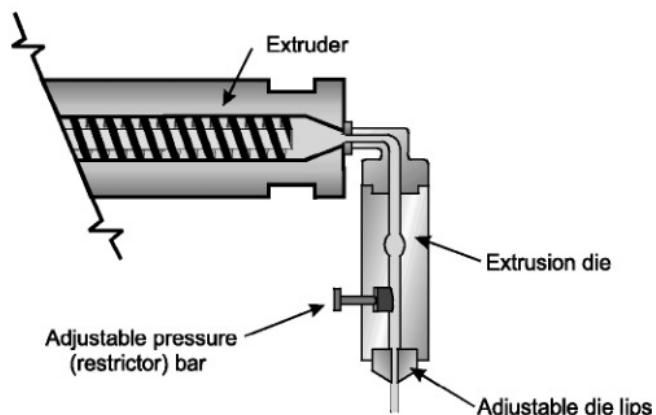
Extruded Profile Applications

Thin-walled tubes cut to length and with an applied injection-molded head are made into collapsible plastic tubes such as those used for personal care products. After the tube is filled, the lower end is flattened and heat-sealed. Most tubes are made from polyethylene (PE) for its softness. Where flavor barrier or oxygen barrier are required, the tube would be coextruded with a layer of a barrier polymer such as ethylene-vinyl alcohol (EVOH).

Heavy-walled extruded plastic tubes, cut to length and given an added injection-molded nozzle, are used for caulking tubes. The bottom is sealed with a sliding piston.

Any tubular package of constant cross-section and with no seam along its length started as an extruded profile. To make an enclosed package, a closure method must be added. The most common closure method is a friction-fit plug, although in some instances a thread to accept a screw-type closure has been rolled onto the tube end.

For novelty markets, tubes are extruded from cellulose-based plastics. Cellulose butyrate or cellulose propionate exhibit excellent stiffness and clarity and end plugs are easy to attach via solvent bonding. Applications include glass thermometer tubes, drill bit tubes, confectionery containers, small parts tubes and other novelty containers.

**Figure 11.4**

Cross-section of a slot-orifice die. This is an end view, and the die may be a meter or more wide.

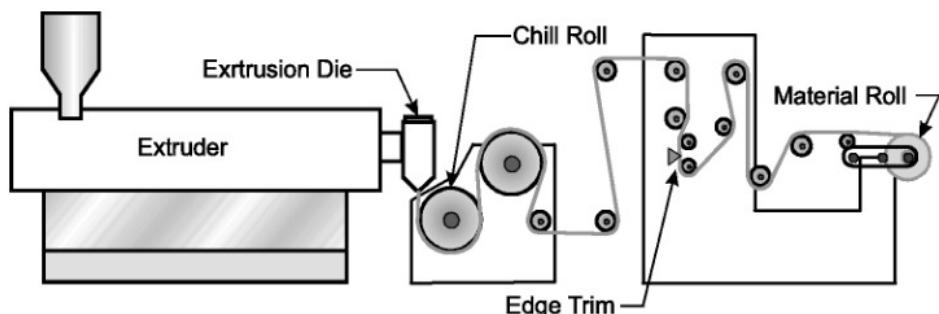


Figure 11.5
General layout of a cast-film extrusion line.

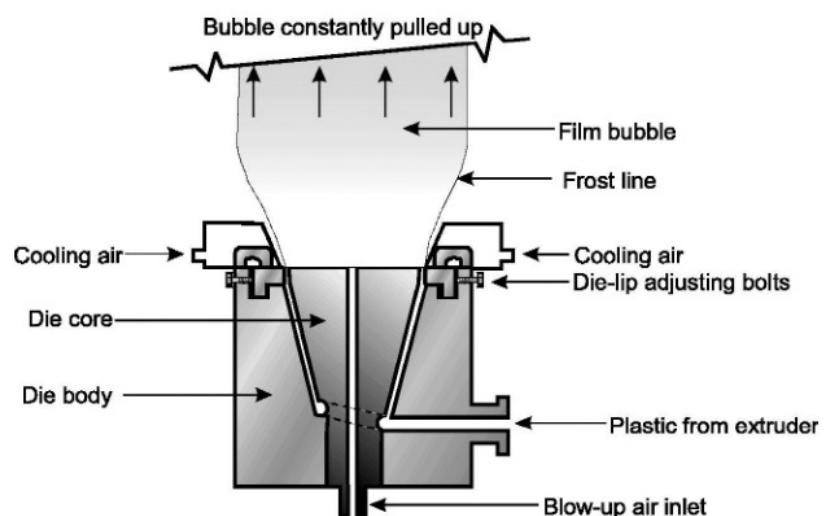


Figure 11.6
Cross-section of a blown-film die.

Sheet and Film Extrusion

Sheet extrusion is an application of profile extrusion, but it uses a die with a slot orifice. (The dies also are called “coat-hanger” or “T-shape” dies.) The dies have a narrow opening between the die lips through which the plastic melt is extruded in a thin film. (See Figure 11.4) The film is immediately cooled and solidified on chill rolls. (See Figure 11.5) The dies can be a meter or more wide. Depending on thickness, the end product may be called “film” or “sheet.” There is no clear division between the two. Film product formed by this process is referred to as “cast film.”

Thicker sheet is used for thermoforming or is die-cut and folded into carton-type constructions similar to paperboard cartons. Thinner extruded films are used alone or laminated with other materials in a variety of flexible packaging applications.

Blown-film Extrusion

Plastic film also can be manufactured by extruding the polymer through a circular die into a closed circular bubble and expanding the bubble with air. (See Figure 11.6) The material is extruded upward, and by pulling the inflated bubble upward and

continuously extruding more plastic, a continuous seamless tube of thin film is created. (See Figure 11.7) Airflow along the outside of the bubble provides cooling and an air cushion. After the film has cooled, it is flattened in a collapsing frame and wound into rolls. The bubble can be wound up as a seamless tube or can be cut to length and sealed at one end to make seamless plastic bags. Alternatively, the bubble can be slit and rolled into one or several flat rolls of film. (See Figure 11.8)

Figure 11.7

A blown-film extrusion die. The point at which significant crystallinity appears is readily visible at the frost line where the film changes from translucent to opaque.



Figure 11.8

This blown-film line produces a tubular film that is slit into two flat sheets.

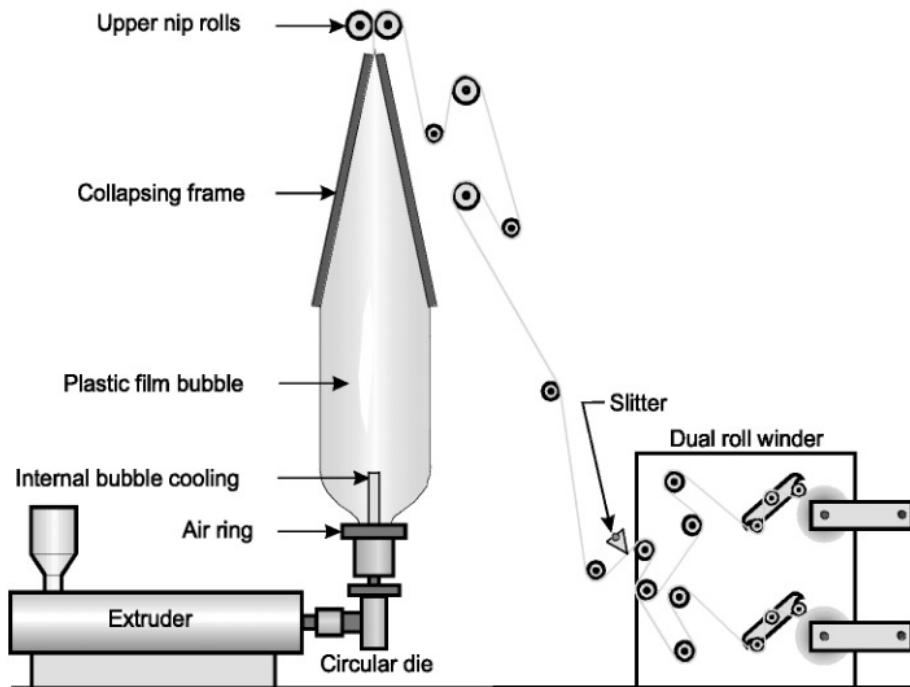


Table 11.1
Comparison of films made by the blown and cast processes.

	Blown Film	Cast Film
Required melt flow rate	lower	higher
Process temperature	lower	higher
Crystallinity	more (slower cooling)	less (rapid cooling)
Optics	hazy, less gloss	better, glossy
Gauge variation	± 5–10%	± 2%
Output	lower	higher
Web control	size adjustable	neck-in, more rework
Flatness	less	better

In addition to devices that control size and shape, other process units, such as those for printing and embossing, gusseting, vacuum forming, slitting and folding, can be introduced into the downstream system. This layout provides more integrated product manufacturing lines. The blown-film process is used to make nearly all PE and other films.

The blown-film method can produce very wide sheets. A 2-meter (m) (6.5-foot) diameter bubble, when slit, opens out to a sheet 6 m (19 feet) wide. It would be impractical to make a cast-film die of this width.

The thermal histories and production mechanics of films made by cast and blown methods are completely different: The same resin made into films by the two methods will have different properties. (See Table 11.1)

In cast-film production, the rapid chilling provided by the cold casting rolls favors amorphous molecular behavior, and the product tends to be limper and have better clarity than a blown film. Casting also can produce thinner films.

Blown film uses slower air cooling to remove heat from the polymer extrusion. Crystalline plastics such as PE or polypropylene (PP) exit the die in a clear form, but at some point above the die, as the temperature drops and the polymer begins to crystallize, there will be a distinct change from clear to opaque. (See Figure 11.7). The transition zone is quite abrupt and is known as the “frost line.”

Film thickness and surface irregularities are harder to control for blown film than for cast film. Film thickness around the circumference of a blown bubble can vary by as much as 10%. If simply wound up on a roll, these thicker areas would produce a hard ring, or gauge band, around the roll. To avoid this problem, most blown-film dies rotate while the film is blown to ensure distribution of any small thickness and surface irregularities over the width of the rolled material.

Blown-film production machinery is significantly lower in cost than a cast-film and tenter-frame orientation combination.

Orientation

The properties of cast and blown film and sheet can be improved by physically orienting the polymer molecules. Cast sheet is oriented in the machine direction by being pulled away faster than it is being extruded, thus stretching it in the machine direction. This usually is accomplished by passing the cast film through a series of rolls, each roll rotating progressively faster than the previous roll. (See Figure 11.9, top)

Cross- or transverse-direction orientation is done in a tenter frame. (See Figure 11.9, bottom.) Clips traveling down diverging tracks grasp the film along each edge and stretch it in the cross direction up to about seven times its original cast width. Film oriented in two directions is said to have "biaxial orientation."

Both machine and cross-direction orienting are done at somewhat elevated temperatures. If the stretching and cooling processes are rapid, the film will retain some memory of its original dimensions. It will want to return to these dimensions if reheated; in effect, it will be a "shrink plastic." Oriented films are heat-stabilized by keeping them at an elevated temperature (annealing) for a brief time.

Blown film is orientated by adjusting the inflation ratio and take-away speed relative to the tube-forming rate. Blown film cannot be oriented to the extent that is available with cast-film extrusion, however well-balanced the biaxial orientation is.

Coextrusion

Both cast- and blown-film extrusion dies can be designed to be fed from more than one extruder, thus producing a sheet composed of two or more different materials. (See Figure 11.10) Coextrusion systems feeding as many as seven different layers through one die block have been made. High polymer viscosity limits the mixing of the extruded layers, so they exist essentially as separate layers in the finished product.

Most coextrusion is done to combine the performance advantages of two dissimilar materials. For example, heat-sealable PE is extruded onto materials that have

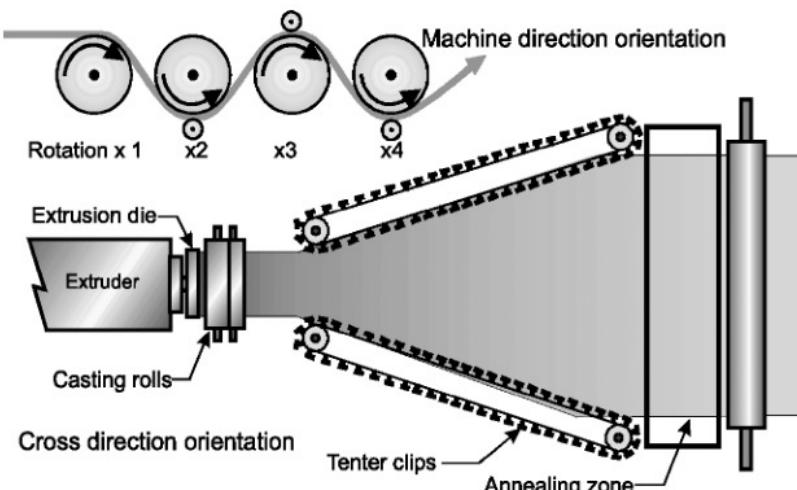


Figure 11.9

Orienting cast film. Machine-direction orientation (top) is done by pulling the film through progressively faster rotating rolls. Cross-direction orientation is done on a tenter frame (bottom). It stretches the film in the transverse direction as illustrated in this perspective that looks down on the process.

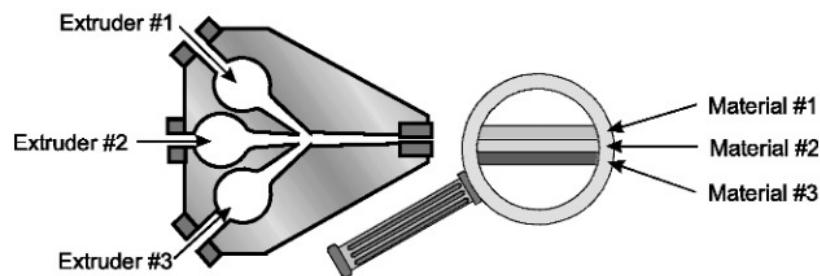


Figure 11.10

A coextrusion, slot-orifice cast-film die. Similar multichannel dies can be made for blown-film extrusion.

poor heat-sealing characteristics or a high-barrier polymer might be extruded between protective layers of a less costly low-barrier material. Coextrusion is used to bury recycled plastics into center layers or to produce sheets with decorative colored stripes or layers.

INJECTION MOLDING

Injection molding uses a powerful extruder with the capability to inject a precise amount of resin into a fully enclosed mold. Very high hydraulic pressures drive hot, relatively viscous molten material through the chilled passages of a part mold and fill the cavity before the plastic solidifies. The process requires substantial molds that do not flex or move under extreme temperature and pressure. An eight-cavity mold for margarine tubs may weigh upward of a ton. This required mold mass and the tooling's complexity make injection molding the highest in tooling cost of the plastic forming methods.

Injection molding is the leading method of manufacturing closures, wide-mouth thermoplastic tubs, jewel boxes and other complex dimensional shapes. Because part dimensions are completely controlled by metal mold surfaces, injection molding delivers the most dimensionally accurate part. Tooling sophistication, accompanied by newly developed high melt flow rate (low melt viscosity) thermoplastics, permits the manufacture of thin-walled plastic containers with wall thickness on the order of 180 micrometers (μm) (0.007 inch).

Injection-molding Machines

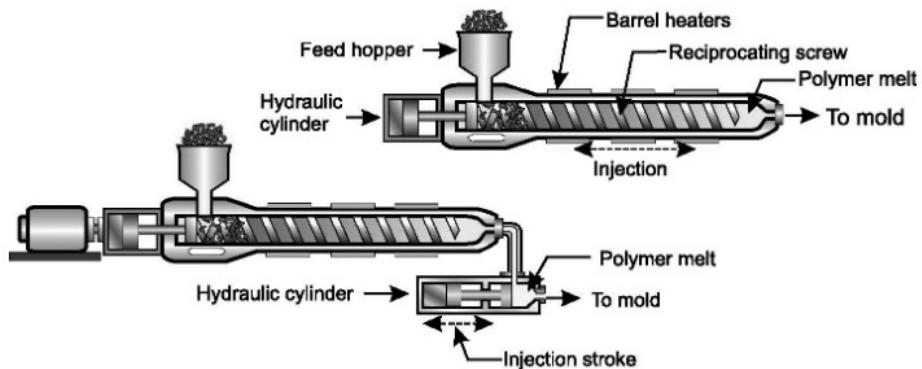
The extruder section of an injection-molding machine must have provision for ejecting a precise amount, or "shot," of polymer melt into the mold. Ram-screw-type (reciprocating screw) machines use a melt-conveyance screw designed to provide reciprocal as well as rotary motion, combining the function of screw and piston. A disadvantage of this system is that a great deal of power is required to move the entire screw and its attendant load of plastic resin.

Screw-plunger (two-stage) machines have a separate chamber and piston for injecting the molten polymer, allowing for faster injection of the plastic into the mold. (See Figure 11.11)

The mold cavity is exactly in the form of the desired part. When the part has cooled, the mold opens, and the part is ejected.

Figure 11.11

"Shot" size for an injection-molded part can be metered by a reciprocating screw (top) or an extruder with a separate hydraulic piston (bottom).



The injection machine's mold clamp section must be large enough to hold the mold and provide adequate space for the part to be readily removed when the mold opens. It must have sufficient clamping force to hold the mold tightly closed against the pressure of the material being injected into the mold. Inadequate clamping pressures (or excessive shot size) will force the mold open and result in prominent parting lines or unsightly flash.

An injection-molding machine is rated by available clamping force tonnage. A 600-ton injection-molding machine has 600 tons of clamping force to hold the mold closed. The required clamping tonnage is not related to the amount of plastic in the part, but rather to the part surface area. The greater the area over which the fluid can act, the greater the hydraulic force.

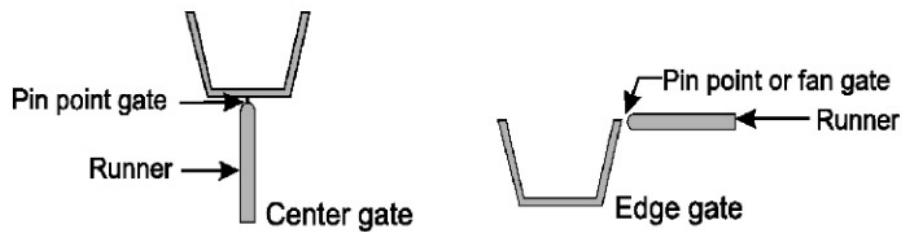
Injection Molds

A simple injection mold is comprised of a core and cavity halves. Wall thickness of the molded part is determined by the space between the mold's core and cavity. A mold assembly may be designed to have a single cavity or multiple cavities; however, for packaging purposes essentially all molds are multicavity.

Mold temperature control must be accurate. Auxiliary cooling systems, either with water or water-glycol mixtures, provide consistent coolant temperature. Good part molding also depends on material condition. Hygroscopic plastics—such as polyethylene terephthalate (PET), nylon and polycarbonate—are continuously preconditioned and dried online.

Simple, open-topped tubs are easily made with a mold consisting of a cavity half that is mounted to the machine in a stationary position and a core half that is mounted on a sliding frame so the mold can open and close. The molten plastic follows various channels to fill the cavity of the closed mold:

- The "gate" is the small opening through which the molten plastic enters the mold cavity. (See Figure 11.12).
- The "sprue" is the main channel through which molten plastic enters the mold. If the mold has only one cavity, then the sprue leads directly to the gate

**Figure 11.12**

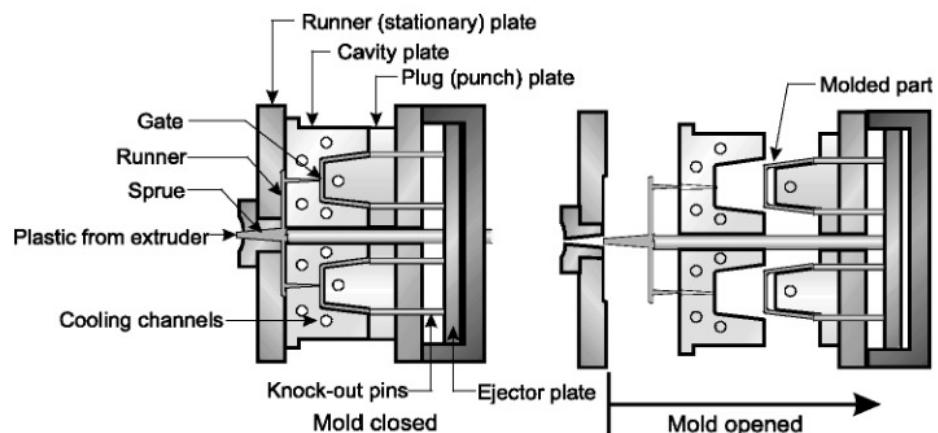
The gate is the small opening through which plastic melt enters the mold cavity. Mold makers try to hide the gate mark in the most unobtrusive location.

