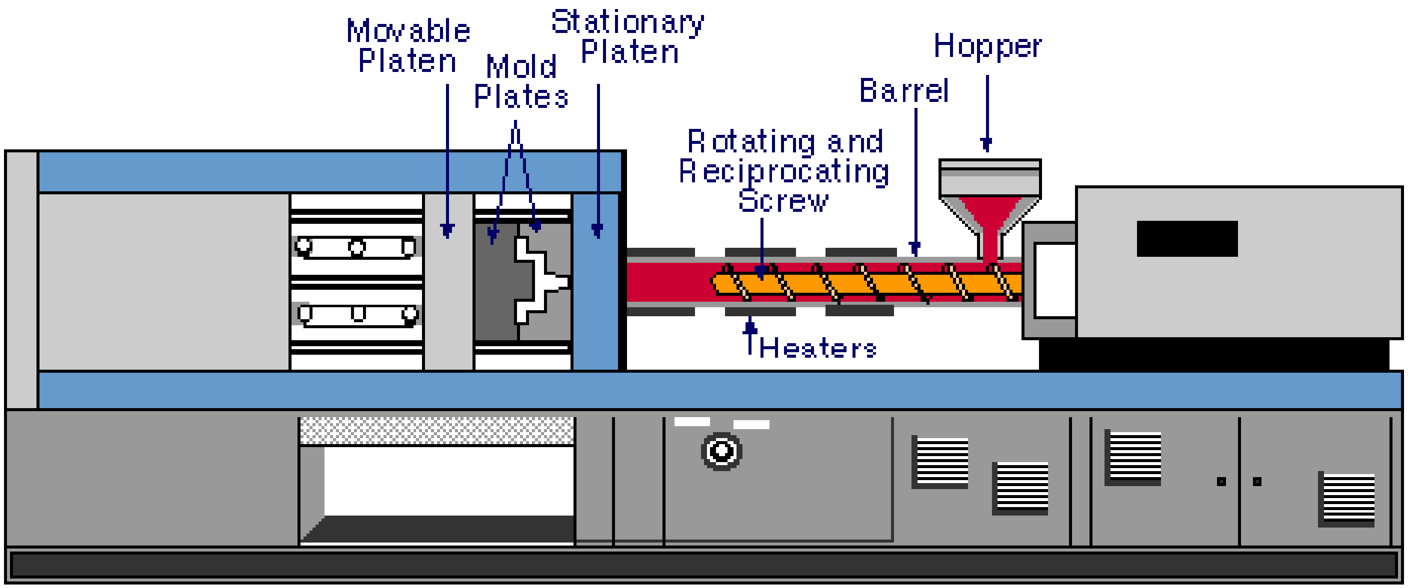
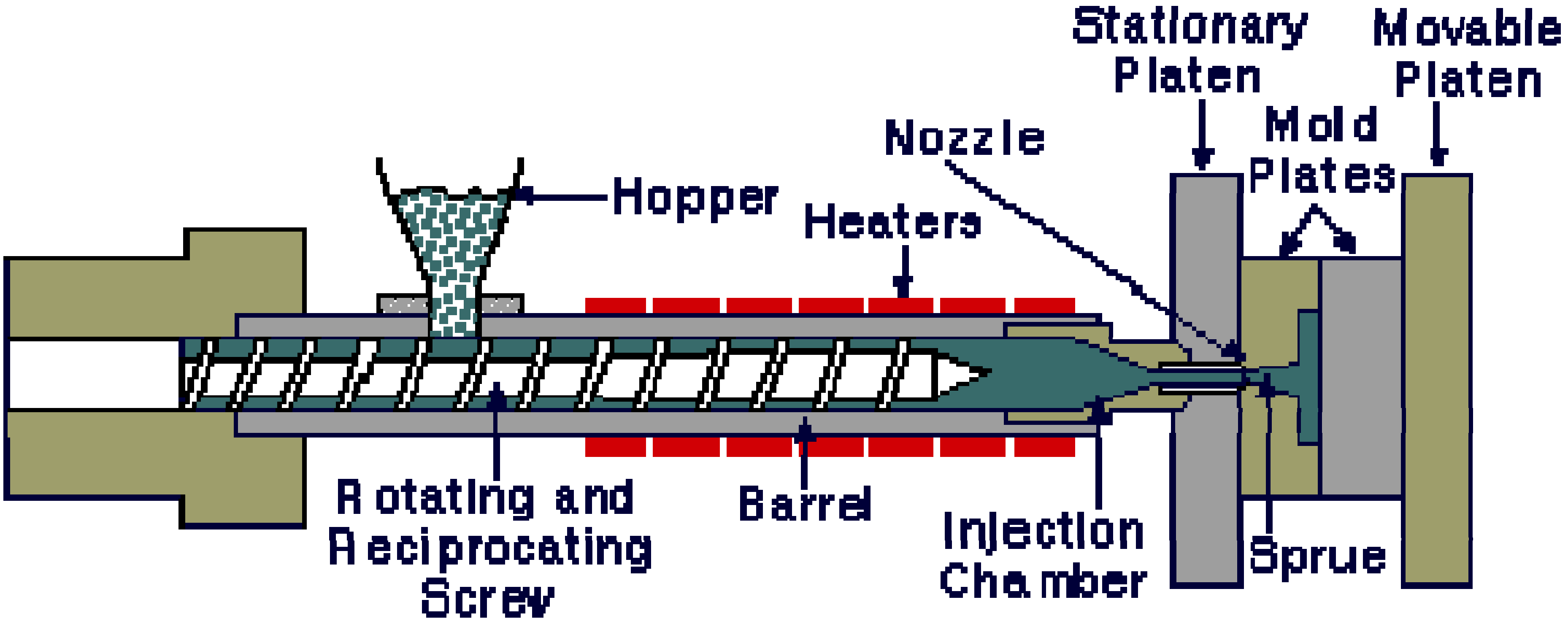
Injection Molding



Injection Molding Product Examples

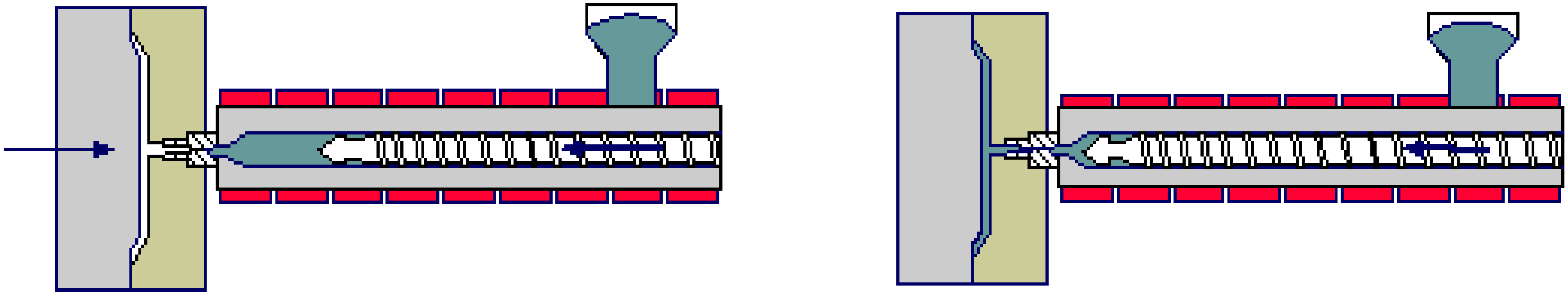
Injection Molding Product Examples

Injection Molding Machine Basics

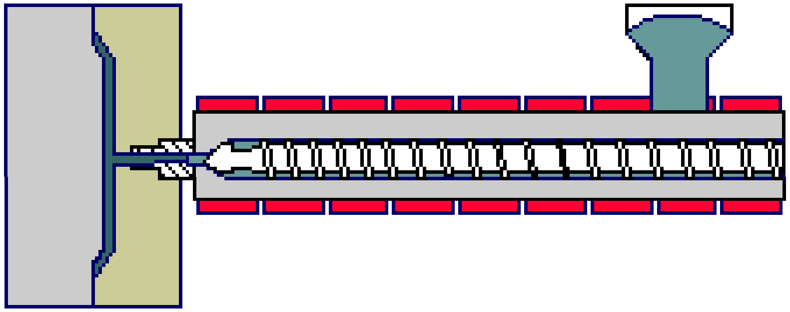


INJECTION MOULDING OPERATIONS

(a) After the mould closes, the screw (not rotating) pushes forward to inject melt into the cooled mould. The air inside the mould will be pushed out through small vents at the furthest extremities of the melt flow path

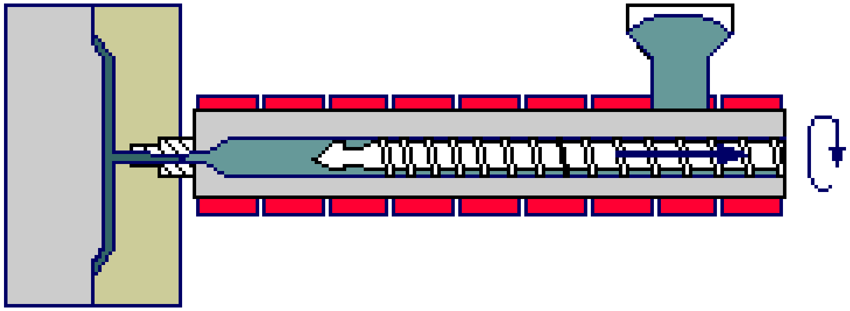


(b) When the cavity is filled, the screw continues to push forward to apply a holding pressure. This has the effect of squeezing extra melt into the cavity to compensate for the shrinkage of the plastic as it cools. This holding pressure is only effective as long as the gate(s) remain open.



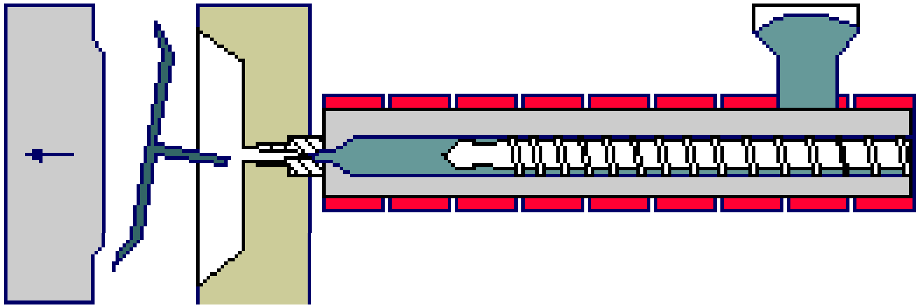
INJECTION MOULDING OPERATIONS

(c) Once the gate(s) freeze, no more melt can enter the mould and so the screw-back commences. At this stage the screw starts to rotate and draw in new plastic from the hopper. This is conveyed to the front of the screw but as the mould cavity is filled with plastic, the effect is to push the screw backwards. This prepares the next shot by accumulating the desired amount of plastic in front of the screw. At a pre-set point in time, the screw stops rotating and the machine sits waiting for the solidification of the moulding and runner system to be completed.



