Lecture 7. Plastic Part Manufacture, Injection Molding

In the last 30 years, plastics have become the most dominant engineering material for most products. We take a brief look at the most common types of plastics, and how they are processed.

All plastics are polymers; these polymers are further divided into two basic types: thermoplastics and thermosets. Thermoplastics melt when heated – so they can be melted and re-formed again and again. Thermosets harden when they are heated, if heated further, they will break down chemically and lose their properties. Some thermosets have properties very similar to rubber, and are used as synthetic rubber; they are categorized as elastomers. Here are some typical plastics and their uses:

Thermosets

General properties: more durable, harder, tough, light.

Typical uses: automobile parts, construction materials.

Examples:

- **Unsaturated Polyesters**: lacquers, varnishes, boat hulls, furniture
- **Epoxies and Resins**: glues, coating of electrical circuits, composite materials like fiberglass used in helicopter blades, boats etc

Elastomers

General properties: these are thermosets, and have rubber-like properties.

Typical uses: medical masks, gloves, rubber-substitutes

Examples:

- **Polyurethanes**: mattress, cushion, insulation, toys
- **Silicones**: surgical gloves, oxygen masks in medical and other applications, joint seals,…

Thermoplastics

General properties: low melting point, softer, flexible.

Typical uses: bottles, food wrappers, toys, …

Examples:

- **Polyethylene:** packaging, electrical insulation, milk and water bottles, packaging film
- **Polypropylene:** carpet fibers, automotive bumpers, microwave containers, prosthetic body parts for disabled people
- **Polyvinyl chloride (PVC**): sheathing for electrical cables, floor and wall coverings, siding, credit cards, automobile instrument panels

- **Polystyrene:** disposable spoons, forks etc., also used to make Styrofoam™ (soft packaging material)
- **Acrylics (PMMA**: polymethyl methacrylate): paints, fake fur, plexiglass
- **Polyamide (nylon):** textiles and fabrics, gears, bushing and washers, bearings
- **PET (**polyethylene terephthalate): bottles for acidic foods like juices, food trays, mylar tapes
- **PTFE** (polytetrafluoroethylene): non-stick coating, Gore-Tex™ (raincoats), dental floss.

The most common methods of processing plastics to manufacture plastic parts are similar to methods we have learnt for metals and glass. These include Extrusion, Injection molding, Blow molding, Casting, etc. Among these, perhaps injection molding is the most significant for local industry – almost all manufacturing companies use parts that are injection molded, whether they make toys, home-appliances, electronics or electrical parts, watches, computers, etc.

7.1. Plastic Extrusion

Extrusion can be used for thermoplastics. The raw material is in the form of pellets (~10mm sized pieces), granules (~5 mm), or powder. Extrusion machines are used to make long pieces of constant cross-section. The cross-section geometry can be solid or hollow, and may be quite complex in shape. Usually, extruded parts are used as raw stock for use in manufacture of other products (e.g. channels on the sides of windows, etc. You can find plastic extruded parts in many bathroom and kitchen fittings). Figure 1 shows a typical extrusion machine. Figure 2 shows some examples of extruded shapes.

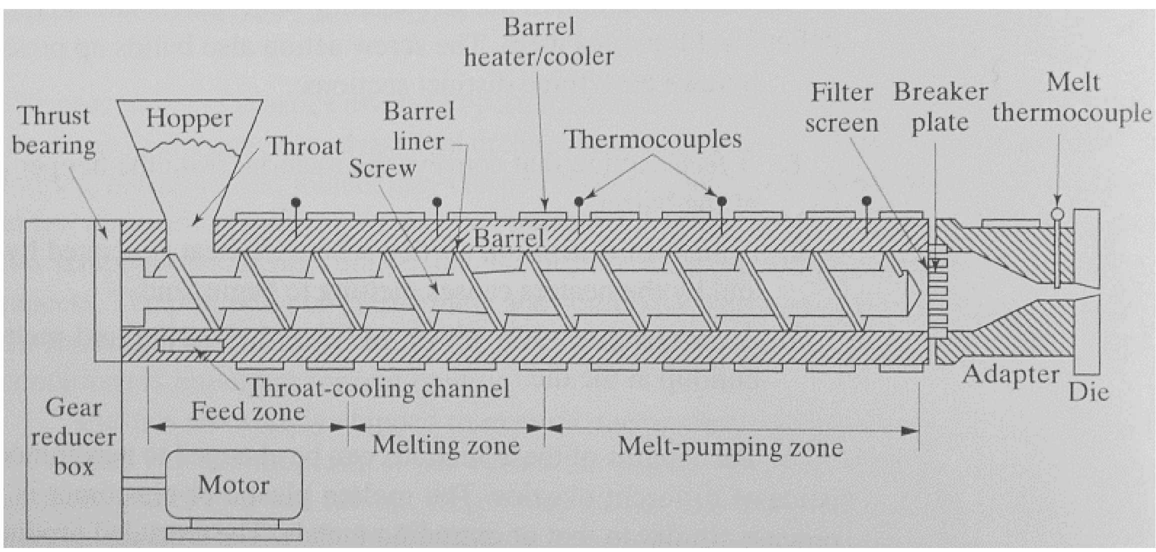


Figure 1. Extrusion machine schematic [source: Kalpakjian and Schmid]

Figure 2. Parts made by extrusion [sources: websites of keltrol.com, seilerpc.com]

The main difference from metal extrusion is the mechanism for pumping out the molten plastic: plastic extrusion uses a large screw in a cylinder, which simultaneously mixes, and pushes the pellets/granules towards the die; along the way, the heating chamber melts the plastic.

Interesting note: many plastic processes use plastic pellets as raw material; these pellets are the shape of short cylinders, which are themselves formed by plastic extrusion.

7.2. Blow Molding

This process is almost identical to the blow-molding of glass that we studied earlier.

7.3. Thermoforming

In thermoforming, a sheet of plastic is used to cover a shape (e.g. a die) by heating the sheet till it is semi-fluid, and then pulling it over the die using vacuum suction (this method is called vacuum forming). In an alternate form, called pressure forming, the pressure is applied using high pressure air from above the plastic sheet. This process is most commonly seen in packaging of food, toys etc.; it is also used to make appliance housings, etc. The following schematic shows different types of thermoforming.