- “Runners” are channels that distribute molten plastic to various cavities in a multi-cavity mold. Runner geometry must be precise since the distance from the sprue to any gate must be exactly the same

As the cooling plastic shrinks, the part will adhere to the plug half of the mold. Compressed air might be used to push the tubs off the cores. For more complex parts, knockout pins move forward when the mold opens to physically eject the part.

A simple, two-piece mold where the sprues or runners connect directly to the gate would produce a part with the sprue and runner still attached to the part. This is done for very low-volume applications where it is important to keep mold costs down but is rarely seen in packaging applications. A three-plate mold has a third plate that automatically pulls the sprue and runners away from the molded parts. (See Figure 11.13) These would be cycled back into the molding feed-stream.

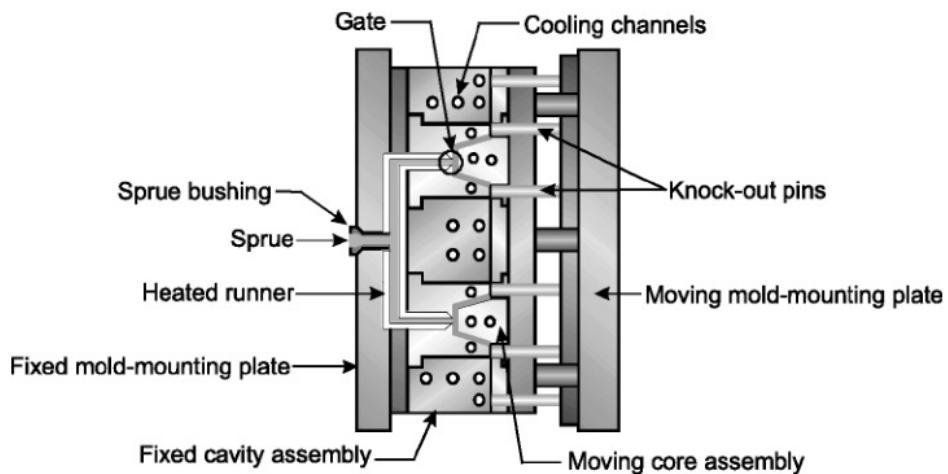
Figure 11.14 shows a more advanced mold having heating elements, insulated from the chilled mold, along the sprue and runners. In this mold, the cavity plate remains stationary, and the cold part pulls away from the still molten plastic in the immediate gate/runner area. Such “runnerless” molds add considerably to mold cost but eliminate the need for separating the sprues and runners and regrinding the material to a form that can be reintroduced into the injection molding cycle.

**Figure 11.13**

A three-plate mold strips sprue and runners away from the part. Knockout pins push the parts off the cores.

Figure 11.14

"Runnerless" or "hot runner" molds are designed with material feed runners and gate systems that are insulated from the cooled mold cavity and core. Auxiliary heaters often are incorporated into the runner system to ensure that the plastic is kept in a hot, fluid state.



An injection machine's productivity can be increased by stacking two mold sets back-to-back. (See Figure 11.15) This configuration doubles part output without the need to go to a machine with double the clamp tonnage.

"Undercut" designs, featured for some packaging such as the pedestal-base yogurt cup, prevent a mold from opening in a normal back-and-forth motion. (See Figure 11.16) Undercuts, or other complications such as closure threads, require that some mold components be designed to move away before the part can be ejected. For example, the yogurt cup mold would need to be assembled from several pieces, including a pedestal ring portion in two halves. Since these halves need to open and move away at right angles to the normal mold-opening movement, power and drive mechanisms need to be incorporated into the mold.

In the instance of threaded closures, provision needs to be made for removing the closure from the core. This can be done by unscrewing the core from the closure, by collapsing the core so it can be pulled away from the threads, or in certain situations, by stripping the closure off the threaded core by momentarily stretching the plastic over the threads. (The relationship of closure thread undercuts and mold design is discussed in Chapter 13, Closures.) Seemingly simple design variations that include undercuts can increase mold costs significantly.

Figure 11.15

A stack mold puts two molds back-to-back. The runners are kept hot so that the chilled part separates at the gate.

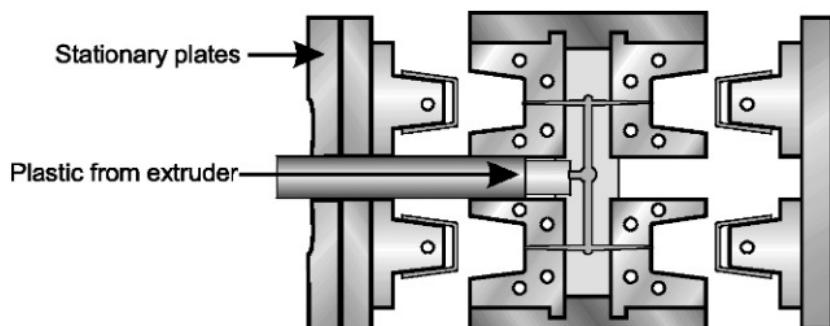
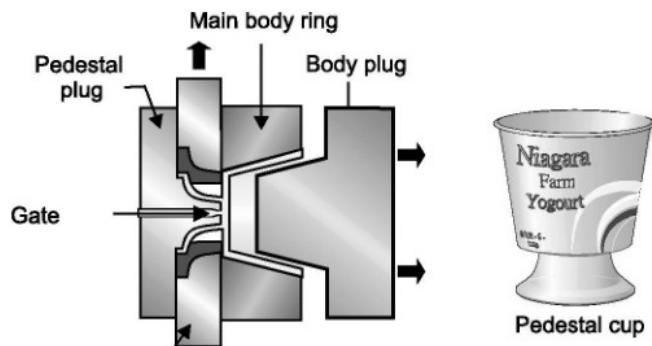
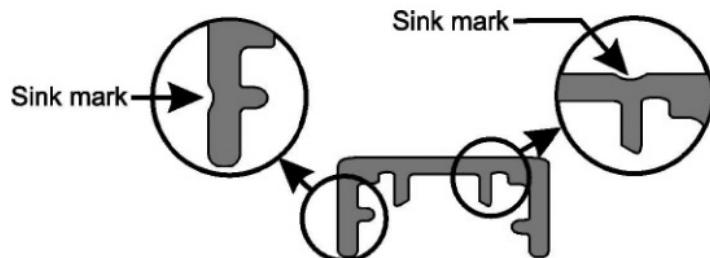


Figure 11.16

A part with undercuts, such as this pedestal cup, requires a mold with components that move away from the undercut so the part can be removed from the mold.

**Figure 11.17**

Sink marks occur where there is a substantial variation in the thickness of the plastic.



Plastic shrinks as it cools and solidifies from the melt state. Each polymer has a characteristic shrinkage rate. Shrink allowance must be designed into the mold cavity and core section dimensions. Because of the varying rates of shrinkage, molds built for a specific material may not be suited for molding containers of a different material if fit and container capacity control are to be maintained.

Where a molded part has substantial and abrupt wall thickness changes, the part may develop “sink marks.” (See Figure 11.17) These marks are mostly due to plastics’ high expansion coefficients. Sink marks usually can be seen on closures opposite the thread-on-thread closures and opposite the sealing ring on valve-type closures.

Other changes in wall thickness result in different crystallinity, as the cooling rate will be slower in the thicker cross-section. When the plastic at the gate area pulls away from the part, it can cause a sucking effect on still-soft plastic in the heavy cross-sections.

Co-injection Molding

Co-injection molding is injection molding’s counterpart to coextrusion. Co-injection of multiple polymer layers can be done by injecting the first material and then moving the mold core with the first material form on it into a second cavity. The second cavity has a clearance between it and the first material shape. The second material is then injected around the first.

Another method uses multiple runners that converge just before the gate. The materials flow into the mold cavity as concentric layers. Multilayer, injection-molded preforms have been made for blowing into beverage bottles using PET and EVOH in one application and PET and nylon in another.

Injection Molding Design Example

The complexities of injection molding can be illustrated by examining some of the issues that need to be resolved when injection molding the common dairy tub and lid. (See Figure 11.18)

Most dairy tubs are injection molded from relatively stiff PP. (The most significant exceptions are frozen-product tubs. PE is preferred for this application since PP can become brittle at freezer temperatures.) But the lids for PP tubs need to stretch a bit to snap over the interference fit on the tub's lip. PE is the preferred material for lids because of its ability to stretch slightly.

Different plastics have different expansion coefficients, and in designing the mold cavities for the tub and matching lid, different allowances need to be made in the mold dimensions to ensure that the tub and lid snap together properly.

Most plastic parts need a slight body taper, or “draft,” to aid removal from the mold core. For dairy tubs, the draft angle is considerable, so the tubs can be nested into compact stacks for shipping. Tub with a straight angle from base to lip would jam together and be difficult to de-nest on the production line. Jamming is prevented by designing a nesting wall and ledge that prop the tubs up slightly and ensure a small separation between the sidewalls of nested containers.

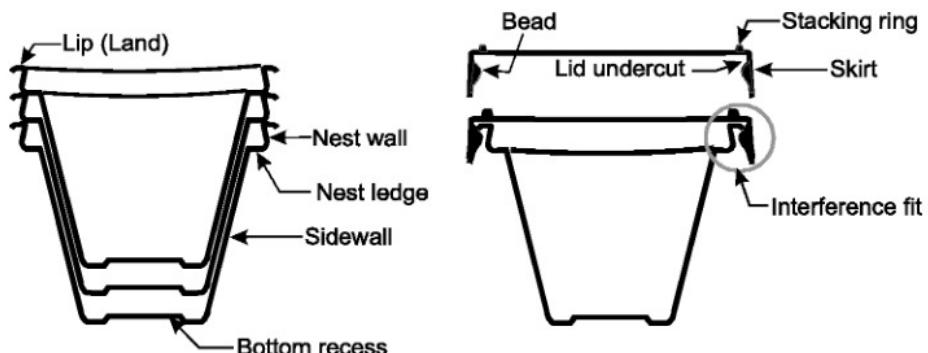
Lip dimensions need to be accurate if the tub has an interference-fit, snap-on lid. In some designs, small ribs are placed on the lip's underside to stiffen the tub edge. This leads to a series of sink marks on the lip's top surface that can interfere with attaching foil or laminated, adhesive-bonded lidstock material.

The gate marks for both lids and tubs are on the part's cavity side. The bottom recess on the tub provides for a more positive flat base for the tub, but it also raises the center of the tub bottom so that any gate projection does not interfere with the tub's stability. The gate mark is on the top visible surface of the lid.

Lids usually have a small, raised stacking ring on their top surface. This prevents stacked lids from sliding over each other and enables easier handling and machining. A slightly raised gate mark can interfere with printing in those instances or with propping up an applied paper label.

Figure 11.18

Design details for an injection-molded dairy tub and lid. The nest wall and nest ledge keep sidewalls of nested containers from touching and becoming difficult to separate on a production line.



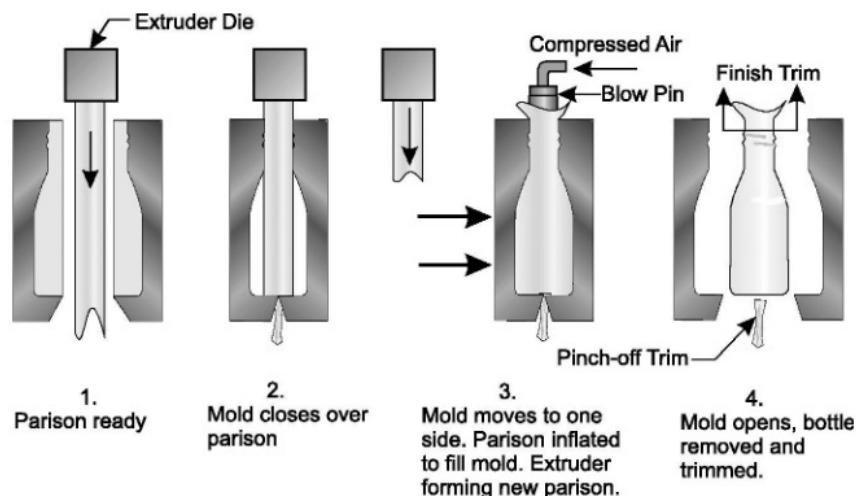


Figure 11.19
Typical extrusion blow molding sequence.

EXTRUSION BLOW MOLDING

Thermoplastic bottles are made by one of two processes: extrusion blow molding (EBM) or injection blow molding. As the name implies, EBM combines extrusion with a blowing step. The majority of detergent, oil and other household chemical bottles are made by EBM.

Most plastics can be extrusion blow molded, providing they have enough strength in the melt form (i.e., a low melt flow rate) to hold together when extruded into a parison. PE, PP and polyvinyl chloride (PVC) account for the majority of extrusion-blow-molded bottles.

EBM can accommodate many creative designs, including bottles with through-handles (handleware), two-part containers, pinch grips and containers with integral measuring chambers. Circumferential rings can be molded into a circular cross-section to produce a flexible trunk or an accordion-type flexible section that can be used as a pump. Most packages will have a single opening, but EBM can produce dispensing packages with multiple openings and fittings.

All EBM processes are based on a common underlying sequence. (See Figure 11.19) First, a hollow plastic tube, or parison, is extruded. While in a soft, formable state, the parison is captured between the mating halves of a bottle mold. Air is blown into the hollow parison, stretching the deformable parison to conform to the mold walls. The newly formed bottle is held in the mold until it cools sufficiently to retain its shape.

Parison size and position are related to the container's finished configuration. The parison centerline does not necessarily coincide with the mold centerline. Off-centered designs and handleware may position the mold centerline on an angle to the parison centerline to achieve the desired material distribution. For larger bottles and some handleware, the parison may be pre-inflated by a small puff of air prior to the mold closing and final bottle blow.

One of the more critical areas of a bottle is its base. The mechanical action of forming the molten plastic and pinching the parison off to form the weld line can introduce a great deal of stress into the plastic material. Poorly formed weld lines might occur if the plastic is too cool to fuse adequately or if the weld line is grooved be-

cause of improper tool design. (See Figure 11.20) Either condition will result in a bottle with low impact strength.

Extrusion Blow Molds

Blow molds (see Figure 11.21 and Figure 11.22) are moderate in cost, allowing most users the option of using a custom-designed mold. Most high-speed bottle molds are made from aluminum or copper alloys. The neck, finish, bottom pinch-off and pinch-off areas for blown handles are critical high-wear areas and usually consist of replaceable steel inserts.

Hard, high-gloss materials such as PVC and polystyrene (PS) with low shrink factors require polished mold surfaces. Higher shrink materials (PE, PP) use sand-blasted mold surfaces for optimum container appearance.

Mold clamp force must be sufficient to clamp, weld and shear the parison at pinch-off points (the neck, handle and bottom areas) and must have enough force to withstand the pressures developed during the blowing portion of the operating cycle. However, compared to injection molding, these pressures are within the range of shop air. Special food-grade, oil-free, dry-air compressors are used for any food or beverage application as shop air typically has lubricants that are not compliant with food-contact regulations. Blow molding typically requires high volumes of dry air and compressors must be sized properly to provide consistent air pressure.

Blow-molding cycle time usually is controlled by how quickly the blown part can be cooled and ejected. Water channels drilled into the mold body provide cooling. Trimming devices for finishing the bottle neck area and for removal of the bottom tab are preferably incorporated into the mold. Where this is not economically feasible or practical, trimming, neck finish, facing and reaming devices are used in secondary operations downstream of the blowing operation. Special trimming dies are required if large “flash” areas or the center waste area of handled bottles are to be trimmed away.

An extruder can produce parisons at a faster rate than a typical bottle-blowing cycle. Multiple-parison blow-molding machines allow increased productivity from an extruder. Blow-molding machines that extrude double or triple parisons are common, and many machines have been made that extrude even more. In such instances, molds are grouped into blocks and several bottles are blown at a time.

A “shuttle” blow molder is the most common machine configuration. A mold or mold set is located on either side of the parison extruder. When the parison is



Figure 11.20

A properly designed mold will force some plastic back up into the bottle to form a uniform bead at the weld line. Poor weld lines will have a groove that significantly weakens the bottle.

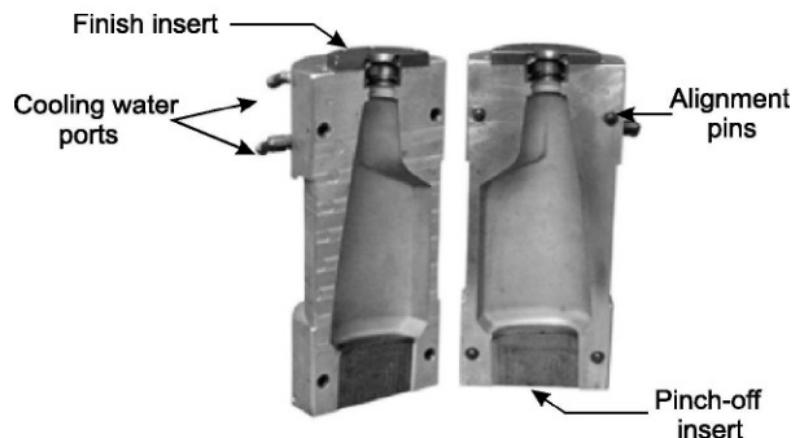


Figure 11.21

An aluminum extrusion blow mold with steel inserts for the finish and pinch-off. The mold has connections for water cooling.

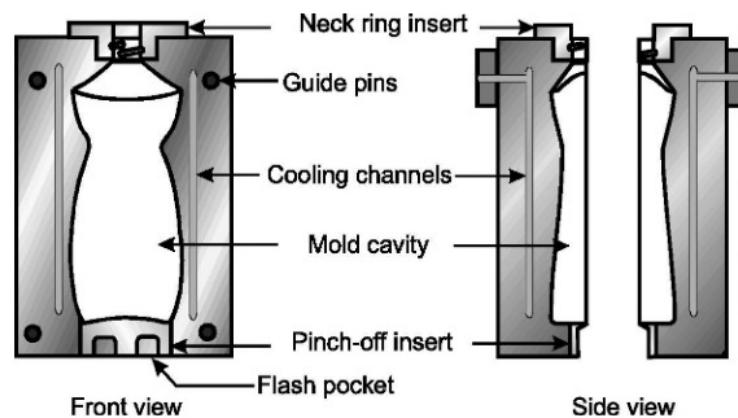


Figure 11.22

Blow molds must be cooled. Vent holes drilled into the cavity allow air to escape during the inflation cycle. The bottom pinch-off closes the parison and cuts off excess plastic.

ready, a mold slides into position, closes over the parison, cuts it off and slides off to one side for the blowing and cooling cycle. While this is happening, the alternate mold set moves over the continuously extruding parison to start its cycle.

A lesser-used arrangement places a group of molds on a rotating turntable. Each mold rotates past the extruder to receive a parison and then moves away to complete the blowing and cooling cycle, while other molds are rotated under the extruder.

Another method locates the molds in a Ferris-wheel-like arrangement. The parison is extruded as a continuous pipe into the closely located molds. The system is mechanically more complex but has the advantage of minimizing trim regrind. This can be important in multilayer constructions where comingled plastic trim might cause a recycling problem.

Multilayer Bottles

Bottles with two or more material layers can be made from coextruded parisons. View Stripe bottles are produced with two- or three-layer dies, which provide a gap in the color layer that corresponds with the desired location for the feature.

A major application of coextrusion technology is the manufacture of plastic bottles using high oxygen-barrier polymers such as EVOH. Although an exceptionally good oxygen barrier, EVOH is detrimentally affected by moisture. This shortcoming can be eliminated by sandwiching the EVOH layer between two good moisture-barrier layers.

The choice of the outside layers depends on the final properties required. PE is satisfactory for applications such as dental pastes. However, PE's low softening temperature makes it unsuitable for hot-filled sauce bottles. A common construction co-extrudes EVOH with surface layers of PP. (See Figure 11.23) PE or PP do not bond well to EVOH, so an additional material, the tie or adhesive layer, must be introduced to bind the laminate together. In most applications, a sixth layer composed of process regrind is introduced between the outer skin and the outer tie layer.

