

CHAPTER 4 – Processing of Plastics

4.1 Introduction

One of the most outstanding features of plastics is the ease with which they can be processed. In some cases semi-finished articles such as sheets or rods are produced and subsequently fabricated into shape using conventional methods such as welding or machining. In the majority of cases, however, the finished article, which may be quite complex in shape, is produced in a single operation. The processing stages of heating, shaping and cooling may be continuous (eg production of pipe by extrusion) or a repeated cycle of events (eg production of a telephone housing by injection moulding) but in most cases the processes may be automated and so are particularly suitable for mass production. There is a wide range of processing methods which may be used for plastics. In most cases the choice of method is based on the shape of the component and whether it is thermoplastic or thermosetting. It is important therefore that throughout the design process, the designer must have a basic understanding of the range of processing methods for plastics since an ill-conceived shape or design detail may limit the choice of moulding methods.

In this chapter each of the principal processing methods for plastics is described and where appropriate a Newtonian analysis of the process is developed. Although most polymer melt flows are in fact Non-Newtonian, the simplified analysis is useful at this stage because it illustrates the approach to the problem without concealing it by mathematical complexity. In practice the simplified analysis may provide sufficient accuracy for the engineer to make initial design decisions and at least it provides a quantitative aspect which assists in the understanding of the process. For those requiring more accurate models of plastics moulding, these are developed in Chapter 5 where the Non-Newtonian aspects of polymer melt flow are considered.

4.2 Extrusion

4.2.1 General Features of Single Screw Extrusion

One of the most common methods of processing plastics is **Extrusion** using a screw inside a barrel as illustrated in Fig. 4.1. The plastic, usually in the form of granules or powder, is fed from a hopper on to the screw. It is then conveyed along the barrel where it is heated by conduction from the barrel heaters and shear due to its movement along the screw flights. The depth of the screw channel is reduced along the length of the screw so as to compact the material. At the end of the extruder the melt passes through a die to produce an extrudate of the desired shape. As will be seen later, the use of different dies means that the extruder screw/barrel can be used as the basic unit of several processing techniques.

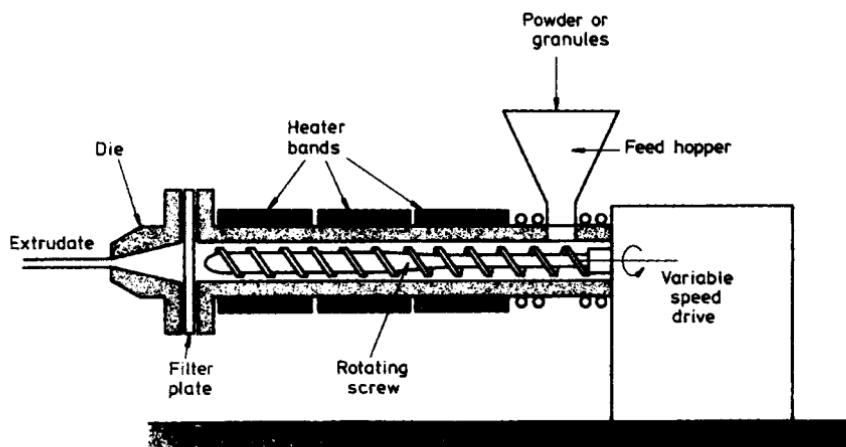


Fig. 4.1 Schematic view of single screw extruder

Basically an extruder screw has three different zones.

(a) Feed Zone The function of this zone is to preheat the plastic and convey it to the subsequent zones. The design of this section is important since the constant screw depth must supply sufficient material to the metering zone so as not to starve it, but on the other hand not supply so much material that the metering zone is overrun. The optimum design is related to the nature and shape of the feedstock, the geometry of the screw and the frictional properties of the screw and barrel in relation to the plastic. The frictional behaviour of the feed-stock material has a considerable influence on the rate of melting which can be achieved.

(b) Compression Zone In this zone the screw depth gradually decreases so as to compact the plastic. This compaction has the dual role of squeezing any

trapped air pockets back into the feed zone and improving the heat transfer through the reduced thickness of material.

(c) Metering Zone In this section the screw depth is again constant but much less than the feed zone. In the metering zone the melt is homogenised so as to supply at a constant rate, material of uniform temperature and pressure to the die. This zone is the most straight-forward to analyse since it involves a viscous melt flowing along a uniform channel.

The pressure build-up which occurs along a screw is illustrated in Fig. 4.2. The lengths of the zones on a particular screw depend on the material to be extruded. With nylon, for example, melting takes place quickly so that the compression of the melt can be performed in one pitch of the screw. PVC on the other hand is very heat sensitive and so a compression zone which covers the whole length of the screw is preferred.

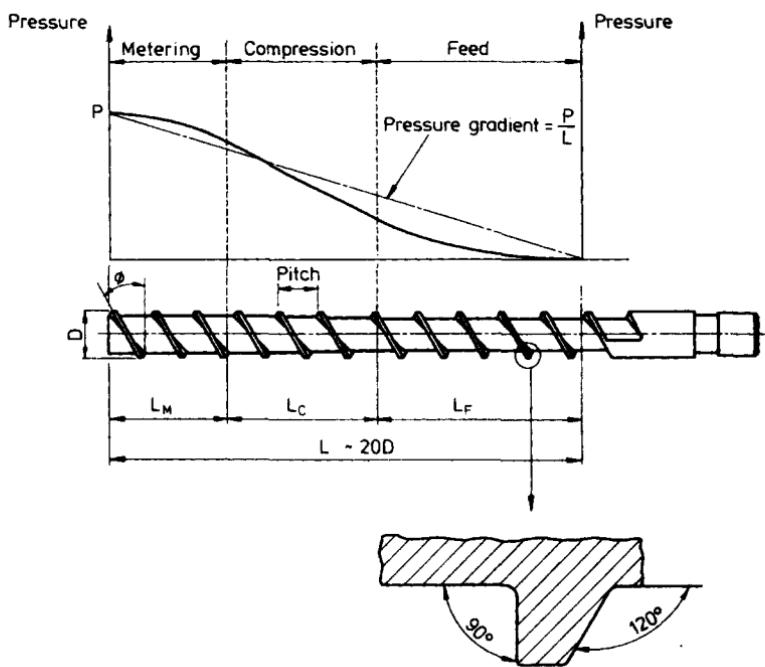


Fig. 4.2 Typical zones on a extruder screw

As plastics can have quite different viscosities, they will tend to behave differently during extrusion. Fig. 4.3 shows some typical outputs possible with different plastics in extruders with a variety of barrel diameters. This diagram is to provide a general idea of the ranking of materials – actual outputs may vary $\pm 25\%$ from those shown, depending on temperatures, screw speeds, etc.

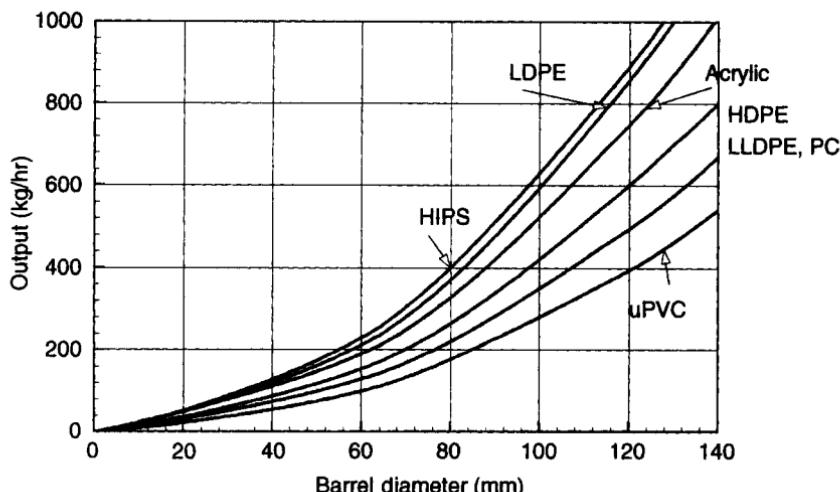


Fig. 4.3 Typical extruder outputs for different plastics

In commercial extruders, additional zones may be included to improve the quality of the output. For example there may be a mixing zone consisting of screw flights of reduced or reversed pitch. The purpose of this zone is to ensure uniformity of the melt and it is sited in the metering section. Fig. 4.4 shows some designs of mixing sections in extruder screws.



Parallel interrupted mixing flights



Undercut spiral barrier-type



Ring - type barrier mixer



RAPRA cavity transfer mixer



Mixing pins

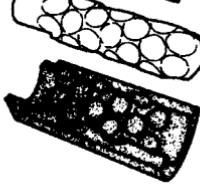


Fig. 4.4 Typical designs of mixing zones

Some extruders also have a venting zone. This is principally because a number of plastics are hygroscopic – they absorb moisture from the atmosphere. If these materials are extruded wet in conventional equipment the quality of the output is not good due to trapped water vapour in the melt. One possibility is to pre-dry the feedstock to the extruder but this is expensive and can lead to contamination. Vented barrels were developed to overcome these problems. As shown in Fig. 4.5, in the first part of the screw the granules are taken in and melted, compressed and homogenised in the usual way. The melt pressure is then reduced to atmospheric pressure in the decompression zone. This allows the volatiles to escape from the melt through a special port in the barrel. The melt is then conveyed along the barrel to a second compression zone which prevents air pockets from being trapped.

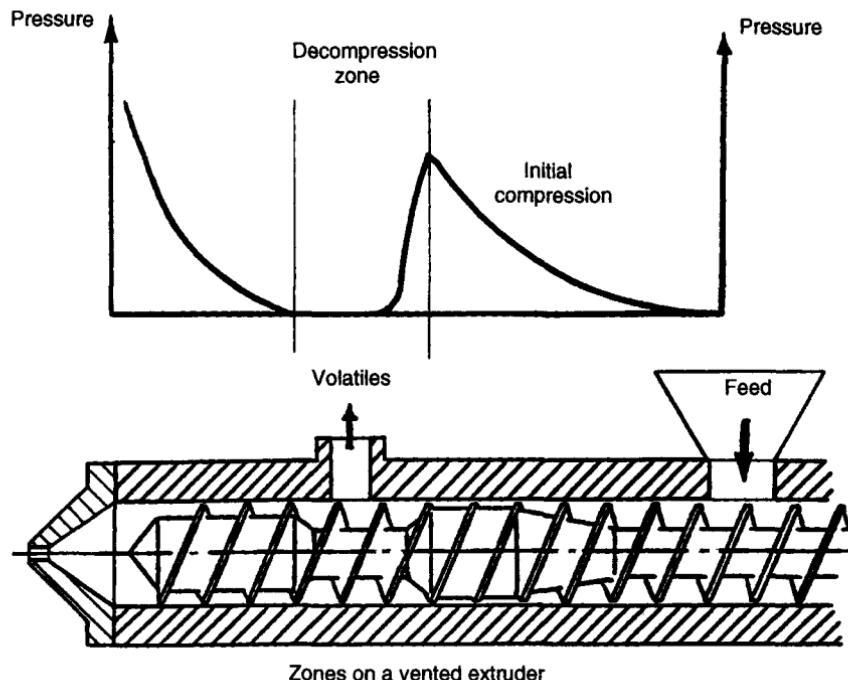


Fig. 4.5 Zones on a vented extruder

The venting works because at a typical extrusion temperature of 250°C the water in the plastic exists as a vapour at a pressure of about 4 MN/m^2 . At this pressure it will easily pass out of the melt and through the exit orifice. Note that since atmospheric pressure is about 0.1 MN/m^2 the application of a vacuum to the exit orifice will have little effect on the removal of volatiles.

Another feature of an extruder is the presence of a gauze filter after the screw and before the die. This effectively filters out any inhomogeneous material which might otherwise clog the die. These *screen packs* as they are called, will normally filter the melt to 120–150 µm. However, there is conclusive evidence to show that even smaller particles than this can initiate cracks in plastics extrudates e.g. polyethylene pressure pipes. In such cases it has been found that fine melt filtration ($\approx 45 \mu\text{m}$) can significantly improve the performance of the extrudate.

Since the filters by their nature tend to be flimsy they are usually supported by a breaker plate. As shown in Fig. 4.6 this consists of a large number of countersunk holes to allow passage of the melt whilst preventing dead spots where particles of melt could gather. The breaker plate also conveniently straightens out the spiralling melt flow which emerges from the screw. Since the fine mesh on the filter will gradually become blocked it is periodically removed and replaced. In many modern extruders, and particularly with the fine filter systems referred to above, the filter is changed automatically so as not to interrupt continuous extrusion.