INJECTION MOULDING OPERATIONS

(d) When the moulding has cooled to a temperature where it is solid enough to retain its shape, the mould opens and the moulding is ejected. The mould then closes and the cycle is repeated



INJECTION MOULDING CYCLE

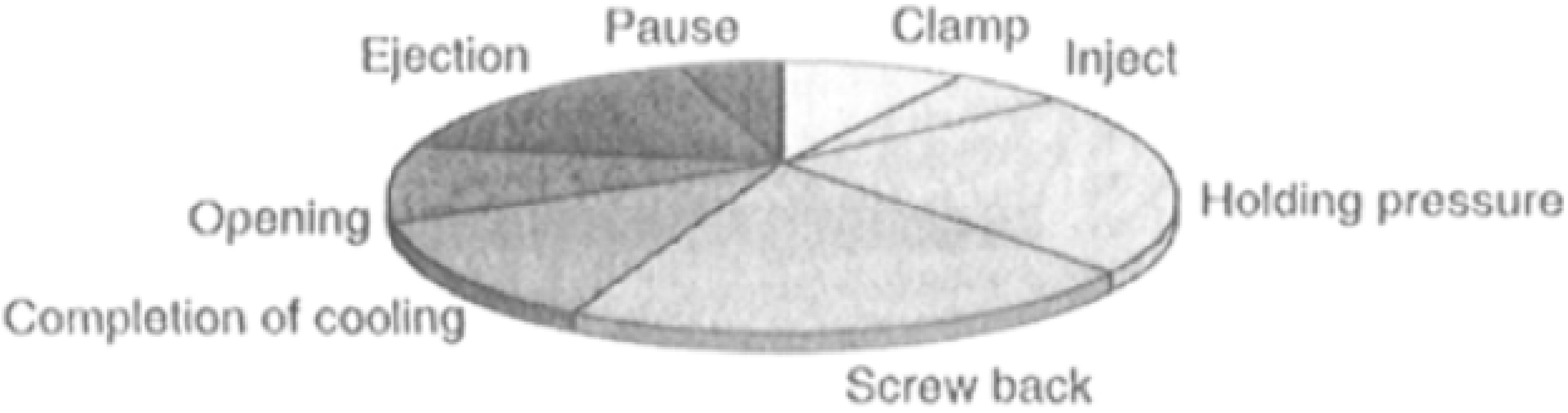
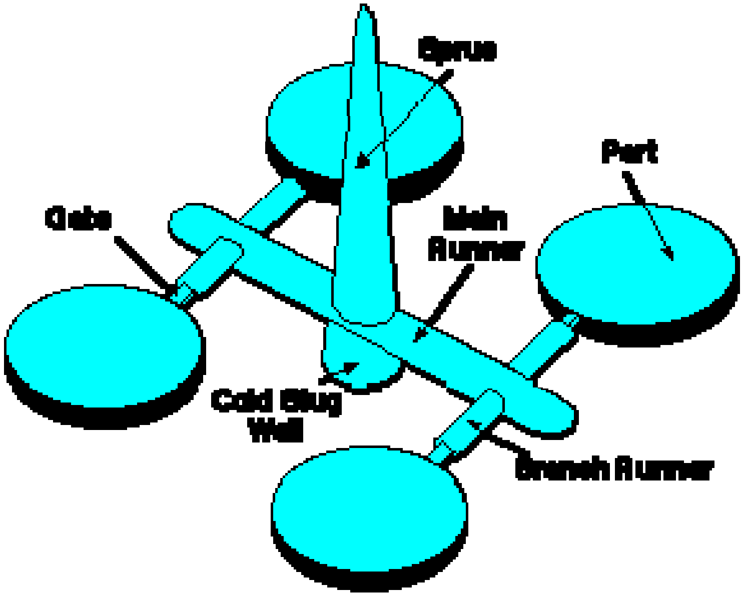


Fig. 4.32 **Stages during injection moulding**

Injection Moulded Component



Sprues: The sprue is the channel along which the molten plastic first enters the mould. It delivers the melt from the nozzle to the runner system.

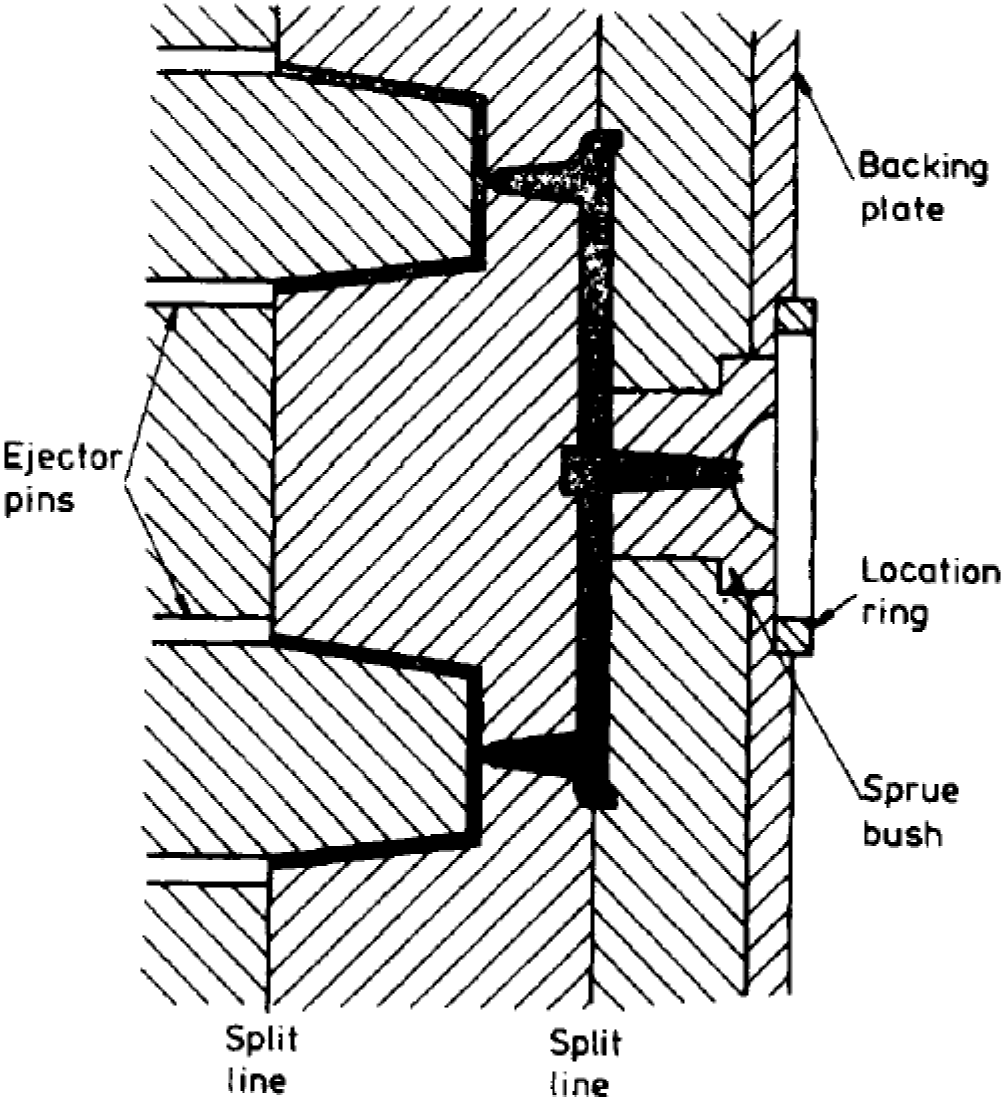
Runners: The runner is the flow path by which the molten plastic travels from the sprue to the gates (i.e. the cavity). To prevent the runner freezing off prematurely, its surface area should be small so as to minimise heat transfer to the mould.

Gates: It is the small orifice which connects the runner to the cavity.

1) Convenient weak link by which the moulding can be broken off from the runner system.
2) In some moulds the degating may be automatic when the mould opens.
3) The gate also acts like a valve in that it allows molten plastic to fill the mould but being small it usually freezes off first. The cavity is thus sealed off from the runner system which prevents material being sucked out of the cavity during screw-back.

Multi-Daylight Moulds

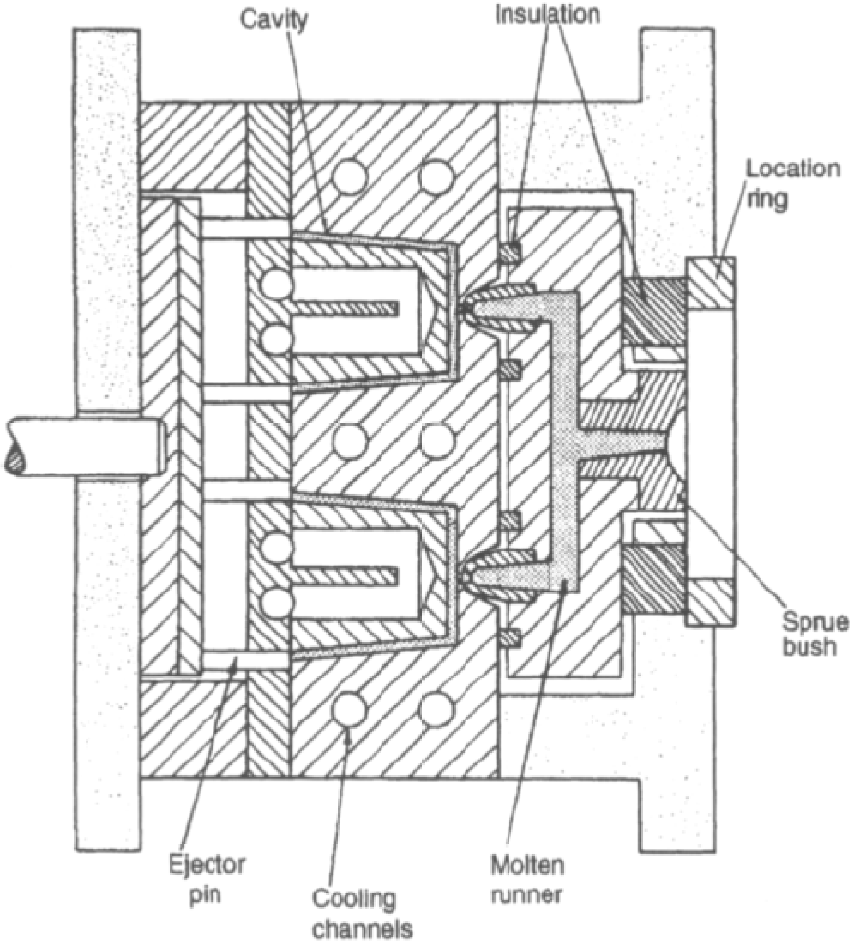
This type of mould, also often referred to as a three plate mould, is used when it is desired to have the runner system in a different plane from the parting line of the moulding. This would be the case in a multi-cavity mould where it was desirable to have a central feed to each cavity. In this type of mould there is automatic degating and the runner system and sprue are ejected separately from the moulding.