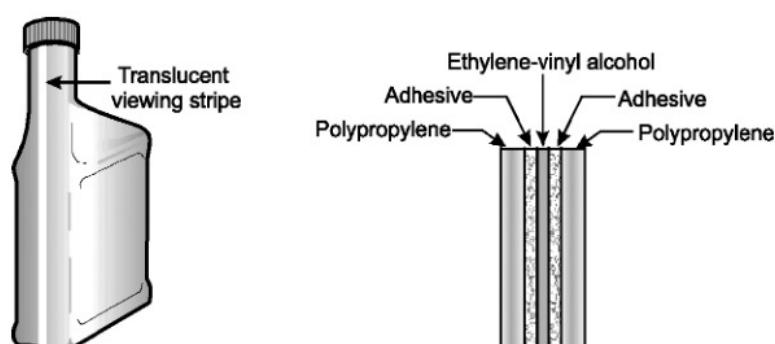
Where high clarity is desired, the skin layers can be made with clarified grades of PP using a nylon barrier layer. MXD6, a proprietary nylon with higher oxygen barrier properties than the nylon 6 and nylon 66 usually used in packaging, is being laminated with PP for high-barrier bottles.

Other examples of multilayer bottle applications are:

- **Use of recycled plastic layers.** Recycled plastics are not as consistent in properties as virgin resin, and may contain contaminants that might interfere with the product or may simply result in undesirable colors. Two-layer coextrusions can use an outer layer of virgin plastic to cover a recycle layer, or the recycle layer can be isolated completely by making it the core of a three-layer construction.
- **Cost reduction.** Some pigments, such as pearlescents, are costly. In some instances, savings can be achieved by pigmenting only the bottle's outer skin.
- **Light barrier.** Many pharmaceutical and some food products are sensitive to ultraviolet (UV) light. A construction used to create a high UV-light barrier consists of a three-layer high-density polyethylene (HDPE) with the core layer heavily pigmented with carbon black.

Coextrusions also can be made with parallel bands of material. Incorporating a clear or translucent stripe into an opaque bottle to provide a viewing port for observing content level is a common application. (See Figure 11.23) It's also possible to produce colored stripes for novel decorative effects.

Figure 11.23
A bottle with a coextruded translucent stripe allows viewing of content level (left). A typical coextruded construction used for high oxygen-barrier bottles (right).



Material Distribution

When a parison is extruded, the weight of the polymer melt tends to pull it down, thinning the upper part. This results in containers having proportionately more material at the bottom. Container geometries also can cause material distribution problems.

The simplest containers to produce are round in cross-section. In such designs, the parison expands equally in all directions. However, paneling is easily visible in round containers and, therefore, oval or oblong sections are popular. Paneling is the term blow molders use to describe when a smooth surface becomes warped. In extreme cases, the surface buckles. Paneling also can be caused by changes in pressure inside the container that might occur due to shipping filled packages from high to low elevations, hot-filling or loss of product over time due to permeation.

Oblong containers require that the material flow farther to fill the corners than to the closest wall. Therefore, material tends to be thickest at the panel and thinnest at the corners. Narrow-waisted containers tend to have the greatest thickness at the narrowest point. (See Figure 11.24) A programmed parison overcomes these problems.

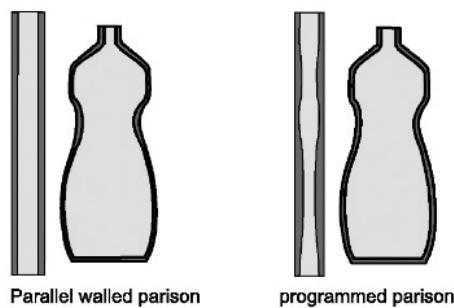


Figure 11.24

Inflation of parallel-walled parisons into variable-diameter containers will yield uneven wall thickness (left). The use of a programmed parison (right) results in a more uniform wall thickness.

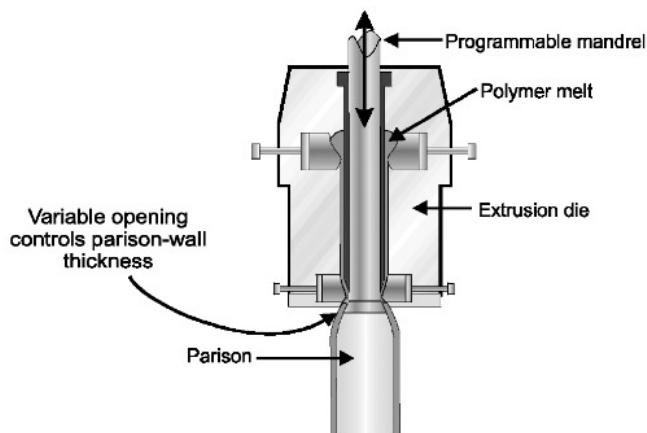
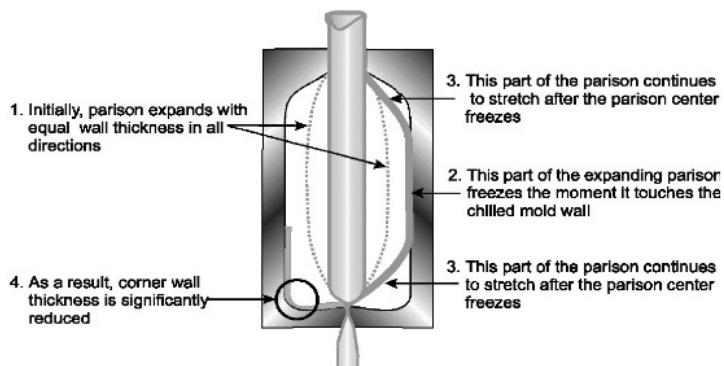


Figure 11.25

The programmed parison die mandrel moves up and down to provide different clearances for parison formation.

Figure 11.26

The process of expanding a parison to form a bottle tends to favor producing thicker side-panel cross-sections and thinner cross-sections at the shoulder and base.



Such parisons are created by having a parison extruder die-core mandrel that moves according to a preset program. (See Figure 11.25) The mandrel position determines wall thickness at each point on the parison along the height of the bottle. Parison wall thickness is set to be greater where more material is needed to accommodate a greater expansion and less where the bottle is narrower.

The mechanics of expanding the parison to fit the mold and then chilling the formed plastic make it difficult to maintain good wall thickness at the bottle's shoulder and base areas. (See Figure 11.26) The initial blowup of the parison expands it equally in all directions. The moment that any part of the expanding parison touches the mold, the plastic freezes and can no longer expand. Normally, the first parts of the pillow-shaped expanding parison to freeze are the central areas of the major panels. From then on, the only stretching that can occur is in the still-hot plastic in the top and bottom corners of the mold.

Bottle Terminology and Markings

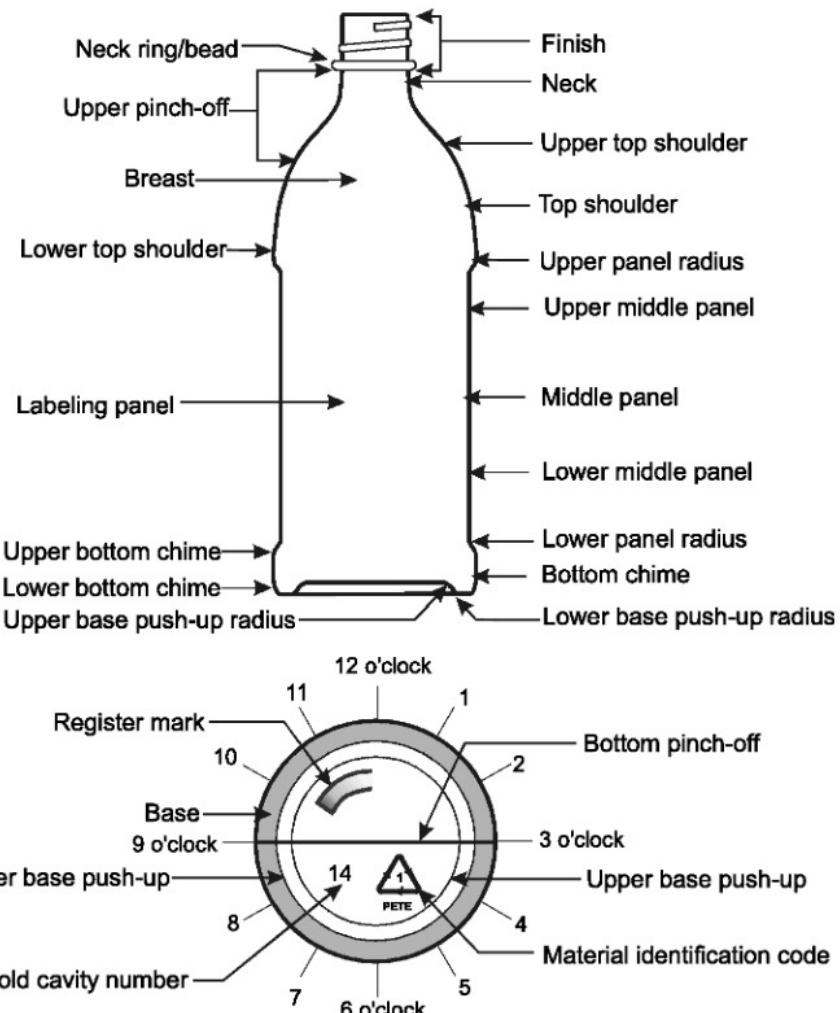
Most bottles are made in multiple molds, and it is standard practice to put a mold identification number on a bottle's bottom. Investigation of any irregularity or bottle failure should start by determining whether there is a correlation between mold numbers and the observed phenomenon.

The symbol identifying the bottle material for purposes of recycling also will be on the bottom of all but the smallest bottles. (See Chapter 5, Environmental and Sustainability Issues, for symbols)

The Society of the Plastics Industry, now the Plastics Industry Association, has developed standard terminology that should be used when discussing design features or for identifying problem areas. (See Figure 11.27)

INJECTION BLOW MOLDING

Injection blow molding (IBM) combines injection molding and blow molding. Instead of extruding a parison, as in EBM, a parison or "preform" is injection molded.

**Figure 11.27**

Standard bottle terminology: The 12 o'clock position is at right angles to the parting line when the container is turned so that mold numbers and other text are right-side-up.

Economics generally confines IBM to higher volume production, since two molds are required to make a container: the injection mold(s) to produce the preform and the companion blow mold(s) to blow the container.

Injection molding of a preform allows more exact control over material distribution than available when extruding a parison. After the injection cycle, the preform, still retained on the core pin, is transferred to the blow-molding station. The final blowing operation is similar to EBM. (See Figure 11.28)

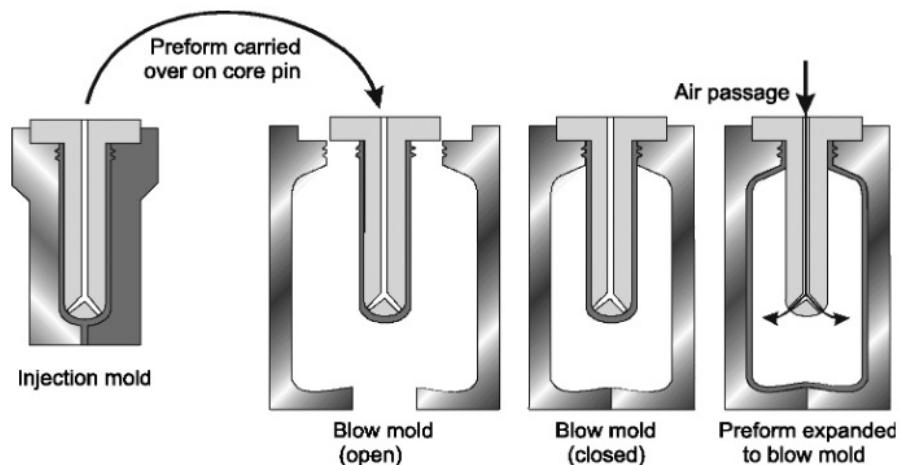
When injection and blowing are done on a single machine, the process is described as “one-step.” (See Figure 11.29)

Injection-stretch Blow Molding

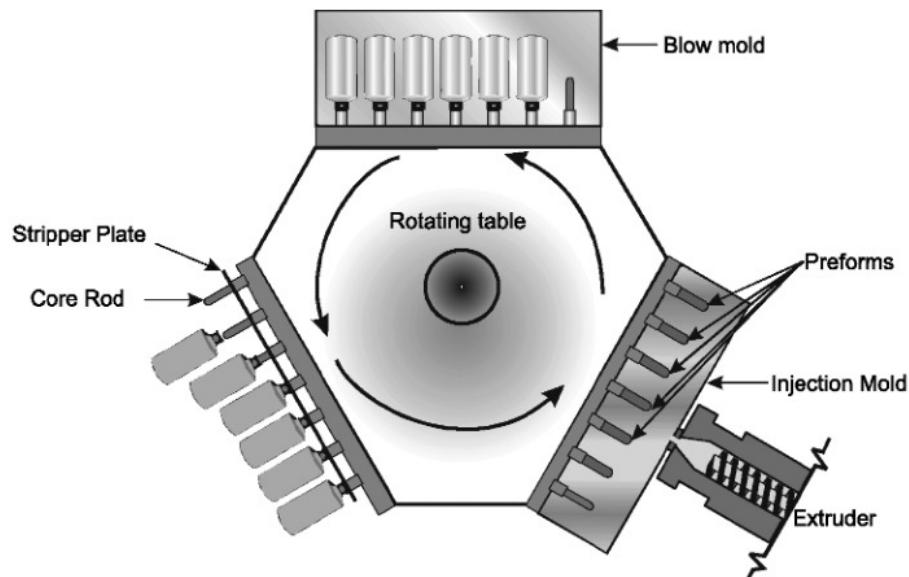
A variation of IBM, injection-stretch blow molding (ISBM), uses a rod to stretch the preform during blowing. (See Figure 11.30) In a typical operation, at the point that the core rod touches the bottom of the preform, a small amount of air is introduced

Figure 11.28

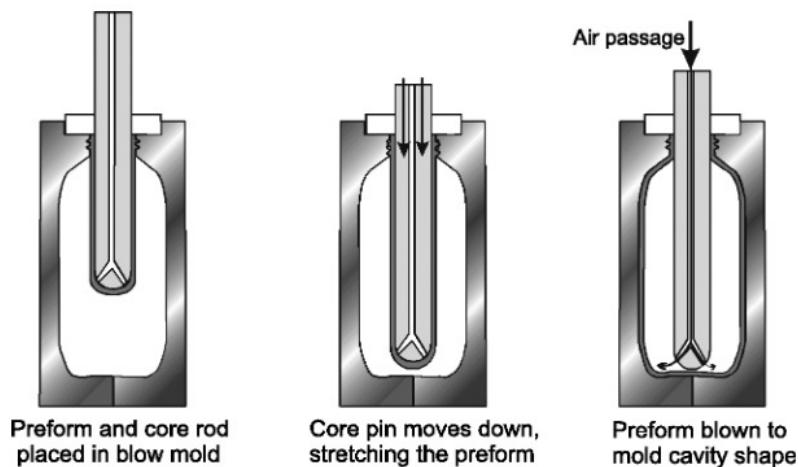
The injection blow molding process combines preform molding and a bottle blowing cycle.

**Figure 11.29**

Configuration of a one-step injection blow molding machine. One core rod is shown empty for illustration purposes.

**Figure 11.30**

A major application for injection-stretch blow molding is the manufacture of PET carbonated beverage bottles.



to start the blowing process. When the core rod reaches the bottom of the mold, the full volume of inflating air is introduced. This mechanical stretching orients the polymer molecules and improves stiffness and barrier properties. For deep bottles, the core rod ensures that the inflation is evenly centered in the mold.

Single-step ISBM machines mold the preforms in an injection station and release them from the core before transfer to the blowing station. There also are two-step machines where preforms are injection molded in large-cavity molds and stored in bins prior to blow molding.

In two-step ISBM, it is common practice for preforms to be injection molded at a central location and then transported to filling plants for blowing into the final bottle form. This saves money both in the cost of injection machines and in transport. Preform injection molds may carry as many as 216 cavities.

Two-step ISBM is the favored process for making PET carbonated beverage bottles. In this application, the injection-molding machine can be optimized for production needs in terms of cavitation and size and can be operated 24 hours a day, seven days a week. The blowing machine is run according to daily production requirements and often is linked directly to the filler. For oxygen-sensitive beverages, the preform can be molded with multiple layers, incorporating barrier or oxygen-scavenging materials to provide longer shelf life.

The thermal history of an ISBM part is similar to the thermal history used to make a shrink plastic. (Heat the plastic to about glass transition temperature, stretch and cool quickly.) One drawback of conventional ISBM bottles is that they will shrink if hot-filled. Several heat-setting processes have been devised to circumvent this problem. Such heat-set bottles can be hot-filled at 88–95°C.

In a representative process, the preform is blown at about 100°C and then held in the mold at 150°C for several seconds. Crystallization level is about 35%. Production rates for hot-fill are typically about 25% slower than conventional ISBM.

Both EBM and IBM can be used to produce narrow- and wide-mouth bottle shapes. IBM, however, can produce bottle finishes that are more complex and with closer tolerances. Producing a close tolerance finish for a wide-mouth jar is particularly difficult for EBM. The absence of any trim and scrap with IBM is an advantage when manufacturing pharmaceutical and medical containers. Good manufacturing practice for these containers does not allow the inclusion of reground material. Table 11.2 compares the advantages and limitations of EBM and IBM. Table 11.3 lists the general properties and applications of polymers commonly used for plastic bottles.

BOTTLE DESIGN

When designing a bottle or jar, the first considerations are the product's nature and how the consumer uses or extracts the product from its container.

If the product is a semisolid—cosmetic creams, peanut butter or jam, for example—the product is removed with a tool. This tool might be a spoon, butter knife, or in the instance of cosmetic creams, a finger. Easy access and product removal demand a wide-mouth jar with a depth no greater than that of the tool that will be used. The jars should have minimal shoulders and no other features that would create a dead space difficult to reach with the tool. (See Figure 11.31)

Table 11.2
Extrusion blow molding and injection blow molding comparison.

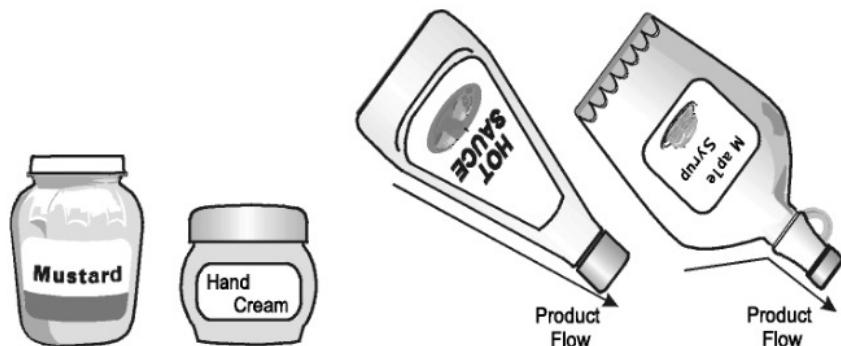
Advantages	Disadvantages
<i>Extrusion Blow Molding</i>	
Requires single mold	Produces trim regrind
Handleware readily produced	Limited precision
Coextruded bottles readily produced	Limited number of cavities
Large containers possible (e.g., 200-L drums)	Cold weld is a weak area
	Wide-mouth jars awkward
<i>Injection Blow Molding</i>	
No secondary operations (ream, trim, regrind)	Requires two mold sets
No regrind generated	Limited size containers
High-precision neck and finish	Handleware difficult
More cavities possible for small bottles	Multilayer constructions difficult
Better material distribution	
Wide-mouth jars easy to make	

Table 11.3
Properties of common bottle plastics.

Plastic	Clarity	Barrier Properties						Density	Typical Bottle Applications
		Water	Oxygen	CO ₂	Rigidity	Impact			
PETG	E	G	F	F	G	G	1.27	EBM, high-clarity bottles	
PET	E	G	E	G	G	F	1.33	IBM, high-clarity bottles	
OPET	E	G	G	G	E	G	1.36	ISBM, carbonated beverages	
PVC	G	G	F	G	G	F	1.35	solvent resistant and cosmetic bottles	
LDPE	P	E	P	P	P	G	0.92	soft, squeezable bottles	
HDPE	P	E	P	F	F	G	0.96	most opaque consumer bottles	
PP	P	E	P	F	F	F	0.91	hot-fill applications	
BOPP	P–F	F	P	F	F	G	0.91	as PP but better clarity	
PS	E	F	P	P	E	P	1.05	cosmetic, hard, high gloss	
PC	E	P	P	P	G	E	1.20	exceptional impact, hot fill	
AN	G–E	F	E	E	E	F	1.15	high solvent-resistance barrier	

P = poor, F = fair, G = good, E = excellent

Figure 11.31
Examples of good designs for semisolid products (left) and viscous fluids (right). Embossed or textured shoulders tend to trap product and present a cleaning problem.