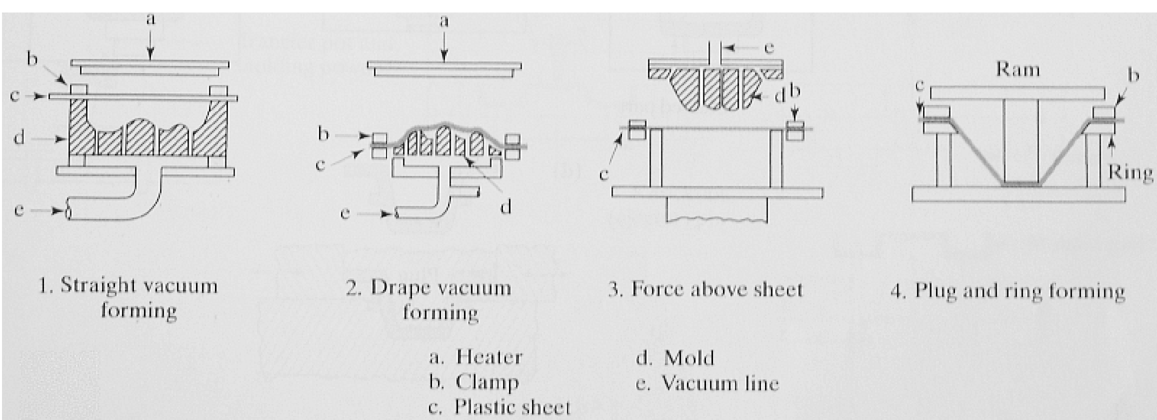


Figure 3. Schematic of thermoforming processes [source: Kalpakjian and Schmid]

(a) plastic sheet loaded into frame

(b) frame slides out above mold

(c) heated mold is raised, forming convex shapes

(d) vacuum lines pull the plastic into concave ‘holes’

(e) frame returns to reload; mold lowered; part removed

Figure 4. Stages in a vacuum thermoforming process [source: www.ymlf.com.hk]

The advantage of thermoforming is that the tooling (usually made by machining Aluminum) is cheap to produce. The vacuum forming process leaves tiny marks where the mold has holes for vacuuming out the air; these holes are made small, e.g. 0.5mm. The main quality control issues include non-uniform thickness of parts, warping of parts when they cool, and tearing of the sheet. The figure below shows images of parts that can be made using thermoforming processes.

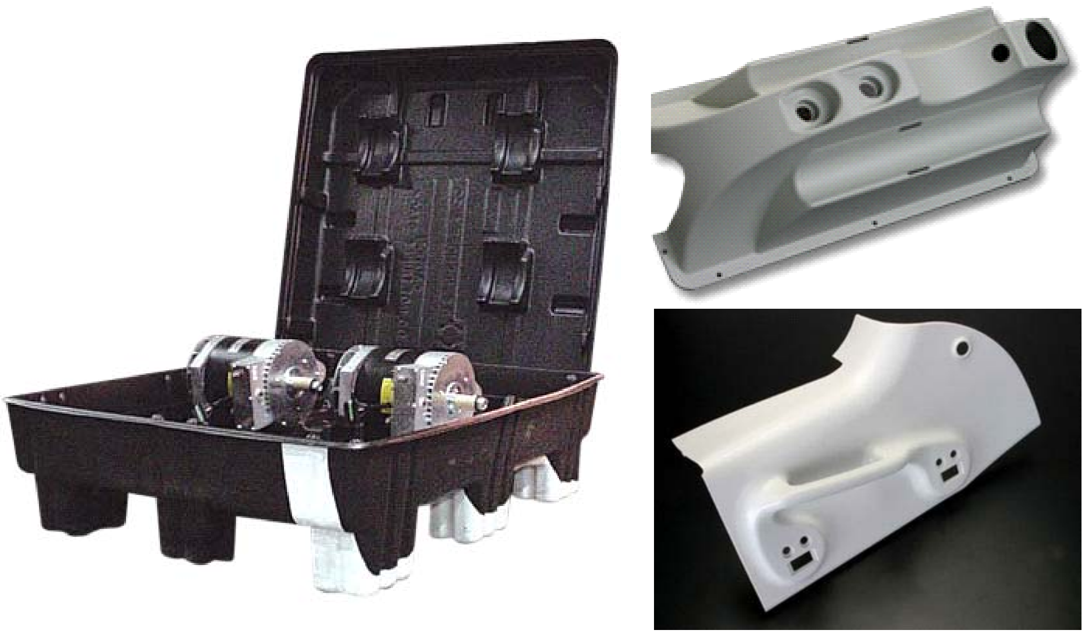


Figure 5. Thermoformed parts

7.4. Compression and Transfer Molding

These two processes are used mostly for thermosetting polymers. In compression molding, the raw material is placed inside the mold in semi-solid or solid (i.e. as *granules*, or a single piece called a *plug*). The mold is heated and closed using pressure, and the plastic flows to fills the cavity. Excess material may leak out from the parting lines creating flash, which must be trimmed away.

If the part shape is more complex, transfer molding may be used. Here, the charge (thermoset grains) are placed in a heated cylinder till they are soft; a hole at the bottom of the cylinder is connected to the die cavity by a sprue. A plunger pushes the semi-solid plastic into the die through the sprue, using high pressure.

These methods are used to make dishes, handles for cooking pots, skis, housing for high-voltage switches, some rubber parts like shoe soles, and even composites such as fiber-reinforced parts. These processes commonly used with thermosetting polymers, where the initial charge is in semi-solid state (partial polymerization), and the heating causes the plastic to set as it forms the shape of the mold.