Hot Runner Moulds

The runners and sprues are necessary in a mould but they are not part of the end-product. A system has been developed to do this and it is really a logical extension of three plate moulding. In this system, strategically placed heaters and insulation in the mould keep the plastic in the runner at the injection temperature. During each cycle therefore the component is ejected but the melt in the runner channel is retained and injected into the cavity during the next shot.

Additional advantages of hot runner moulds are (i) elimination of trimming and (ii) possibility of faster cycle times because the runner system does not have to freeze off. However, these have to be weighed against the disadvantages of the system. Since the hot runner mould is more complex than a conventional mould it will be more expensive.



Insulated Runner Moulds

This is similar in concept to the hot runner mould system. In this case, instead of having a specially heated manifold in the mould, large runners (13-25 mm diameter) are used. The relatively cold mould causes a frozen skin to form in the runner which then insulates its core so that this remains molten. As in the previous case the runner remains in the mould when the moulding is ejected and the molten part of the runner is then injected into the cavity for the next shot.

This type of system is widely used for moulding of fast cycling products such as flower pots and disposable goods. The main disadvantage of the system is that it is not suitable for polymers or pigments which have a low thermal stability or high viscosity, as some of the material may remain in a semi-molten form in the runner system for long periods of time.

Screws

The screws used in these machines are basically the same as those described earlier for extrusion.

- ✓ Compression ratios - 2.5 : 1 to 4 : 1
- ✓ L/D ratios - 15 to 20

Barrels and Heaters

- ➢ These are also similar to those in extruder machines.
- ➢ Vented barrels have become available to facilitate the moulding of water sensitive plastics without the need for pre-drying.

Nozzles

The nozzle is screwed into the end of the barrel and provides the means by which the melt can leave the barrel and enter the mould. It is also a region where the melt can be heated both by friction and conduction from a heater band before entering the relatively cold channels in the mould. Contact with the mould causes heat transfer from the nozzle and in cases where this is excessive it is advisable to withdraw the nozzle from the mould during the screw-back part of the moulding cycle. Otherwise the plastic may freeze off in the nozzle.

Clamping Systems

1) **Hydraulic type** - oil under pressure is introduced behind a piston connected to the moving platen of the machine. Clamp force can be adjusted so that there is no leakage of molten plastic from the mould.

2) **Mechanical or toggle type** - Preferred for high speed machines and where the clamping force is relatively small.

   Advantages

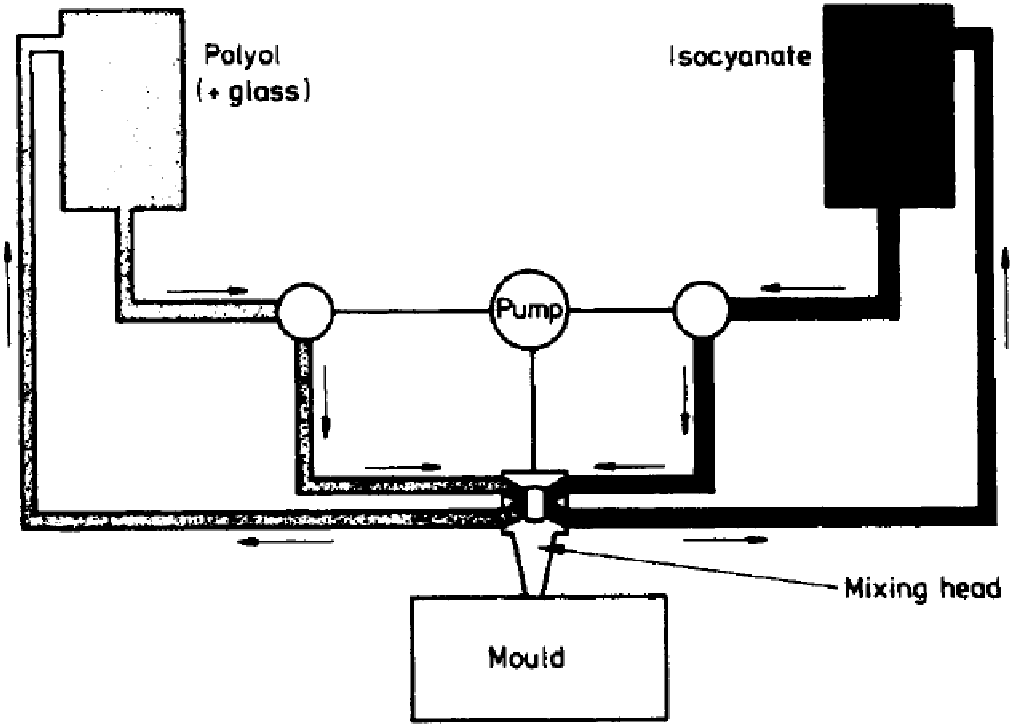
   i. more economical to run the small hydraulic cylinder
   ii. the toggle is self locking it is not necessary to maintain the hydraulic pressure throughout the moulding cycle.

3) **Combination of the above two**

Reaction Injection Moulding

Liquid reactants are brought together just prior to being injected into the mould. In-mould polymerisation then takes place which forms the plastic at the same time as the moulding is being produced. In some cases reinforcing fillers are incorporated in one of the reactants and this is referred to as Reinforced Reaction Injection Moulding (RRIM)

Since the reactants have a low viscosity, the injection pressures are relatively low in the RIM process. Thus, comparing a conventional injection moulding machine with a RIM machine having the same clamp force, the RIM machine could produce a moulding with a much greater projected area (typically about 10 times greater).



Mould materials other than steel may be considered. Aluminium has been used successfully and this permits weight savings in large moulds. Moulds are also less expensive than injection moulds

Gas Injection Moulding

In recent years major developments have been made in the use of an inert gas to act as the core in an injection moulded plastic product. This offers many advantages including greater stiffness/weight ratios and reduced moulded-in stresses and distortion.

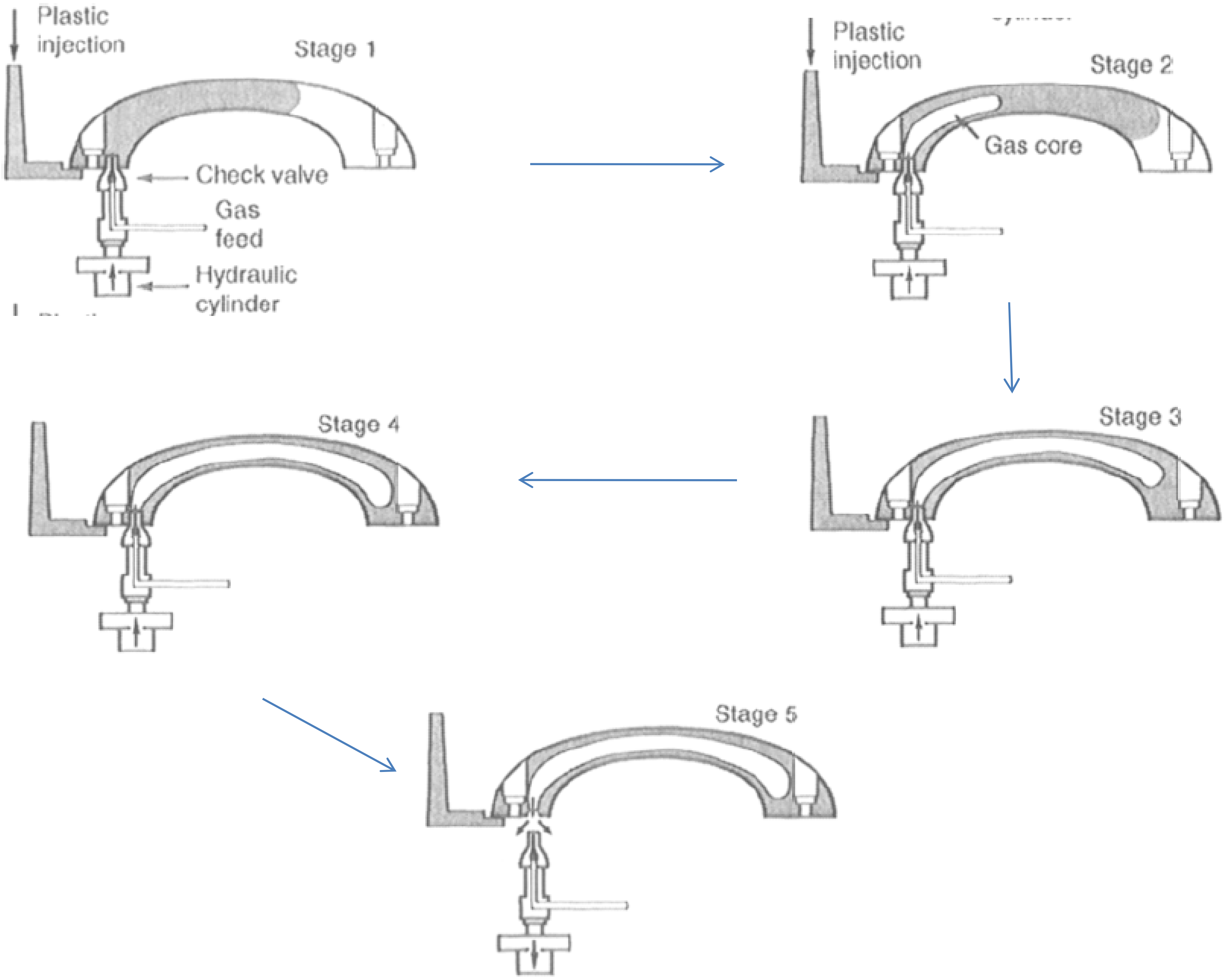
The first stage of the cycle is the flow of molten polymer into the mould cavity through a standard feed system. Before this flow of polymer is complete, the injection of a predetermined quantity of gas into the melt begins through a special nozzle located within the cavity or feed system as shown in Fig. 4.45. The timing, pressure and speed of the gas injection is critical.

The flow of gas cores out a hollow centre extending from its point of entry towards the last point of fill. By controlling the amount of gas injected into the hollow core, the pressure on the cooling polymer is controlled and maintained until the moulding is packed. The final stage is the withdrawal of the gas nozzle, prior to mould opening, which allows the gas held in the hollow core to vent.

The gas injection process overcomes many of the limitations of injection mouldings such as moulded-in stress and distortion. These limitations are caused by laminar flow and variation in pressure throughout the moulding.