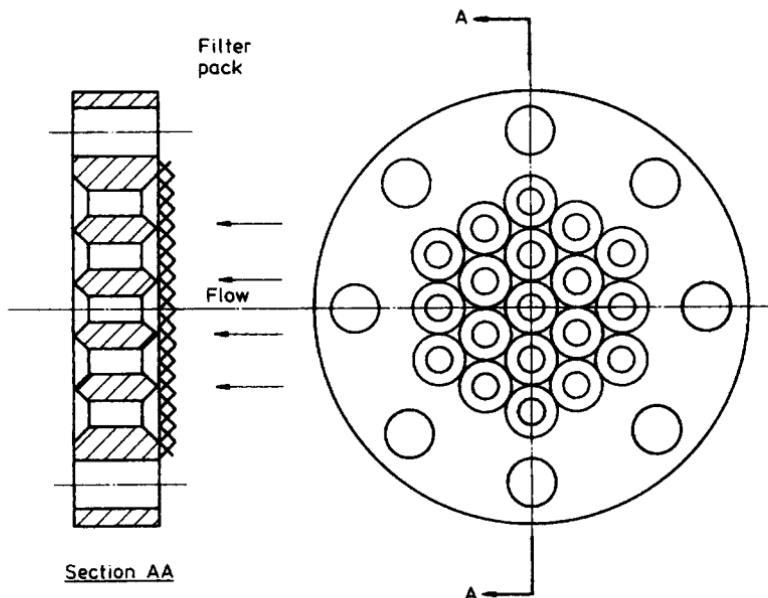


Fig. 4.6 Breaker plate with filter pack

It should also be noted that although it is not their primary function, the breaker plate and filter also assist the build-up of back pressure which improves

mixing along the screw. Since the pressure at the die is important, extruders also have a valve after the breaker plate to provide the necessary control.

4.2.2 Mechanism of Flow

As the plastic moves along the screw, it melts by the following mechanism. Initially a thin film of molten material is formed at the barrel wall. As the screw rotates, it scrapes this film off and the molten plastic moves down the front face of the screw flight. When it reaches the core of the screw it sweeps up again, setting up a rotary movement in front of the leading edge of the screw flight. Initially the screw flight contains solid granules but these tend to be swept into the molten pool by the rotary movement. As the screw rotates, the material passes further along the barrel and more and more solid material is swept into the molten pool until eventually only melted material exists between the screw flights.

As the screw rotates inside the barrel, the movement of the plastic along the screw is dependent on whether or not it adheres to the screw and barrel. In theory there are two extremes. In one case the material sticks to the screw only and therefore the screw and material rotate as a solid cylinder inside the barrel. This would result in zero output and is clearly undesirable. In the second case the material slips on the screw and has a high resistance to rotation inside the barrel. This results in a purely axial movement of the melt and is the ideal situation. In practice the behaviour is somewhere between these limits as the material adheres to both the screw and the barrel. The useful output from the extruder is the result of a drag flow due to the interaction of the rotating screw and stationary barrel. This is equivalent to the flow of a viscous liquid between two parallel plates when one plate is stationary and the other is moving. Superimposed on this is a flow due to the pressure gradient which is built up along the screw. Since the high pressure is at the end of the extruder the pressure flow will reduce the output. In addition, the clearance between the screw flights and the barrel allows material to leak back along the screw and effectively reduces the output. This leakage will be worse when the screw becomes worn.

The external heating and cooling on the extruder also plays an important part in the melting process. In high output extruders the material passes along the barrel so quickly that sufficient heat for melting is generated by the shearing action and the barrel heaters are not required. In these circumstances it is the barrel cooling which is critical if excess heat is generated in the melt. In some cases the screw may also be cooled. This is not intended to influence the melt temperature but rather to reduce the frictional effect between the plastic and the screw. In all extruders, barrel cooling is essential at the feed pocket to ensure an unrestricted supply of feedstock.

The thermal state of the melt in the extruder is frequently compared with two ideal thermodynamic states. One is where the process may be regarded as

adiabatic. This means that the system is fully insulated to prevent heat gain or loss from or to the surroundings. If this ideal state was to be reached in the extruder it would be necessary for the work done on the melt to produce just the right amount of heat without the need for heating or cooling. The second ideal case is referred to as **isothermal**. In the extruder this would mean that the temperature at all points is the same and would require immediate heating or cooling from the barrel to compensate for any loss or gain of heat in the melt. In practice the thermal processes in the extruder fall somewhere between these ideals. Extruders may be run without external heating or cooling but they are not truly adiabatic since heat losses will occur. Isothermal operation along the whole length of the extruder cannot be envisaged if it is to be supplied with relatively cold granules. However, particular sections may be near isothermal and the metering zone is often considered as such for analysis.

4.2.3 Analysis of Flow in Extruder

As discussed in the previous section, it is convenient to consider the output from the extruder as consisting of three components – drag flow, pressure flow and leakage. The derivation of the equation for output assumes that in the metering zone the melt has a constant viscosity and its flow is isothermal in a wide shallow channel. These conditions are most likely to be approached in the metering zone.

(a) Drag Flow Consider the flow of the melt between parallel plates as shown in Fig. 4.7(a).

For the small element of fluid ABCD the volume flow rate dQ is given by

$$dQ = V \cdot dy \cdot dx \quad (4.1)$$

Assuming the velocity gradient is linear, then

$$V = V_d \left[\frac{y}{H} \right]$$

Substituting in (4.1) and integrating over the channel depth, H , then the total drag flow, Q_d , is given by

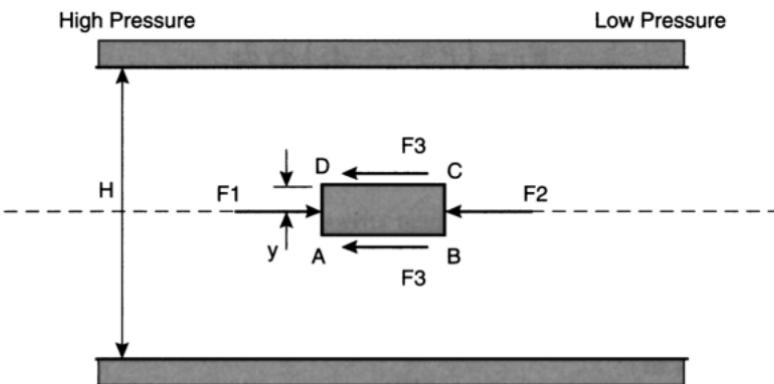
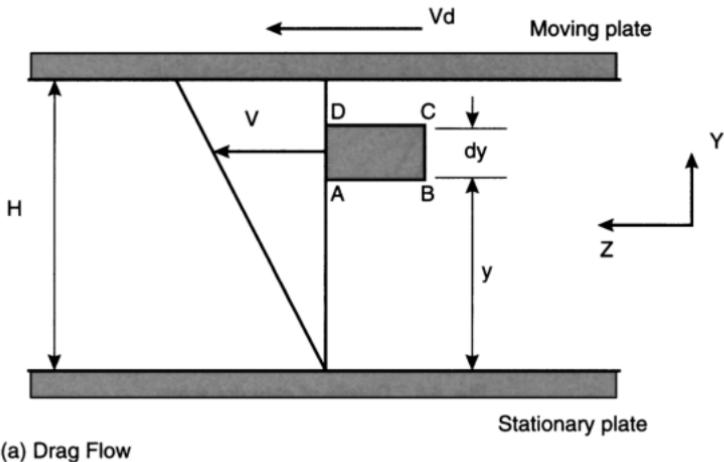
$$Q_d = \int_0^H \int_0^T \frac{V_d y}{H} \cdot dy \cdot dx$$

$$Q_d = \frac{1}{2} THV_d \quad (4.2)$$

This may be compared to the situation in the extruder where the fluid is being dragged along by the relative movement of the screw and barrel. Fig. 4.8 shows the position of the element of fluid and (4.2) may be modified to include terms relevant to the extruder dimensions.

For example

$$V_d = \pi DN \cos \phi$$



(b) Pressure Flow

In both cases, $AB = dz$, element width = dx and channel width = T

Fig. 4.7 Melt Flow between parallel plates

where N is the screw speed (in revolutions per unit time).

$$T = (\pi D \tan \phi - e) \cos \phi$$

$$\text{So } Q_d = \frac{1}{2}(\pi D \tan \phi - e)(\pi DN \cos^2 \phi)H$$

In most cases the term, e , is small in comparison with $(\pi D \tan \phi)$ so this expression is reduced to

$$Q_d = \frac{1}{2}\pi^2 D^2 NH \sin \phi \cos \phi \quad (4.3)$$

Note that the shear rate in the metering zone will be given by V_d/H .

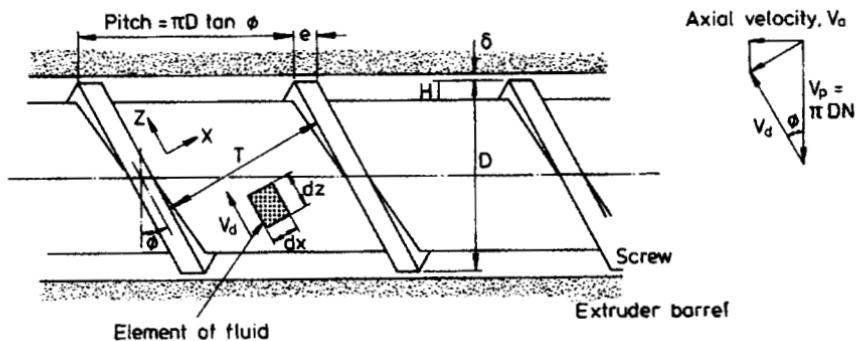


Fig. 4.8 Details of extruder screw

(b) Pressure flow: Consider the element of fluid shown in Fig. 4.7(b). The forces are

$$F_1 = \left(P + \frac{\partial P}{\partial z} \cdot dz \right) dy dx$$

$$F_2 = P \cdot dy dx$$

$$F_3 = \tau_y dz dx$$

where P is pressure and $d\tau$ is the shear stress acting on the element. For steady flow these forces are in equilibrium so they may be equated as follows:

$$F_1 = F_2 + 2F_3$$

which reduces to

$$y \frac{dP}{dz} = \tau_y \quad (4.4)$$

Now for a Newtonian fluid, the shear stress, τ_y , is related to the viscosity, η , and the shear rate, $\dot{\gamma}$, by the equation

$$\tau_y = \eta \dot{\gamma} = \eta \frac{dV}{dy}$$

Using this in equation (4.4)

$$y \frac{dP}{dz} = \eta \frac{dV}{dy}$$

Integrating

$$\int_0^y dV = \frac{1}{\eta} \frac{dP}{dz} \int_{H/2}^y y dy$$

So

$$V = \frac{1}{\eta} \frac{dp}{dz} \left(\frac{y^2}{2} - \frac{H^2}{8} \right) \quad (4.5)$$

Also, for the element of fluid of depth, dy , at distance, y , from the centre line (and whose velocity is V) the elemental flow rate, dQ , is given by

$$dQ = VT dy$$

This may be integrated to give the pressure flow, Q_p

$$\begin{aligned} Q_p &= 2 \int_0^{H/2} \frac{1}{\eta} \frac{dP}{dz} \cdot T \left(\frac{y^2}{2} - \frac{H^2}{8} \right) dy \\ Q_p &= -\frac{1}{12\eta} \frac{dP}{dz} \cdot TH^3 \end{aligned} \quad (4.6)$$

Referring to the element of fluid between the screw flights as shown in Fig. 4.8, this equation may be rearranged using the following substitutions. Assuming e is small, $T = \pi D \tan \phi \cdot \cos \phi$

$$\text{Also, } \sin \phi = \frac{dL}{dz} \text{ so } \frac{dP}{dz} = \frac{dP}{dL} \sin \phi$$

Thus the expression for Q_p becomes

$$Q_p = -\frac{\pi D H^3 \sin^2 \phi}{12\eta} \cdot \frac{dP}{dL} \quad (4.7)$$

(c) Leakage The leakage flow may be considered as flow through a wide slit which has a depth, δ , a length ($e \cos \phi$) and a width of ($\pi D / \cos \phi$). Since this is a pressure flow, the derivation is similar to that described in (b). For convenience therefore the following substitutions may be made in (4.6).

$$h = \delta$$

$$T = \pi D / \cos \phi$$

$$\text{Pressure gradient} = \frac{\Delta P}{e \cos \phi} \text{ (see Fig. 4.9)}$$

So the leakage flow, Q_L , is given by

$$Q_L = \frac{\pi^2 D^2 \delta^3}{12\eta e} \tan \phi \frac{dP}{dL} \quad (4.8)$$

A factor is often required in this equation to allow for eccentricity of the screw in the barrel. Typically this increases the leakage flow by about 20%.