Figure 6. A compression molding machine

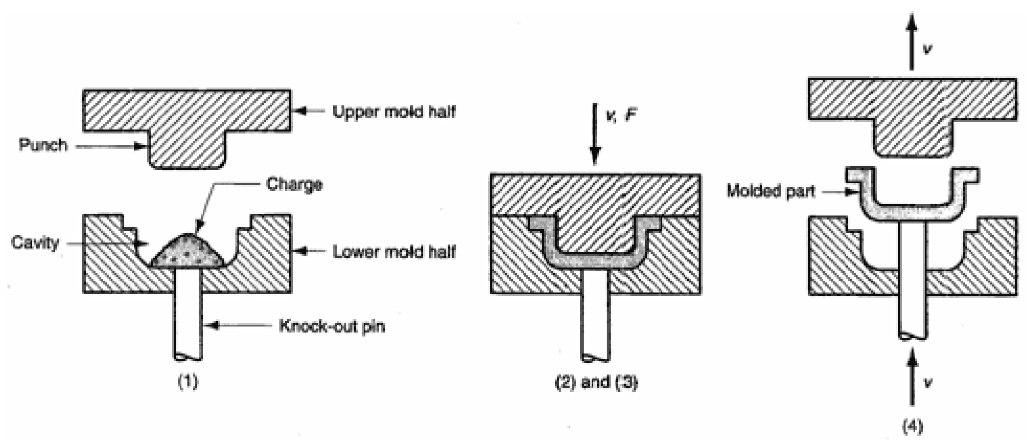


Figure 7. Schematic of Compression Molding

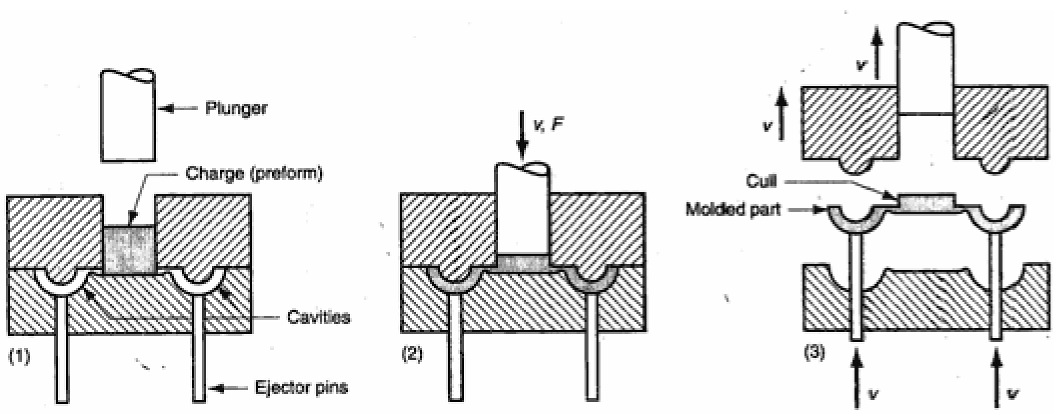


FIGURE 8. Schematic of Transfer Molding

7.5. Injection Molding

Injection molding is perhaps the most common and important of all plastic processing processes. The process is extremely versatile, and can produce very complex shaped parts, with the use of multi-sided molds. Even parts with metal inserts can be produced. While injection molding dies are expensive to produce, each die can be used to make tens of thousands of components at very rapid rate, so that per-part cost is very low. The simplest form of injection molding is shown in the schematic below.

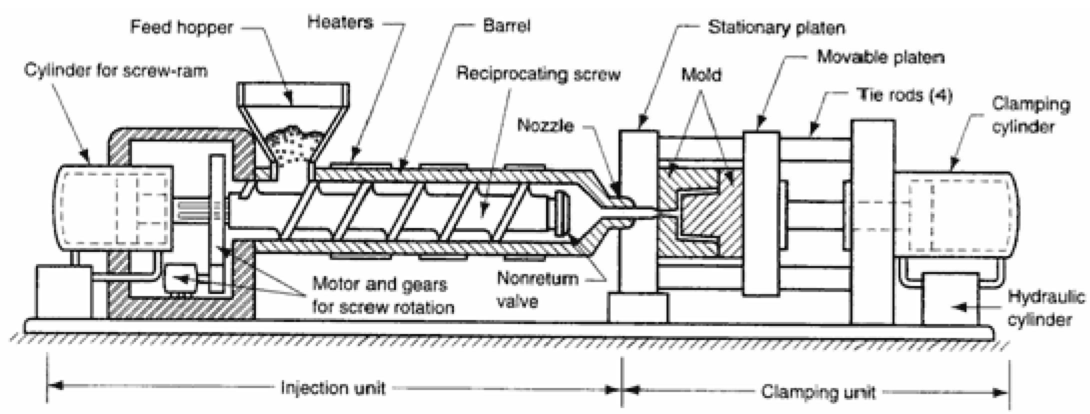


Figure 9. A simple reciprocating screw injection molding machine [source: www.offshoresolutions.com]

Figure 10 shows the cycle of operations during production of a molded part. The moving platen puts the mold together; the mold halves are held with large force, and the molten charge is forced into the cavity; the plastic solidifies, and finally, the moving platen is retracted, and ejector pins in the mold push the part out.