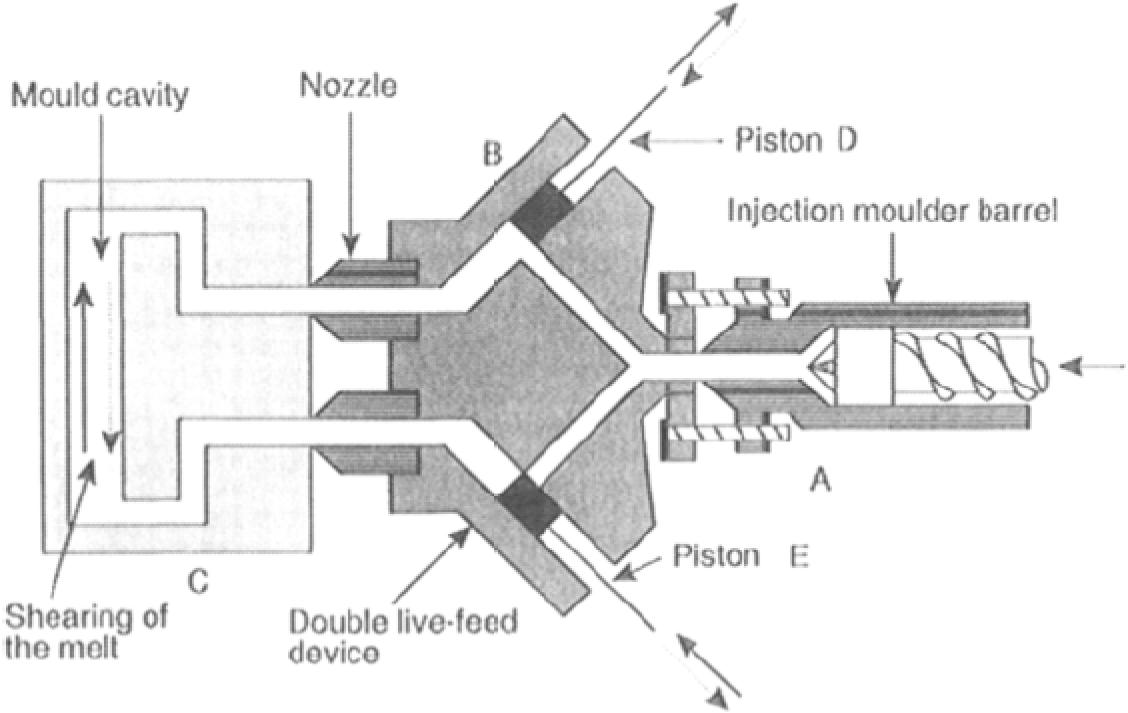
With the gas injection process, laminar flow is considerably reduced and a uniform pressure is maintained. The difficulty of transmitting a very high pressure uniformly throughout a moulding can also cause inconsistent volumetric shrinkage of the polymer, and this leads to isolated surface sink marks. Whilst cycle times are comparable with those of conventional injection moulding, clamping forces are much lower. Also, by using gas to core out the polymer instead of mixing with it, gas-injection overcomes a number of shortcomings of the structural foam process. In particular there are no surface imperfections (caused by escaping gas bubbles in structural foam moulding) and cycle times are lower because thinner sections are being cooled.

Stages in the gas injection moulding of an automotive handle



Shear Controlled Orientation in Injection Moulding (SCORIM)

One of the major innovations in recent years is the use of pulsed pressure through the gates to introduce and control the orientation of the structure (or fillers) in injection moulded products. A special manifold is attached to the machine nozzle as illustrated in Fig. 4.46. This diagram relates to the *double live feed of melt although up to four pistons, capable of applying oscillating* pressure may be used.



One embodiment of SCORIM where the device (B) for producing shear during solidification, by the action of pistons (D) and (E), is placed between the injection moulding machine barrel (A) and the mould ©

Structural Foam Moulding

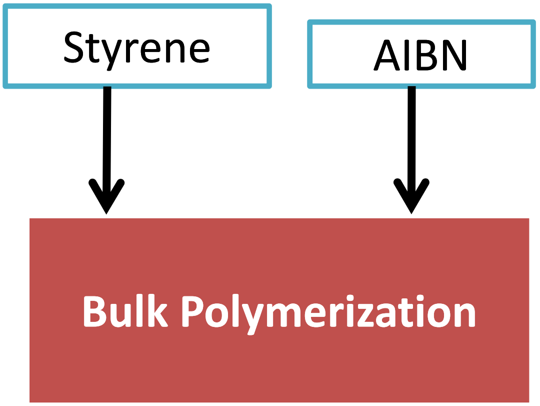
EXPANDED / FOAMED POLYSTYRENE(XPS)

Structural Foam is a term commonly used to describe thermoplastic injection moulding components made by the injection moulding process which have a cellular core.

MANUFACTURING PROCESS

1) Bulk Process –

Expansion and polymerisation occur simultaneously.

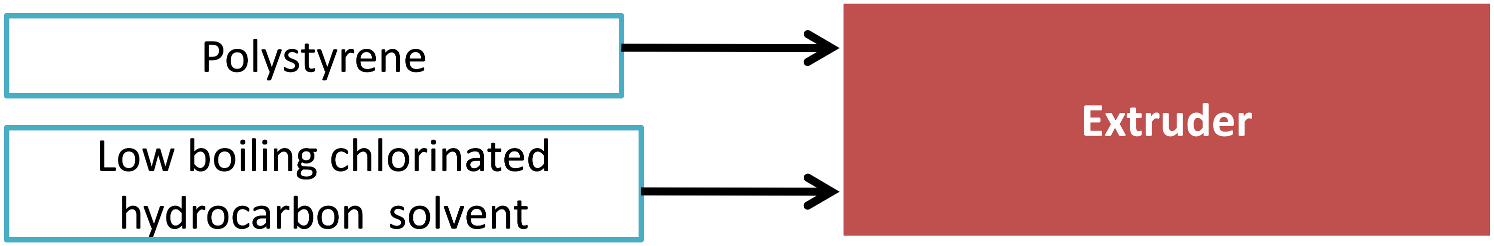


Styrene

AIBN

Bulk Polymerization

2) **The Dow ‘Log’ Process** –



Polystyrene

Low boiling chlorinated hydrocarbon solvent

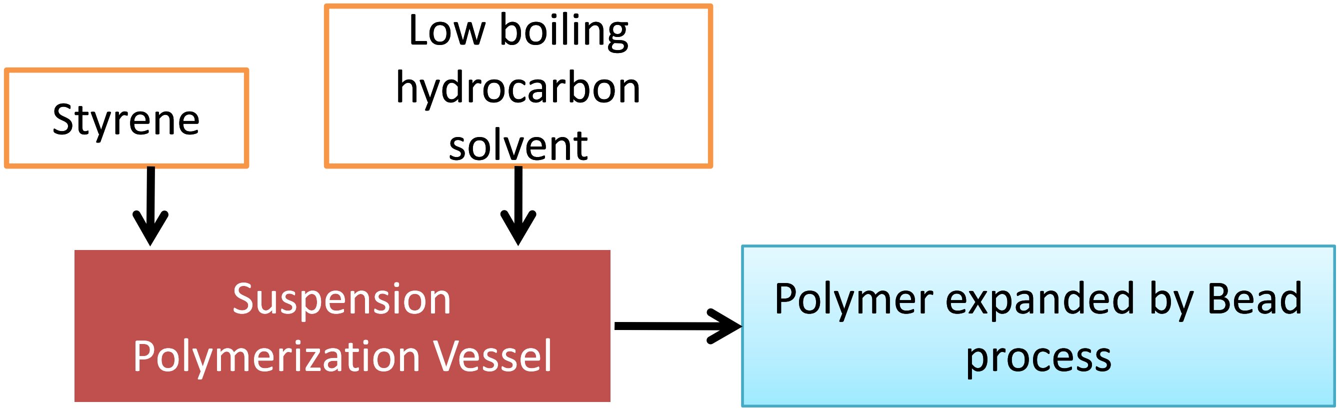
Extruder

The solvent volatilizes as the blend emerges from the die and the mass expands.

EXPANDED / FOAMED POLYSTYRENE(XPS)

MANUFACTURING PROCESS(Contd.)

3) **The BASF Process** –


Styrene

Low boiling hydrocarbon solvent

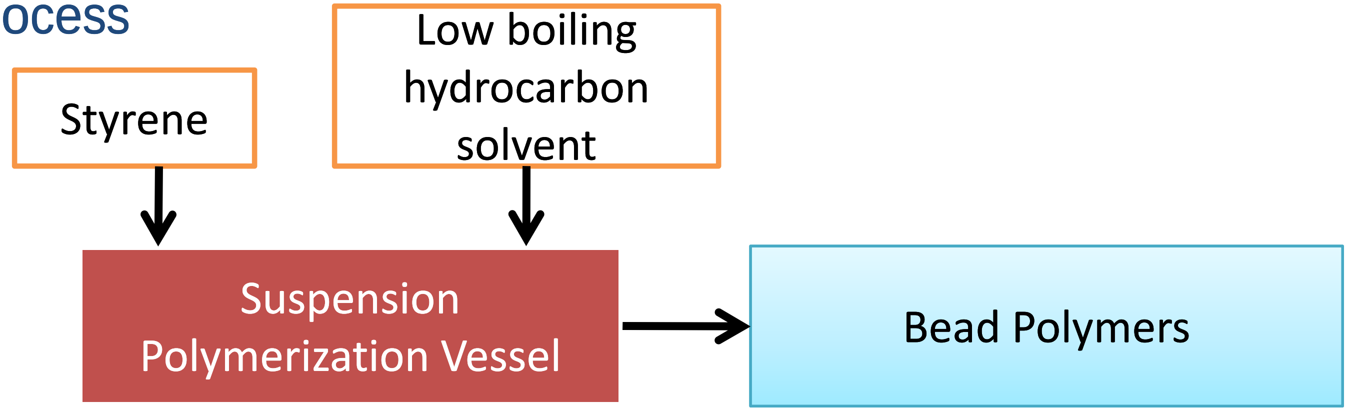
Suspension Polymerization Vessel

Polymer expanded by Bead process

4) **Bead Processes** –

Two stage process

Stage I


Styrene

Low boiling hydrocarbon solvent

Suspension Polymerization Vessel

Bead Polymers

Low Boiling Hydrocarbon like n-pentane

EXPANDED / FOAMED POLYSTYRENE(XPS)

MANUFACTURING PROCESS(Contd.)

Stage II

Bead expansion by

(a) the steam moulding process, OR

(b) direct injection moulding or extrusion.

Steam Moulding Process

✓ Beads are first ‘prefoamed’ **by heating** them in a steam bath - beads to expand to about 40 times but should not fuse or stick together in any way. Expansion is due to volatilisation of the low boiling liquid and steam diffusion .

✓ Prefoamed beads charged into mould with perforated top, bottom and sides through which steam are blown.