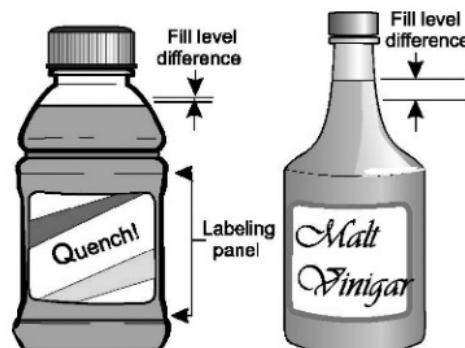
Viscous products such as syrups, sauces and salad dressings can be poured. Bottles for these products should have the largest possible opening consistent with an acceptable appearance. Larger diameter openings also allow for easier and faster filling. Other desirable bottle features are smooth walls and no shoulders or other shapes that could interrupt product flow. Rather, the bottle should slope gently like a funnel toward the opening. (See Figure 11.31)

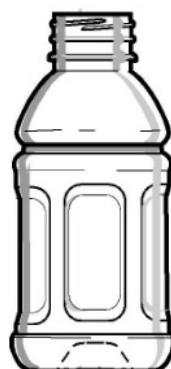
Neck designs affect visual fill height levels. The same variation in fill volume will be much more obvious if the fill point is in a narrow neck. (See Figure 11.32) Neck bands sometimes are used to conceal the fill level. Where shipping costs are a concern, the bottle should be compact and have a minimum neck length.

A bottle may have to accommodate internal pressures without bursting. Round, cross-section bottles provide the highest circumferential (hoop) strength. All carbonated beverage bottles and other bottles that may have to withstand internal pressure will be round.

A bottle may have to accommodate a partial internal vacuum without paneling—the deformation of the bottle wall as it “sucks in” in response to the partial vacuum. Hot-filled bottles panel inward as the hot product cools and contracts. Where the temperature change is small, curved surfaces, thicker wall sections and carefully selected vertical and horizontal design elements may be sufficient to prevent visible paneling. With larger bottles and greater temperature changes, expansion panels (usually deeply countersunk rectangular forms placed around the bottle’s circumference) move in and out to accommodate the pressure changes. Expansion panels usually are hidden by the label. (See Figure 11.33)

Figure 11.32
Fill-level discrepancies are more obvious in a narrow-neck bottle.



**Figure 11.33**

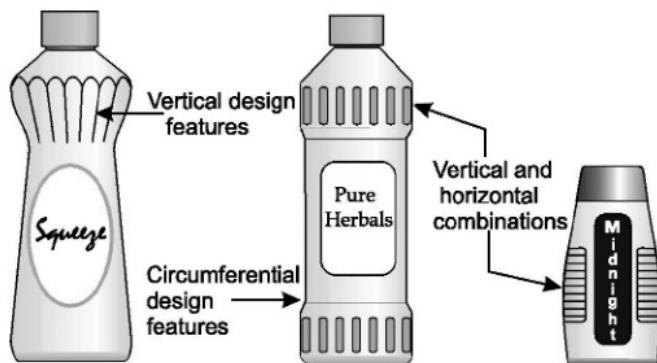
Expansion panels on a bottle intended for hot-filling.

Straight-walled bottles have less physical strength than similar bottles with added circumferential and vertical design elements. Circumferential rings increase a bottle's hoop strength, resulting in a container that resists paneling inward or bulging outward. Vertical design elements act primarily to increase the bottle's top-to-bottom load-bearing ability. Many bottles have incorporated embossing or decorative facets that act to improve physical properties and aesthetics. (See Figure 11.34)

Sometimes a design needs both stiffened sections and flexible sections. The "squeeze" dishwashing detergent bottle uses vertical elements to stiffen the shoulder area but has a large flexible center panel that can be squeezed to dispense detergent. (See Figure 11.34) Typically, a narrowed waist makes this bottle easier to hold with wet, slippery hands.

While circumferential rings or grooves help stiffen the bottle in that axis, they make the bottle more flexible or springy in the top-to-bottom axis. This springiness is amplified if the rings have sharp radii and are deep. The greater the top-to-bottom flexibility, the greater the possibility of transport vibrations causing a resonance condition. Designs with unusual vertical flexibility should be tested for resonance frequency response using established preshipment testing methods.

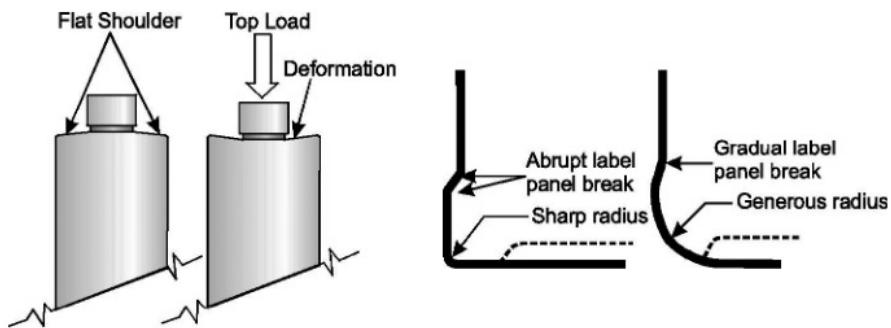
Bottles should be designed with generous curves and radii. Sharp corners act as stress risers and can momentarily trap air between the expanding parison and mold and should be avoided.

**Figure 11.34**

Vertical and horizontal design features. Vertical design lines and features add to the top-to-bottom stiffness, while circumferential features increase hoop strength.

Figure 11.35

Flat panels leading up to the finish should be avoided (left). Gently sloping shoulders carry loads best. Provide generous radii at breaks for labeling panels and in high abuse areas such as the bottle base (right).

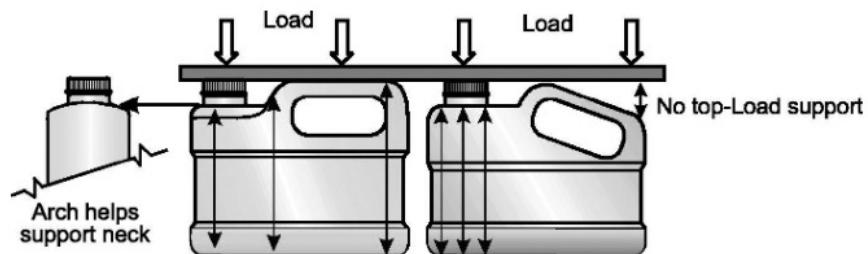


Flat shoulders leading up to the finish will deform easily, and under prolonged loading, likely will fracture the bottle at the finish/shoulder junction. (See Figure 11.35, left) Smoothly sloped shoulders with generous curves provide for even load distribution.

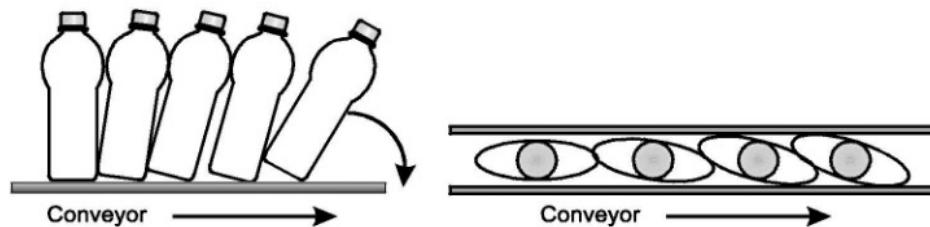
Generous radii and long curves reduce built-in molding stresses and provide better material distribution and strength. This is particularly important at the base where material distribution tends to be difficult to control and the bottle is most abused. Label panel breaks should have a gentle radius rather than a sharp break. (See Figure 11.35, right) Do not design bottles with abrupt cross-section changes—for example, a bottle with a round upper section and a square base.

Large jugs with built-in handles are an effective way to deliver large quantities of liquid product. Since they are heavy, top-to-bottom compression strength can become a vital issue. The most effective way of gaining top-to-bottom compression strength is to design a center-opening jug with gently sloping walls, but these can be awkward to pour in the larger sizes. Off-centered pour openings (F-style) jugs are more popular, but when stacked, can have almost the entire top-to-bottom load concentrated down one side of the container.

The best designs are those that raise the handle so that it is on the same level as the closure surface, allowing the load to be more evenly distributed across the bottle walls. (See Figure 11.36)

**Figure 11.36**

The highest top-to-bottom compression strength will be in those jugs that are able to better distribute the load across the jug's walls. The inset label panel prevents the label from rubbing against other surfaces during shipping.

**Figure 11.37**

Good bottle design should take machine handling and conveying into account. Poor designs can result in problems such as tip-over when bottles are larger at the top than at the base (left). Shingling occurs with narrow, oval bottles (right).

The easiest bottles to handle on a filling line are those with a low center of gravity. Bottles that are wider at the top than at the base can cause conveying problems such as tip-over when bottles press against each other. (See Figure 11.37) “Shingling,” another possible conveying problem, occurs with narrow, oval bottles. With just a slight rotation, bottles overlap and wedge or jam between the conveyor rails. Designing small flats at the bottle ends can prevent shingling.

Consider labeling requirements before committing to a bottle design. Round cross-sections are preferred where high labeling speeds are important. By comparison, three-side-wrap labels on a square bottle will not be as amenable to high labeling speeds. Plastic shrink labels can conform to complex curved shapes. Paper, however, can be curved in only one axis and will not conform to surfaces curving in two axes. A shoulder label on a round bottle can be applied properly only if the shoulder is a true straight-sided cone.

Bottle design can reduce label abrasion damage. Labels on bottles with sloped shoulders and tapered bodies will not come into contact with another surface during transport and handling. Straight-walled bottle designs usually inset the labeling panel so labels do not rub against each other or the corrugated box during shipment. Figures 11.32, 11.34 and 11.36 illustrate design features to accommodate labels. A label located where there will be contact with other bottles or the shipper will be prone to abrasion damage.

Sometimes, a label needs to be precisely positioned on a round bottle. The packager might not want the label to align with a mold parting line, might want one label to align with another or might want the label to align with a directional closure. In these cases, the bottle must incorporate a device to allow precise label orientation. The most common device is a small, depressed wedge shape molded into the bottle’s base. A mechanical sensor on the machine detects this register mark (wedge), and the bottle can be rotated to its appropriate orientation.

Bottle designers also should consider end-of-life outcomes at the outset. HDPE and PET, in particular, are widely recycled materials, and new designs should not create problems in the recycling streams. Guides for designing for recyclability are available from several packaging and sustainability organizations. (See Association of Plastic Recyclers for more information.)

Table 11.4
Common thermoforming materials and their forming temperatures.

<i>Material</i>	Typical Forming Temperature	
	<i>Celsius</i>	<i>(Fahrenheit)</i>
Polyvinyl chloride	138–176	(280–350)
Polystyrene	143–176	(290–350)
Oriented polystyrene	176–193	(350–380)
High-impact polystyrene	171–182	(340–360)
Polypropylene	148–199	(300–390)
High-density polyethylene	148–190	(300–375)
Polyethylene terephthalate glycol	129–162	(264–324)
Crystallized polyethylene terephthalate	148–176	(300–350)

THERMOFORMING

Principles and Applications

Many containers and other draw-formed packaging components can be manufactured readily from thermoplastic sheet by a thermoforming process. All variations heat the thermoplastic sheet to a point where it becomes soft and pliable, but below the temperature at which melt flow might occur.

Most thermoplastic materials can be thermoformed, including single-polymer materials, coextrusions and laminated sheets. (See Table 11.4) Multilayer laminated sheet can provide specialized physical and chemical properties that are not economically attainable by other means. Thermoforms made on automated, high-performance equipment provide a possible alternative to injection-molded containers such as tubs, cups, clamshells and coffee capsules.

Pliable plastic sheet can be formed by mechanical means, with vacuum, with pressure or by a combination of both. In all cases, the relationship of the part surface area to the available sheet determines the average material thickness. Material distribution is governed by the part's geometry and the method used to form the shape. Sheet gauge and mold accuracy are important.

Since molding temperatures and pressures are relatively low, thermoform molds are economical. It is not unusual for prototype molds to be made of wood or epoxy/aluminum. Production molds are either aluminum or steel.

A sheet being formed should be heated to its optimum temperature to reduce residual stresses set up when the material is stretched. Manual operations do not lend themselves to good, consistent qualities due to the variables of manual time se-

quencing. Automatic, servo-driven, accurately timed, thermally-controlled equipment is preferred.

All drawn parts must have a draft angle so that the part can be removed from the mold. Draft angles are a function of part geometry—the deeper the draw, the greater the angle required. Angles from 2 to 8 degrees are typical.

While thermoforming cannot make narrow-necked containers directly in the mold, two formed halves can be joined to create narrow-necked or other partly or completely enclosed containers. (See Figure 11.38) The two halves can be joined by adhesive bonding, spin welding or ultrasonic bonding, though this process is rarely used in commercial practice.

The thermoforming industry traditionally is defined by its two processing segments: thin-gauge (roll-fed, up to 3-mm/0.118-inch thick) and heavy-gauge (sheet-fed, thicker than 3 mm). Much thin-gauge thermoforming is bound up in food packaging where consumer demands and the brand equity of global companies pull innovation from package designers, material scientists and equipment suppliers. From North America to Southeast Asia, thin-wall packaging is an important driver of growth.

Heavy-gauge thermoforming offers a large variety of material options (10 to 15 times more than thin-gauge), so machinery must be able to process all material types. While the automotive sector continues to extract innovation from the heavy-gauge thermoforming ecosystem (resin suppliers, material suppliers, converters, original equipment manufacturers), the medical, building materials and logistics sectors also contribute to the increased adoption of thermoformed solutions.

The most common application of thermoforms is blister or clamshell display packaging, in various forms. PET (and recycled PET, or rPET), PS, PP, and polylactic acid are the most commonly thermoformed plastics for the packaging sector. Many package inserts, retaining devices and countertop point-of-purchase displays are thermoformed from PS. Many medical and operating room supplies are arranged in easily visible and readily accessible thermoformed trays.

Some food and product tubs are thermoformed rather than injection molded. There is an obvious tooling cost advantage. A thermoformed part, however, may not have the precision required for consistent fit of a snap-on lid.

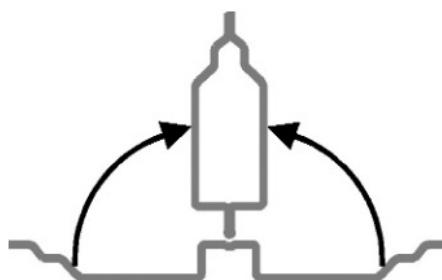
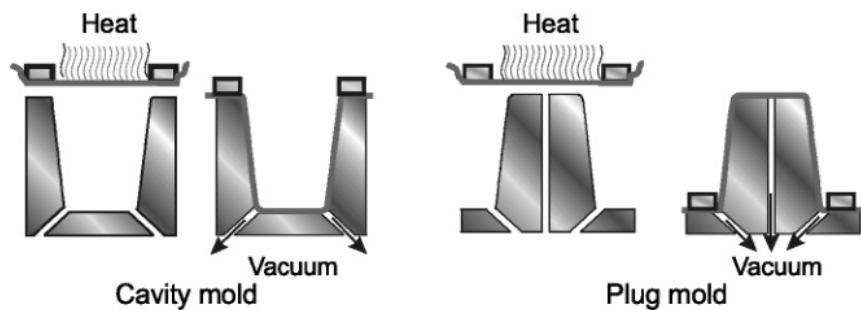
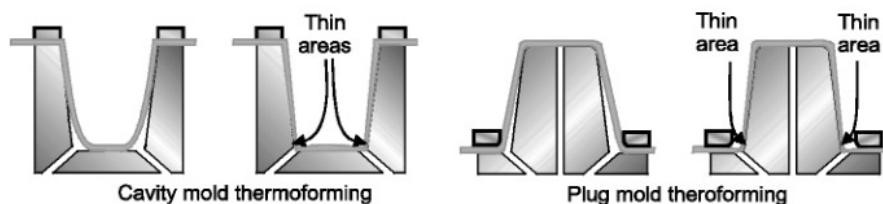


Figure 11.38

Bottles and other closed-package systems cannot be directly molded by thermoforming. However, thermoformed halves can be bonded together to make an inexpensive, bottle-like container.

**Figure 11.39**

Simple vacuum forming over cavity and plug molds: The material is pulled to the mold shape when a vacuum is applied between the mold and sheet interfaces.

**Figure 11.40**

Although cavity or plug molds create similar shapes, material distribution differs considerably. The thinnest areas occur in the last portion of the part cooled by contact with the mold.

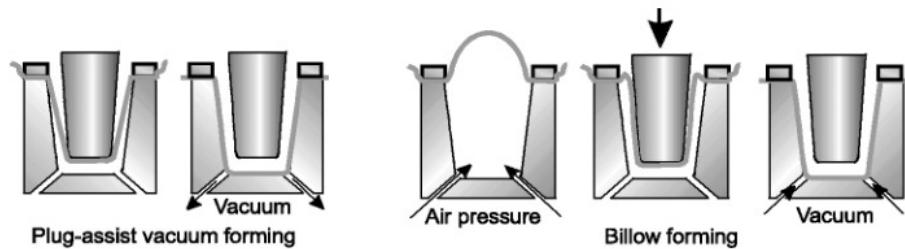
Thermoforming Methods

Vacuum, pressure, twin-sheet and matched metal describe thermoforming methods. Depending on whether the process is sheet-fed or roll-fed, different terminology can be used. Generally speaking, low-volume applications will be the least sophisticated while high-volume or premium segments will see greater complexity and cost.

Vacuum forming into a cavity mold or over a plug mold is the simplest form of vacuum molding. (See Figure 11.39) Vacuum holes are required in the cavity's lowest point. Vacuum forming into a cavity or over a plug has deficiencies similar to those of matched die molding—limited draw and poor control over material distribution. (See Figure 11.40) Cavity molds, or negative molds, allow for easier part removal, since the hot plastic shrinks away from the cavity when it cools, whereas the cooled plastic tends to tighten around a male, or positive, mold.

Material distribution problems are reduced when forming methods are combined. In plug-assist vacuum forming, the plug mold is above the sheet. (See Figure 11.41) The sheet is heated until it begins to sag, the plug moves the sheet into the mold and a vacuum pulls it into conformity with the mold. This gives better material distribution to the corners than vacuum forming alone.

Billow forming uses air pressure to billow the sheet upward 50% to 75% of the anticipated mold draw. (See Figure 11.41) A plug pushes the billowed material into a cavity. A vacuum then pulls the intruded material to the cavity shape.

**Figure 11.41**

In plug-assist vacuum forming, the plug moves the sheet into the mold and vacuum pulls it into place. Billow forming inflates the plastic sheet upward to produce a sheet of uniform thickness.

Microwavable Trays and Containers

Microwave-compatible plastic trays or containers have displaced the original aluminum TV dinner tray. Plastic trays can be thermoformed from PP, PS or crystallized polyethylene terephthalate (CPET). The trays are formed from rolls of plastic sheet.

CPET is stiff, strong and stable from -40 to 218°C (-72 to 392°F), offering dual ovenability—meaning it can be used in reheating in both conventional and microwave ovens. The material has better water- and oxygen-barrier qualities than PP or PS, good grease and oil resistance and minimally affects food taste. However, CPET is costly compared to other options due to the slower cycle rates associated with more complex tooling that both heats and cools the material in the mold.

PP has sufficient temperature stability to allow it to be used for most microwavable applications but not in a conventional convection oven. PP also has oxygen-barrier limitations. Where an increased oxygen barrier is required, PP can be coextruded with a barrier resin such as EVOH.

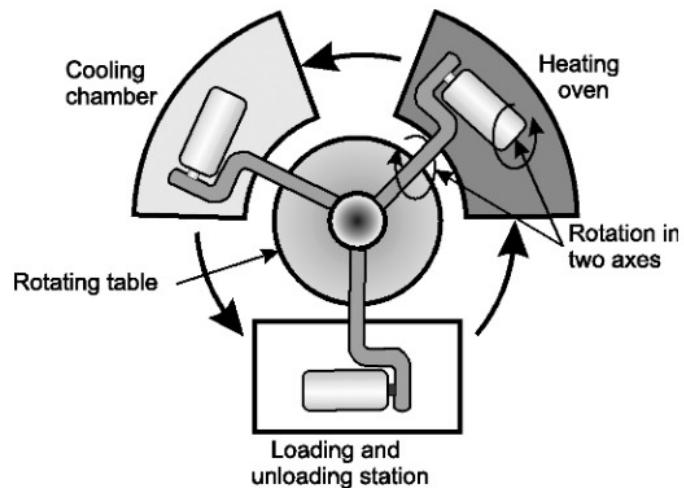
Conventional PS has a low heat-deflection temperature, but low-density blends are available that will not deflect significantly up to about 190°C (375°F), allowing for microwavable applications. Sometimes, trays are made of expanded PS.