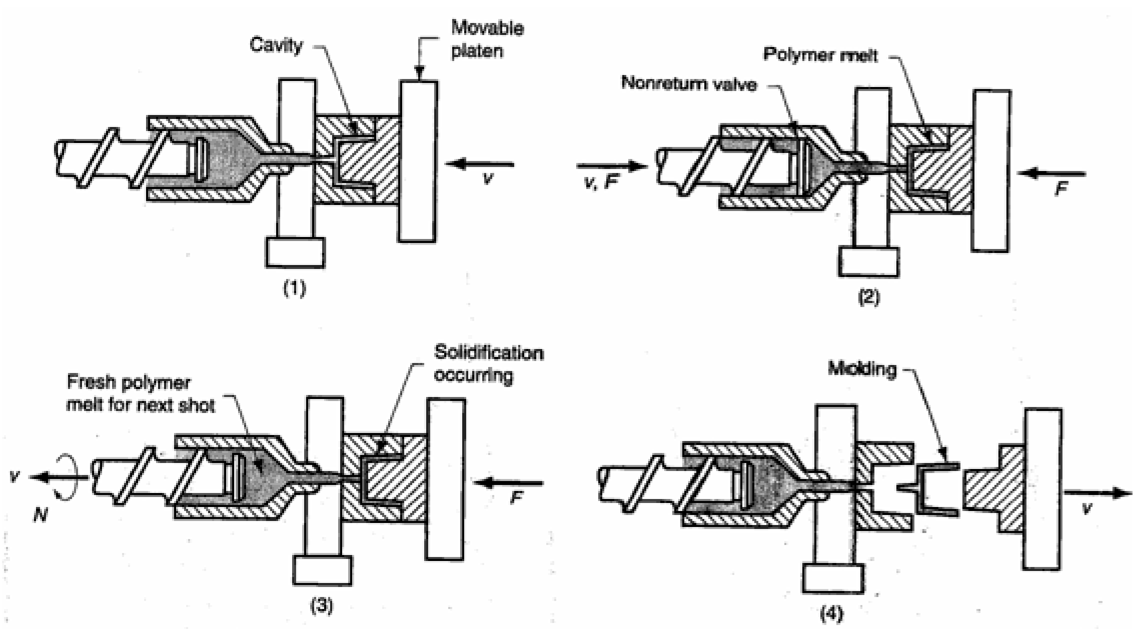


Figure 10. Cycle of operation for injection molding [source: www.offshoresolutions.com]

Just as in die casting, the mold is specially made for each part, and the basic elements of each mold are the same, including ***sprue***, ***gates***, ***runners*** and ***vents***; in addition, the location of ***ejection pins*** is usually specified in the mold design, since there points have visible marks (therefore ejection is usually done from the core side, and is usually mounted into the mold half mounted on the moving platen). The cavity is divided between the two mold halves in such a way that the natural shrinkage of the molding causes the part to stick to the moving half. When the mold opens, the ejector pins push the part out of the mold cavity. We look at the details of molds in more detail below.

Two-Plate Mold: This consists of two halves fastened to the two platens of the molding machine's clamping unit. When the clamping unit is opened, the mold halves separate. Molds can contain one multiple cavities to produce one or multiple parts in a single shot (last example in figure 11 below). The ***parting surface*** is the surface shared by the two mold halves.

Figure 11. Examples of Injection Molding Parts [source: www.ylmf.com.hk]

The **cooling system** is made up of passages in the mold that are connected to an external pump. Water is circulated through them to remove heat from the hot plastic. The air trapped in the cavity passes through the small ejector pin clearances in the mold, and through narrow **vents** that are machined into the parting surface (typically about 0.03 mm deep and 12 to 25 mm wide).

Three-plate mold: This design (see figure below) has some advantages. The molten plastic flows through a gate located at the base of the cup-shaped part, rather than at the side. This allows more even distribution of melt into the sides of the cup. In the side gate design in the two-plate the plastic must flow around the core and join on the opposite side, possibly creating a weakness at the weld line. Secondly, the three-plate mold allows more automatic operation of the molding machine. As the mold opens, the three plates separate; this forces the runner to break from the parts, which drop by gravity or using air-blower into collecting containers put under the mold.

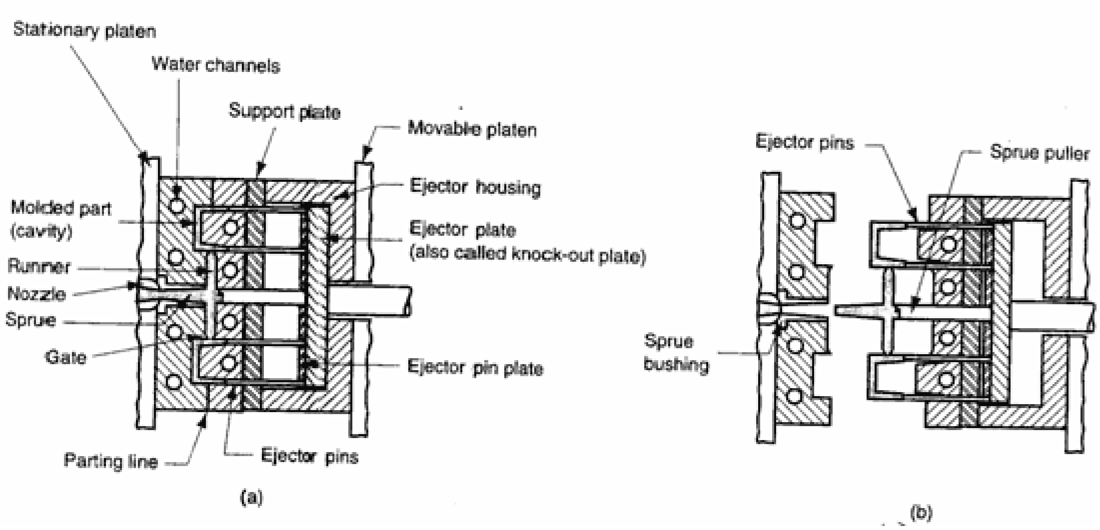


Figure 12(a). A two-plate mold

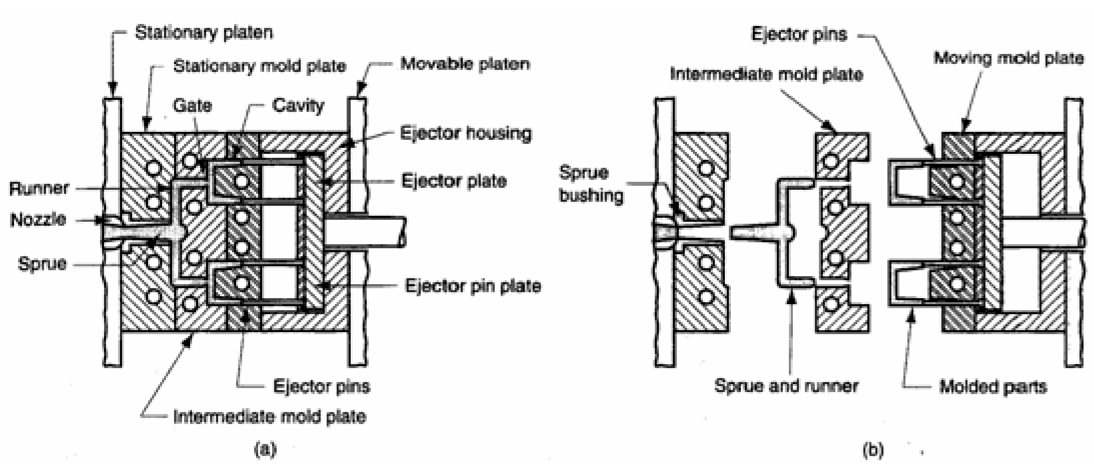


Figure 12(b). A three-plate mold

Molds with cores/cams: Many injection molded parts have some part of the geometry that is inaccessible to either of the mold halves. Such regions must be created by means of extra moving parts in the mold. Figure 13 below shows a cup-shaped part with a through-hole. One method to mold this part is by the use of a core. The figure below shows the steps of the mold opening. Figure 14(a) shows a more complex mold with four side action cams. Typical side-action cam design is shown in Figure 14(b); the top (red) part is connected with the bolt on top to the moving platen. As the mold opens, the green part is forced to slide to the right. The mold-piece that creates the insert geometry is attached to the green piece by the blue bolt.