✓ The beads soften, air within the cells expands on heating, and steam once again permeates into the cells. In consequence the beads expand and, being enclosed in the fixed volume of the mould, consolidate into a solid block

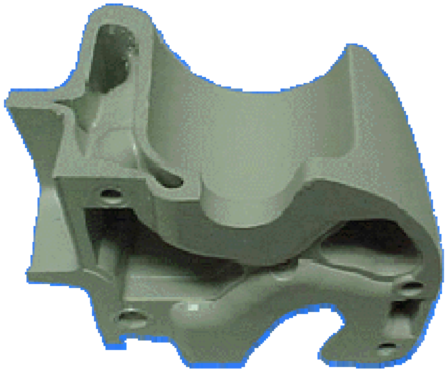
Characteristics of XPS

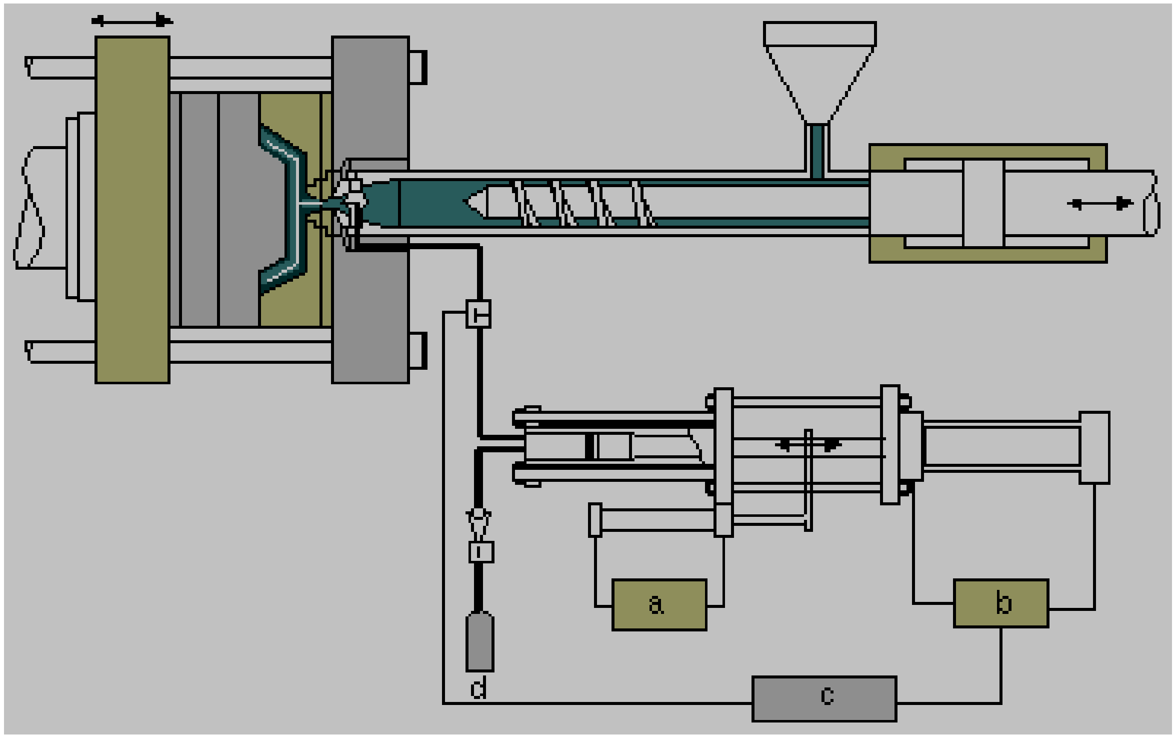
✓Expanded product with densities of 0.016 - 0.24 g/cm^3

✓Very low thermal conductivity(0.031 W/mK)

✓ Very good sound insulation

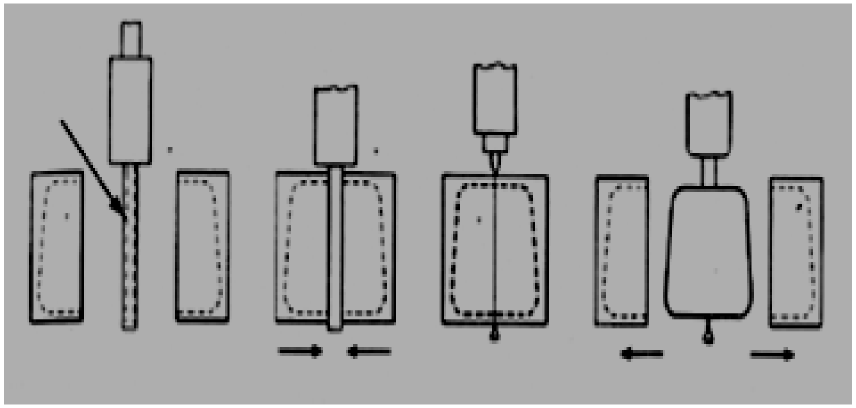
Gas Assist Injection Molding – Hollow parts without interior control



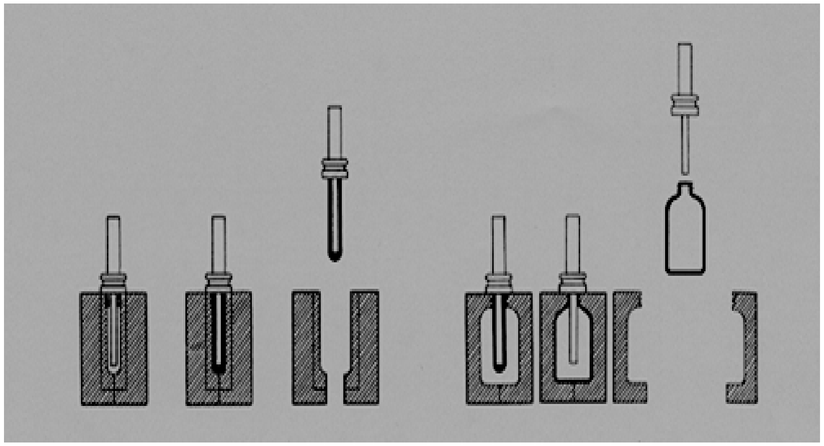


Blow Molding

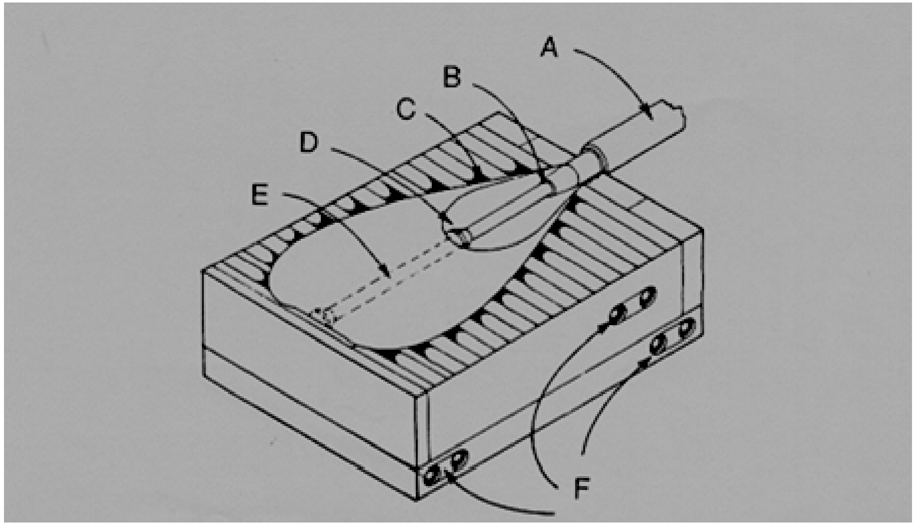
Blow Molding



Extrusion Blow Molding



Injection Blow Molding



Stretch (Parasin) Blow Molding

Blow Molding Cost Analysis

500 ml bottle – using a preform	Cost per bottle	500 ml bottle – direct form mfg	Cost per bottle
Preform	$0.040	Bottle	$0.12
Shipping (500,000 per container @ $3000 per 40')	$0.006	Shipping (50,000 per container @ $3000 per 40’)	$0.06
Labor ($12 per hour)	$0.004		
Waste (5%)	$0.002		
Electricity ($0.20 per Kwh)	$0.004		
TOTAL	$0.056	TOTAL	$0.18

Rotational Moulding

Rotational moulding, like blow moulding, is used to produce hollow plastic articles. However, the principles in each method are quite different. In rotational moulding a carefully weighed charge of plastic powder is placed in one half of a metal mould. The mould halves are then clamped together and heated in an oven. During the heating stage the mould is rotated about two axes at fight angles to each other. After a time the plastic will be sufficiently softened to form a homogeneous layer on the surface of the mould. The latter is then cooled while still being rotated. The final stage is to take the moulded article from the mould.

The process was originally developed in the 1940s for use with vinyl plastisols in liquid form. It was not until the 1950s that polyethylene powders were successfully moulded in this way. Nowadays a range of materials such as nylon, polycarbonate, ABS, high impact polystyrene and polypropylene can be moulded but by far the most common material is polyethylene.

The process is attractive for a number of reasons. Firstly, since it is a low pressure process the moulds are generally simple and relatively inexpensive. Also the moulded articles can have a very uniform thickness, can contain reinforcement, are virtually strain free and their surface can be textured if desired. The use of this moulding method is growing steadily because although the cycle times are slow compared with injection or blow moulding, it can produce very large, thick walled articles which could not be produced economically by any other technique. Wall thicknesses of 10 mm are not a problem for rotationally moulded articles.

There is a variety of ways in which the cycle of events described above may be carried out. For example, in some cases (particularly for very large articles) the whole process takes place in one oven. However, a more common set-up is illustrated in Fig. 4.59. The mould is on the end of an arm which first carries the cold mould containing the powder into a heated oven. During heating the mould rotates about the arm (major) axis and also about its own (minor) axis (see Fig. 4.60). After a pre-set time in the oven the arm brings the mould into a cooling chamber. The rate of cooling is very important. Clearly, fast cooling is desirable for economic reasons but this may cause problems such as warping. Normally therefore the mould is initially cooled using blown air and this is followed by a water spray. The rate of cooling has such a major effect on product quality that even the direction of the air jets on the mould during the initial gradual cooling stage can decide the success or otherwise of the process. As shown in Fig. 4.59 there are normally three arms (mould holders) in a complete system so that as one is being heated another is being cooled and so on. In many machines the arms are fixed rigidly together and so the slowest event (heating, cooling or charging/discharging) dictates when the moulds progress to the next station. In some modem machines, the arms are independent so that if cooling is completed then that arm can leave the cooling bay whilst the other arms remain in position.

It is important to realise that rotational moulding is not a centrifugal casting technique. The rotational speeds are generally below 20 rev/min with the ratio of speeds about the major and minor axes being typically 4 to 1. Also since all mould surfaces are not equidistant from the centre of rotation any centrifugal forces generated would tend to cause large variations in wall thickness. In fact in order to ensure uniformity of all thickness it is normal design practice to arrange that the point of intersection of the major and minor axis does not coincide with the centroid of the mould.

The heating of rotational moulds may be achieved using infra-red, hot liquid, open gas flame or hot-air convection. However, the latter method is the most common. The oven temperature is usually in the range 250-450°C and since the mould is cool when it enters the oven it takes a certain time to get up to a temperature which will melt the plastic. This time may be estimated as follows.