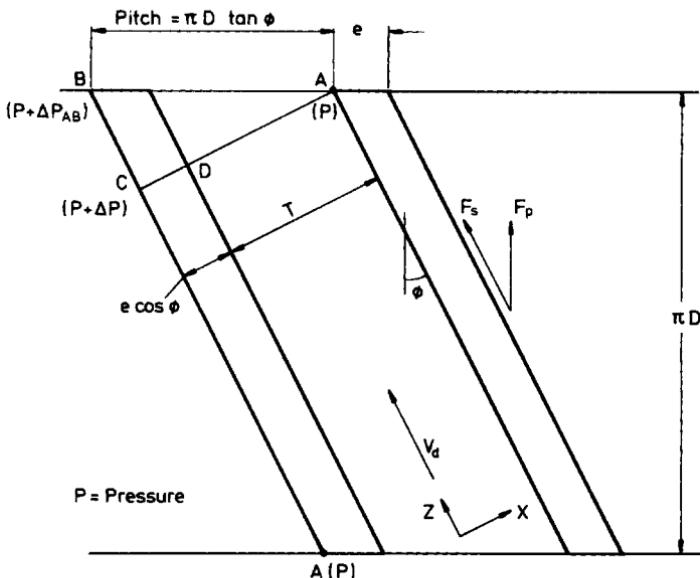


Fig. 4.9 Development of screw

The total output is the combination of drag flow, back pressure flow and leakage. So from (4.3), (4.7) and (4.8)

$$Q = \frac{1}{2} \pi^2 D^2 NH \sin \phi \cos \phi - \frac{\pi D H^3 \sin^2 \phi}{12\eta} \frac{dP}{dL} - \frac{\pi^2 D^2 \delta^3}{12\eta e} \tan \phi \frac{dP}{dL} \quad (4.9)$$

For many practical purposes sufficient accuracy is obtained by neglecting the leakage flow term. In addition the pressure gradient is often considered as linear so

$$\frac{dP}{dL} = \frac{P}{L}$$

where 'L' is the length of the extruder. In practice the length of an extruder screw can vary between 17 and 30 times the diameter of the barrel. The shorter the screw the cooler the melt and the faster the moulding cycle. In the above analysis, it is the melt flow which is being considered and so the relevant pressure gradient will be that in the metering zone. However, as shown in Fig. 4.2 this is often approximated by P/L . If all other physical dimensions and conditions are constant then the variation of output with screw flight angle, ϕ , can be studied. As shown in Fig. 4.10 the maximum output would be obtained if the screw flight angle was about 35° . In practice a screw flight angle of 17.7° is frequently used because

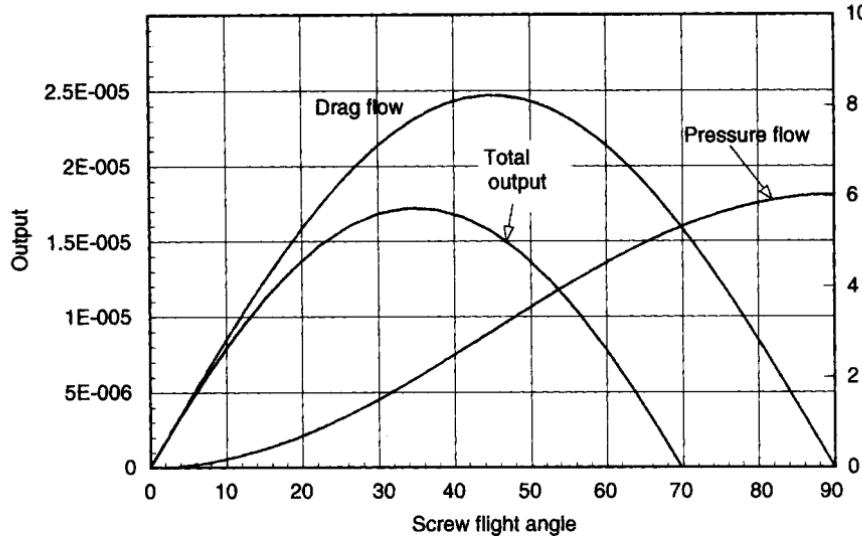


Fig. 4.10 Variation of drag flow and pressure flow

- (i) this is the angle which occurs if the pitch of the screw is equal to the diameter and so it is convenient to manufacture,
- (ii) for a considerable portion of the extruder length, the screw is acting as a solids conveying device and it is known that the optimum angle in such cases is 17° to 20° .

It should also be noted that in some cases correction factors, F_d , and F_p are applied to the drag and pressure flow terms. They are to allow for edge effects and are solely dependent on the channel width, T , and channel depth, h , in the metering zone. Typical values are illustrated in Fig. 4.11.

4.2.4 Extruder/Die Characteristics

From equation (4.9) it may be seen that there are two interesting situations to consider. One is the case of free discharge where there is no pressure build up at the end of the extruder so

$$Q = Q_{\max} = \frac{1}{2}\pi^2 D^2 NH \sin \phi \cos \phi \quad (4.10)$$

The other case is where the pressure at the end of the extruder is large enough to stop the output. From (4.9) with $Q = 0$ and ignoring the leakage flow

$$P = P_{\max} = \frac{6\pi DLN\eta}{H^2 \tan \phi} \quad (4.11)$$

In Fig. 4.12 these points are shown as the limits of the screw characteristic. It is interesting to note that when a die is coupled to the extruder their requirements

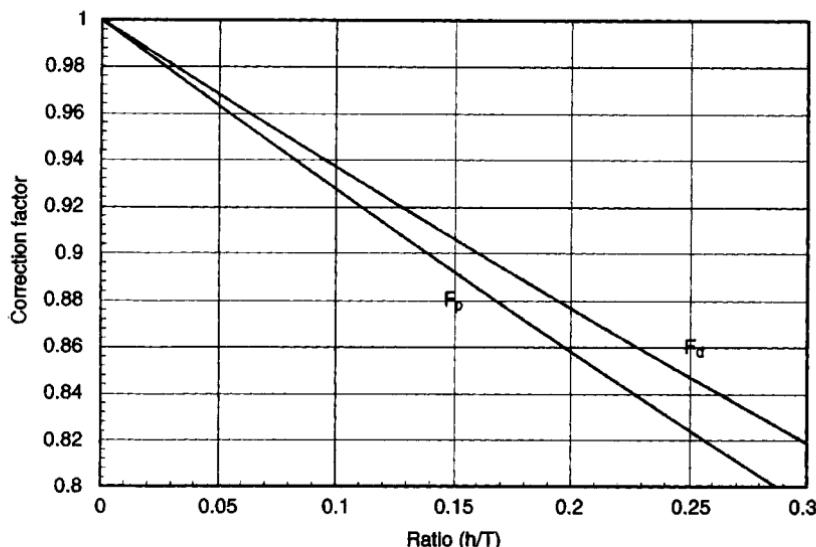


Fig. 4.11 Flow correction factors as a function of screw geometry

are conflicting. The extruder has a high output if the pressure at its outlet is low. However, the outlet from the extruder is the inlet to the die and the output of the latter increases with inlet pressure. As will be seen later the output, Q , of a Newtonian fluid from a die is given by a relation of the form

$$Q = KP \quad (4.12)$$

where $K = \frac{\pi R^4}{8\eta L_d}$ for a capillary die of radius R and length L_d .

Equation (4.12) enables the die characteristics to be plotted on Fig. 4.12 and the intersection of the two characteristics is the operating point of the extruder. This plot is useful in that it shows the effect which changes in various parameters will have on output. For example, increasing screw speed, N , will move the extruder characteristic upward. Similarly an increase in the die radius, R , would increase the slope of the die characteristic and in both cases the extruder output would increase.

The operating point for an extruder/die combination may also be determined from equations (4.9) and (4.12) – ignoring leakage flow

$$Q = \frac{1}{2}\pi^2 D^2 NH \sin \phi \cos \phi - \frac{\pi D H^3 \sin^2 \phi P}{12\eta} \frac{P}{L} = \frac{\pi R^4}{8\eta L_d} \cdot P$$

So for a capillary die, the pressure at the operating point is given by

$$P_{OP} = \left\{ \frac{2\pi\eta D^2 NH \sin \phi \cos \phi}{(R^4/2L_d) + (DH^3 \sin^2 \phi)/3L} \right\} \quad (4.13)$$

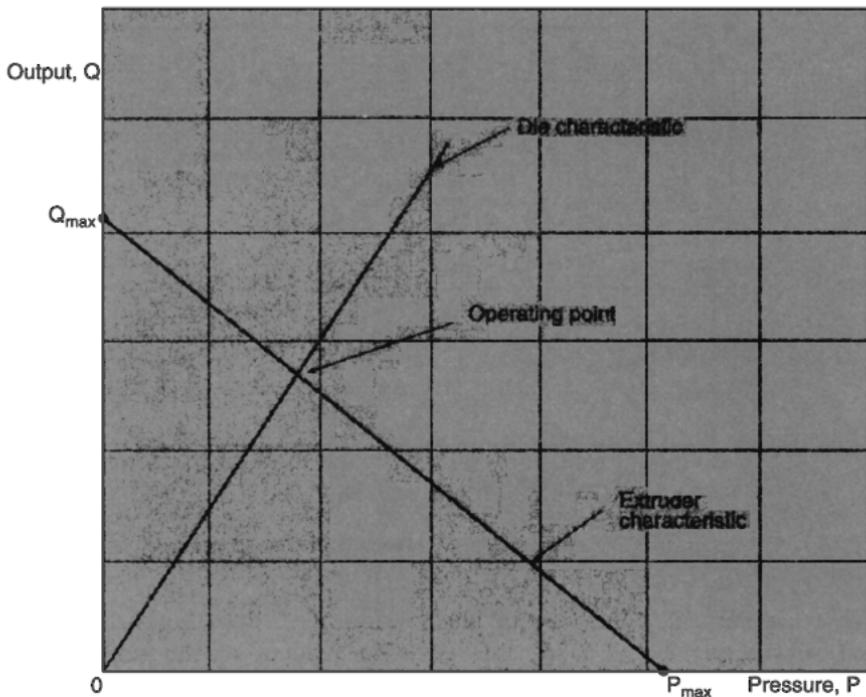


Fig. 4.12 Extruder and die characteristics

4.2.5 Other Die Geometries

For other die geometries it is necessary to use the appropriate form of equation (4.12). The equations for a capillary and a slit die are derived in Chapter 5. For other geometries it is possible to use the empirical equation which was developed by Boussinesq. This has the form

$$Q = \frac{Fbd^3}{12\eta L_d} \cdot P \quad (4.14)$$

where b is the greatest dimension of the cross-section

d is the least dimension of the cross-section

F is a non-dimensional factor as given in Fig. 4.13.

Using equation (4.14) it is possible to modify the expression for the operating pressure to the more general form

$$P_{OP} = \left\{ \frac{2\pi\eta D^4 NH \sin \phi \cos \phi}{\frac{Fbd^3}{3\pi L_d} + (DH^3 \sin^2 \phi / 3L)} \right\} \quad (4.15)$$

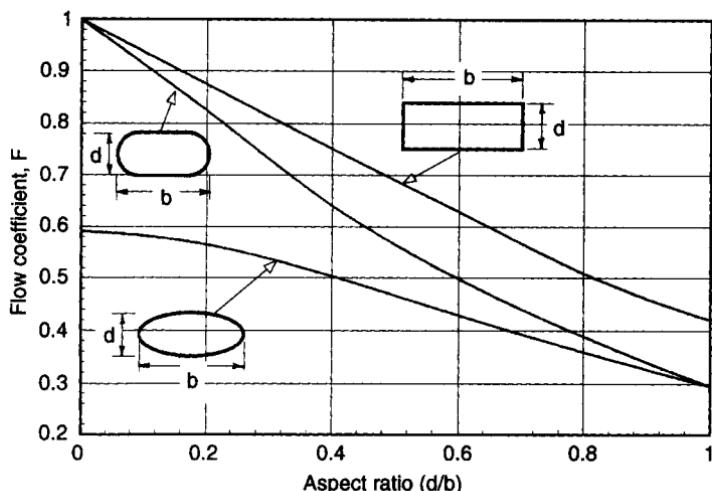


Fig. 4.13 Flow coefficient as a function of channel geometry

For a capillary die, one may obtain a value of F from Fig. 4.13 as 0.295 and substituting $b = d = 2R$, this equation reduces to the same form as equation (4.13).

Example 4.1 A single screw extruder is to be designed with the following characteristics.

L/D ratio = 24, screw flight angle = 17.7°

Max. screw speed = 100 rev/min, screw diameter = 40 mm

flight depth (metering zone) = 3 mm.

If the extruder is to be used to process polymer melts with a maximum melt viscosity of 500 Ns/m^2 , calculate a suitable wall thickness for the extruder barrel based on the von Mises yield criterion. The tensile yield stress for the barrel metal is 925 MN/m^2 and a factor of safety of 2.5 should be used.

Solution The maximum pressure which occurs in the extruder barrel is when there is no output. Therefore the design needs to consider this worst case blockage situation. As given by equation (4.11)

$$P_{\max} = \frac{6\pi DL\eta}{H^2 \tan \phi}$$

$$= \frac{6\pi \times 40 \times (24 \times 10) \times (100/60) \times 500}{(3)^2 \tan 17.7^\circ} = 210 \text{ MN/m}^2$$

The von Mises criterion relates the tensile yield stress of a material to a state of multi-axial stress in a component made from the material. In a cylinder (the

barrel of the extruder in this case), the principal stresses which exist as a result of an internal pressure are

$$\text{hoop stress, } \sigma_1 = \frac{P_{\max}D}{2h}$$

$$\text{axial stress, } \sigma_2 = \frac{P_{\max}D}{4h}$$

where h = wall thickness of the barrel.

The von Mises criterion simply states that yielding (failure) will occur if

$$\left(\frac{\sigma_Y}{FS} \right)^2 \leq \sigma_1^2 + \sigma_2^2 - \sigma_1 \sigma_2$$

where

σ_Y = tensile yield stress of material

FS = factor of safety.

In this case, therefore

$$\left(\frac{925}{2.5} \right)^2 = \left(\frac{(210)40}{2h} \right)^2 + \left(\frac{(210)40}{4h} \right)^2 - \frac{(210)^2(40)^2}{8h^2}$$

$$h = 9.8 \text{ mm}$$

Hence a barrel wall thickness of 10 mm would be appropriate.

Example 4.2 A single screw extruder is to be used to manufacture a nylon rod 5 mm in diameter at a production rate of 1.5 m/min. Using the following information, calculate the required screw speed.