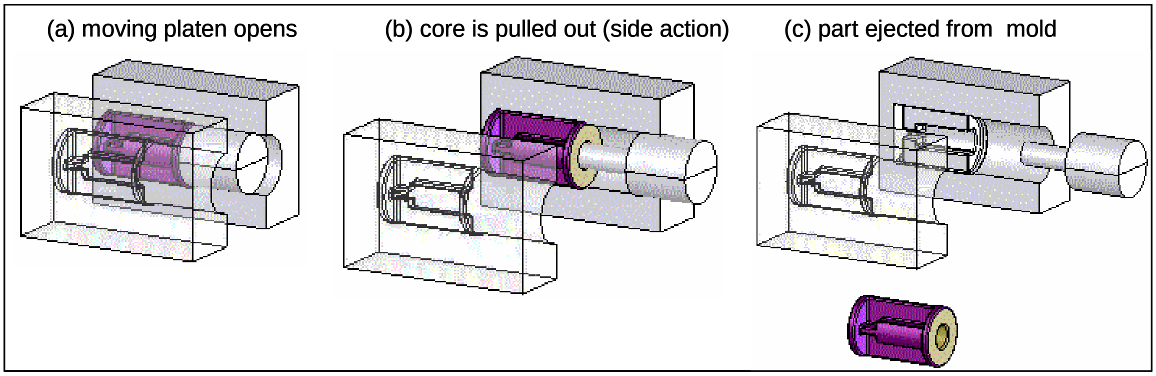


Figure 13. Injection molding a part with side action using core

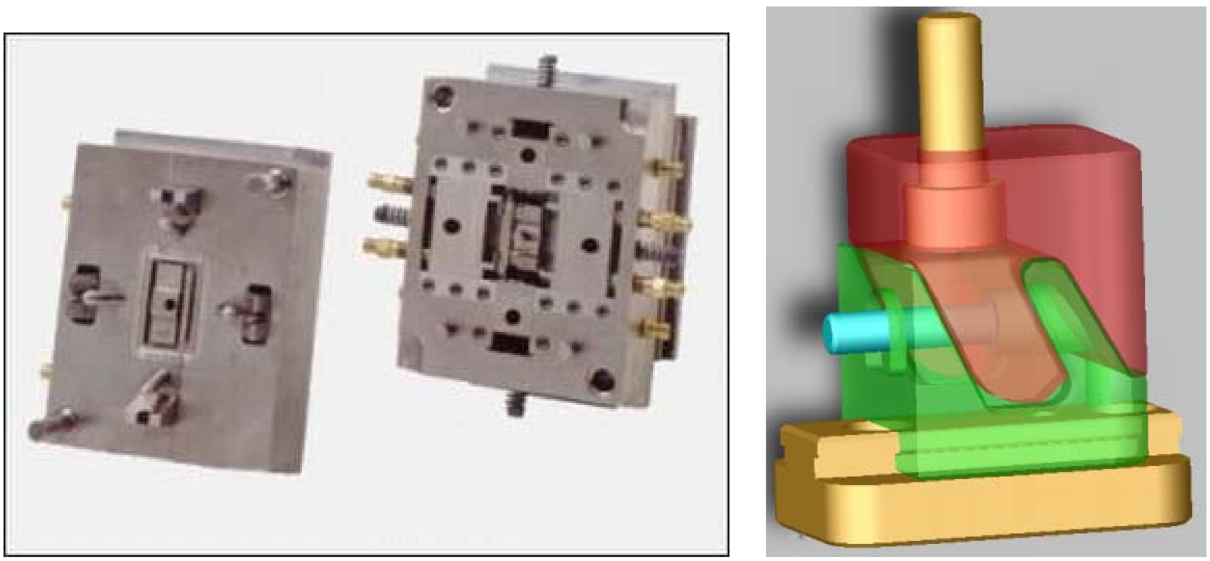


Figure 14 (a). A mold with four side action cams (b) The operation of side action cams

Injection Molding Considerations

Steps in designing an Injection Mold

The design of injection mold tooling requires several steps. The ***molding directions*** will determine the number of inserts/cams required, which severely affects the cost of the tooling. After finding the suitable molding direction, the ***parting lines*** are determined. The parting planes form the surface of the mold halves – usually, the ***parting planes*** are formed by extending the parting line outwards, perpendicular to the molding direction. The ***gating design*** determines where to locate the gate(s). If a ***multiple cavity*** mold is made, the relative positions of the multiple parts is determined. The ***runners*** are designed, and ***sprue*** is located. Then the functional parts of the mold are created next – this includes the part ***ejection system***, systems to eject the solidified runners etc. Finally, the ***alignment rods*** that will keep all mold components aligned during operation are designed. The following figures show a simple example for molding a cup. Figure 15 shows a cup-shaped part. There is only one possible parting line (why ?). The ideal parting surface for this line is a plane. Figure 16 shows the stages of development of the mold. Note that here a plate is used to eject the cup, rather than ejection pins [Exercise: comment on this choice].