OTHER FORMING METHODS AND VARIATIONS

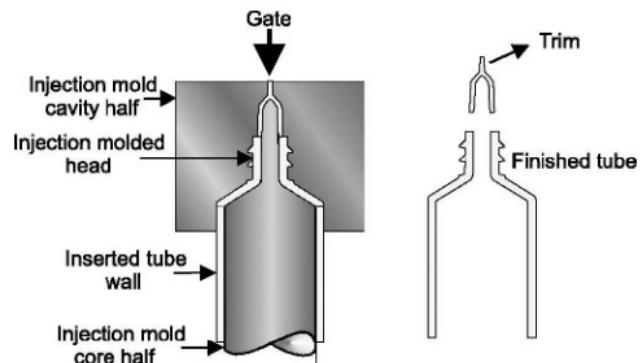
Rotational Molding

Rotational molding does not require an extruder. (See Figure 11.42) In this process, the polymer, usually a finely powdered PE, is placed in a mold that is heated while being rotated in two axes. The heat eventually melts the PE, which flows and evenly coats the inside surfaces of the mold. While still rotating, the plastic is cooled. The mold is opened, and the part is removed. An advantage of this process is the making of a hollow object with no openings.

Since rotational molding is not a pressure process, the molds need not be massive and usually are made from welded steel plate. Rotational molding is used to make very large bins and bulk containers. It is too slow and energy-intensive for small plastic containers.

**Figure 11.42**

Configuration of a typical rotational molding machine.

**Figure 11.43**

Injection molding a head onto an extruded tube body.

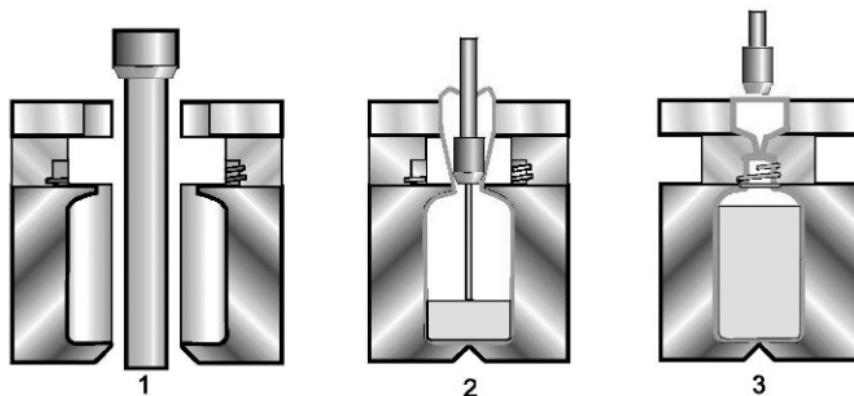
Injection-molding Heads on Extruded Profiles

Occasionally a package is formed by combining two molding processes. For example, profile-extruded collapsible tubes are inserted into an injection mold. (See Figure 11.43) Additional plastic is injected into contact with the extruded tube and fuses to the tube walls. The sprue and gate are trimmed off in a separate operation.

Compression Molding

Compression molding is used primarily to mold thermoset plastics. A measured charge of unpolymerized thermoset plastic is placed into the hot cavity of a mold. A mating core is brought down to squeeze the plastic into close conformity with the mold. The heat from the mold cures the plastic.

The compression molding technique has on occasion been used to mold thermoplastic parts. The main difference is that the thermoplastic is melted in an extruder, and a measured shot is then ejected into a chilled mold cavity. As with thermosets, the core forces the molten plastic to conform to the mold profiles. Compression molding has been used to make thermoplastic closures. One advantage of the method is that it leaves no gate mark.

**Figure 11.44**

Blow-fill-seal sequence: Step 1. A parison is extruded. Step 2. The mold closes over the parison, the bottle is formed, and product is introduced. Step 3. The finish is formed by moveable mold parts, and the bottle is sealed shut.

Blow-fill-seal Molding

Blow-fill-seal molding is similar to EBM in that it starts with an extruded parison. (See Figure 11.44) However, as soon as the bottle is blown, product is introduced through a tube incorporated into the blowhead. Separate mold pieces then move in to form and seal off the finish.

Blow-fill-seal is used to produce single-use bottles that are opened by breaking off the tip rather than removing a closure. It is particularly useful for sterile pharmaceutical preparations where the plastic forming temperature and the closure-less seal ensure sterility.

Expanded Plastics

Expanding a plastic into a low-density cellular foam requires the introduction of a fine network of gas bubbles or cells into the plastic mass. Blowing agents—low-boiling point liquids that can be dispersed into a plastic mass—are the most common way of expanding a plastic into a cellular foam. When the mass is heated, the blowing agent in its gaseous form expands into bubbles in the softened plastic. By controlling the kind and quantity of blowing agent, temperature and time, expanded plastics can be produced in a range of densities.

Expanded polystyrene (EPS) and expanded polyethylene represent the bulk of expanded plastic used in packaging, followed by urethane.

At one time, many blowing agents were based on chlorinated fluorocarbons. Today, these have been replaced with pentane or isopentane (primarily for PS) and higher hydrocarbons (primarily for PE), used alone or in blends. Carbon dioxide also may be used along with the blowing agent. Nucleating agents encourage the formation of very fine gas bubbles.

Smaller bubbles produce a denser foam where the bubbles are divided from each other. Such closed-cell foams will not absorb liquids. As bubble size grows, the di-

viding walls between bubbles eventually collapse to produce an open-cell foam. Open-cell foams are more sponge-like and will take up liquids.

Thin expanded sheet material is extruded from an annular die similar to blown-film extrusion. The blowing agent is introduced in the extruder and expands the plastic sheet as it leaves the extruder. The tube is slit, and the flat sheet is rolled up and sent for conditioning.

Loose PS fill for protective packaging is made by the extrusion process.

A second method of producing EPS is to incorporate the blowing agent into a PS melt and then cool it, capturing the blowing agent inside. The solid PS beads can be transported in bulk to locations where the material will be processed into an expanded form. To make a dimensional part, the beads are pre-expanded slightly and then placed into a mold. Steam heating raises the temperature to a point where the PS becomes thermoelastic and the blowing agent vaporizes, expanding the PS to the shape of the mold cavity.

To make EPS plank (beadboard) that can be fabricated into protective shapes, the beads are poured into a large block mold and expanded. EPS foams are exceptional insulating materials.

A polyurethane (PU) is produced by the polymerization of isocyanate and a glycol. PU can be expanded by gases formed during a chemical reaction between the two prepolymers. PU foams are usually open-celled and can be made into very soft, resilient foams as well as stiff thermoset forms. Shaped forms can be made by mixing the liquid diisocyanate and glycol in a spray-gun type of nozzle directly into a mold. A major packaging application is foam-in-place cushioning where the still liquid foam is directed at, and allowed to expand around the actual object to be protected.

RECOGNIZING MOLDING METHODS

The process used to make a plastic part can be recognized by the part's nature and an examination of the mold markings, or noting a lack of them. Extruded parts have no mold markings. They are simply pushed through a shaped opening. Thermo-formed parts also have no visible markings, since they are cut from a flat sheet. The process can only make containers that can be pulled from an open cavity or off a plug. There are no undercuts.

An extrusion blow-molded bottle, by definition, must be a part that can be inflated. It will have a pinch-off across the bottom where the mold halves came together and cut off the excess parison. A faint parting line will be seen up the container sides.

Injection-molded parts will have a small bit of plastic at the gate point. Mold makers have become adept at hiding this gate mark, and sometimes it is difficult to find. Mold-parting lines on simple tubs are usually put along an edge, which makes them hard to detect. Parting lines can be seen in parts that have undercuts or other features that require the mold to come apart in segments.

Injection-blow-molded parts resemble extrusion-blown parts except that instead of a mold pinch-off, there is a circular bull's-eye pattern on the container bottom. This is the residue of the gate mark from the initial injection molding of the pre-form. Faint parting lines up the container sides sometimes can be seen.

REVIEW QUESTIONS

- 1.** Name four basic ways of forming plastics into semirigid shapes.
- 2.** Molds for plastic manufacture are generally designed for a particular polymer. What problem are you likely to encounter if you switch materials?
- 3.** What is coextrusion, and what advantages does coextrusion offer?
- 4.** To mold plastic into a useful shape, it must first be heated and softened. What is the name of the machine that does this?
- 5.** What is the principal use for a thin-walled extruded tube?
- 6.** Define the following terms: sprue, runner, flash, gate, parison.
- 7.** There are two ways of manufacturing plastic film. What are they?
- 8.** How are plastic bags usually made?
- 9.** What are combinations of vacuum, pressure and mechanical assists used in thermoforming?
- 10.** Discuss the importance of a programmed parison.
- 11.** What is the makeup of a high-oxygen barrier, multilayer bottle of the type typically used for ketchup?
- 12.** What molding process would be used to make a 1,200-liter bulk bin?
- 13.** What is the significance of the number that can be found on most blow-molded bottles and injection-molded parts?
- 14.** Why are carbonated beverage bottles injection-stretch blow molded?
- 15.** What designs can be made by extrusion blow molding that would be more difficult to make by injection blow molding?
- 16.** Why isn't injection molding used to make narrow-mouthed bottles?
- 17.** How does an extruder for injection molding differ from an extrusion profile extruder?
- 18.** Parts made by injection molding have tighter tolerance ranges than parts made by extrusion blow molding or thermoforming. Why?
- 19.** How is a cast film biaxially oriented?
- 20.** What is an "undercut"?
- 21.** What are the advantages of injection blow molding, and for what specific applications and industries are these advantages particularly beneficial?
- 22.** Molded open tubs can be made by injection molding or by thermoforming. What are the implications of choosing one method over the other? What feature can be incorporated easily into a thermoformed tub that would be difficult with injection molding? How can you tell which process was used to make the tub?

- 23.** How can you recognize the process by which a bottle was made?
- 24.** In thermoforming, cavity molds are preferred over plug molds. Why?
- 25.** What is a sink mark, and what might cause it?
- 26.** What does melt flow rate measure, and what is the significance of this value?

PLASTIC APPLICATIONS

12

CONTENTS

Polyethylene (PE)

Production and variations.

High-Density Polyethylene (HDPE)

Application features, North American usage.

Low-Density Polyethylene (LDPE) and Linear Low-Density Polyethylene (LLDPE)

Properties and applications, strengths, limitations, film applications, semirigid applications, metallocene PE, North American usage.

Polystyrene (PS)

Production and properties, applications, unoriented PS film, biaxially oriented crystal PS sheet, injection-molded PS closures, white opaque expanded polystyrene (EPS) cellular sheet, thermoformed EPS food trays.

Polypropylene (PP)

Production and properties, applications, North American usage.

Polyethylene Terephthalate (PET)

Production and properties, applications, recycling.

Polyvinyl Chloride (PVC)

Production, processing and properties; applications; North American usage.

Polyvinylidene Chloride (PVDC)

Production, attributes, monolayer and multilayer film.

Polyvinyl Acetate (PVAC) and Ethylene-Vinyl Acetate (EVA)

Properties and applications.

Polyamide (PA or nylon)

Production and applications.

Polyvinyl Alcohol (PVAL) and Ethylene-Vinyl Alcohol (EVOH)

Applications, production, copolymers, solubility, barrier qualities.

Ethylene Acid Copolymers and Ionomers

Variations and applications.

Other Packaging Polymers

Cellulosics, epoxies, polycarbonates, acrylonitrile copolymer, polyurethanes, polyethylene naphthalate, styrene-butadiene, polychlorotrifluoroethylene, bioplastics, thermoset plastics, other plastics.

Additives

Antistatics, antioxidants, heat stabilizers, plasticizers, slip agents, ultraviolet stabilizers, others.

Characterizing Plastic Materials

Tensile properties, tear strength, impact strength, heat-seal strength, coefficient of friction, haze and

gloss, water-vapor transmission, gas permeability, grease and oil barrier, dimensional stability, maximum and minimum use temperatures, environmental stress-crack resistance, stability with industrial and household chemicals.

POLYETHYLENE (PE)

Production and Variations

Polyethylene (PE) is produced by polymerizing ethylene gas under pressure and elevated temperature in the presence of metal catalysts. Under these conditions, ethylene molecules link up in long chains of 50 to 50,000 units, transforming ethylene gas into a white, partially crystalline solid. The product of this reaction is extruded as a hot ribbon, cooled and chopped into pellets.

Some side branching of the main polymer chain occurs during polymerization. If the branches are relatively few and short (two to four carbon atoms), the long parent chains will fold and pack neatly together in crystalline-like structures as the PE cools from a melt. With small amounts of short-chain branching, the material produced is high-density polyethylene (HDPE). HDPE is defined as a PE with a density between 0.941 and 0.959 grams per cubic centimeter (g/cu cm).

Extensive side-chain branching is encouraged by polymerizing the ethylene at higher temperatures and pressures. Long-chain branching interferes with orderly packing, resulting in low-density polyethylene (LDPE), a material that is less crystalline and less dense. LDPE is defined as having a density between 0.910 to 0.925 g/cu cm.

Linear low-density polyethylene (LLDPE) is a PE in which side branching has been deliberately introduced by including monomers such as butene, hexene or octene with the ethylene. The resulting PE contains sufficient copolymer short-chain branching to decrease density to the LDPE range, but unlike LDPE, the branches tend to be short, giving LLDPE properties somewhat different from LDPE.

The differences in properties between HDPE and LDPE (including LLDPE) grades are so great that their applications are completely different and they are treated as if they were different plastic families.

Many new PE grades have been coming into the market, and it may be expected that further developments will increase the number of variations. These variations usually are based on new copolymer combinations or on controlling molecular

geometry and molecular weight distribution. In the latter field, metallocene, or single-site catalysts (replacing Ziegler-Natta catalysts), provide a way to produce PEs with very narrow molecular weight spreads. Metallocene polyethylenes (mPEs) are somewhat harder to process, but are tougher and provide stronger heat seals than conventional PE.

In another development, bimodal PEs are composed of molecular weights in two distinct molecular weight ranges rather than grouped about a single average molecular weight. The lower molecular weight fractions act as a lubricant, making processing of the higher molecular weight components easier.

PEs are one of the most versatile and economical polymers, and their low softening point results in low processing energy costs. These factors alone have encouraged the use of PE over other resins in many applications.

HIGH-DENSITY POLYETHYLENE (HDPE)

Properties and Applications

The most significant application features of HDPE are its low cost, easy processibility and good moisture barrier. Its low oxygen-, hydrocarbon- and flavor-barrier properties, softness, low softening point, opacity and relatively high cold-flow properties may limit its use for some applications. Table 12.1 lists the most significant HDPE applications.

Some retail bags and sacks, as well as some food wraps and bags, are made from extruded HDPE film. Good moisture-barrier properties encourage the use of HDPE for any application where a moisture barrier is required. Multiwall paper sacks often use an HDPE inner liner to impart water resistance. Extrusion coatings of HDPE improve water or grease hold-out for paperboard products.

Table 12.1
HDPE packaging applications based on a total
North American usage of 13,750 million lb.

Blow-molded liquid food bottles	10%
Household and industrial chemical bottles	9%
Injection-molded pails	8%
Blown and cast film	3%
Injection-molded tubs and containers	3%
Injection-molded crates and totes	2%
Blow-molded motor oil bottles	2%
Blow-molded industrial drums	2%

Most consumer and industrial blow-molded containers are HDPE. Containers have a milky translucence, and many blow-molded containers are pigmented to improve appearance. Natural HDPE is used for many packaging applications, particularly for food. Because it is relatively soft, PE is easily scratched and abraded. For appearance purposes, most blow-molded PE bottles have a matte surface finish.

Blow-molded bottles for food products are the largest single market for HDPE bottles, followed closely by the household and industrial chemical market. Household chemicals include household cleaners, shampoos, motor oils and lawn and garden care products. Blow-molded drums and tight head pails (i.e., a pail without a removable cover) are used mostly for shipping and storing industrial chemicals and materials.

PE exhibits a relatively poor barrier to hydrocarbon solvents. Despite this, many solvent-containing compounds are packed in HDPE bottles. Solvent loss eventually will lead to bottle paneling. (See Figure 12.1) Fluorination, a process where the finished bottle's interior is flooded with fluorine compounds, sometimes is used to increase barrier properties.

Injection-molded pails are open-topped containers, for which 20-liter (L) or 5-gallon (gal.) sizes are the most common. Used for a broad range of consumer and industrial products, pails hold prepared plasters and grouts, swimming pool chemicals, fertilizers, institutional foods, industrial chemicals, institutional paints and agricultural chemicals.

Many industrial boxes, crates, pallets, totes and other material handling and storage containers are made from injection-molded HDPE. Crates and totes include "dairy crates," a generic term used to describe all manner of crates used to handle more than just dairy products.

Almost a third of HDPE caps and closures are milk bottle caps. Covers for open-head pails and some screw-thread closures also are made from HDPE. Some yogurt, sour cream, margarine and other product tubs are injection-molded from HDPE, although polypropylene (PP) tends to be more common. (Injection-molded PP, however, can become brittle at freezer temperatures. To avoid the possibility of cracking, frozen products such as ice cream come in HDPE tubs.) Snap-on lids for PP tubs usually are made from PE to take advantage of its higher elongation qualities.



Figure 12.1
Permeation of volatile solvents through high-density polyethylene has resulted in paneling.

LOW-DENSITY POLYETHYLENE (LDPE) AND LINEAR LOW-DENSITY POLYETHYLENE (LLDPE)

Properties and Applications

Like HDPE, LDPE has low cost, easy processibility and a good moisture barrier. LDPE and LLDPE have good heat sealability at temperatures as low as 106–112°C (223–234°F). This is the lowest softening point of conventional packaging polymers and accounts for one of the larger applications of LDPE and LLDPE. Other significant features are clarity, high elongation and softness. Low gas-barrier properties, softness, low softening point and relatively high cold-flow properties may limit usage for some applications. Table 12.2 and Table 12.3 list the most significant LDPE and LLDPE packaging applications (the material is used in many other applications, as well).

For the LDPE family of materials, properties such as tear strength, impact strength, elongation and flexibility decrease as density increases. For example, with an increase in density comes a corresponding increase in stiffness. Conversely, LDPE's poor grease-barrier properties improve as density increases. PE film alone will not hold a vacuum because of its high gas permeability. Other LDPE limitations include poor scuff-resistance, high odor transmission, dust attraction (through static) and low grease/oil resistance.

Table 12.2
LDPE packaging applications as a percentage of the total North American usage of 6,400 million lb.

Extruded food-packaging film	17.0%
Extruded non-food-packaging film	12.5%
Stretch and shrink films	5.2%
Injection-molded components and parts	5.0%
Blow-molded bottles	0.1%

Table 12.3
LLDPE packaging applications as a percentage of total North American usage of 7,740 million lb.

Stretch-wrap and shrink-wrap films	15%
Non-food-packaging films	13%
Food-packaging films	6%

About half of all packaging uses for LDPE and LLDPE are as film made by either blown or cast extrusion. Blown film typically is used for most light- and heavy-duty consumer and industrial packaging. Cast film is used for pallet stretch wrap and overwraps. PE also can be extruded as a coating onto another substrate. Trash bags are the single largest user of LDPE.

A variety of food packaging applications such as bread bags, shipping sacks and other bagged products—where clarity and economy are required—depend on LDPE and LLDPE. Nonfood applications include light and heavy agricultural product bags, garment bags, bag liners and bags for industrial chemicals.

Stretch film for unitizing loads for shipment is a major LLDPE market. Ethylene-vinyl acetate (EVA) is another major stretch-wrap material. Shrink films are used to overwrap product or bundle multiple units for shipping. PE industrial liners are used for bins, boxes, drums and even the interiors of entire intermodal or bulk shipping containers to reduce water damage or contamination.

Heavy-duty bags contain products such as fertilizers, agricultural chemicals and industrial chemicals. Some products might come in a multiwall paper bag with a PE liner.