When the mould is placed in the heated oven, the heat input (or loss) per unit time must be equal to the change in internal energy of the material (in this case the mould).

$$hA(T_0 - T) = \rho C_p V \left(\frac{dT}{dt}\right)$$

where h is the convective heat transfer coefficient
A is the surface area of mould
T_0 is the temperature of the oven
T_t is the temperature of the mould at time t
ρ is the density of the mould material
C_p is the specific heat of the mould material
V is the volume of the walls of the mould
and t is time

Rearranging this equation and integrating then

$$hA \int_0^t dt = \rho C_p V \int_{T_i}^{T_t} \frac{dT}{(T_0 - T)}$$

$$hAt = -\rho C_p V \log_e \left(\frac{T_0 - T_t}{T_0 - T_i}\right)$$

$$\left(\frac{T_0 - T_t}{T_0 - T_i}\right) = \exp\left[-h\beta\left(\frac{t}{\rho}\right) C_p\right]$$

where T is the initial temperature of the mould and β is the surface area to volume ratio (A/V).

This equation suggests that there is an exponential rise in mould temperature when it enters the oven, and in practice this is often found to be the case.

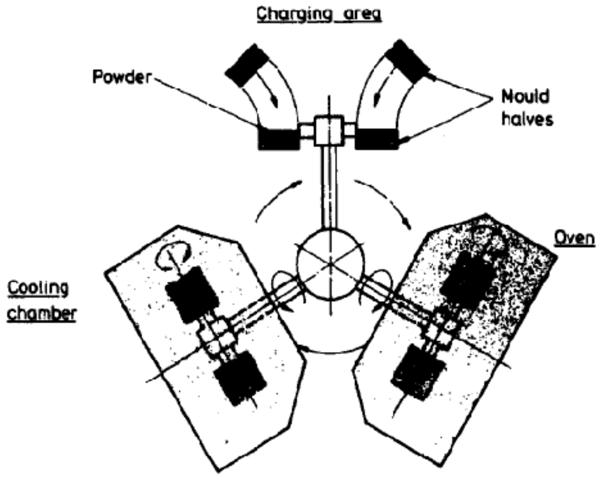


Fig. 4.59 Typical rotational moulding process

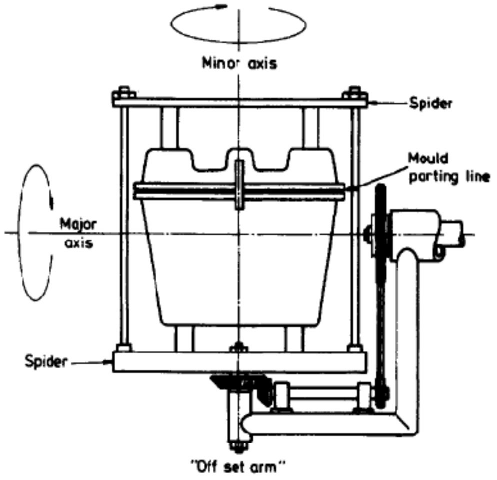


Fig. 4.60 Typical 'off-set arm' rotation

$T_0 = 300°C$, $T_i = 30°C$, $T_t = 20°C$
$h = 22\ W/m^2K$ $C_p = 917\ J/kg\ K$, $\rho = 2700\ kg/m^3$

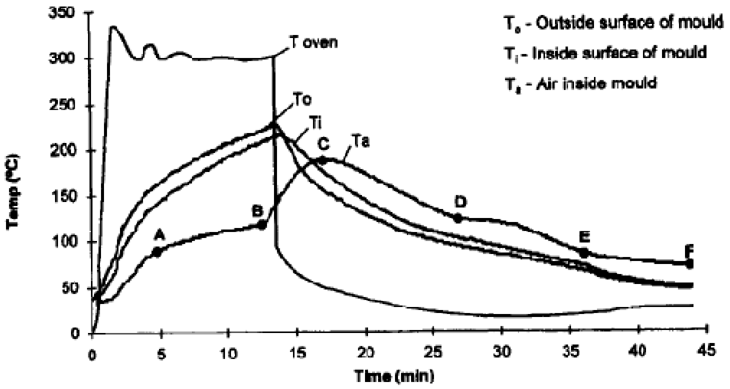


Fig. 4.61 Temperature profiles during rotational moulding

then for an aluminium cube mould 330 mm side and 6 mm thick, as was used to produce Fig. 4.61 then

$$t = \frac{-\rho C_p}{\beta h} \log_e \left\{ \frac{T_o - T_t}{T_o - T_i} \right\} = \frac{-2700 \times 917}{1000 \times 22} \log_e \left\{ \frac{330 - 220}{330 - 30} \right\}$$

$$t = 1.9 \text{ minutes}$$

For a steel mould of the same dimensions and thickness, a quick calculation ($h = 11$ W/m^{2}K, $Cp = 480$ J/kg.K and $\rho = 7850$ kg/m^3) shows that the steel mould would take three times longer to heat up. However, in practice, steel moulds are less than a third of the thickness of aluminium. Therefore, although aluminium has a better thermal conductivity, steel moulds tend to heat up more quickly because they are thinner.

It is important to note that the above calculation is an approximation for the time taken to heat the mould to any desired temperature. Fig. 4.61 shows that in practice it takes considerably longer for the mould temperature to get to 220°C. This is because although initially the mould temperature is rising at the rate predicted in the above calculation, once the plastic starts to melt, it absorbs a significant amount of the thermal energy input.

Fig. 4.61 illustrates that the mould temperature is quite different from the set oven temperature (330°C or indeed the actual oven temperature, throughout the moulding cycle. An even more important observation is that in order to control the rotational moulding process it is desirable to monitor the temperature of the air inside the mould. This is possible because there is normally a vent tube through the mould wall in order to ensure equal pressures inside and outside the mould. This vent tube provides an easy access for a thermocouple to measure the internal air temperature.

The internal air temperature characteristic has a unique shape, which shows clearly what is happening at all stages throughout the process. **Up to point A** in Fig. 4.61 there is simply **powder tumbling** about inside the mould. **At point A**, the mould has become sufficiently hot that plastic starts **to melt and stick to the mould**. The **melting process absorbs energy** and so over the region AB, the **internal air temperature rises less quickly**. It may also be seen that the temperature of the mould now starts to rise less quickly. **At B, all the plastic has melted** and so a larger proportion of the thermal energy input goes to heating the inner air. This temperature rises more rapidly again, at a rate similar to that in the initial phase of the process.

Over **the region BC** the **melt is effectively sintering** because **at B** it is a powdery mass loosely **fused** together whereas **at C it has become a uniform melt**. The value of temperature and duration at C is very important because if the oven period is too short, then the material will not have sintered properly and there will be an excess of **pin-holes**. These are caused where the powder particles have fused together and trapped a pocket of air. If the oven period is too long then the pin-holes will all have disappeared but **thermal/oxidative degradation** will have started at the inner surface of the moulding. Extensive tests have shown that this is a source of brittleness in the mouldings and so the correct choice of temperature at C is a very important quality control parameter. For most grades of polyethylene the **optimum temperature** is in the region of **200±5°C**

Once the mould is removed from the oven the mould starts to cool at a rate determined by the type of cooling- blown air (slow) or water spray (fast). There may be a overshoot in the internal air temperature due to the thermal momentum of the melt. This overshoot will depend on the wall thickness of the plastic product. In Fig. 4.61 it may be seen that the inner air temperature continues to rise for several minutes after the mould has been taken out of the oven (at about 13.5 minutes).

During cooling, a **point D** is reached where the internal air temperature decreases less quickly for a period. This represents the **solidification of the plastic** and because this process is exothermic, the inner air cannot cool so quickly. Once solidification is complete, the inner air cools more rapidly again. Another kink (**point E**) may appear in this cooling curve and, if so, it represents the point where the **moulding has separated from the mould wall**. In practice this is an important point to keep consistent because it affects shrinkage, warpage, etc in the final product. Once the moulding separates from the mould, it will cool more slowly and will tend to be more crystalline, have greater shrinkage and lower impact strength.

Developments in rotational moulding are continuing, with the ever increasing use of features such as

i) mould pressurisation (to consolidate the melt, remove pin-holes, reduce cycle times and provide more consistent mould release),

ii) internal heating/cooling (to increase cycle times and reduce warpage effects).

In overall terms the **disadvantages** of rotational moulding are its relative slowness and the limited choice of plastics which are commercially available in powder form with the correct additive package. However, the **advantages** of rotational moulding in terms of stress-free moulding, low mould costs, fast lead times and easy control over wall thickness distribution (relative to blow moulding) means that currently rotational moulding is the fastest growing sector of the plastics processing industry. Typical annual growth rates are between 10 and 12% p.a.

Thermoforming

When a thermoplastic sheet is heated it becomes soft and pliable and the techniques for shaping this sheet are known as thermoforming. This method of manufacturing plastic articles developed in the 1950s but limitations such as poor wall thickness distribution and large peripheral waste restricted its use to simple packaging applications. In recent years, however, there have been major advances in machine design and material availability with the result that although packaging is still the major market sector for the process, a wide range of other products are made by thermoforming. These include aircraft window reveals, refrigerator liners, baths, switch panels, car bumpers, motorbike fairings etc.

The term 'thermoforming' incoroporates a wide range of possibilities for sheet forming but basically there are two sub-divisions - vacuum forming and pressure forming.

(a) Vacuum Forming

In this processing method a sheet of thermoplastic material is heated and then shaped by reducing the air pressure between it and a mould. The simplest type of vacuum forming is illustrated in Fig. 4.51 (a). This is referred to as *Negative Forming* and is capable of providing a depth of draw which is 1/3-1/2 of the maximum width. The principle is very simple. A sheet of plastic, which may range in thickness from 0.025 mm to 6.5 mm, is clamped over the open mould.