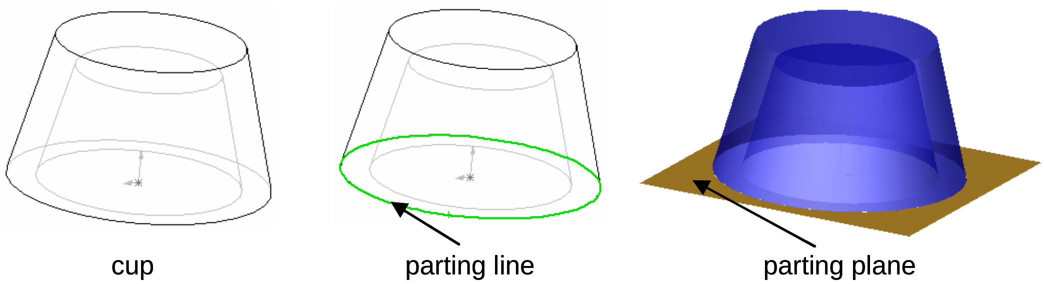


Figure 15. A simple part

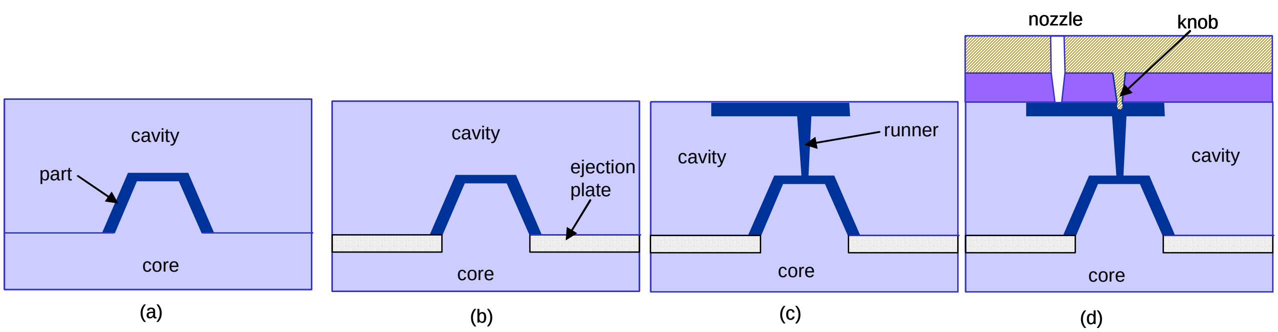


Figure 16. Stages of development of the injection mold

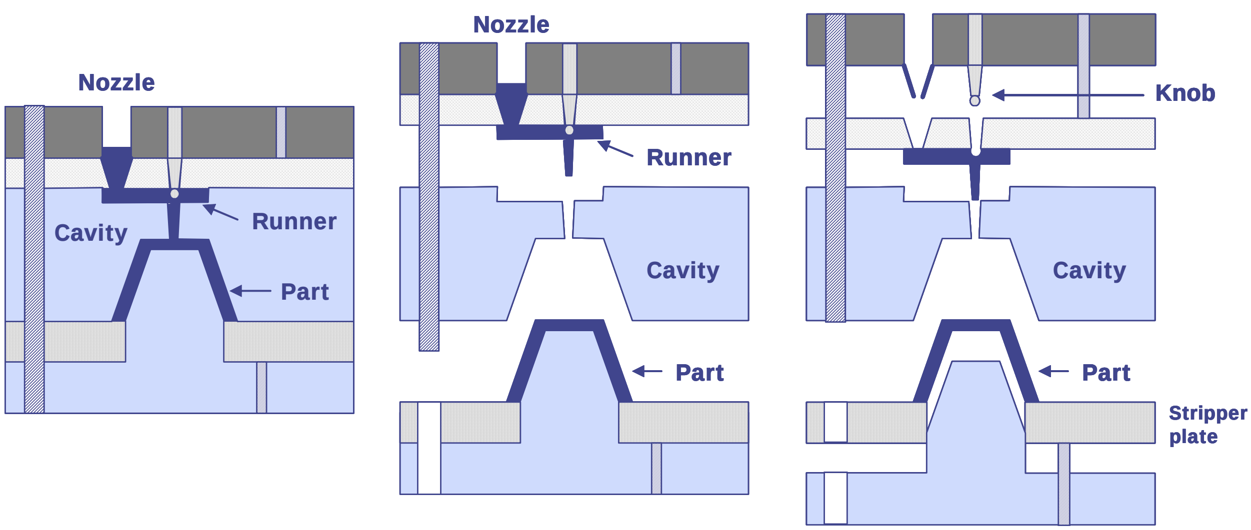


Figure 17. The mold in operation

Finally, we consider some more complex shape features in injection molded parts. Some such typical features are shown in the figure below.

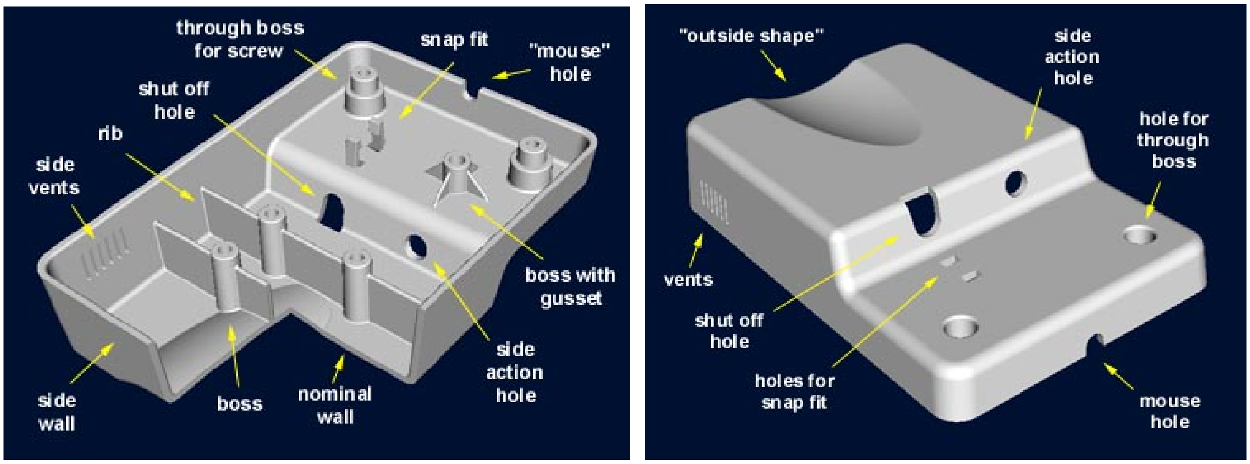


Figure 18. Examples of different shape features in typical injection molded parts [source: www.idsa-mp.org]

In some cases, by the use of non-planar parting lines, we may be able to create the shape with 2-piece molds (i.e. without the use of side action cams). An example of this is the mouse hole. In fact, even the shut-off hole may be created without side action, as shown in the figure below. In other cases, (e.g. to create the holes for the vents in the figure above) a side action cam is required.