Nylon	Extruder	Die
Viscosity = 42.0 Ns/m ²	Diameter = 30 mm	Length = 4 mm
Density (solid) = 1140 kg/m ³	Length = 750 mm	Diameter = 5 mm
Density (melt) = 790 kg/m ³	Screw flight angle = 17.7° Metering channel depth = 2.5 mm	

Die swelling effects may be ignored and the melt viscosity can be assumed to be constant.

$$\begin{aligned} \text{Solution The output rate of solid rod} &= \text{speed} \times \text{cross-sectional area} \\ &= 1.5 \times \pi(2.5 \times 10^{-3})^2 / 60 \\ &= 49.1 \times 10^{-6} \text{ m}^3/\text{s} \end{aligned}$$

As the solid material is more dense than the melt, the melt flow rate must be greater in the ratio of the solid/melt densities. Therefore

$$\text{Melt flow rate through die} = 49.1 \times 10^{-6} \left(\frac{1140}{790} \right) = 70.8 \times 10^{-6} \text{ m}^3/\text{s}$$

The pressure necessary to achieve this flow rate through the die is obtained from

$$Q = \frac{\pi PR^4}{8\eta L_d}$$

$$P = \frac{8 \times 420 \times 4 \times 10^{-3} \times 70.8 \times 10^{-6}}{\pi(2.5 \times 10^{-3})^4} = 7.8 \text{ MN/m}^2$$

At the operating point, the die output and the extruder output will be the same. Hence

$$Q = 70.8 \times 10^{-6} = \frac{1}{2}\pi^2(30 \times 10^{-3})^2 N(2.5 \times 10^{-3}) \sin 17.7 \cos 17.7$$

$$-\frac{\pi(30 \times 10^{-3})(2.6 \times 10^{-3})^3 \sin 17}{12 \times 420} \left(\frac{7.8 \times 10^6}{0.75} \right)$$

$$N = 22 \text{ rev/min}$$

4.2.6 General Features of Twin Screw Extruders

In recent years there has been a steady increase in the use of extruders which have two screws rotating in a heated barrel. These machines permit a wider range of possibilities in terms of output rates, mixing efficiency, heat generation, etc compared with a single screw extruder. The output of a twin screw extruder can be typically three times that of a single screw extruder of the same diameter and speed. Although the term 'twin-screw' is used almost universally for extruders having two screws, the screws need not be identical. There are in fact a large variety of machine types. Fig. 4.14 illustrates some of the possibilities with counter-rotating and co-rotating screws. In addition the screws may be conjugated or non-conjugated. A non-conjugated screw configuration is one in which the screw flights are a loose fit into one another so that there is ample space for material between the screw flights (see Fig. 4.15).

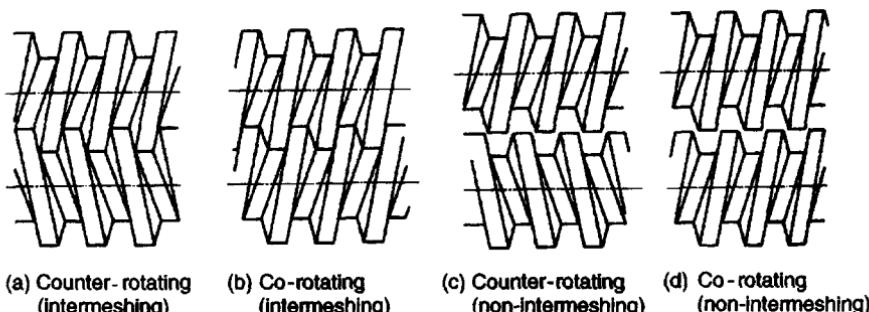
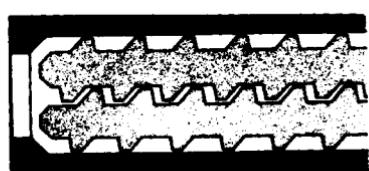


Fig. 4.14 Different types of twin screw extruder



(a) Non-conjugated screws showing some passages around each screw



(b) Conjugated screws showing closed passages around each screw

Fig. 4.15 Two types of twin screw extruder

In a counter-rotating twin screw extruder the material is sheared and pressurised in a mechanism similar to calendering (see Section 4.5), i.e. the material is effectively squeezed between counter-rotating rolls. In a co-rotating system the material is transferred from one screw to the other in a figure-of-eight pattern as shown in Fig. 4.16. This type of arrangement is particularly suitable for heat sensitive materials because the material is conveyed through the extruder quickly with little possibility of entrapment. The movement around the screws is slower if the screws are conjugated but the propulsive action is greater.

Table 4.1

Comparison of single-screw, co-rotating and counter-rotating twin-screw extruders

Type	Single screw	Co-rotating screw		Counter-rotating twin screw
		Low speed type	High speed type	
Principle	Friction between cylinder and materials and the same between material and screw	Mainly depend on the frictional action as in the case of single screw extruder		Forced mechanical conveyance based on gear pump principle
Conveying efficiency	Low	Medium		High
Mixing efficiency	Low	Medium/High		High
Shearing action	High	Medium	High	Low
Self-cleaning effect	Slight	Medium/High	High	Low
Energy efficiency	Low	Medium/High		High
Heat generation	High	Medium	High	Low
Temp distribution	Wide	Medium	Narrow	Narrow
Max. revolving speed (rpm)	100–300	25–35	250–300	35–45
Max. effective length of screw L/D	30–32	7–18	30–40	10–21

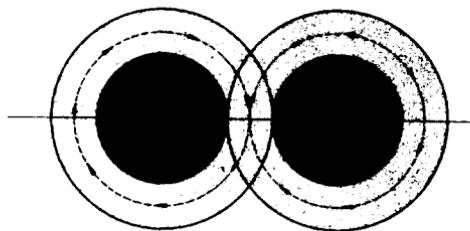


Fig. 4.16 Material flow path with co-rotating screws

The following table compares the single screw extruder with the main types of twin screw extruders.

4.2.7 Processing Methods Based on the Extruder

Extrusion is an extremely versatile process in that it can be adapted, by the use of appropriate dies, to produce a wide range of products. Some of the more common of these production techniques will now be described.

(a) Granule Production/Compounding

In the simplest case an extruder may be used to convert polymer formulations and additives into a form (usually granules) which is more convenient for use in other processing methods, such as injection moulding. In the extruder the feedstock is melted, homogenised and forced through a capillary shaped die. It emerges as a continuous lace which is cooled in a long water bath so that it may be chopped into short granules and packed into sacks. The haul-off apparatus shown in Fig. 4.17 is used to draw down the extrudate to the required dimensions. The granules are typically 3 mm diameter and about 4 mm long. In most cases a multi-hole die is used to increase the production rate.

(b) Profile Production

Extrusion, by its nature, is ideally suited to the production of continuous lengths of plastic mouldings with a uniform cross-section. Therefore as well as producing the laces as described in the previous section, the simple operation of a die change can provide a wide range of profiled shapes such as pipes, sheets, rods, curtain track, edging strips, window frames, etc (see Fig. 4.18).

The successful manufacture of profiled sections depends to a very large extent on good die design. Generally this is not straightforward, even for a simple cross-section such as a square, due to the interacting effects of post-extrusion swelling and the flow characteristics of complex viscoelastic fluids. Most dies are designed from experience to give approximately the correct shape and then sizing units are used to control precisely the desired shape. The extrudate is then cooled as quickly as possible. This is usually done in a water bath the length of which depends on the section and the material being cooled. For example,

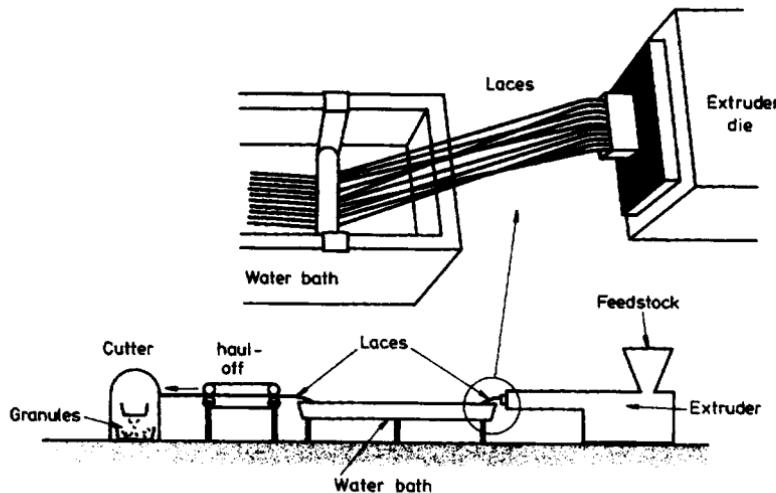


Fig. 4.17 Use of extruder to produce granules

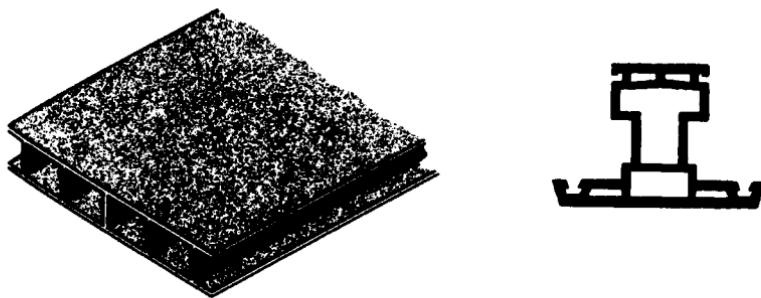


Fig. 4.18 (a) Extruded panel sections (b) Extruded window profile

longer baths are needed for crystalline plastics since the recrystallisation is exothermic.

The storage facilities at the end of the profile production line depend on the type of product (see Fig. 4.19). If it is rigid then the cooled extrudate may be cut to size on a guillotine for stacking. If the extrudate is flexible then it can be stored on drums.

(c) Film Blowing

Although plastic sheet and film may be produced using a slit die, by far the most common method nowadays is the film blowing process illustrated in Fig. 4.20. The molten plastic from the extruder passes through an annular die and emerges as a thin tube. A supply of air to the inside of the tube prevents it from collapsing and indeed may be used to inflate it to a larger diameter.

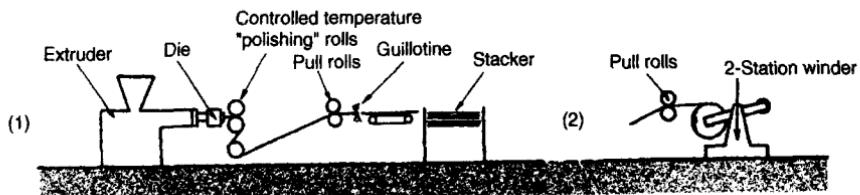


Fig. 4.19(a) Sheet extrusion (1) thick sheet (2) thin sheet

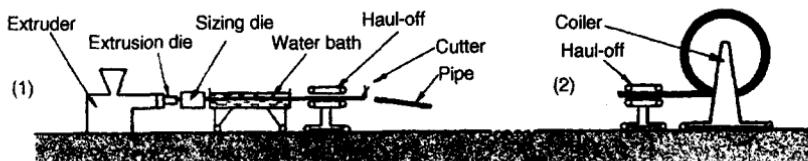


Fig. 4.19(b) Pipe extrusion (1) rigid pipe (2) flexible pipe

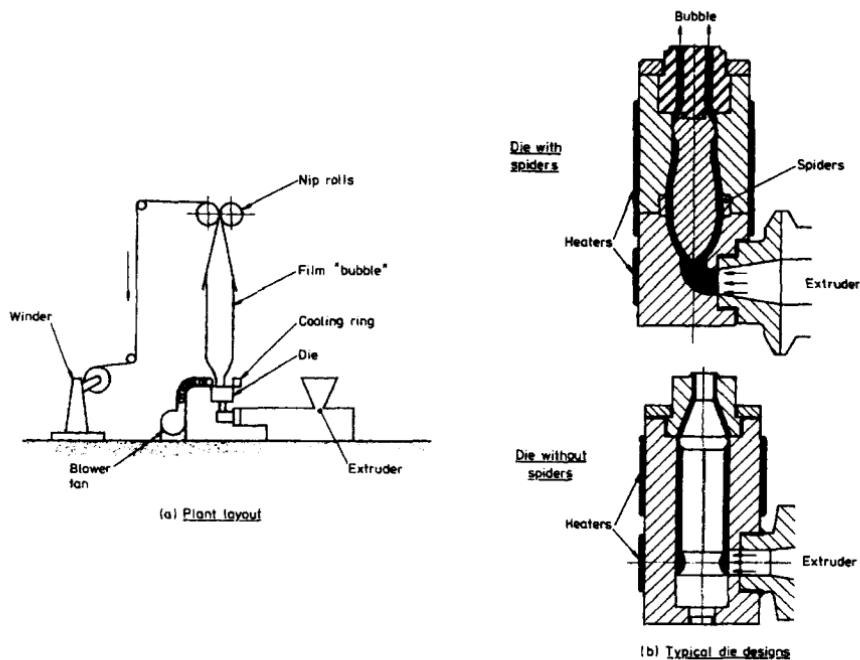


Fig. 4.20 Film blowing process

Initially the bubble consists of molten plastic but a jet of air around the outside of the tube promotes cooling and at a certain distance from the die exit, a freeze line can be identified. Eventually the cooled film passes through collapsing guides and nip rolls before being taken off to storage drums or, for example, gussetted and cut to length for plastic bags. Most commercial systems are provided with twin storage facilities so that a full drum may be removed without stopping the process.