A heater panel is then placed above the sheet and when sufficient softening has occurred the heater is removed and the vacuum is applied. For the thicker sheets it is essential to have heating from both sides. In some cases Negative Forming would not be suitable because, for example, the shape formed in Fig. 4.51 would have a wall thickness in the comers which is considerably less than that close to the clamp. If this was not acceptable then the same basic shape could be produced by *Positive Forming. In* this case a male (positive) mould is pushed into the heated sheet before the vacuum is applied. This gives a better distribution of material and deeper shapes can be formed - depth to width ratios of 1:1 are possible. This thermoforming method is also referred to as ***Drape Forming***. Another alternative would be to have a female mould as in Fig. 4.51 but after the heating stage and before the vacuum is applied, a plug comes down and guides the sheet into the cavity. When the vacuum is applied the base of the moulding is subjected to less draw and the result is a more uniform wall thickness distribution. This is called

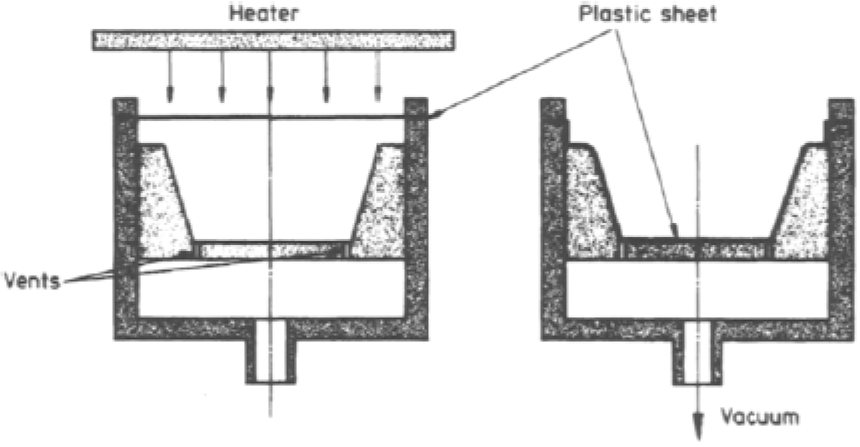


Fig. 4.51 Vacuum forming process

Plug Assisted Forming. Note that both Positive Forming and Plug Assisted Forming effectively apply a pre-stretch to the plastic sheet which improves the performance of the material quite apart from the improved wall thickness distribution.

In the packaging industry *skin* and *blister* vacuum machines are used. Skin packaging involves the encapsulation of articles between a fight, flexible transparent skin and a rigid backing which is usually cardboard. Blister packs are preformed foils which are sealed to a rigid backing card when the goods have been inserted.

The heaters used in thermoforming are usually of the infra red type with typical loadings of between 10 and 30 kW/m^2. Normally extra heat is concentrated at the clamped edges of the sheet to compensate for the additional heat losses in this region. The key to successful vacuum forming is achieving uniform heating over the sheet. One of the major attractions of vacuum forming is that since only atmospheric pressure is used to do the shaping, the moulds do not have to be very strong. Materials such as plaster, wood and thermosetting resins have all been used successfully. However, in long production runs mould cooling becomes essential in which case a metal mould is necessary. Experience has shown that the most satisfactory metal is undoubtedly aluminium. It is easily shaped, has good thermal conductivity, can be highly polished and has an almost unlimited life.

Materials which can be vacuum formed satisfactorily include polystyrene, ABS, PVC, acrylic, polycarbonate, polypropylene and high and low density polyethylene. Co-extruded sheets of different plastics and multi-colour laminates are also widely used nowadays. One of the most recent developments is the thermoforming of crystalisable PET for high temperature applications such as oven trays. The PET sheet is manufactured in the amorphous form and then during thermoforming it is permitted to crystallise. The resulting moulding is thus capable of remaining stiff at elevated temperatures.

(b) Pressure Forming

This is generally similar to vacuum forming except that pressure is applied above the sheet rather than vacuum below it. This advantage of this is that higher pressures can be used to form the sheet. A typical system is illustrated in Fig. 4.52 and in recent times this has become attractive as an alternative to injection moulding for moulding large area articles such as machine housings.

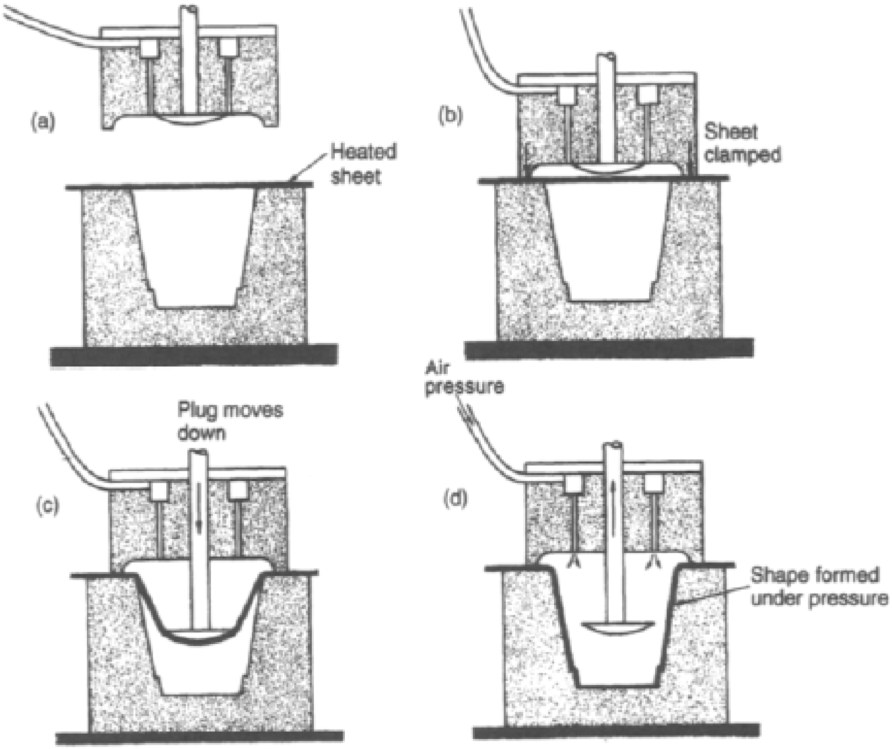


Fig. 4.52 Pressure forming process

(c) Matched Die Forming

A variation of thermoforming which does not involve gas pressure or vacuum is matched die forming. The concept is very simple and is illustrated in Fig. 4.53. The plastic sheet is heated as described previously and is then sandwiched between two halves of a mould. Very precise detail can be reproduced using this thermoforming method but the moulds need to be more robust than for the more conventional process involving gas pressure or vacuum.

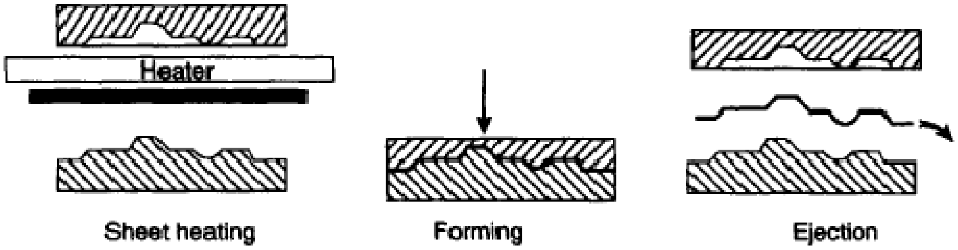


Fig. 4.53 Thermoforming between matched dies

(d) Dual-Sheet Thermoforming

This technique, also known as Twin-Sheet Forming, is a recent development. It is essentially a hybrid of blow moulding and thermoforming. Two heated sheets are placed between two mould halves and clamped as shown in Fig. 4.54. An inflation tube at the parting line then injects gas under pressure so that the sheets are forced out against the mould. Alternatively, a vacuum can be drawn between the plastic sheet and the mould in each half of the system. This technique has interesting possibilities for further development and will compete with blow moulding, injection moulding and rotational moulding in a number of market sectors. It can be noted that the two mould halves can be of different shapes and the two plastic sheets could be of different materials, provided a good weld can be obtained at the parting line.

Analysis of Thermoforming

If a thermoplastic sheet is softened by heat and then pressure is applied to one of the sides so as to generate a freely blown surface, it will be found that the shape so formed has a uniform thickness. If this was the case during thermoforming, then a simple volume balance between the original sheet and the final shape could provide the wall thickness of the end product.

$$A_i h_i = A_f h_f \qquad (4.28)$$

where A = surface area, and h = wall thickness ('i' and ' f ' refer to initial and final conditions).

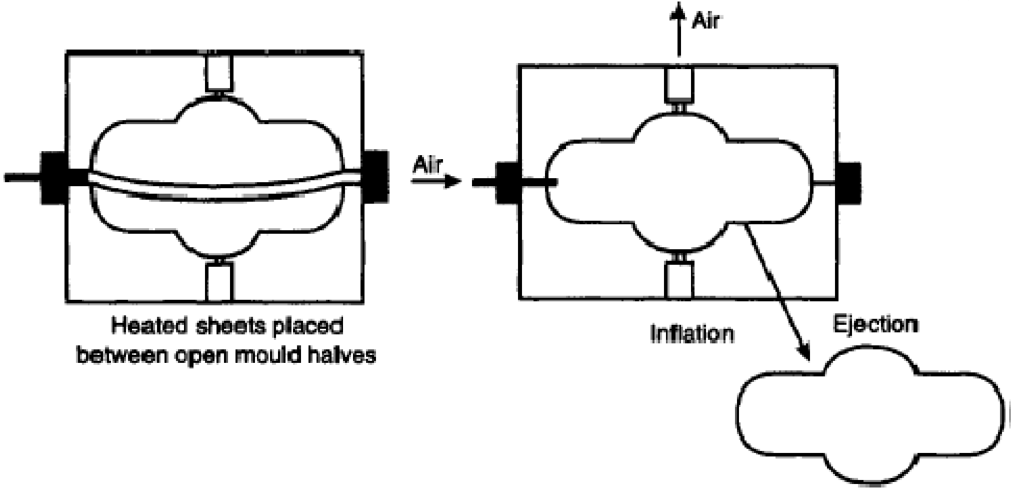


Fig. 4.54 Dual sheet forming

Example 4.7 A rectangular box 150 mm long, 100 mm wide and 60 mm deep is to be thermoformed from a flat sheet 150 mm x 100 mm x 2 mm. Estimate the average thickness of the walls of the final product if (a) conventional vacuum forming is used and (b) plug assisted moulding is used (the plug being 140 mm x 90 mm).

Solution

(a) The initial volume of the sheet is given by

$$A_i h_i = 150 \times 100 \times 2 = 3 \times 10^4 \text{ mm}^3$$

The surface area of the final product is

$$\begin{aligned} A_f &= (150 \times 100) + 2(100 \times 60) + 2(150 \times 60) \\ &= 4.5 \times 10^4 \text{ mm}^2 \end{aligned}$$

Therefore, from equation (4.28)

$$h_f = \frac{3 \times 10^4}{4.5 \times 10^4} = 0.67 \text{ mm}$$

(b) If plug assist is used then it could be assumed that over the area 140 mm × 90 mm, the wall thickness will remain at 2 mm. The volume of this part of the moulding will be

$$\text{Vol} = 140 \times 90 \times 2 = 2.52 \times 10^4 \text{ mm}^3$$

This would leave a volume of $(3 \times 10^4 - 2.52 \times 10^4)$ to form the walls. The area of the walls is

$$A_w = (2 \times 100 \times 60) + (2 \times 150 \times 60) = 3 \times 10^4 \text{ mm}^2$$

This ignores a small area in the base of the box, outside the edges of the plug. Hence, the thickness of the walls in this case would be

$$h_w = \frac{(3 \times 10^4) - (2.52 \times 10^4)}{3 \times 10^4} = 0.16 \text{ mm}$$

These calculations can give a useful first approximation of the dimensions of a thermoformed part. However, they will not be strictly accurate because in a real situation, when the plastic sheet is being stretched down into the cold mould it will freeze off at whatever thickness it has reached when it touches the mould.