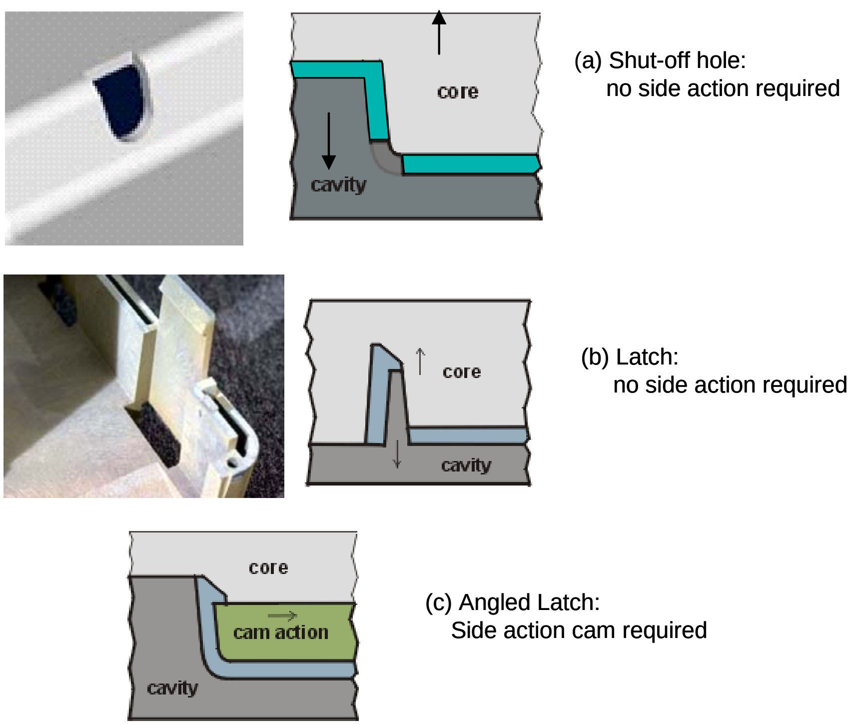


Figure 19. Examples of molds with complex parting lines, and a multi-part mold

Considerations in design of injection molded parts

There are several geometric and design considerations for parts manufactured using injection molding. Many of these considerations have resulted in a large set of guidelines for geometric features in the design. The two biggest *geometric concerns* are (i) proper flow of the plastic to all parts of the mold cavity before it solidifies, and (ii) shrinking of the plastic resulting in sink holes. Some examples of the first concern include: if the part thickness is too small, plastic flow is restricted due to high friction; if the gate is too far away from some small features of the geometry, or is there is a constriction in the path along which the plastic will flow; another guideline is that the cross section of the part should not change abruptly, since this leads to poor flow. Regarding the second concern, guidelines include (a) maintaining uniform cross-section thickness throughout the part; use of ribs and gussets to provide mechanical strength instead of using thicker sections etc. Figure 20 shows a comparison of strength of parts of the same length but different cross-sections – the examples demonstrate that the use of ribs will result in lighter parts for a given stiffness. Figures 21-23 below demonstrate some of the guidelines for common molded geometry.

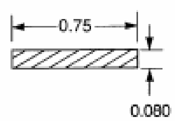
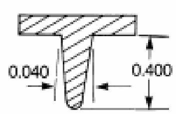
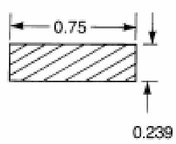
Geometry	Cross-Section Area (square inches)	Max. Stress (psi)	Max. Deflection (inches)
 ORIGINAL SECTION	0.0600	6250	0.694
 ORIGINAL SECTION WITH RIB	0.0746	2273	0.026
 THICK SECTION	0.1793	699	0.026

Figure 20. Comparison of breaking stress under bending moments on bars of different cross-section geometry

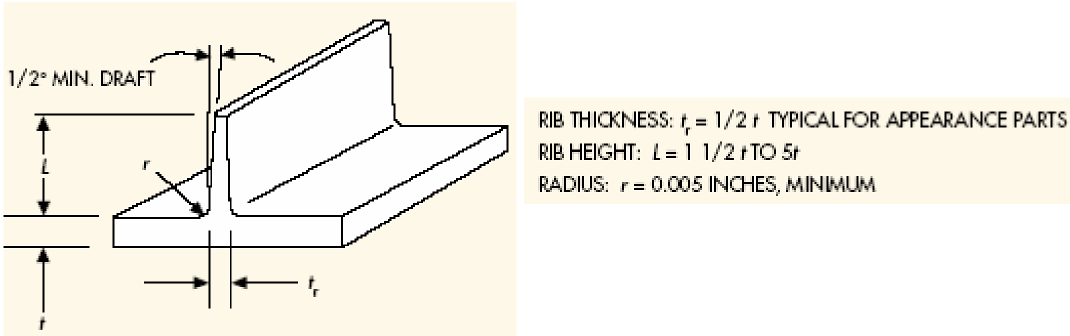


Figure 21. Guidelines for rib dimensions

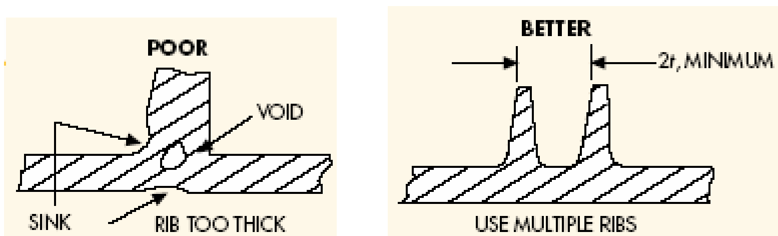


Figure 22. Molding problems (sink holes and voids) occur if the part has thick sections