The major advantage of film blowing is the ease with which biaxial orientation can be introduced into the film. The pressure of the air in the bubble determines the *blow-up* and this controls the circumferential orientation. In addition, axial orientation may be introduced by increasing the nip roll speed relative to the linear velocity of the bubble. This is referred to as *draw-down*.

It is possible to make a simple estimate of the orientation in blown film by considering only the effects due to the inflation of the bubble. Since the volume flow rate is the same for the plastic in the die and in the bubble, then for unit time

$$\pi D_d h_d L_d = \pi D_b h_b L_b$$

where D , h and L refer to diameter, thickness and length respectively and the subscript 'd' is for the die and 'b' is for the bubble.

So the orientation in the machine direction, O_{MD} , is given by

$$O_{MD} = \frac{L_b}{L_d} = \frac{D_d h_d}{h_b D_b} = \frac{h_d}{h_b B_R}$$

where B_R = blow-up ratio (D_b/D_d)

Also the orientation in the transverse direction, O_{TD} , is given by

$$O_{TD} = \frac{D_b}{D_d} = B_R$$

Therefore the ratio of the orientations may be expressed as

$$\frac{O_{MD}}{O_{TD}} = \frac{h_d}{h_b (B_R)^2} \quad (4.16)$$

Example 4.3 A plastic shrink wrapping with a thickness of 0.05 mm is to be produced using an annular die with a die gap of 0.8 mm. Assuming that the inflation of the bubble dominates the orientation in the film, determine the blow-up ratio required to give uniform biaxial orientation.

Solution Since $O_{MD} = O_{TD}$

$$\begin{aligned} \text{then the blow-up ratio, } B_R &= \sqrt{\frac{h_d}{h_b}} \\ &= \sqrt{\frac{0.8}{0.05}} = 4 \end{aligned}$$

Common blow-up ratios are in the range 1.5 to 4.5.

This example illustrates the simplified approach to film blowing. Unfortunately in practice the situation is more complex in that the film thickness is influenced by draw-down, relaxation of induced stresses/strains and melt flow phenomena such as die swell. In fact the situation is similar to that described for blow moulding (see below) and the type of analysis outlined in that section could be used to allow for the effects of die swell. However, since the most practical problems in film blowing require iterative type solutions involving melt flow characteristics, volume flow rates, swell ratios, etc the study of these is delayed until Chapter 5 where a more rigorous approach to polymer flow has been adopted.

(d) Blow Moulding

This process evolved originally from glass blowing technology. It was developed as a method for producing hollow plastic articles (such as bottles and barrels) and although this is still the largest application area for the process, nowadays a wide range of technical mouldings can also be made by this method e.g. rear spoilers on cars and videotape cassettes. There is also a number of variations on the original process but we will start by considering the conventional extrusion blow moulding process.

Extrusion Blow Moulding

Initially a molten tube of plastic called the *Parison* is extruded through an annular die. A mould then closes round the parison and a jet of gas inflates it to take up the shape of the mould. This is illustrated in Fig. 4.21(a). Although this process is principally used for the production of bottles (for washing-up liquid, disinfectant, soft drinks, etc.) it is not restricted to small hollow articles. Domestic cold water storage tanks, large storage drums and 200

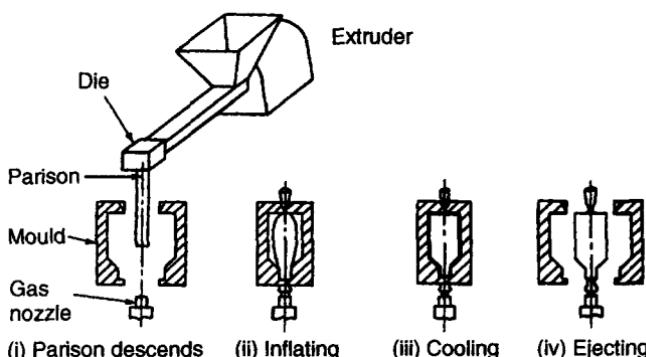


Fig. 4.21 Stages in blow moulding

gallon containers have been blow-moulded. The main materials used are PVC, polyethylene, polypropylene and PET.

The conventional extrusion blow moulding process may be continuous or intermittent. In the former method the extruder continuously supplies molten polymer through the annular die. In most cases the mould assembly moves relative to the die. When the mould has closed around the parison, a hot knife separates the latter from the extruder and the mould moves away for inflation, cooling and ejection of the moulding. Meanwhile the next parison will have been produced and this mould may move back to collect it or, in multi-mould systems, this would have been picked up by another mould. Alternatively in some machines the mould assembly is fixed and the required length of parison is cut off and transported to the mould by a robot arm.

In the intermittent processes, single or multiple parisons are extruded using a reciprocating screw or ram accumulator. In the former system the screw moves forward to extrude the parisons and then screws back to prepare the charge of molten plastic for the next shot. In the other system the screw extruder supplies a constant output to an accumulator. A ram then pushes melt from the accumulator to produce a parison as required.

Although it may appear straightforward, in fact the geometry of the parison is complex. In the first place its dimensions will be greater than those of the die due to the phenomenon of post extrusion swelling (see Chapter 5). Secondly there may be deformities (e.g. curtaining) due to flow defects. Thirdly, since most machines extrude the parison vertically downwards, during the delay between extrusion and inflation, the weight of the parison causes sagging or draw-down. This sagging limits the length of articles which can be produced from a free hanging parison. The complex combination of swelling and thinning makes it difficult to produce articles with a uniform wall thickness. This is particularly true when the cylindrical parison is inflated into an irregularly shaped mould because the uneven drawing causes additional thinning. In most cases therefore to blow mould successfully it is necessary to program the output rate or die gap to produce a controlled non-uniform distribution of thickness in the parison which will give a uniform thickness in the inflated article.

During moulding, the inflation rate and pressure must be carefully selected so that the parison does not burst. Inflation of the parison is generally fast but the overall cycle time is dictated by the cooling of the melt when it touches the mould. Various methods have been tried in order to improve the cooling rate e.g. injection of liquid carbon dioxide, cold air or high pressure moist air. These usually provide a significant reduction in cycle times but since the cooling rate affects the mechanical properties and dimensional stability of the moulding it is necessary to try to optimise the cooling in terms of production rate and quality.

Extrusion blow moulding is continually developing to be capable of producing even more complex shapes. These include unsymmetrical geometries and double wall mouldings. In recent years there have also been considerable

developments in the use of in-the-mould transfers. This technology enables labels to be attached to bottles and containers as they are being moulded. Fig. 4.22 illustrates three stages in the blow moulding of a complex container.

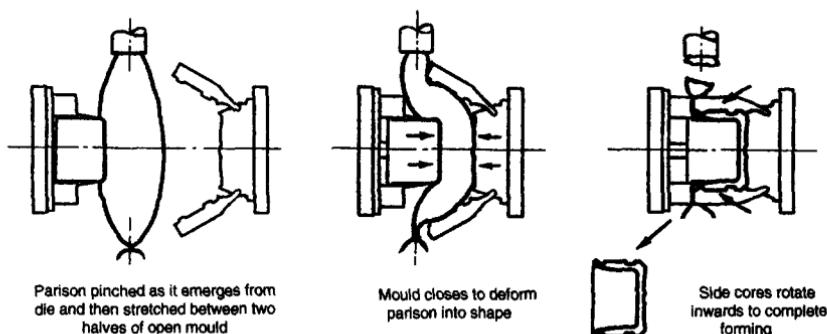


Fig. 4.22 Stages in blow moulding of complex hollow container

Analysis of Blow Moulding

As mentioned previously, when the molten plastic emerges from the die it swells due to the recovery of elastic deformations in the melt. It will be shown later that the following relationship applies:

$$B_{SH} = B_{ST}^2 \text{ (from Chapter 5)}$$

where

$$B_{SH} = \text{swelling of the thickness} (= h_1/h_d)$$

$$B_{ST} = \text{swelling of the diameter} (= D_1/D_d)$$

therefore

$$\frac{h_1}{h_d} = \left(\frac{D_1}{D_d} \right)^2$$

$$h_1 = h_d (B_{ST})^2 \quad (4.17)$$

Now consider the situation where the parison is inflated to fill a cylindrical die of diameter, D_m . Assuming constancy of volume and neglecting draw-down effects, then from Fig. 4.23

$$\begin{aligned} \pi D_1 h_1 &= \pi D_m h \\ h &= \frac{D_1}{D_m} h_1 \\ &= \frac{D_1}{D_m} (h_d \cdot B_{ST}^2) \\ &= \frac{B_{ST} \cdot D_d}{D_m} (h_d \cdot B_{ST}^2) \end{aligned}$$

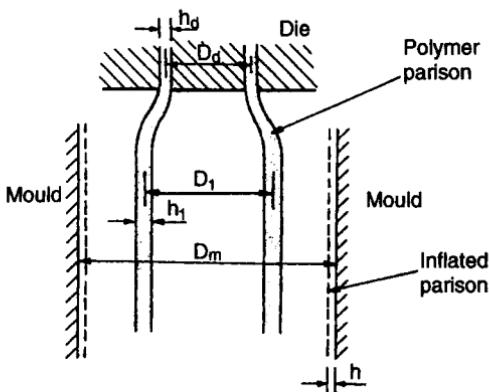


Fig. 4.23 Analysis of blow moulding

$$h = B_{ST}^3 h_d \left(\frac{D_d}{D_m} \right) \quad (4.18)$$

This expression therefore enables the thickness of the moulded article to be calculated from a knowledge of the die dimensions, the swelling ratio and the mould diameter. The following example illustrates the use of this analysis. A further example on blow moulding may be found towards the end of Chapter 5 where there is also an example to illustrate how the amount of sagging of the parison may be estimated.

Example 4.4 A blow moulding die has an outside diameter of 30 mm and an inside diameter of 27 mm. The parison is inflated with a pressure of 0.4 MN/m² to produce a plastic bottle of diameter 50 mm. If the extrusion rate used causes a thickness swelling ratio of 2, estimate the wall thickness of the bottle. Comment on the suitability of the production conditions if melt fracture occurs at a stress of 6 MN/m².

Solution

From equation (4.18)

$$\text{wall thickness, } h = B_{ST}^3 h_d \left(\frac{D_d}{D_m} \right)$$

Now $h_d = \frac{1}{2}(30 - 27) = 1.5 \text{ mm}$

$$B_{ST} = \sqrt{B_{SH}} = \sqrt{2} = 1.414$$

$$D_d = \frac{1}{2}(30 + 27) = 28.5 \text{ mm}$$

So $h = (1.414)^3 (1.5) \left(\frac{28.5}{50} \right) = 2.42 \text{ mm}$

The maximum stress in the inflated parison will be the hoop stress, σ_θ , which is given by

$$\begin{aligned}\sigma_\theta &= \frac{PD_m}{2h} = \frac{0.4 \times 50}{2 \times 2.42} \\ &= 4.13 \text{ MN/m}^2\end{aligned}$$

Since this is less than the melt fracture stress (6 MN/m^2) these production conditions would be suitable. These are more worked examples on extrusion blow moulding towards the end of Chapter 5.

Extrusion Stretch Blow Moulding

Molecular orientation has a very large effect on the properties of a moulded article. During conventional blow moulding the inflation of the parison causes molecular orientation in the hoop direction. However, bi-axial stretching of the plastic before it starts to cool in the mould has been found to provide even more significant improvements in the quality of blow-moulded bottles. Advantages claimed include improved mechanical properties, greater clarity and superior permeation characteristics. Cost savings can also be achieved through the use of lower material grades or thinner wall sections.

Biaxial orientation may be achieved in blow moulding by

- (a) stretching the extruded parison longitudinally before it is clamped by the mould and inflated. This is based on the Neck Ring process developed as early as the 1950s. In this case, molten plastic is extruded into a ring mould which forms the neck of the bottle and the parison is then stretched. After the mould closes around the parison, inflation of the bottle occurs in the normal way. The principle is illustrated in Fig. 4.24.

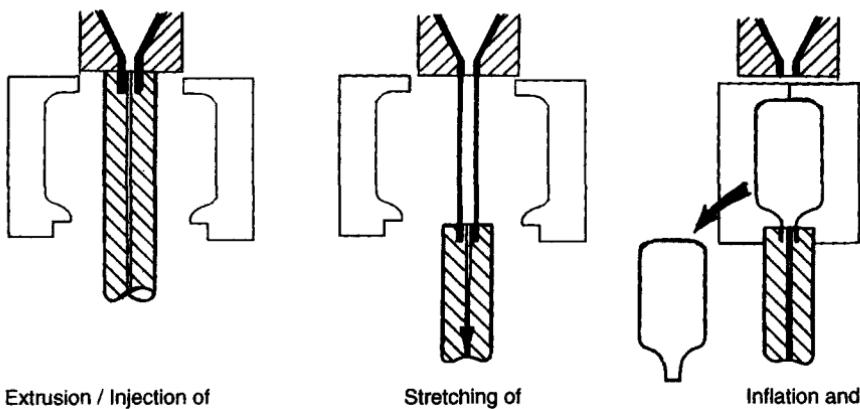


Fig. 4.24 Neck ring stretch blow moulding

- (b) producing a preform 'bottle' in one mould and then stretching this longitudinally prior to inflation in the full size bottle mould. This is illustrated in Fig. 4.25.