Compression Moulding

Compression moulding is one of the most common methods used to produce articles from thermosetting plastics. The process can also be used for thermoplastics but this is less common - the most familiar example is the production of LP records. The moulding operation as used for thermosets is illustrated in Fig. 4.62. A pre-weighed charge of partially polymerised thermoset is placed in the lower half of a heated mould and the upper half is then forced down. This causes the material to be squeezed out to take the shape of the mould. The application of the heat and pressure accelerates the polymerisation of the thermoset and once the crosslinking ('curing') is completed the article is solid and may be ejected while still very hot. Mould temperatures are usually in the range of 130-200°C. Cycle times may be long (possibly several minutes) so it is desirable to have multi-cavity moulds to increase production rates. As a result, moulds usually have a large projected area so the closing force needed could be in the region of 100-500 tonnes to give the 7-25 MN/m^2 cavity pressure needed. It should also be noted that compression moulding is also used for Dough Moulding Compounds (DMC).

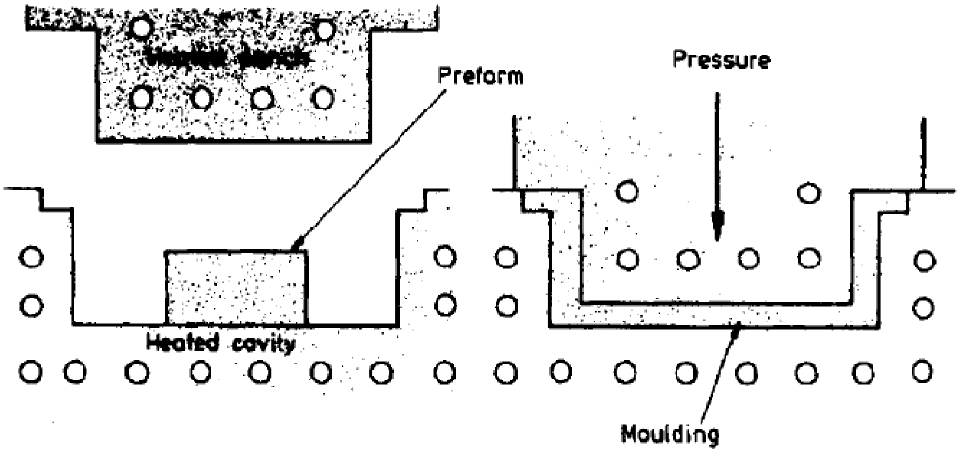


Fig. 4.62 Principle of compression moulding

There are two different types of compounds most frequently used in compression molding: Bulk Molding Compound (BMC) and Sheet Molding Compound (SMC). SMC costs higher but can be pre-cut to conform to the surface area of the mold. The more evenly distributed material over the mold surface usually results in less flow orientation during the compression stage and, therefore, higher product consistency.

There are four primary factors in a successful compression molding process:

- Amount of material
- Heating time and technique
- Force applied to the mold
- Cooling time and technique

Pros

- Low initial setup costs
- Fast setup time
- Capable of large size parts beyond the capacity of extrusion techniques
- Allows intricate parts
- Good surface finish (in general)
- Wastes relatively little material
- Can apply to composite thermoplastics with unidirectional tapes, woven fabrics, randomly orientated fiber mat or chopped strand
- Compression molding produces fewer knit lines and less fiber-length degradation than injection molding.

Cons

- Production speed is not up to injection molding standards
- Limited largely to flat or moderately curved parts with no undercuts
- Less-than-ideal product consistency

During compression moulding, the charge of material may be put into the mould either as a powder or a preformed 'cake'. In both cases the material is preheated to reduce the temperature difference between it and the mould. If the material is at a uniform temperature in the mould then the process may be analysed as follows.

Consider a 'cake' of moulding resin between the compression platens as shown in Fig. 4.63. When a constant force, F, is applied to the upper platen the resin flows as a result of a pressure gradient. If the flow is assumed Newtonian then the pressure flow equation derived in Section 4.2.3 may be used

$$\text{flow rate, } Q_p = \frac{1}{12\eta}\left(\frac{dP}{dz}\right)TH^3$$

For the annular element of radius, r, in Fig. 4.63 it is more convenient to use cylindrical co-ordinates so this equation may be rewritten as

$$Q_p = \frac{1}{12\eta}\left(\frac{dP}{dr}\right)\cdot(2\pi r)H^3$$

Now if the top platen moves down by a distance, *dH, the* volume displaced is $(\pi r^2 dH)$ and the volume flow rate is $\pi r^2(dH/dt)$. Therefore,

$$\pi r^2\left(\frac{dH}{dt}\right) = \frac{1}{12\eta}\left(\frac{dP}{dr}\right)\cdot(2\pi r)H^3$$

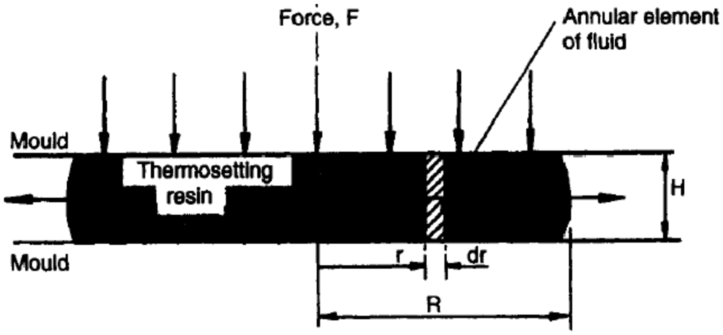


Fig. 4.63 Analysis of compression moulding

$$\frac{12\eta}{H^3}\cdot\frac{dH}{dt} = \frac{2}{r}\frac{dP}{dr} \tag{4.44}$$

This simple differential equation is separable and so each side may be solved in turn.

Let $\qquad \frac{2}{r}\frac{dP}{dr} = A$ where $A = f(H)$

so $\qquad \int_0^P dP = \frac{A}{2}\int_R^r r\,dr$

or $\qquad P = \frac{A}{4}(r^2 - R^2)$

Now the force on the element is $2\pi r dr(P)$ so the total force, F, is given by integrating across the platen surface.

$$F = \int_0^R 2\pi r\left(\frac{A}{4}\right)(r^2 - R^2)dr = -\frac{\pi A R^4}{8}$$

This may be rearranged to give

$$A = -\frac{8F}{\pi R^4} = -\frac{8\pi F H^2}{V^2}$$

where $V = \pi R^2 H$

Substituting for A in (4.44)

$$-\frac{8\pi F H^2}{V^2} = \frac{12\eta}{H^3}\frac{dH}{dt}$$

So
$$-\int_0^t \frac{2\pi F}{3\eta V^2}dt = \int_{H_0}^{H} \frac{dH}{H^5}$$

$$\frac{2\pi F t}{3\eta V^2} = \frac{1}{4}\left(\frac{1}{H^4} - \frac{1}{H_0^4}\right)$$

Since $H_0 >> H$ then $(1/H_0^4)$ may be neglected. As a result the compaction force F, is given by

$$F = \frac{3\eta V^2}{8\pi t H^4} \tag{4.45}$$

where H is the platen separation at time, t.

Example 4.10 A circular plate with a diameter of 0.3 m is to be compression moulded from phenol formaldehyde. If the preform is cylindrical with a diameter of 50 mm and a depth of 36 mm estimate the platen force needed to produce the plate in 10 seconds. The viscosity of the phenol may be taken as 10^3Ns/m^2.

Solution

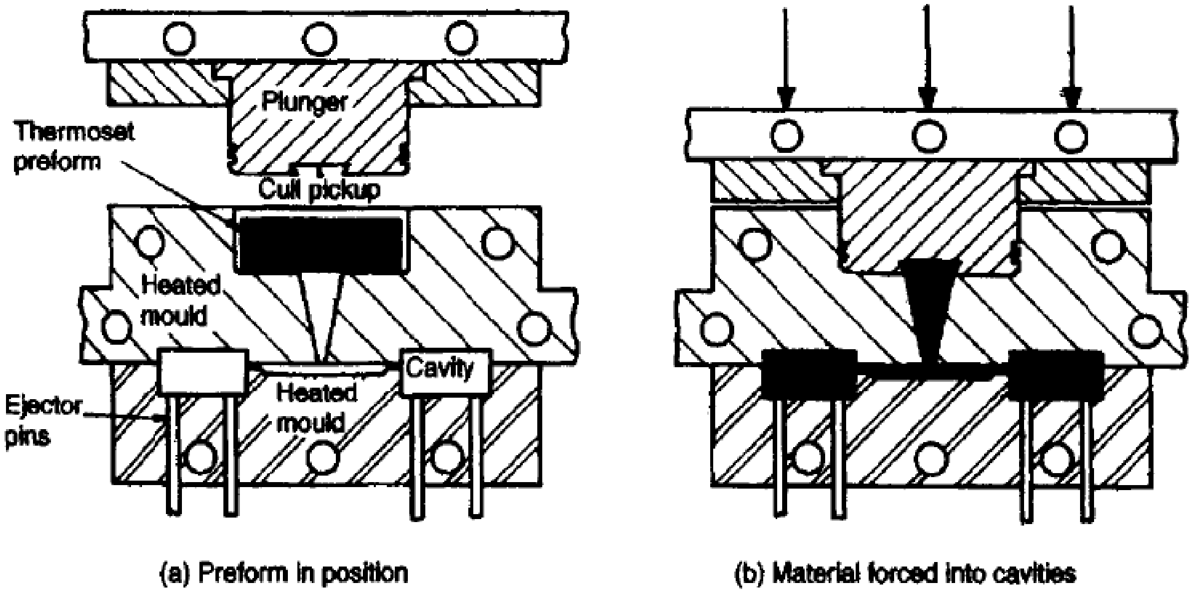
Volume, $V = \pi\left(\frac{50}{2}\right)^2 \times 36 = \pi\left(\frac{300}{2}\right)^2 H$

So $H = 1$ mm

From (4.45) $F = \frac{3\eta V^2}{8\pi t H^4} = \frac{3 \times 10^3 \times (\pi \times 625 \times 36)^2}{10^6 \times 8\pi \times 10 \times (1)^4} = 59.6$ kN

Transfer Moulding

Transfer moulding is similar to compression moulding except that instead of the moulding material being pressurized in the cavity, it is pressurized in a separate chamber and then forced through an opening and into a closed mould. Transfer moulds usually have multi-cavities as shown in Fig. 4.64. The advantages of transfer moulding are that the preheating of the material and injection through a narrow orifice improves the temperature distribution in the material and accelerates the crosslinking reaction. As a result the cycle times are reduced and there is less distortion of the mouldings. The improved flow of the material also means that more intricate shapes can be produced.



(a) Preform in position

(b) Material forced into cavities

Fig. 4.64 Transfer moulding of thermosetting materials