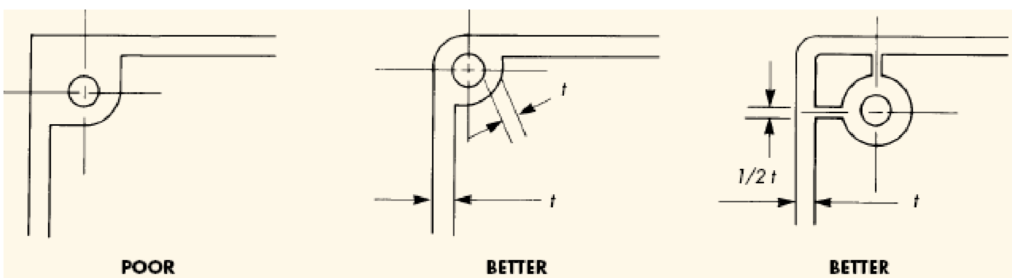


Figure 23. Example of improving design for injection molded parts

The main ejection-related guideline is the same as for all casting/molding processes: providing for tapered shapes by applying a draft angle to all part surfaces with normal vector perpendicular to the molding direction.

Another consideration in injection molding is regarding weld lines. As the plastic flows to fill the mold, there are some regions where the advancing front of the plastic flowing from different directions meets. At this point the two flows mix together – however, the solidified plastic has slightly less strength along the line where this occurs. Lines along which this happens are called weld lines. An example is shown in the molding of a phone cover plate in Figure 24 below.

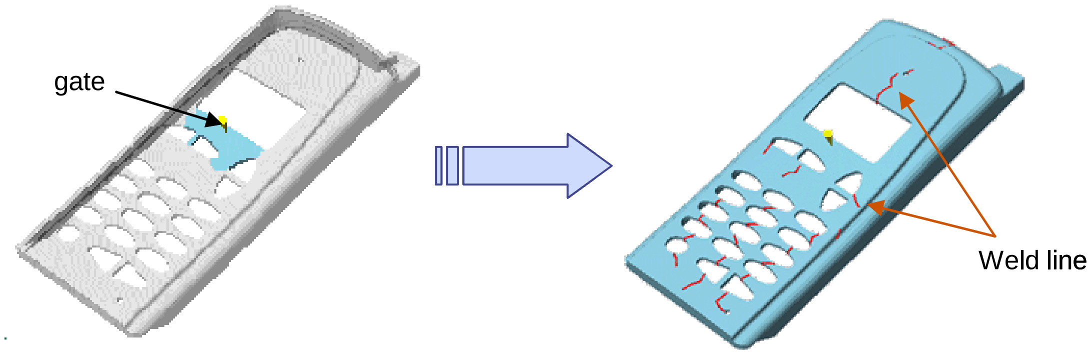


Figure 24. Due to location of the gate and the geometry of the cavity, the front of the flowing plastic meets along several lines, called weld lines

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APPENDIX: Common plastics and their uses

Acrylonitrile-Butadiene-Styrene (ABS) A class of thermoplastic terpolymers including a range of resins, all prepared with usually more than 50% styrene and varying amounts of acrylonitrile and butadiene. The three components are combined by a variety of methods involving polymerization, graft copolymerization, physical mixtures and combinations thereof. Typical applications are found in appliances, automotive parts, pipe, and business machine and telephone components.

Polycarbonates (PC) Group of clear, thermoplastic polymers used mainly as molding compounds. Polycarbonates are prepared by the reaction of an aromatic difunctional phenol with either phosgene or an aromatic or aliphatic carbonate. The commercially important polycarbonates use 2,2-bis (4-hydroxyphenol)-propane (bisphenol A) and diphenyl carbonate. This polymer is a clear plastic with a slight yellow discoloration. It has excellent electrical properties and a high impact strength.

Low & High Density Polyethylene (PE) Widely used plastic. It is a polymer of ethylene, CH2=CH2, having the formula (-CH2-CH2-)n, and is produced at high pressures and temperatures in the presence of any one of several catalysts, depending on the desired properties for the finished product. Polyethylene is resistant to water, acids, alkalies, and most solvents. Its many applications include films or sheets for packaging, shower curtains, unbreakable bottles, pipes, pails, drinking glasses, tubing, and insulation for wire and cable.

Polypropylene (PP) Plastic noted for its lightweight, being less dense than water; it is a polymer of propylene. It resists moisture, oils, and solvents. Since its melting point is 121°C (250°F), it is used in the manufacture of objects that are sterilized in the course of their use. Polypropylene is also used to make textiles, coating of wire and cable, packaging material, tubing, and trim molding.

Polystyrene (HIPS) Widely used plastic; it is a polymer of styrene. Polystyrene is a colorless, transparent thermoplastic that softens slightly above 100°C (212°F) and becomes a viscous liquid at around 185°C (365°F). It is resistant to acids, alkalies, oils, and alcohols. It is produced either as a solid or as a foamed plastic marketed under the trade name Styrofoam. Its many uses include electrical and thermal insulation, translucent window and signage panels, storage-battery cases, toilet articles, and display signage.

Polyvinyl chloride (PVC) Thermoplastic that is a polymer of vinyl chloride. Resins of polyvinyl chloride are hard, but with the addition of plasticizers a flexible, elastic plastic can be made. This plastic has found extensive use as an electrical insulator for wires and cables, tubing, gaskets, and trim molding.

Provista/PETG A clear thermoplastic copolymer (copolyester) with high melt strength used mainly for profile extrusion. Provista/PETG is often used as a replacement for Acrylic due to cost and ease of processing. It has excellent chemical resistant and high clarity. It is also UV resistant and is FDA compliant for food contact applications. It's many uses include display signage, tubing, trim molding, and clear window panels.

Thermo Plastic Elastomers (TPE) Diverse family of rubber like materials that, unlike vulcanized rubber can be processed like thermoplastic materials. TPE's are used in a variety of applications in the automotive, construction, medical, food and beverage, electrical, appliance and electronic markets.