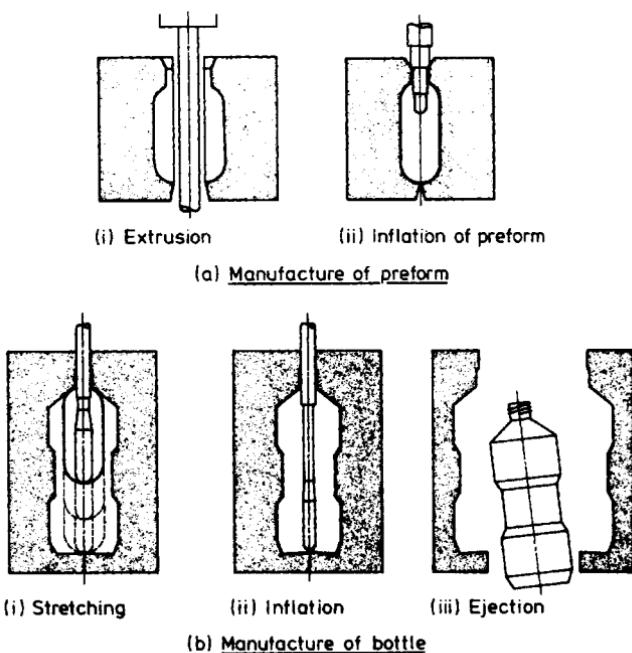


Fig. 4.25 Extrusion stretch blow moulding

Injection Stretch Blow Moulding

This is another method which is used to produce biaxially oriented blow moulded containers. However, as it involves injection moulding, the description of this process will be considered in more detail later (Section 4.3.9).

(e) Extrusion Coating Processes

There are many applications in which it is necessary to put a plastic coating on to paper or metal sheets and the extruder provides an ideal way of doing this. Normally a thin film of plastic is extruded from a slit die and is immediately brought into contact with the medium to be coated. The composite is then passed between rollers to ensure proper adhesion at the interface and to control the thickness of the coating (see Fig. 4.26).

Another major type of coating process is wire covering. The tremendous demand for insulated cables in the electrical industry means that large tonnages of plastic are used in this application. Basically a bare wire, which may be heated or have its surface primed, is drawn through a special die attached

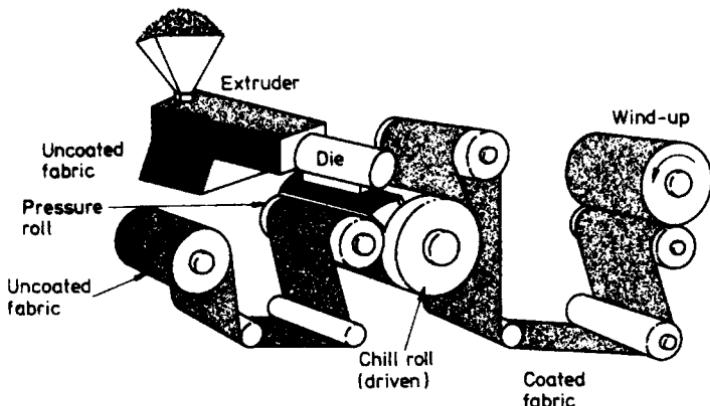


Fig. 4.26 Extrusion coating process

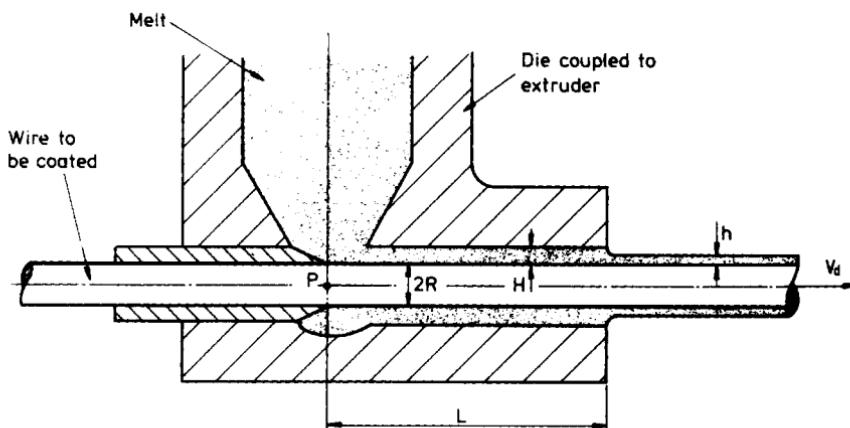


Fig. 4.27 Wire Covering Die

to an extruder (see Fig. 4.27). The drawing speed may be anywhere between 1 m/min and 1000 m/min depending on the diameter of the wire. When the wire emerges from the die it has a coating of plastic, the thickness of which depends on the speed of the wire and the extrusion conditions. It then passes into a cooling trough which may extend for a linear distance of several hundred metres. The coated wire is then wound on to storage drums.

Wire covering can be analysed in a very similar manner to that described for extrusion. The coating on the wire arises from two effects:

- Drag Flow* due to the movement of the wire
- Pressure Flow* due to the pressure difference between the extruder exit and the die exit.

From (4.2) the drag flow, Q_d , is given by

$$Q_d = \frac{1}{2} THV_d \quad \text{where } T = 2\pi \left(R + \frac{h}{2} \right)$$

From (4.6) the pressure flow, Q_p , is given by

$$Q_p = \frac{1}{12\eta} \frac{dP}{dz} \cdot TH^3$$

So combining these two equations, the total output, Q , is given by

$$Q = \frac{1}{2} THV_d + \frac{TH^3}{12\eta} \cdot \frac{P}{L} \quad (4.19)$$

This must be equal to the volume of coating on the wire so

$$\begin{aligned} Q &= \pi V_d ((R + h)^2 - R^2) \\ Q &= \pi V_d h (2R + h) \end{aligned} \quad (4.20)$$

Combining equations (4.19) and (4.20)

$$\pi V_d h (2R + h) = \frac{1}{2} THV_d + \frac{TH^3}{12\eta} \cdot \frac{P}{L}$$

from which

$$P = \frac{6\eta LV_d}{H^3} (2H - H) \quad (4.21)$$

This is an expression for the pressure necessary at the extruder exit and therefore enables the appropriate extrusion conditions to be set.

(f) Recent Developments in Extrusion Technology

(i) Co-Extrusion As a result of the wide range of requirements which occur in practice it is not surprising that in many cases there is no individual plastic which has the correct combination of properties to satisfy a particular need. Therefore it is becoming very common in the manufacture of articles such as packaging film, yoghurt containers, refrigerator liners, gaskets and window frames that a multi-layer plastic composite will be used. This is particularly true for extruded film and thermoforming sheets (see Section 4.4). In co-extrusion two or more polymers are combined in a single process to produce a multi-layer film. These co-extruded films can either be produced by a blown film or a cast film process as illustrated in Figs 4.28(a) and (b). The cast process using a slot die and chill roll to cool the film, produces a film with good clarity and high gloss. The film blowing process, however, produces a stronger film due to the transverse orientation which can be introduced and this process offers more flexibility in terms of film thickness.

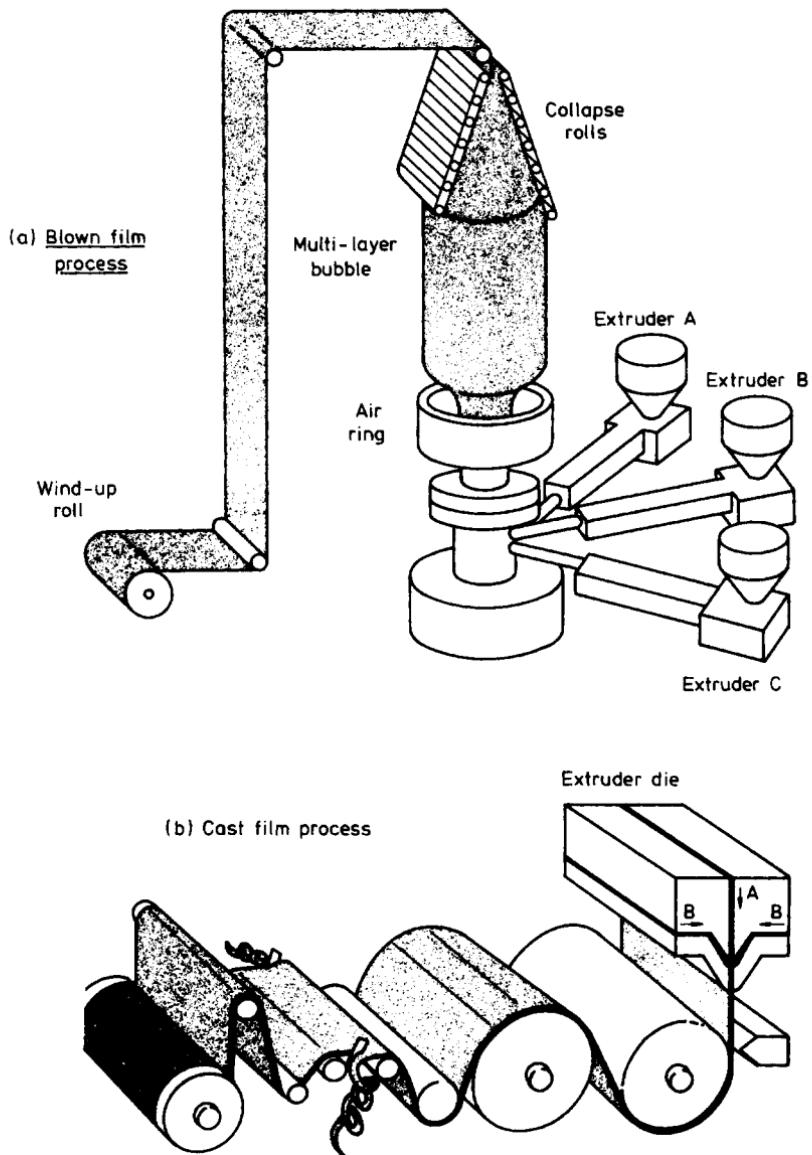


Fig. 4.28 Co-extrusion of plastic film

In most cases there is insufficient adhesion between the basic polymers and so it is necessary to have an adhesive film between each of the layers. Recent investigations of co-extrusion have been centred on methods of avoiding the need for the adhesive layer. The most successful seems to be the development

of reactive bonding processes in which the co-extruded layers are chemically cross-linked together.

The main reason for producing multi-layer co-extruded films is to get materials with better barrier properties – particularly in regard to gas permeation. The following Table shows the effects which can be achieved. Data on permeability of plastics are also given in Figs 1.13 and 1.14.

Table 4.2
Transmission rates for a range of plastics

Polymer	Layer distribution (μm)	Density (kg/m ³)	Transmission rates	
			Oxygen (cm ³ /m ² 24 hr atm)	Water vapour (g/m ² 24 hr)
ABS	1000	1050	30	2
uPVC	1000	1390	5	0.75
Polypropylene	1000	910	60	0.25
PET	1000	1360	1	2
LDPE	1000	920	140	0.5
HDPE	1000	960	60	0.3
PS/EVOH*/PE	825/25/150	1050	5†	1.6
PS/PVdC/PE	825/50/125	1070	1	0.4
PP/EVOH/PP	300/40/660	930	1†	0.25

*EVOH ethyl vinyl alcohol.

†Depends on humidity.

(ii) Highly Oriented Grids: Net-like polymer grids have become an extremely important development – particularly to civil engineers. The attraction in civil engineering applications is that the open grid structure permits soil particles to interlock through the apertures thus providing an extremely strong reinforcement to the soil. These geogrids under the trade name 'Tensar' are now widely used for road and runway construction, embankment supports, landslide repairs, etc.

The polymer grid achieves its very high strength due to the orientation of the polymer molecules during its manufacture. The process of manufacture is illustrated in Fig. 4.29. An extruded sheet, produced to a very fine tolerance and with a controlled structure, has a pattern of holes stamped into it. The hole shapes and pattern can be altered depending on the performance required of the finished product. The perforated sheet is then stretched in one direction to give thin sections of highly orientated polymer with the tensile strength of mild steel. This type of grid can be used in applications where uniaxial strength is required. In other cases, where biaxial strength is necessary, the sheet is subjected to a second stretching operation in the transverse direction. The advantages of highly oriented grids are that they are light and very easy to

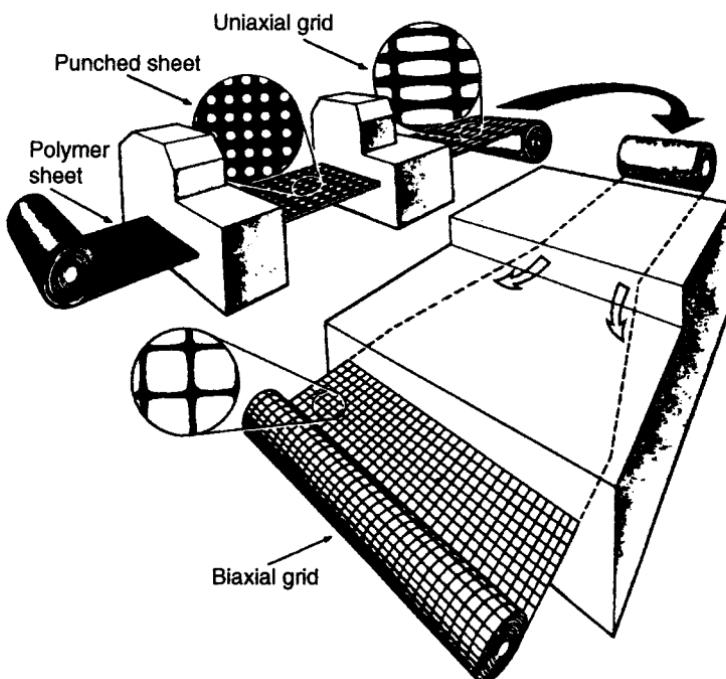


Fig. 4.29 Tensar manufacturing process

handle. The advantage of obtaining a highly oriented molecular structure is also readily apparent when one compares the stiffness of a HDPE grid ($\approx 10 \text{ GN/m}^2$) with the stiffness of unoriented HDPE ($\approx 1 \text{ GN/m}^2$).