A significant proportion of the LDPE family is used to produce multilayer laminated structures where the materials serve as a heat-seal medium. The LDPE/LLDPE may be incorporated in the lamination as a previously made film that is adhesive-laminated to a substrate, or it can be applied directly as an extrusion coating. LDPE has good heat-seal properties and is readily sealed by various heat-sealing techniques. Medium-density PE also seals well, but HDPE can present problems that are normally remedied with an LDPE heat-seal coating or by blending the polymer with LDPE or EVA. Many laminated structures also take advantage of LDPE's clarity and low water-vapor transmission rate. Other substrates are used to provide the required gas-barrier properties.

LDPE and LLDPE are used for injection- and blow-molded containers where softness, high flexibility or squeezability is required. Bottles for sauces and other viscous fluids or semi-solids, where squeezability is an advantage, are made from LDPE. (See Figure 12.2)

Snap-on or interference-fit closures such as snap-on caps for margarine or sour cream tubs require some elongation for the cap to stretch and snap over a slightly enlarged friction ring around the tub's opening perimeter. (See Chapter 11, Shaping Plastics, Figure 11.18) LDPE and LLDPE have suitably high elongation.



Figure 12.2

Examples of squeezable bottles made from low-density polyethylene.

One of the newer members of the PE family, mPE, has up to 40% greater tensile strength, up to 10 times higher dart impact strength, better hot tack and produces stronger heat seals, compared with LLDPE. Disadvantages include a high coefficient of friction, more difficult processing and higher cost than LLDPE. Current mPE applications are for tough, high-performance films and heat sealants. Another significant application is for high-oxygen/low-moisture-permeable film for precut salads.

POLYSTYRENE (PS)

Production and Properties

Styrene is produced by combining ethylene with benzene to form ethyl benzene and then converting this to styrene. Styrene is polymerized with the aid of oxygen, oxidizing agents or light as a catalyst.

PS is available as a hard, clear, brittle homopolymer known as “crystal” PS. (“Crystal” in this context describes PS clarity, not molecular crystallinity.) Homopolymer PS has excellent clarity and high surface gloss. It can be brightly colored with opaque or transparent colorants. High-impact polystyrene (HIPS) is a PS copolymer that has been modified with elastomeric molecules such as butadiene to form a material with significantly improved impact qualities. PS is inexpensive and easily processed.

Expanded polystyrene (EPS) is made into a variety of trays, tubs and cups. It is formed by incorporating a blowing agent with the PS that will expand the plastic into a low-density cellular foam, which includes many protective packaging forms such as planks, molded forms and loose-fill cushioning. EPS foams are exceptional insulating materials. (Styrofoam is Dow Chemical Company’s proprietary name for a construction material and should not be used in reference to packaging materials.)

PS Applications

Table 12.4 lists the major packaging applications of PS. It has good dimensional stability, superior opticals, good chemical resistance to food acids and alkalis and good

Table 12.4
PS packaging applications as a percentage of the total
North American usage of 6,200 million lb.*

Extruded film and sheet	22%
Injection molding	10%

**Data does not include packaging markets for EPS packaging forms.*

printing characteristics. Crystal PS film lends itself to coextruded structures, where a thin layer of PS provides high surface gloss. Typical packaging applications include windowed cartons, windowed envelopes and “breathable” wrap for fresh produce.

Unoriented PS film has low tear, impact, tensile and heat-seal strengths; it has poor gas and water-vapor barrier properties. PS has poor resistance to many solvents, although this quality is used in some applications to produce solvent bonding of PS components.

Biaxially oriented crystal PS sheet possesses strength and clarity properties that are suited to thermoformed blister packs, candy and pastry trays and a variety of related food packages. Sheet PS is thermoformed into various point-of-purchase displays, product support or containment trays. Thicker sheet can be drawn into large tubs for dairy products.

Injection-molded PS closures take advantage of the material's exceptional clarity and have a hard, glossy surface. PS is injection-molded into a variety of glossy, crystal clear boxes and containers used in hardware, toy, cosmetic and jewelry applications. These boxes are generically called “jewel boxes,” regardless of the contents. Various interior supports and fitments to hold objects such as jewelry or wristwatches also are made from PS.

White opaque EPS cellular sheet material has excellent decorative qualities and can be made in a heat-shrinkable form. Cellular sheet is commonly used as label-stock for glass and plastic bottles.

Thermoformed EPS food trays of the type used to hold meat, produce and eggs are the principal products made from extruded EPS sheet. Heavier board stock can be cut to shape and fabricated for use as protective forms where volume does not justify the cost of a mold. Where volumes are significant, protective EPS forms are molded to shape. EPS loose-fill bead products are used mostly for inner packing to protect fragile products from impact and vibration.

POLYPROPYLENE (PP)

Production and Properties

PP is polymerized from propylene gas, a relatively low-cost feedstock, and processed into pellets by a method similar to that used to create PE. PP molecules differ from PE molecules only in having an extra carbon atom in the gaseous monomer. This altered monomer building block results in polymer side chains that are more uniform in length, resulting in more consistent physical and chemical properties. PP's properties can be tailored by catalyst selection, copolymerization and molecular weight control.

Homopolymer PP resin is available in two general classifications, depending on whether the location of the pendent methyl group is regular or random. Regular PP molecular structure (isotactic) gives superior properties and is used for most packaging applications. Random (atactic) PP polymerization yields a gummy PP, which has some limited applications as an adhesive base.

PP has lower crystallinity than HDPE and is easier to produce in an amorphous state. PP clarity can be improved by incorporating nucleating agents that deliberately precipitate crystals but limit their growth to a range that does not diffract light.

Copolymerizing with ethylene increases the randomness in the chain, reducing crystallinity and improving clarity; however, it also decreases the melting point and increases flexibility.

PP is a low-density material that is comparatively easy to process. Compared with PE, it has better resistance to cold flow and reduced deformation at elevated temperatures. It has good stiffness, tensile strength and surface hardness. PP has low ultraviolet (UV) light resistance and requires UV inhibitors for any application where there will be significant UV exposure. Unoriented PP becomes brittle at low temperatures. Copolymer PP has better cold performance but sacrifices other physical properties.

PP is an economical material essentially on a par with PE. It has a higher softening point, and therefore, is used for bottles where hot filling or some other thermal exposure occurs. Medical supplies that will be steam-sterilized often use PP. Although both PP and PE blow-molded bottles are somewhat opaque, PP has contact clarity when a wet product is filled into the bottle.

PP has outstanding integral hinge (live hinge) properties and is used in many injection-molded boxes, containers and closures where an integral hinge is a part of the design. Most plastic threaded closures are injection-molded from PP.

PP film can be made by blown- or cast-extrusion methods. As a plain, unoriented, uncoated film, PP possesses superior optical properties, good water-vapor barrier properties, good dimensional stability and good heat-seal strength, although in a relatively narrow temperature range. In this form, it has low tensile and impact strength, high gas permeability and poor low-temperature durability; it has only fair chemical resistance, machine performance and abrasion resistance.

Orienting PP improves its tensile strength, stiffness, moisture- and grease-barrier properties, low-temperature durability, clarity and gloss. However, oriented PP will not heat seal. This limitation is overcome by the use of heat-seal coatings (e.g., PE, polyvinylidene chloride (PVDC), EVA or acrylic), by modifying the film resins or by coextrusion with a heat-sealable material.

PP Applications

Table 12.5 lists major North American packaging markets for PP. PP films are classified by their orientation and by further groupings such as the following:

Table 12.5
PP packaging applications as a percentage of total
North American usage of 14,000 million lb.

Injection-molded containers and parts	10.2%
Film	9.0%
Blow-molded bottles	1.2%

- Heat-stabilized (i.e., nonshrink), non-heat-sealable film is used widely in laminate structures such as snack-food packaging or combined with paper as a bag liner for cookies or dry pet food. Clear labels may use this stock.
- Heat-stabilized, heat-sealable films have been modified, coated or coextruded to make them heat-sealable. Coated films (most commonly PVDC or acrylic) are grouped as gas-barrier and non-gas-barrier types. These are used as overwraps for cigarette packaging, candies and so on. Coextruded, heat-sealable films are used in form-fill-seal applications.
- White opaque films have excellent decorative qualities, similar to paper, without the disadvantages of water and fat absorption. Primary uses include single-web wrap for candy bars and labelstock.
- Heat-shrinkable films are used as shrink-wrapping stock and when printed, as clear or opaque shrink labels.

Biaxially oriented polypropylene (BOPP) films in various combinations are the backbone of snack-food and confection packaging. In a typical application, a thin-gauge OPP film is reverse-printed and then laminated to another OPP film. The second film may be metallized to improve gas barrier and usually will have a heat-sealable coating.

Some paperboard is extrusion-coated with PP to provide liquid holdout for microwavable food products. A PE would have too low of a softening point.

Most injection-molded, thin-walled containers such as those used for butter, margarine and yogurt are PP. PP ice cream tubs would risk cold fracture at freezer temperatures, so these are usually PE or a copolymer. Snap-on lids for PP tubs are usually PE to provide the elongation needed to produce the interference fit and still be easily removable.

POLYETHYLENE TEREPHTHALATE (PET)

Production and Properties

An “ester” is the reaction product of an organic acid and an organic base. Polyesters can be produced from any number of organic acids and bases, resulting in both thermoset and thermoplastic variations. Among the most widely used thermoplastic polyester materials are those formed by reacting ethylene glycol (base) and terephthalic acid to form PET. The polymerization process is a condensation reaction rather than an addition reaction as with PE or PP. The 249°C (480°F) melting point of homopolymer PET is one of the highest of the common packaging plastics.

PET is made in many copolymer variations, each designed to enhance some desirable property. Most PET copolymers are made by including an additional dibasic acid or glycol in the polymerization reaction. For example, including cyclohexanedimethanol produces a polyester (PCTA) that can be made into films with brilliant clarity, good toughness and high tear strength. A slight alteration of the copolymer proportions produces a highly crystallized form with a melting point of about 285°C (545°F). This crystallized form (CPET) is used for dual-ovenable tray applications.

Another PET copolymer is made with additional glycol components (PETG). This copolymer has very little tendency to crystallize, allowing injection molding of high-clarity parts. PETG's high melt strength allows it to be thermoformed or extrusion blow molded into clear bottles, unlike PET homopolymer that does not have enough melt strength to maintain an extruded parison.

All PET polymers are subject to hydrolytic breakdown if heated in the presence of water. This requires that the resins be dried to less than 0.003% moisture content before processing. The need for a drying step and PET's high melting temperature makes processing more involved than that for the PE and PP polymer families.

Careful control of processing temperatures is important to reduce thermal degradation that would release acetaldehyde, which, even in small amounts, can cause off-flavors in food and beverage products.

PET Applications

PET films are manufactured by cast extrusion and are usually biaxially oriented. PET films have high tensile strength, low elongation, a high melting point, excellent grease/oil barrier properties, low gas and moisture permeability, good printing characteristics, a high use-temperature range, high impact strength, high scuff resistance and excellent dimensional stability.

Limitations of PET film include lack of heat sealability, poor machine performance, a propensity for generating static and poor package openability. Most of these plain-film shortcomings are addressed by coating or laminating with other materials. Heat-seal performance can be provided with a coating such as PVDC, which also enhances the already-good barrier properties, or by combining with a heat-sealing agent such as PE. Primary end uses are as the base film for cheese and luncheon meat packages and for applications requiring high tensile strength, stiffness or high temperature resistance.

PET's heat resistance and microwave transparency make it an ideal dual-ovenable film. Added heat-sealable layers enable the film to seal to itself, to PS containers or to PET trays.

Metallized PET films offer barrier properties and abrasion resistance for coffee vacuum packs. Metallized PET also has been used for pouching electronic components where it provides static-charge dissipation in addition to strength.

Almost 70% of North American PET packaging usage is for bottles. The largest single application is injection-blow-molded carbonated-beverage bottles. Conventional PET has low melt strength (very fluid at its melt temperature) and would be difficult to extrusion blow mold because of the difficulty in holding a stable parison shape in the melt form. Injection blow molding circumvents this problem by injecting a parison and subsequently blowing it to a bottle shape. Barrier and strength properties are further improved by mechanically stretching and orienting the preform during blowing; referred to as injection stretch blow molding.

Price reductions in the early 2000s encouraged the growth of PET in markets beyond carbonated-beverage bottles. Vegetable oils, alcoholic beverages and many home and personal-care products now come in PET bottles. PET also has made significant inroads into thermoformed shapes.

About 7% of PET is made into film and sheet. PET's high use temperature favors it in applications such as dual-ovenable prepared food trays. Allowing the polyester to crystallize (CPET) improves PET's already good temperature resistance.

PET's high tensile strength is utilized for strapping applications where high strength and relatively low elongation are needed.

The development of a depolymerizing process (methanolysis) and PET's high value make it a favorite of recyclers. Methanolysis reverts the polymer back to the original monomers, which are then repolymerized. PET has replaced polyvinyl chloride (PVC) in many applications where clarity was a prime consideration.

POLYVINYL CHLORIDE (PVC)

Production, Processing and Properties

PVC is produced by the suspension, or emulsion, polymerization of vinyl chloride, a gas derived from an ethylene base. PVC differs from PE in having a chlorine atom replace one hydrogen atom. PVC alone is hard and brittle with low thermal stability (decomposition can start as low as 100°C or 212°F) and is essentially unusable unless compounded with additives. PVC has poor thermal processing stability, and its tendency to decompose can cause processing and recycling difficulties. Decomposition is retarded by the addition of thermal-stabilizing agents.

PVC is compounded with a range of additives, making it a versatile material with properties ranging from hard and rigid to the softest of cling films.

PVC resins are dry-blended with multiple additives to accomplish specified results. The mix may include any or all of the following: slip agents, plasticizers, pigments, waxes, fillers, processing aids, impact modifiers and liquid epoxy stabilizers. Plasticizers, which are among the most important additives, are not necessarily suitable for food-packaging applications. Plasticizers soften PVC; the more plasticizer added, the softer and more pliant it becomes. Some plasticizers can migrate or be absorbed and can plasticize other materials such as adhesives.

PVC Applications

About 4% of the 14,320 million lb. of PVC is used in packaging.

Most PVC films have high impact strength, good scuff resistance, good dimensional stability, good optics and excellent grease- and oil-barrier properties. PVC has a maximum use temperature in the 93°C (200°F) range. Its moisture-barrier properties range from poor to fair. Even with thermal stabilizers added to the dry blend, PVC remains heat sensitive and inherently more difficult to produce than PE or PP films.

Varying the formulation allows production of films with tensile strengths ranging from low to medium, elongation ranging from medium to high, gas-barrier properties from poor to medium, and tear strengths from medium to good. This marked range of properties is largely influenced by the type and amount of plasticizer used. For example, less-plasticized films are stiffer and possess better barrier properties than heavily plasticized types.

Highly plasticized PVC films have excellent stretch properties and unique "cling," making them ideal for hand-wrapping fresh meats and produce. Less-plasticized films are used for a variety of product-wrapping applications, including cassettes, toys and books. They also are used for medical-product packaging and considered

suitable for gamma-ray sterilization. Some plastics burn readily and some burn only with difficulty. PVC and other halogen-bearing (chlorine, fluorine, bromine) plastics tend to be self-extinguishing and burn with difficulty.

PVC films can be produced with superior shrink properties. Therefore, it is the preferred shrink material for many tamper-evident bands and shrink-label stock.

Clarity and thermoforming properties make PVC the material of choice for most thermoformed shells for blister packaging as well as some condiment portion packs.

Its good clarity, excellent stiffness and resistance to oils and alcohols make it a good material for blow-molded bottles where one or more of these properties is important. Many coatings, adhesives and closure seal materials are based on PVC polymers.

Some environmental groups have targeted PVC on environmental and health issues and successfully restricted its use in some jurisdictions. Their contentions have not been substantiated to date, but PVC has acquired a negative image in some segments of the population. In response, some manufacturers have been switching to materials such as PET.

More environmentally-friendly alternatives have begun to emerge. Coca-Cola's PlantBottle, for example, differs from traditional PET plastic bottles in that rather than relying on petroleum and other fossil fuels to make a key ingredient in the plastic, these bottles include materials that are as much as 30% plant-based. The plant-based material has been shown to perform well. This advancement falls under the umbrella of emerging bioplastics packaging (see the Bioplastics section later in this chapter).

POLYVINYLDENE CHLORIDE (PVDC)

Production and Properties

Vinylidene chloride is a vinyl monomer with one more chlorine than a vinyl chloride monomer. It polymerizes with itself or with monomers such as vinyl chloride or acrylates to form commercially useful resins. Various types of PVDC can be produced, depending on the ratio of comonomer to vinylidene chloride in the copolymer. PVDC films can be produced by extrusion casting or by the blown-tube process. The processing temperature must be below 205 C (400 F) to prevent decomposition. Its relatively high cost limits its use to films and coatings; it is not made into dimensional parts. PVDC often is referred to as "Saran," a Dow trade name.

The most notable attributes of PVDC polymers and copolymers are exceptionally low permeability to water vapor and gases. PVDC resins are used in food and pharmaceutical packaging to provide moisture, flavor and gas barriers. PVDC also has good grease, oil and chemical resistance.

PVDC can be used as monolayer and multilayer film or applied as a coating in the form of solutions and lattices. Films can be coextruded, and various processes are used to combine PVDC with PP, PET, nylon and other polymers into multilayer structures, with PVDC contributing barrier qualities and other substrates providing strength and stiffness. PVDC can be used as a combination barrier and heat-sealable coating in some applications.

Monolayer film is widely used as household wrap. Industrial monolayer films are used in laminating, in pharmaceutical unit-dose packaging and as liners for moisture-, gas- or solvent-sensitive products.

POLYVINYL ACETATE (PVAC) AND ETHYLENE-VINYL ACETATE (EVA)

Properties and Applications

PVAC is a highly polar, resilient thermoplastic that can be easily dispersed into water to make an emulsion. PVAC polymers and copolymers have significant uses in the manufacture of a broad range of emulsion adhesives. The familiar white glue used at home and in industry almost always contains PVAC.

EVA is a PVAC copolymer of PE. The vinyl acetate (VA) content can be varied from 5% to 50% depending on the desired properties. Packaging films usually are made with lower VA levels. As VA content increases, the film becomes more elastomeric.

Many EVA film applications are similar to those of the LDPE family. EVA film has high clarity and particularly good flex crack resistance, puncture resistance and cold temperature performance. Stretch-wrap films, ice bags, bag-in-box containers and heat-sealable films or coatings are major applications. In some instances, EVA is blended with PE to improve toughness, heat-seal or cling properties.

Higher VA content EVAs are used in adhesive production; the greatest proportion being for hot-melt formulations.

POLYAMIDE (PA OR NYLON)

Production

PA or nylon (formerly a DuPont trade name) is formed by condensing a diamine and a dibasic acid or by the polymerization of certain amino acids. PAs are identified by a number representing the number of carbon atoms in the basic amino acid (such as nylon 6) or by the number of carbon atoms in the reacting amine and dibasic acid, respectively (such as nylon 66). Of the possible PAs, only types 6 and 66 are commonly used for packaging purposes.

Nylon 6 and nylon 66 have similar physical and chemical properties. The most significant difference is maximum use temperature: nylon 6 is good to 219°C (426°F) while nylon 66 is good to 266°C (510°F). Both have excellent optical properties and resist grease, oil and many chemicals. Nylons are tough, resisting abrasion, impacts, puncturing and cracking when repeatedly flexed. PA is not resistant to strong inorganic acids and is not heat-sealable by conventional means. It has poor slip properties. PA has been one of the more expensive packaging films.

PAs provide good barriers to aromatics, oxygen, nitrogen and carbon dioxide, but have poor water-vapor barrier properties. Water-barrier properties often are improved by application of a PVDC coating.

A semi-crystalline PA, trade named MXD6 (Mitsubishi), is made by condensing m-xylene and adipic acid. The presence of the aromatic ring structure gives this nylon higher heat resistance, stiffness, tensile strength and lower moisture sensitivity than the more common nylon 6. It also offers higher oxygen barrier properties than nylon 6 or nylon 66. The polymer melts at about 240°C and is processed at 260–300°C. Cost limits MXD6 applications.

**Figure 12.3**

Examples of products in a drawn nylon film. The flat side of these packages is lower-cost polyethylene terephthalate.

PA Applications

Most PAs used in packaging is in film form, usually produced by extrusion casting. Nylon can be monoaxially or biaxially oriented, enhancing strength and barrier properties. Although PA can be blow molded and injection molded, there are few packaging applications for these forms.

Unoriented nylon 6 film is widely used in meat and cheese vacuum packaging, where its good oxygen barrier properties, grease resistance and ability to be easily drawn into a thermoformed shape are advantages. (See Figure 12.3) Neither oriented nylon, nor OPP, can be thermoformed.