(iii) Reactive Extrusion: The most recent development in extrusion is the use of the extruder as a 'mini-reactor'. Reactive extrusion is the name given to the process whereby the plastic is manufactured in the extruder from base chemicals and once produced it passes through a die of the desired shape. Currently this process is being used the manufacture of low tonnage materials (<5000 tonnes p.a.) where the cost of a full size reactor run could not be justified. In the future it may be simply part of the production line.

4.3 Injection Moulding

4.3.1 Introduction

One of the most common processing methods for plastics is injection moulding. Nowadays every home, every vehicle, every office, every factory contains a multitude of different types of articles which have been injection moulded. These include such things as electric drill casings, yoghurt cartons, television

housings, combs, syringes, paint brush handles, crash helmets, gearwheels, typewriters, fascia panels, reflectors, telephones, brief cases – the list is endless.

The original injection moulding machines were based on the pressure die casting technique for metals. The first machine is reported to have been patented in the United States in 1872, specifically for use with Celluloid. This was an important invention but probably before its time because in the following years very few developments in injection moulding processes were reported and it was not until the 1920s, in Germany, that a renewed interest was taken in the process. The first German machines were very simple pieces of equipment and relied totally on manual operation. Levers were used to clamp the mould and inject the melted plastic with the result that the pressures which could be attained were not very high. Subsequent improvements led to the use of pneumatic cylinders for clamping the injection which not only lifted some of the burden off the operator but also meant that higher pressures could be used.

The next major development in injection moulding, i.e. the introduction of hydraulically operated machines, did not occur until the late 1930s when a wide range of thermoplastics started to become available. However, these machines still tended to be hybrids based on die casting technology and the design of injection moulding machines for plastics was not taken really seriously until the 1950s when a new generation of equipment was developed. These machines catered more closely for the particular properties of polymer melts and modern machines are of the same basic design although of course the control systems are very much more sophisticated nowadays.

In principle, injection moulding is a simple process. A thermoplastic, in the form of granules or powder, passes from a feed hopper into the barrel where it is heated so that it becomes soft. It is then forced through a nozzle into a relatively cold mould which is clamped tightly closed. When the plastic has had sufficient time to become solid the mould opens, the article is ejected and the cycle is repeated. The major advantages of the process include its versatility in moulding a wide range of products, the ease with which automation can be introduced, the possibility of high production rates and the manufacture of articles with close tolerances. The basic injection moulding concept can also be adapted for use with thermosetting materials.

4.3.2 Details of the Process

The earliest injection moulding machines were of the plunger type as illustrated in Fig. 4.30 and there are still many of these machines in use today. A pre-determined quantity of moulding material drops from the feed hopper into the barrel. The plunger then conveys the material along the barrel where it is heated by conduction from the external heaters. The material is thus plasticised under pressure so that it may be forced through the nozzle into the mould cavity. In order to split up the mass of material in the barrel and improve the heat transfer, a torpedo is fitted in the barrel as shown.

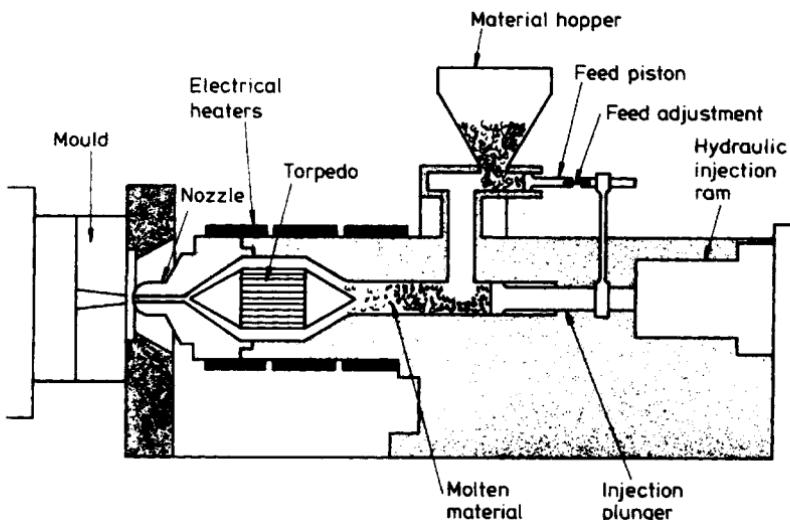


Fig. 4.30 Plunger type injection moulding machine

Unfortunately there are a number of inherent disadvantages with this type of machine which can make it difficult to produce consistent moulding. The main problems are:

- (a) There is little mixing or homogenisation of the molten plastic.
- (b) It is difficult to meter accurately the shot size. Since metering is on a volume basis, any variation in the density of the material will alter the shot weight.
- (c) Since the plunger is compressing material which is in a variety of forms (varying from a solid granule to a viscous melt) the pressure at the nozzle can vary quite considerably from cycle to cycle.
- (d) The presence of the torpedo causes a significant pressure loss.
- (e) The flow properties of the melt are pressure sensitive and since the pressure is erratic, this amplifies the variability in mould filling.

Some of the disadvantages of the plunger machine may be overcome by using a pre-plasticising system. This type of machine has two barrels. Raw material is fed into the first barrel where an extruder screw or plunger plasticises the material and feeds it through a non-return valve into the other barrel. A plunger in the second barrel then forces the melt through a nozzle and into the mould. In this system there is much better homogenisation because the melt has to pass through the small opening connecting the two barrels. The shot size can also be metered more accurately since the volume of material fed to the second barrel can be controlled by a limit switch on its plunger. Another advantage is that there is no longer a need for the torpedo on the main injection cylinder.

However, nowadays this type of machine is seldom used because it is considerably more complicated and more expensive than necessary. One area of application where it is still in use is for large mouldings because a large volume of plastic can be plasticised prior to injection using the primary cylinder plunger.

For normal injection moulding, however, the market is now dominated by the reciprocating screw type of injection moulding machine. This was a major breakthrough in machine design and yet the principle is simple. An extruder type screw in a heated barrel performs a dual role. On the one hand it rotates in the normal way to transport, melt and pressurize the material in the barrel but it is also capable, whilst not rotating, of moving forward like a plunger

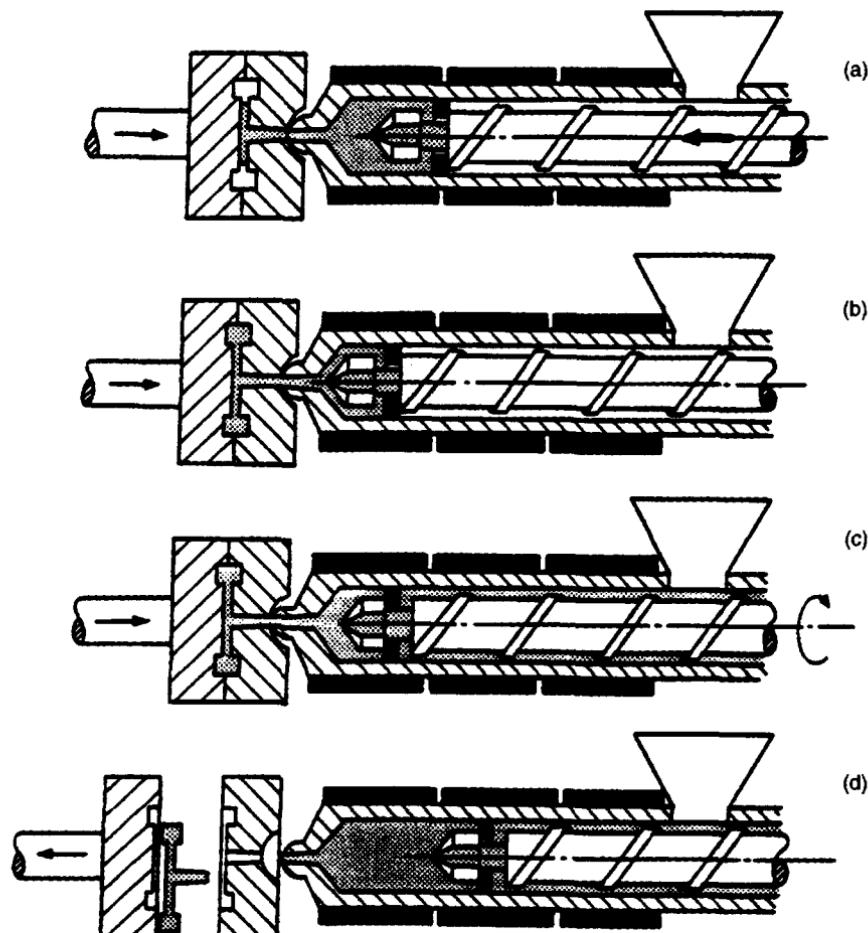


Fig. 4.31 Typical cycle in reciprocating screw injection moulding machine

to inject melt into the mould. A typical injection moulding machine cycle is illustrated in Fig. 4.31. It involves the following stages:

- 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.
- When the cavity is filled, the screw continues to push forward to apply a holding pressure (see Fig. 4.31). 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.
- 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.
- 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 (see Fig. 4.32).

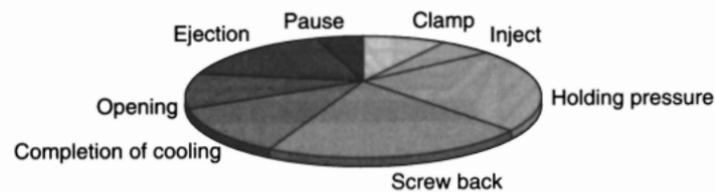
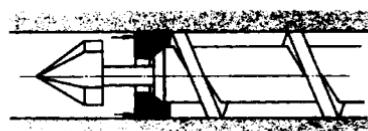


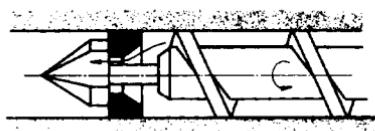
Fig. 4.32 Stages during injection moulding

There are a number of important features in reciprocating screw injection moulding machines and these will now be considered in turn.

Screws The screws used in these machines are basically the same as those described earlier for extrusion. The compression ratios are usually in the range 2.5:1 to 4:1 and the most common L/D ratios are in the range 15 to 20. Some screws are capable of injecting the plastic at pressures up to 200 MN/m². One important difference from an extruder screw is the presence of a back-flow check valve at the end of the screw as illustrated in Fig. 4.33. The purpose of this valve is to stop any back flow across the flights of the screw when it is acting as a plunger. When material is being conveyed forward by the rotation of the screw, the valve opens as shown. One exception is when injection moulding



(a) Valve closed



(b) Valve open

Fig. 4.33 Typical check valve

heat-sensitive materials such as PVC. In such cases there is no check valve because this would provide sites where material could get clogged and would degrade.

Barrels and Heaters These are also similar to those in extruder machines. In recent years, vented barrels have become available to facilitate the moulding of water sensitive plastics without the need for pre-drying. Water sensitivity in plastics can take several forms. If the plastic absorbs water then dimensional changes will occur, just as with wood or paper. The plastic will also be plasticised by the water so that there will be property changes such as a reduction in modulus and an increase in toughness. All these effects produced by water absorption are reversible.

Another event which may occur is *hydrolysis*. This is a chemical reaction between the plastic and water. It occurs extremely slowly at room temperature but can be significant at moulding temperatures. Hydrolysis causes degradation, reduction in properties (such as impact strength) and it is irreversible. Table 4.3 indicates the sensitivity of plastics to moisture. Note that generally extrusion requires a lower moisture content than injection moulding to produce good quality products.

Table 4.3
Water sensitivity of some common plastics

Drying not required (Materials do not hydrolyse)	Absorbs only	Drying required	Hydrolyses
Polyethylene	Acrylic (0.02/0.08)*	PET (0.002/0.002)	
Polypropylene	ABS (0.02/0.08)	Polycarbonate (0.01/0.02)	
Polystyrene	SAN (0.02/0.08)		Nylon 66 (0.08/0.15)
PVC			

*Required maximum moisture content for extrusion/injection moulding (%)

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.

There are several types of nozzle. The simplest is an open nozzle as shown in Fig. 4.34(a). This is used whenever possible because pressure drops can be minimised and there are no hold up points where the melt can stagnate and decompose. However, if the melt viscosity is low then leakage will occur from this type of nozzle particularly if the barrel/nozzle assembly retracts from the mould each cycle. The solution is to use a shut-off nozzle of which there are many types. Fig. 4.34(b) shows a nozzle which is shut off by external means. Fig. 4.34(c) shows a nozzle with a spring loaded needle valve which opens when the melt pressure exceeds a certain value or alternatively when the nozzle is pressed up against the mould. Most of the shut-off nozzles have the disadvantage that they restrict the flow of the material and provide undesirable stagnation sites. For this reason they should not be used with heat sensitive materials such as PVC.