Oriented nylons usually are employed in packaging as a component in a laminated structure, typically with PE. Nylon is used in laminated structures for many retail and institutional cook-in-bag foods and as an abrasion-resistant base material for coffee vacuum-brick packages. Other uses include packaging for surgical instruments. Nylon's exceptional abrasion resistance and toughness make it a material of choice for bulk bagging of frozen primal meat cuts and other applications requiring resistance to abrasion and cut-through.

MXD6's excellent combination of physical properties and excellent oxygen barrier properties has found application as the oxygen-barrier layer in some PET beer bottles. A typical construction is PET/MXD6/PET/MXD6/PET. Although ethylene-vinyl alcohol (EVOH) has better oxygen barrier qualities, these are lost under conditions of high humidity. MXD6 has better oxygen barrier properties than EVOH when the humidity is higher than 80%. MXD6 also is blended with nylon 6 and nylon 66 to improve their properties.

POLYVINYL ALCOHOL (PVAL) AND ETHYLENE-VINYL ALCOHOL (EVOH)

Production and Applications

PVAL is water-soluble, and packaging applications include water-soluble pouches. These pouches hold a premeasured amount of product; pouch and product are thrown into the blending tanks where the PVAL dissolves, releasing the product. Some dry agricultural chemicals are offered in PVAL inner bags. The approach averts a serious environmental disposal problem since the contaminated PVAL liner bag dis-

solves with the active ingredients. PVAL offers superior oxygen-barrier properties, but its water solubility and processing difficulty limit applications in this area.

PVAL has been surface applied to substrates such as PP to improve oxygen- and flavor-barrier qualities. Because of PVAL's solubility, this material combination is strictly limited to dry-product applications.

EVOH is made by hydrolyzing the copolymer of ethylene and vinyl acetate. EVOH has the highest useable oxygen barrier of the packaging polymers. Though not completely soluble like PVAL, EVOH is adversely affected by water. So, in most packaging applications, other films must be used to protect it from water contact. This has led to coextrusions of five and six layers, typically using PE or PP as the outside layers and bonding these to the EVOH core with suitable adhesives. It is also coextruded into multilayer barrier bottles.

ETHYLENE ACID COPOLYMERS AND IONOMERS

Variations and Applications

Ethylene acid copolymers and ethylene-ethyl acrylate copolymers can be regarded as PE copolymers. Ethylene can be copolymerized with varying amounts of acrylic acid, methacrylic acid or ethyl acrylate. These copolymer groups reduce crystallinity, lower heat-seal temperature and add functionality that allows for good adhesion to polar substrates. By varying the amount of comonomer content and adjusting molecular weights, a range of products can be tailored to produce useful film, coating and adhesive base materials.

Ionomers (commonly known by the DuPont trade name "Surlyn") are copolymers of ethylene and methacrylic acid that have been further modified by the inclusion of sodium or zinc ions. Ionomers can be made into tough, clear films that have properties particularly suitable for skin-packaging applications. Ionomers form excellent heat-seal bonds and can form a seal through fat contaminants. They have excellent adhesion to aluminum foils and are used in many laminated constructions where superior bonding to the foil is essential.

OTHER PACKAGING POLYMERS

Cellulosics

At one time, cellulosics were the only clear packaging film choice. Cellophane (a former DuPont trade name) is unusual in that it is based on wood cellulose rather than petrochemicals and that it is a thermoset rather than a thermoplastic. Cellophane has superior dead-fold properties and machinability. Its tendency to generate static is lower than other packaging films. However, cellulose films have a cost and performance disadvantage compared to more modern materials. Thus, the cellulose film market is small compared to other films. However, growing interest in sustainable materials has renewed interest in cellulosic materials.

A small amount of cellulose propionate and cellulose butyrate is extruded into high-clarity tubular shapes, which, unlike other packaging plastics, can have an end

cap easily attached by solvent bonding. The clear tubular containers are used to package a range of products such as drill bits, laboratory thermometers, novelty foods, confections and gift items.

Epoxies

Epoxies are thermoset polymers based primarily on epichlorohydrin and bisphenol-A (BPA). They form particularly strong bonds with many materials and are found in adhesives and protective coatings. BPA has been implicated in human health issues. (See section, Polycarbonates, below)

Polycarbonates (PC)

PC is made from carbonic acid and BPA. It is a particularly tough plastic and has the highest impact resistance of packaging plastics as well as an unusually high use temperature. Its clarity equals that of glass, and a major application is as a replacement for glass glazing in high-risk areas.

Packaging applications that require toughness and environmental stability have used PC. Applications include returnable milk jugs and large, returnable water bottles. The material is relatively high in cost.

Recent research has identified BPA as a suspected contributor to several human health issues, including endocrine disruption, carcinogenic effects and obesity. In packaging, the two significant applications are large refillable water bottles and the coating material for the inside liners of many food cans. In 2007 and 2008, many retailers removed PC baby bottles and refillable water bottles from their shelves. In 2010, Canada declared BPA a toxic substance. In 2012, the U.S. Food and Drug Administration said manufacturers could no longer include BPA in baby bottles and children's drinking cups.

Acrylonitrile Copolymer

An acrylonitrile-methyl acrylate copolymer from BP Chemicals, trade named "Barex," is the only resin in this family marketed for packaging purposes. Barex has good oxygen- and gas-barrier properties but relatively poor water-vapor barrier properties. It offers excellent resistance to many aggressive solvents not readily contained by other polymers. It is made into film and dimensional shapes.

Polyurethanes (PUR)

PURs, formed by a reaction between an isocyanate and a polyol, are used in several specialty applications. Thermoset types, frequently cured by the presence of moisture, are used as adhesive and coating base resins. PUR can be blown in foams of varying densities, and these find use as protective packaging forms. A particular application creates "foam-in-place" systems, where the two reacting chemicals are mixed just before being sprayed around the object to be protected. The mixed components foam up within seconds to encapsulate the item.

Polyethylene Naphthalate (PEN)

PEN is a more recently commercialized resin that can be used as a blend with PET or as a PET/PEN copolymer. The monomer is dimethyl 2,6 naphthalate or naphthalene dicarboxylate (NDC). The cited advantages of PEN resins are:

- Thermal properties allow it to be used for hot-fill and retort applications.
- PEN completely blocks UV light. Even a 2% PEN/PET copolymer will block 90% of UV light. This makes it a good candidate for beer, juices, pharmaceuticals, edible oils and milk.
- Copolymers and blends show marked improvement in oxygen and water-vapor barrier and better thermal and mechanical properties. Generally, property improvement is proportional to the amount of PEN.
- It offers a high potential for replacing glass in some critical applications.

PEN's price, about two to four times that of PET, limits its use as a packaging material.

Styrene-Butadiene Copolymer (SBC)

“K-Resin” is the trade name for a high-clarity, tough and easily processed styrene-butadiene copolymer (SBC), developed by Chevron Phillips Chemical Company and now owned by INEOS Styrolution. Limitations are low surface hardness, low stiffness, low resistance to organic solvents and poor performance when exposed to UV light. K-Resin SBCs have relatively high gas permeation rates. Food-wrap films where barrier is not desired make use of its high clarity and softness. Some thermoforms, skin-packaging, shrink wraps and blow-molded bottles use K-Resin SBC.

Polychlorotrifluoroethylene (PCTFE)

A PCTFE copolymer, marketed under the trade name “Aclar,” has the highest moisture-barrier properties of any packaging polymer and is a good barrier to other gases. It has excellent optical properties and is readily thermoformed. These properties in one material have made it the choice for many thermoformed blister packs for sensitive unit-dose pharmaceutical tablets. High cost prohibits most other packaging applications.

PCTFE will tolerate cryogenic temperatures and ionizing radiation.

Bioplastics

The arrival of bio-feedstocks as well as bio-based polymers, in times of rising oil prices and increased consumer awareness about protecting the environment, has brought about the commercialization of bioplastics and prospects for strong growth. Bioplastics are developed from renewable resources, thus far including materials

such as cellulose, starches and other biopolymers. Some resins that fall within the bioplastics spectrum may not be biodegradable but are recyclable.

Polylactide acid, also referred to as polylactic acid (PLA), early on has been the most used resin in the bioplastics market. It is a polymeric material derived from cornstarch rather than petrochemical feedstocks.

PLA is a stiff, clear polymer that, when thermoformed into a tray, easily could be mistaken for PS. It thermoforms easily at comparatively low temperatures, but at the same time, its low heat distortion temperature (about 40 C) limits its use for other applications. PLA has limited barrier properties. The material is biodegradable in industrial composting facilities, typically operating at 56 C. Market applications continue to grow along with production capacity. PLA and other bioplastics processes and products are detailed in Figure 12.4.

Another bioplastic, bio-based PE, is also attracting interest. In Brazil, Braskem has introduced feedstock sourced from sugarcane-based ethanol/ethylene. Also in Brazil, a partnership between Dow Chemical and Mitsui aims to launch a venture for renewable PE. Price presents a barrier for potential early adopters of bioplastics; for example, ICIS.com says bio-based PE is available at a price premium of 15% to 20% over petrochemical-based plastics.

Going forward, the use of bioplastics will grow as more bio-based PE producers enter the market and further technical innovations emerge that provide for improved material properties and lower prices.

Thermoset Plastics

Thermoset plastics such as phenol-formaldehyde and urea-formaldehyde are used occasionally for applications such as specialty closures. Superior solvent resistance makes thermosets ideal for aggressive solvent-contact materials. They have a particularly hard surface and are not prone to developing sink marks when molded.

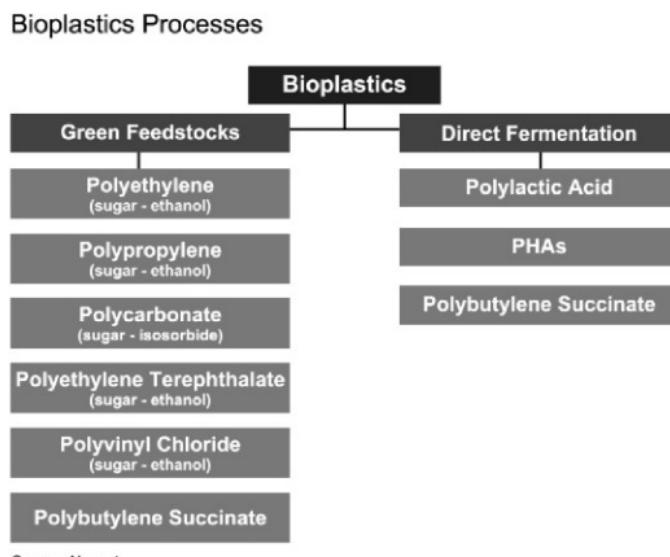


Figure 12.4
Listing of bioplastics processes and some of the most familiar products.

These are useful features when molding massive or heavy-walled cosmetic closures. When metallized, they have the feel of metal.

Thermoset polyesters and epoxies are used in conjunction with fiberglass or other fibers to produce large, highly durable shipping containers as would be used by the military.

Other Plastics

Other plastics have been used to make containers to meet some unusual performance criteria. For example, acrylonitrile-butadiene-styrene (ABS) is a tough, high-impact-resistant material. It finds some packaging use for large industrial and military shipping and storage cases. (Plastic briefcases and luggage are made from ABS.)

Some plastics used for special applications would fall into the engineering or exotic plastic classification. These would include polyacetals, polysulfones, polymethyl pentane, liquid crystal polymers and others.

ADDITIVES

Most polymers are blended with additives before or during processing into their finished forms. Depending on the resin and application, some or many ingredients may be added. Although the purpose of these additives is to control or enhance specific performance characteristics, they affect other properties in some manner. Thus, an antistatic agent, while reducing static accumulation, might detrimentally affect adhesive bonding.

- Antioxidants protect the resin from deteriorating during thermal processing.
- Heat stabilizers inhibit degradation during thermal processing.
- Plasticizers impart flexibility or softness and assist in processing. PVC formulations use plasticizers heavily.
- Antiblock and slip agents, such as amides and finely divided silica, are used primarily in LDPE film. Antiblock agents prevent film layers in a roll from “blocking” or sticking together. Slip agents reduce frictional properties, allowing the film to slide smoothly over itself. This improves high-speed packaging and handling processes.
- UV stabilizers are used with UV-sensitive plastics, such as PP, when it will have direct exposure to UV light. (PP exposed to UV light cross-links and becomes brittle.)
- Pigments, usually master batch color concentrates, are blended in at the forming machine. Different pigment types and concentrations will affect the polymer's base properties differently. Thus, the same bottle design in different colors may not necessarily have identical performance characteristics. Some of the most brilliant and stable pigments are complexes of toxic heavy metals, and their presence poses serious environmental and health concerns. Their continued use is being restricted, and in some instances, banned.

- Mineral fillers improve mechanical properties and reduce cold-flow characteristics.
- Cross-linking agents improve physical and chemical attributes.
- Antistatic agents enable plastic materials to dissipate static electrical charges. High static charges can attract atmospheric dust or interfere with processing. The discharge of even small levels of static electricity can damage microcircuits.
- Lubricants improve flow and processing properties.
- Nucleating agents encourage the formation of crystallinity. The formation of minute crystalline regions (rather than large crystals that will diffract light) is used as a means of improving the clarity of PP.
- Blowing agents are used to create expanded plastic foams. PS and PE account for most expanded foams used in packaging. Blowing agents are liquids with low boiling points such as pentane, isopentane and other hydrocarbons. (PUR foams are expanded by gases produced by the chemical reaction of diisocyanate and a glycol).

CHARACTERIZING PLASTIC MATERIALS

Test procedures help characterize materials but may vary. Different measurement units may be used from supplier to supplier. When discussing or comparing material test results or properties, the following three factors must be identical:

- Test method.
- Test conditions.
- Unit of measurement.

If data sets differ in any of these criteria, comparisons will be invalid.

ASTM International (ASTM) establishes most packaging test procedures used in North America. Other technical associations may sponsor special test procedures related to their area of interest. The majority of procedures recommended by these agencies specify the precise methodology for characterizing a property but do not normally give pass/fail or minimum performance criteria.

The selection of a polymer, as either a standalone material or a component in a laminated or composite structure, is based upon a wide range of end-use, machine efficiency and cost criteria. These criteria define the properties a material must have and often the maximum and minimum performance range for each property.

Plastic properties can be classified into four general groups: physical, optical, chemical and permanence. Physical or mechanical properties relate to a polymer's various strength characteristics and its machinability. Opticals have to do with the plastic's appearance and surface and are particularly important with films. Chemical properties are the material's resistance to grease, oils, soaps, acids, solvents and other chemical agents. This classification includes gas and water-vapor permeability. Properties of permanence relate to the film's ability to retain its strength and dimensions in varying environmental conditions, such as temperature and relative humidity.

Tensile Properties

Tensile strength is a material's ability to resist a direct pull. Ultimate tensile strength defines the maximum stress a material can withstand before breaking. Stress, as defined in the *Illustrated Glossary of Packaging Terminology*, published by the Institute of Packaging Professionals, is defined as the force producing or tending to produce deformation in a (package) body, divided by the area over which the force is acting. If the stress is tensile or compressive, the area is perpendicular to the stress; if shear, it is parallel to the stress. The SI unit of stress is the pascal (Pa) equal to 1 newton per square meter (N/m²).

When measured up to the point of permanent material deformation, it is reported as "yield strength" or "yield point." The force exerted at the yield, or "break point," is divided by the cross-sectional film area, and the tensile strength at the yield or break is expressed in force per unit area (pounds per square inch, PSI).

For example, if the sample's cross-section area is one-thousandth of a square in., and 30 lb. of force is recorded at the break point, tensile strength is expressed as 30,000 PSI. High tensile strength generally is desirable in a packaging film. This property would be a key consideration for a suspended retail bag for a relatively heavy hardware or automotive product. The force or pull applied to a plastic during machining should not exceed its yield point.

A material's "elongation" is the difference between the length of an unstretched tensile-strength sample and its length at the break point or the yield point. The property is expressed as a percentage of the original length. Elongation usually is observed during a tensile strength test. Low elongation is desirable in applications where the material will bear steady weight. High elongation is a positive property for applications such as stretch wraps or heavy-duty bags. However, it is difficult to hold printing register with a high elongation material. Some typical tensile property values are given in Table 12.6.

The following are standard ASTM test methods for tensile properties:

ASTM D638, Tensile Properties of Plastics.

ASTM D882, Tensile Properties of Thin Plastic Sheeting.

ASTM D2923, Rigidity of Polyolefin Film and Sheeting.

Tear Strength

Film "tear strength" is measured using an Elmendorf tear tester in much the same way as for paper. One end of a sample is held in a fixed clamp; the other end is attached to a pendulum. A small cut is made in the film edge, the pendulum is released, and the force required to continue the tear is recorded. Another, less common test, measures the force required to start a tear on an uncut film edge. This is known as "tear initiation," as opposed to "tear propagation."

Tear strength usually is expressed as grams per mil (0.001 in.) of thickness. Films such as PP are difficult to tear at a clean, unnickled edge, yet reveal relatively low tear strength in Elmendorf tests when a small cut is introduced at the film edge to initiate the tear. Tear strength must be considered in terms of protective values, as well as in terms of the strength required to open the package if it must be torn open.

Table 12.6
General comparison of tensile and elongation properties of common packaging plastics.

	Tensile (psi)	Elongation
<i>Best Tensile Property Materials</i>		
Poly(ethylene terephthalate) (PET)	32,000	50%
Oriented polypropylene (OPP)	30,000	80%
Acrylonitrile copolymer (Barex)	9,500	3%
<i>Good Tensile Property Materials</i>		
Polyamide (nylon)	7,000	400%
Unoriented polypropylene	6,000	600%
High-density polyethylene (HDPE)	5,000	400%
<i>Low Tensile Property Materials</i>		
Low-density polyethylene (LDPE)	3,500	600%
Linear low-density polyethylene (LLDPE)	3,500	700%
Plasticized polyvinyl chloride (PVC)	2,000	500%

Plastics such as the PE and PE copolymer families that have high elongation have better tear-resistant properties and little or no notch sensitivity.

The following test methods measure tear properties:

ASTM D1004, Initial Tear Resistance of Plastic Film and Sheeting.

ASTM D1922, Propagation Tear Resistance of Plastic Film and Thin Sheeting by Pendulum Method.

ASTM D1938, Tear-propagation Resistance of Plastic Film and Thin Sheeting by a Single-Tear Method.

ASTM D2582, Puncture-propagation Tear Resistance of Plastic Film and Sheeting.

Impact Strength

“Impact strength” describes a material’s ability to withstand direct shock. Tests measure the impact strength of both films and solid plastics. To test a film for impact, a sample is stretched taut horizontally and a “dart” or weight is dropped on it. Values can be expressed as the drop height from which a given mass will puncture the film 50% of the time or as the mass required to puncture the film 50% of the time from a given drop height.

To test solid plastics for impact, a solid bar of plastic is hit with a pendulum-mounted hammer. The force absorbed in fracturing the specimen reduces the pendulum's free swing and is used to calculate energy absorption. The following test methods measure impact properties:

- ASTM D1709, Impact Resistance of Plastic Film by the Free-falling Dart Method.
- ASTM D3420, Pendulum Impact Resistance of Plastic Film.
- ASTM D4273, Total Energy Impact of Plastic Films by Dart Impact.

Heat-Seal Strength

"Heat-seal strength" relates to a film's ability to make a peel-resistant seal. The property is tested by sealing samples under controlled temperature, pressure and dwell-time conditions and then measuring the seal's resistance to peeling on a tensile tester. (The process is similar to determining tensile properties.) Heat-seal strength usually is expressed as grams per unit width of the stressed seal. The heat-seal strength of a properly made seal of most thermoplastic packaging films will approach the basic tensile strength of the film.

"Hot tack" is the ability of a heat seal to withstand stress while the seal is still hot. The higher a heat-seal material's hot-tack strength, the sooner the product can be placed into the package.

A wide heat-seal temperature range is a desirable property. The range gives the difference between the minimum acceptable seal strength and the burning or melting point of the polymer. The practical sealing range will be determined by factors such as machine speed, seal surface, product weight and product density. Lower seal temperatures use less energy and allow the package to be handled quicker; the lower temperatures will have less potential effect on the contained product. Although most plastics will heat-seal given a high enough temperature, in practice, lower-temperature coatings are preferred. PET and OPP do not form practical heat seals. The following test methods measure heat-seal properties:

- ASTM F88, Seal Strength of Flexible Barrier Materials.
- ASTM F1921, Hot Seal Strength of Thermoplastic Polymers and Blends.

Coefficient of Friction (COF)

"Slip" describes the degree of drag, or friction, film experiences when passing over itself or surfaces such as machine parts. Friction characteristics are an important consideration for laminating, printing and package-forming machine operations, as well as for some end-use and retailing situations. "Hot slip" relates to a film's performance when running over heated machine parts at elevated temperatures. A high degree of slip is desirable for optimum film-running performance on most wrapping and bag-making machines but can cause problems when products are stacked on a retail shelf.

“Static slip,” or “static coefficient of friction (COF),” defines the force required to start the film moving (slipping) over another surface. “Kinetic,” or “dynamic,” COF defines the film’s friction as it is moving over other surfaces. The following test measures COF:

ASTM D1894, Static and Kinetic Coefficients of Friction of Plastic Film and Sheeting.

Haze and Gloss

Haze and gloss are optical properties that are important primarily from a merchandising aspect. Haze describes optical clarity and is measured on a device that meters the amount of light scattered by a film surface, compared to the amount of light transmitted. Readability of locked-in print, clarity of design colors and product visibility are some considerations.

Gloss, the brilliance of a film’s surface, is measured by beaming light onto a sample at a known angle and metering the amount of light reflected to a photosensitive receptor. The following test methods measure haze and gloss:

ASTM D1003, Haze and Luminous Transmittance of Transparent Plastic Films.

ASTM D1746, Transparency of Plastic Sheeting.

ASTM D2457, Specular Gloss of Plastic Films and Solid Plastics.

Water-Vapor Transmission

Several methods measure a material’s resistance to the permeation of water vapor. In simplest terms, all test methods place dry air on one side of a film and humid air on the other. The moisture passing through the film in a given time is measured and reported as water-vapor transmission rate (WVTR) in grams per square meter per 24 hours ($\text{g}/\text{m}^2/24 \text{ hr.}$), or as grams per 100 square inches per 24 hours ($\text{g}/100 \text{ sq. in.}/24 \text{ hr.}$).

When comparing films using data in published literature, care must be taken to identify the test method and units of measurement employed. Table 12.7 shows the WVTR for some common plastic films.

The water-vapor permeability of plastic film relates to the ability to retain freshness in a product, preventing the escape of moisture from moist products (e.g., fruit cake) or preventing dry products (e.g., crackers) from picking up moisture from outside. The following test methods measure WVTR:

ASTM E96, Water Vapor Transmission of Materials.

ASTM F372, Water Vapor Transmission Rate of Flexible Barrier Materials Using an Infrared Detection Technique.

ASTM F1249, Water Vapor Transmission Rate Through Plastic Film and Sheeting Using a Modulated Sensor.

Table 12.7**Typical plastic film water-vapor permeabilities.****Data are in g/100 sq. in./24 hr at 90% R.H. Polyvinyl alcohol is water-soluble, and ethylene-vinyl alcohol absorbs water. These polymers would require protection from water in wet or humid environments.**

	Permeability	Comments
<i>Best Water-Vapor Barrier Materials</i>		
Polychlorotrifluoroethylene (PCTFE or Aclar)	0.04	Cost limits use
Polyvinylidene chloride (PVDC or Saran)	0.05	Best universal barrier
High-density polyethylene (HDPE)	0.3	Most economical barrier
Polypropylene (PP)	0.4	
<i>Good Water-Vapor Barrier Materials</i>		
Low-density polyethylene (LDPE)	1.2	
Polyethylene terephthalate (PET)	1.3	
<i>Low Water-Vapor Barrier Materials</i>		
Polyvinyl chloride (PVC)	4	
Acrylonitrile copolymer (Barex)	5	
Polyamide (nylon)	25	

Gas Permeability

Gas transmission or permeability properties relate to gases such as oxygen, nitrogen, carbon dioxide and various volatile essential oils found in foods, confections, personal care and other products. Permeability is associated with the retention of color, flavor and odor in packaged food products. Barrier requirements range from low to high, depending on the product.

Produce wraps require high oxygen permeability to permit respiration. In contrast, coffee needs a film with low oxygen and aroma permeability to preserve flavor. Similarly, specific gas-barrier properties are required for controlled-atmosphere packaging applications. Table 12.8 shows typical oxygen-barrier qualities.

In a typical gas-permeability measurement, a film sample is clamped between two chambers, one of which is filled with an inert gas. The test gas is introduced into the other chamber and remains there for a given time at a known temperature and 1-atmosphere pressure. Permeability is expressed as milliliters of gas permeating 1 square meter of film in 24 hr for a specified thickness. It may be expressed as cubic centimeters of gas permeating 100 square in. of 0.001-in.-thick film in 24 hr (cc/0.001 in./100 sq. in./24 hr). Table 12.8 shows oxygen transmission rates for some common plastic films. The following tests measure gas transmission rates:

ASTM D2684, Permeability of Thermoplastic Containers to Packaging Reagents or Proprietary Products.

ASTM D3985, Oxygen Gas Transmission Rate Through Plastic Film Using a Coulometric Sensor.

ASTM F1307, Oxygen Gas Transmission Rate Through Dry Packages Using a Coulometric Sensor.

Grease and Oil Barrier

Grease and oil barrier properties describe a film's ability to resist penetration by greases and oils, with or without degradation of the film. Such migration can cause structure delamination, smearing or lifting of non-grease-resistant printing inks and package staining.

A common test involves placing a film sample on a paper sheet and weighing the sample with a uniform layer of dry sand. A measured amount of oil or grease is placed at several locations, and migration is measured by the time it takes for a stain to appear (or not appear) on the paper sheet below. The following test method measures grease and oil barrier:

ASTM F119, Rate of Grease Penetration of Flexible Barrier Materials.

Table 12.8
Typical film oxygen-barrier qualities.
Data are given in cc/0.001 in./100 sq. in./24 hr.

	Permeability	Comments
<i>Best Oxygen-Barrier Materials</i>		
Ethylene-vinyl alcohol (EVAL)	0.02	Water sensitive
Polyvinylidene chloride (PVDC or Saran)	0.05	Best universal barrier
Acrylonitrile copolymer (Barex)	1.0	Poor water-vapor barrier
<i>Good Oxygen-Barrier Materials</i>		
Polyamide (PA or nylon)	3	Poor water-vapor barrier
Polychlorotrifluoroethylene (PCTFE or Aclar)	4	Cost limits use
Polyethylene terephthalate (PET)	5	Good universal barrier
<i>Low Oxygen-Barrier Materials</i>		
High-density polyethylene (HDPE)	110	
Polypropylene (PP)	150	Frequently metallized
Low-density polyethylene (LDPE)	450	

Dimensional Stability

Plastics vary in their reaction to the environment, notably to changes in temperature and/or relative humidity. "Dimensional stability" is the capacity to retain original size/shape when exposed to environmental changes.

Materials that shrink even slightly with the application of heat during processing, hot filling or heat sealing will produce distorted packages of unreliable volume and with puckered heat-seal areas. The following tests measure dimensional stability:

ASTM D1204, Linear Dimension Changes of Nonrigid Thermoplastic Sheeting or Film at Elevated Temperatures (quantifies dimensional changes caused by heat).

ASTM D648, Deflection Temperature of Plastics Under Flexural Load (identifies how the material might perform at elevated temperature by measuring the temperature at which a specified cross-section bar deflects 0.25 millimeter (0.010 in.) under specified loading and temperature conditions).

Maximum and Minimum Use Temperature

Maximum use temperature is a vital consideration where end-use involves exposure to elevated temperatures such as boil-in-bag packaging, retortable forms, ovenable applications, heat-sterilized medical-product packaging and hot-fill packaging. (See Table 12.9)

Table 12.9

Typical maximum use temperatures. It is assumed that the materials are heat-stabilized.

Material	Maximum Use Temperature (Celsius/Fahrenheit)
Polyethylene terephthalate (PET)	204/400
Polyamide (PA or nylon)	177/350
Unoriented polypropylene (PP)	116/240
High-density polyethylene (HDPE)	100/212
Polyvinyl chloride (PVC)	93/200
Linear low-density polyethylene (LLDPE)	77/170
Low-density polyethylene (LDPE)	66/150

Materials vary in their ability to withstand shock-loading or vibration at low temperatures. Films such as PE and PET, which can withstand these stresses below -18°C (0°F), are said to have good low-temperature durability. By comparison, un-oriented PP and PVDC films are very brittle under these conditions.

Most plastics, except unoriented PP and PVDC, can be used at typical freezer conditions and lower. The low-temperature performance of PVC varies depending on the plasticizer used. If a package is to go from freezer to microwave, the film must possess a wide use-temperature range.

Environmental Stress-Crack Resistance (ESCR)

Molded plastic parts, particularly those made of HDPE, in addition to exhibiting creep properties when under load, also are susceptible to a phenomenon known as “environmental stress cracking” (ESC). This results in cracking of the plastic and possible loss of contents. It’s widely estimated that ESC causes 35% of failures in new applications.

ESC is a surface-initiated physical phenomenon resulting from the operation of tensile stresses (loads). It occurs when the product has solubility parameters similar to the polymer. So, for HDPE, high polar solvents have no effect on this non-polar polymer. However, if the product formula contains a reactive chemical, the liquid can migrate into microscopic surface imperfections and cause a loss of container integrity. Individual compounds should be evaluated to determine impact on ESC. It should be noted that high temperatures and stresses can exacerbate ESC.

Semi-crystalline polymers offer greater environmental stress crack resistance (ESCR) than amorphous polymers. In fact, some amorphous polymers will stress-crack in air. Other polymer characteristics that influence ESCR include molecular weight, molecular weight distribution and the type, length and complexity of chain branching.

A typical ESCR test method partly fills the container with a 10% solution of nonylphenoxy poly(ethyleneoxy)ethanol (Igepal 630), a known stress-crack agent. The containers are stored at elevated temperatures and specified load conditions. Periodic inspections determine the approximate exposure time at which cracking begins. The following tests determine ESCR:

ASTM D1975, Environmental Stress-crack Resistance of Plastic Injection Molded Open Head Pails.

ASTM D1693, Environmental Stress-cracking of Ethylene Plastics.

ASTM D2561, Environmental Stress-crack Resistance of Blow-molded Polyethylene Containers.

ASTM D5419, Environmental Stress-crack Resistance of Threaded Plastic Closures.

Polymer Stability

An important polymer characteristic is its stability when in contact with other chemicals. In a typical test, the plastic material is placed in direct contact with the chemical (or product) in question for a given time. Frequently, the test will be “ac-

**NOTE**

Information in Tables 12.6 through 12.11 is compiled from several sources and intended to serve only as an indicator of a particular property's general magnitude. There are a great many polymeric materials, many of them modified by copolymerization, additives and processing. The data given here should be used for general information only. Always obtain current application data from suppliers.

celerated" by conducting the exposure at somewhat elevated temperatures. If no significant chemical activity takes place between the product and the chosen polymer, it's deemed stable. Stability should not be confused with permeability or stress-crack resistance, both of which are governed by different chemical and physical rules.

Stability may be observed visually, but for greater accuracy, a quantified measurement should be taken. For example, the tensile and elongation strengths of a material can be measured before and after exposure.

Stability varies widely with the nature of the chemical. For the most part, plastics are not stable with aggressive solvents, such as benzene, xylene and other aromatic compounds, nor with carbon tetrachloride and most other chlorinated solvents. These solvents are packaged in metal or glass containers.

Of the packaging polymers, PE and PP accommodate the widest range of chemicals, while PS is the most sensitive to chemical action. Six common packaging polymers (PE, PP, PVC, PET, PA and PS) provide stable packaging for most food products. However, some flavoring ingredients, such as oil of wintergreen, may be aggressive and need verification.

Common packaging polymers work with most cosmetic and toiletry preparations, which are based on water emulsions, petroleum jellies, waxes, low alcohols and other chemicals having low chemical activity. But products with more aggressive solvents and components (such as colognes, nail polish and nail polish remover) are not likely to be contained by PS or PET. Other possibilities would need to be tested carefully.

Table 12.10 and Table 12.11 have been compiled from information provided by The Society of the Plastics Industry, now known as the Plastics Industry Association. If stability offered by the polymer is sufficient, the container should show no visible change or loss of product under normal storage conditions. The tables do not address barrier qualities or ESCR.

The following test evaluates chemical resistance:

ASTM D543, Evaluating the Resistance of Plastics to Chemical Reagents.

Table 12.10
Polymer stability with industrial chemicals.

Chemical	LDPE	HDPE	PP	PVC	PET	PS
Acetic acid, glacial	2	1	1	X	X	X
Acetone	2	1	1	X	X	X
Alcohol, ethyl	2	1	1	1	1	2
Alcohol, methyl and N-propyl	1	1	1	1	1	2
Aliphatic hydrocarbons	X	2	2	1	1	X
Ammonia 28%	2	1	1	2	?	2
Battery electrolyte	1	1	1	2	2	2
Chloroform	X	2	X	X	?	X
Chromic acid	2	1	1	1	?	X
Creosote	X	X	1	X	?	X
Ethers, simple	X	X	X	2	?	X
Ethyl acetate and simple esters	2	2	2	X	X	X
Formaldehyde 36%	1	1	1	1	?	X
Formic acid	1	1	1	1	?	2
Hydrochloric acid 36%	1	1	1	1	2	2
Hydrofluoric acid < 52%	1	1	1	1	?	X
Hydrogen peroxide to 30%	1	1	1	1	1	2
Kerosene, naphtha	X	2	?	2	2	X
Methyl ethyl ketone (MEK)	2	2	2	X	X	X
MEK peroxide	?	1	?	X	?	X
Mineral spirits, petroleum distillates	X	2	?	2	2	X
Nitric acid	2	2	2	1	?	X
Oil of wintergreen	2	2	?	X	?	X
Oxalic acid	1	1	1	1	?	1
Phenol	?	?	1	?	X	X
Phosphoric acid	1	1	1	1	?	2
Potassium hydroxide	1	1	1	1	?	2
Sodium hydroxide 50%	1	1	1	1	2	2
Sodium hypochlorite to 15% CL	1	1	2	1	2	2
Sulfuric acid to 93%	2	2	1	2	X	X
Trichloroethane	X	X	1	X	?	X
Turpentine	X	X	2	1	1	X

1 satisfactory performance

2 probably satisfactory but should be verified for specific applications

X not compatible

? information not available

Table 12.11
Polymer stability with household chemicals.

Household Product	LDPE	HDPE	PP	PVC	PET	PS
Ammonia	2	1	1	1	?	2
Antifreeze, ethylene glycol	1	1	1	1	2	1
Camphor oil	X	X	X	2	?	2
Charcoal starter fluid	X	2	2	2	2	X
Chlorine bleach	1	1	1	1	?	2
Detergents	2	1	1	2	2	2
Drain cleaner, dry	2	1	1	1	?	2
Drain cleaner, liquid	2	2	1	2	?	X
Fabric softener	1	1	1	1	2	2
Floor polish, naphtha base	X	2	2	1	?	X
Floor wax remover	2	2	2	1	?	X
Furniture polish	2	2	1	1	1	2
Gasoline	X	2	2	2	2	X
Glue, solvent base	2	2	?	2	?	X
Glue, vinyl acetate base	?	1	1	X	?	X
Hydraulic brake fluid	2	1	1	2	X	2
Insecticide, solvent base	2	2	1	2	?	X
Insecticide, powder	1	1	1	2	?	X
Insect repellent	2	2	1	?	?	X
Kettle cleaner	2	1	1	2	2	2
Lemon oil	X	X	2	1	2	X
Lighter fluid	X	X	2	1	2	X
Linseed oil	1	1	1	1	2	2
Lubricating oil	1	1	1	1	2	2
Moth-proofing, naphthalene	X	X	?	X	?	2
Moth-proofing, p-dichlorobenzine	X	2	2	X	?	X
Oven cleaner	?	1	1	1	?	X
Room deodorants	2	2	1	1	?	2
Shellac	X	2	1	1	?	X
Shoe polish	2	2	1	1	?	2
Silver polish	2	2	1	1	?	2
Weed killer	2	2	2	2	?	X

1 satisfactory performance

2 probably satisfactory but should be verified for specific applications

X not compatible

? information not available

REVIEW QUESTIONS

- 1.** Name the commodity packaging plastic that:
 - a.** Does not burn (self-extinguishes).
 - b.** Is used mostly for thermoforming.
 - c.** Is an exceptionally high all-around gas barrier.
 - d.** Is strongest and stiffest.
 - e.** Has the lowest melting point.
 - f.** Has the highest melting point.
 - g.** Is used most often for closures.
 - h.** Is used most often for detergent and oil bottles.
 - i.** Forms the best “live hinge.”
 - j.** Is used for thermoformed film when packaging luncheon meat.
 - k.** Is lowest in cost.
 - l.** Is made into soda bottles.
 - m.** Is an exceptionally high-oxygen barrier but is water-soluble.
 - n.** Is an exceptionally high-oxygen barrier.
 - o.** Is used for most hot-filled bottles.
 - p.** Would be used to make a squeezable bottle.
- 2.** Define stress.
- 3.** Define yield point. What is its practical significance?
- 4.** Define elongation and ultimate tensile strength.
- 5.** What is static coefficient of friction (COF), and how does it differ from dynamic COF?
- 6.** What are we testing when we test the “dimensional change” in a plastic film, and when would it be important to know this value?
- 7.** Which plastic would you use to make a clear presentation box for a gold watch?
- 8.** Name two materials used for heat sealing and state where each would be used.
- 9.** Why are many medical bottles molded from polypropylene rather than polyethylene?
- 10.** Which two plastics would you most likely use for a microwave application?
- 11.** Which two materials are the best moisture barriers, and which two are the worst?
- 12.** What is the difference between chemical compatibility and stress-crack resistance?

- 13.** Describe how an expanded polystyrene is made.
- 14.** Most dairy tubs are injection molded from polypropylene except for ice cream. What material is ice cream tubs made of and why?
- 15.** What is a bioplastic?
- 16.** What is the feedstock for bio-based polyethylene?
- 17.** What is PLA made from and what is its main attribute?
- 18.** Where is BPA used and why is it being banned by governments?
- 19.** What are plasticizers used for in packaging?
- 20.** What is “hot tack?”

CLOSURES

13

CONTENTS

Selection Considerations

Product compatibility, container compatibility, ease of handling, contain and protect functions, hermetic seal, reclosability, user-friendliness, economy, convenience, safety, demographic considerations, decorative appeal.

Container and Closure Dimensioning

Finish specifications, dimension terminology, thread styles, closure naming conventions, L and M threads, thread mismatch, finish defects.

Metal Closures

Threaded metal closures, lug-style closures, roll-on metal caps, press-on/twist-off metal closures, crown closures, friction-fit pry-off metal closures.

Closure Seals

Lined closures, induction innerseals, linerless closures.

Plastic Closures

Thermoset closures, thermoplastic closures, polypropylene, polyethylene, bio-based and recy-

aled-content options, plastic closure advantages, press-fit designs.

Closure Ejection

Unscrewing the cores, stripping the closure off the core, collapsing core.

Closure Application

Closure torque, application angle/DOR, pull-up testing.

Tamper-Evident (TE) Closures

FDA definition, TE closure limitations, TE closure systems.

Child-Resistant (CR) Closures

Jurisdiction, design basis, effectiveness, CR testing protocol.

Special Closures and Functions

Corks, decorative applications and styles, multiple lead bottle threads, dispensers and pumps, examples of special technical functions.

SELECTION CONSIDERATIONS

A closure is a mechanical device that seals the contents within a container and can be removed or opened to allow the contents to be dispensed. Options include corks, stoppers, lids, tops and caps, made primarily from metal or plastic. Closures are applied to the “finish” of a glass, metal or plastic container. The finish is that part of a container that receives the closure.

The closure is a part of the container and shares the basic packaging functions of containing, preserving and protecting the contents. Closure specifications require the same up-front thinking as the container design itself: The designer must consider the contents and the end-use situations

- Closure materials must be chemically compatible with the contents and applicable to relevant regulations. Particular attention must be paid to any liner materials or surfaces in direct contact with the product.
- Closure materials must be compatible with, and appropriate to, the container material.
- The closure must be easy to handle on the filling line. This is especially important in high-speed production, where the closure must be located, correctly oriented, aligned with the container, placed on the container finish and sealed in a fraction of a second.
- The closure is a possible path by which gases, contaminants and organisms can enter the package. Alternately, gases, moisture or essential oils can leave the package the same way. The closure must have adequate barrier qualities if these are factors.
- The method of creating a seal between closure and container surfaces must be considered carefully (e.g., inserted liner, flowed-in compound, molded-in seals, induction innerseals, bore seal, etc.).
- The need for reclosability affects closure choice. Some packages are opened once, the product is used and the container discarded. Other products may be used a little at