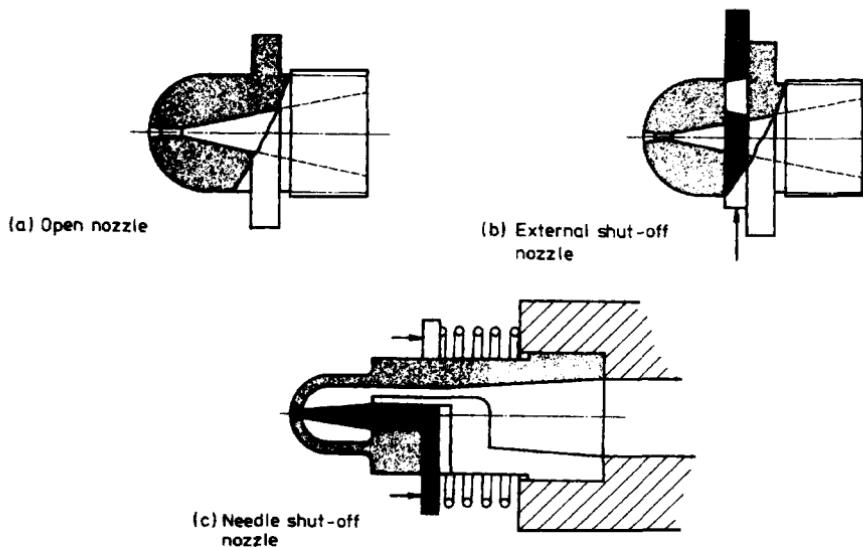


Fig. 4.34 Types of nozzle

Clamping Systems In order to keep the mould halves tightly closed when the melt is being injected under high pressures it is necessary to have a clamping system. This may be either (a) hydraulic or (b) mechanical (toggle) – or some combination of the two.

In the hydraulic system, oil under pressure is introduced behind a piston connected to the moving platen of the machine. This causes the mould to close and the clamp force can be adjusted so that there is no leakage of molten plastic from the mould.

The toggle is a mechanical device used to amplify force. Toggle mechanisms tend to be preferred for high speed machines and where the clamping force is relatively small. The two main advantages of the toggle system are that it is more economical to run the small hydraulic cylinder and since the toggle is self locking it is not necessary to maintain the hydraulic pressure throughout the moulding cycle. On the other hand the toggle system has the disadvantages that there is no indication of the clamping force and the additional moving parts increase maintenance costs.

4.3.3 Moulds

In the simplest case an injection mould (or 'tool') consists of two halves into which the impression of the part to be moulded is cut. The mating surfaces of the mould halves are accurately machined so that no leakage of plastic can occur at the split line. If leakage does occur the flash on the moulding is unsightly and expensive to remove. A typical injection mould is illustrated in Fig. 4.35. It may be seen that in order to facilitate mounting the mould in the machine and cooling and ejection of the moulding, several additions are made to the basic mould halves. Firstly, backing plates permit the mould to be bolted on to the machine platens. Secondly, channels are machined into the mould to allow the mould temperature to be controlled. Thirdly, ejector pins are included so that the moulded part can be freed from the mould. In most cases the ejector pins are operated by the shoulder screw hitting a stop when the mould opens. The mould cavity is joined to the machine nozzle by means of the **sprue**. The sprue anchor pin then has the function of pulling the sprue away from the nozzle and ensuring that the moulded part remains on the moving half of the mould, when the mould opens. For multi-cavity moulds the impressions are joined to the sprue by **runners** – channels cut in one or both halves of the mould through which the plastic will flow without restriction. A narrow constriction between the runner and the cavity allows the moulding to be easily separated from the runner and sprue. This constriction is called the **gate**.

A production injection mould is a piece of high precision engineering manufactured to very close tolerances by skilled craftsmen. A typical mould can be considered to consist of (i) the cavity and core and (ii) the remainder of the mould (often referred to as the bolster). Of these two, the latter is the more straightforward because although it needs to be accurately made, in general, conventional machine tools can be used. The cavity and core, however, may be quite complex in shape and so they often need special techniques. These can include casting, electro-deposition, hobbing, pressure casting, spark erosion and NC machining.

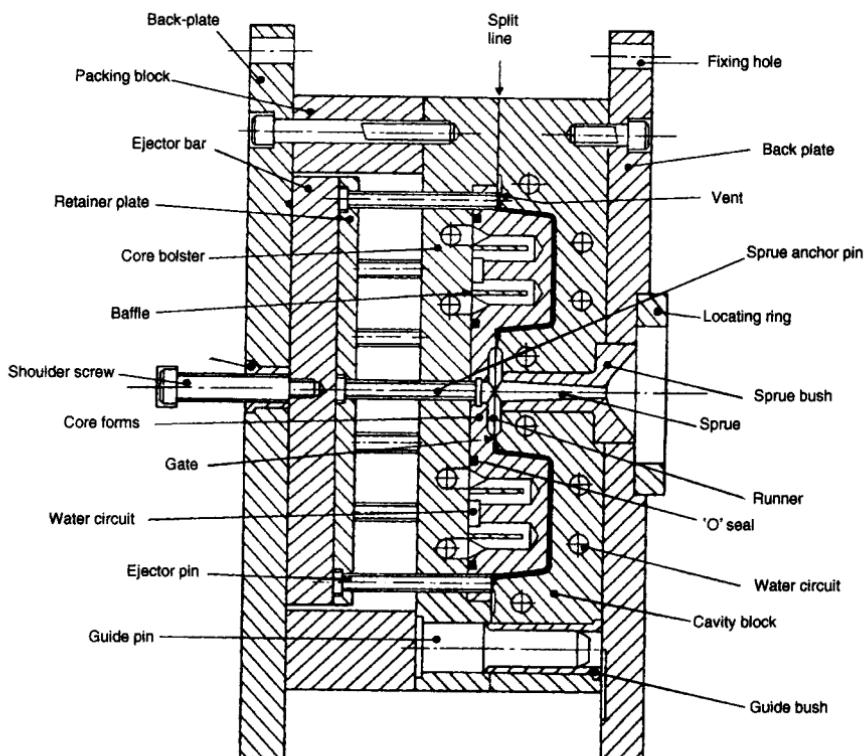


Fig. 4.35 Details of injection mould

Finishing and polishing the mould surfaces is also extremely important because the melt will tend to reproduce every detail on the surface of the mould. Finally the mould will have to be hardened to make it stand up to the treatment it receives in service. As a result of all the time and effort which goes into mould manufacture, it is sometimes found that a very complex mould costs more than the moulding machine on which it is used. Several features of the mould are worthy of special mention.

(a) Gates: As mentioned earlier the gate is the small orifice which connects the runner to the cavity. It has a number of functions. Firstly, it provides a convenient weak link by which the moulding can be broken off from the runner system. In some moulds the degating may be automatic when the mould opens. 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. As a general rule, small gates are preferable because no finishing

is required if the moulding is separated cleanly from the runner. So for the initial trials on a mould the gates are made as small as possible and are only opened up if there are mould filling problems.

In a multi-cavity mould it is not always possible to arrange for the runner length to each cavity to be the same. This means that cavities close to the sprue would be filled quickly whereas cavities remote from the sprue receive the melt later and at a reduced pressure. To alleviate this problem it is common to use small gates close to the sprue and progressively increase the dimensions of the gates further along the runners. This has the effect of balancing the fill of the cavities. If a single cavity mould is multi-gated then here again it may be beneficial to balance the flow by using various gate sizes.

Examples of gates which are in common use are shown in Fig. 4.36. Sprue gates are used when the sprue bush can feed directly into the mould cavity as, for example, with single symmetrical moulding such as buckets. Pin gates are particularly successful because they cause high shear rates which reduce the viscosity of the plastic and so the mould fills more easily. The side gate is the most common type of gate and is a simple rectangular section feeding into the side of the cavity. A particular attraction of this type of gate is that mould filling can be improved by increasing the width of the gate but the freeze time is unaffected because the depth is unchanged.

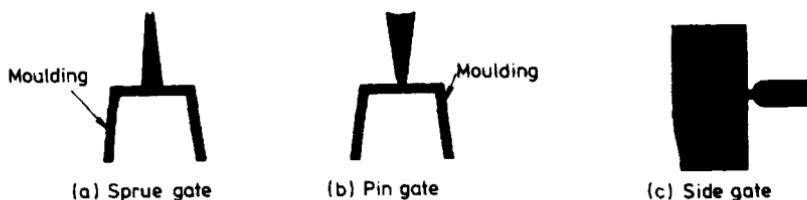


Fig. 4.36 Types of gate

(b) Runners: The runner is the flow path by which the molten plastic travels from the sprue (i.e. the moulding machine) 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. However, the cross sectional area of the runner should be large so that it presents little resistance to the flow of the plastic but not so large that the cycle time needs to be extended to allow the runner to solidify for ejection. A good indication of the efficiency of a runner is, therefore, the ratio of its cross-sectional area to its surface area. For example, a semi-circular channel cut into one half of the mould is convenient to machine but it only has an area ratio of $0.153 D$ where D is the diameter of the semi-circle. A full round runner, on the other hand, has a ratio of $0.25 D$. A square section also has this ratio but is seldom used because it is difficult to

eject. A compromise is a trapezoidal section (cut into one half of the mould) or a hexagonal section.

(c) 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. The sprue is incorporated in a hardened steel bush which has a seat designed to provide a good seal with the nozzle. Since it is important that the sprue is pulled out when the mould opens it is tapered as shown in Fig. 4.35 and there is a sprue pulling device mounted directly opposite the sprue entry. This can take many forms but typically it would be an undercut or reversed taper to provide a key for the plastic on the moving half of the mould. Since the sprue, like the runner system, is effectively waste it should not be made excessively long.

(d) Venting: Before the plastic melt is injected, the cavity in the closed mould contains air. When the melt enters the mould, if the air cannot escape it becomes compressed. At worst this may affect the mould filling, but in any case the sudden compression of the air causes considerable heating. This may be sufficient to burn the plastic and the mould surface at local hot spots. To alleviate this problem, vents are machined into the mating surfaces of the mould to allow the air to escape. The vent channel must be small so that molten plastic will not flow along it and cause unsightly flash on the moulded article. Typically a vent is about 0.025 mm deep and several millimeters wide. Away from the cavity the depth of the vent can be increased so that there is minimum resistance to the flow of the gases out of the mould.

(e) Mould Temperature Control: For efficient moulding, the temperature of the mould should be controlled and this is normally done by passing a fluid through a suitably arranged channel in the mould. The rate at which the moulding cools affects the total cycle time as well as the surface finish, tolerances, distortion and internal stresses of the moulded article. High mould temperatures improve surface gloss and tend to eliminate voids. However, the possibility of flashing is increased and sink marks are likely to occur. If the mould temperature is too low then the material may freeze in the cavity before it is filled. In most cases the mould temperatures used are a compromise based on experience. In Chapter 5 we will consider ways of estimating the time taken for a moulding to cool down in a mould.

Example 4.5 The runner lay-out for an eight cavity mould is illustrated in Fig. 4.37. If the mould is to be designed so that the pressure at the gate is the same in all cases, determine the radius of the runner in section A. The flow may be assumed to be isothermal.

Solution Although this runner system is symmetrical, it is not balanced. If the runner had the same diameter throughout all sections, then the mouldings close to the sprue would fill first and would be over-packed before the outermost

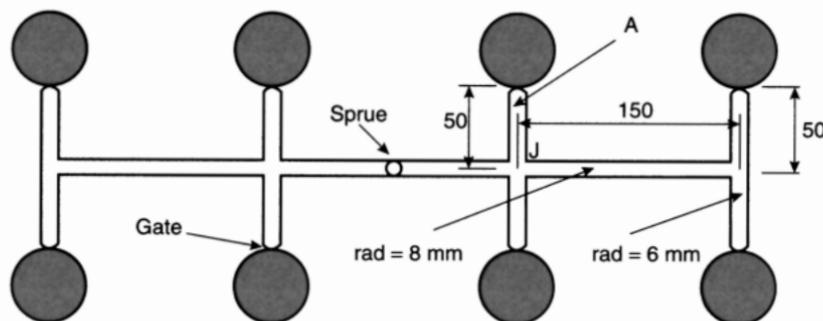


Fig. 4.37 Lay-out for eight cavity mould

cavities were filled. In a good mould design, all the cavities fill simultaneously at the same pressure. In this case it is necessary to ensure that the pressure drop in Sections 1 and 3 is the same as the pressure drop in Section 2.

It will be shown in Chapter 5 that the pressure drop, ΔP , for isothermal flow in a circular section channel is given by

$$\Delta P = \frac{8\eta LQ}{\pi R^4} \quad (4.22)$$

where

η = viscosity of the plastic

L = length of channel

Q = volume flow rate

R = radius of channel

If the volume flow rate towards point J is q (ie the input at the sprue is $2q$) then at J the flow will split as follows:

$$\text{Flow along runner 1} = xq$$

$$\text{Flow along runner 2} = 1/2(1 - x)q$$

$$\text{Flow along runner 3} = 1/2xq$$

where

$$x = \frac{A_1}{A_1 + 2A_2} = \frac{R_1^2}{R_1^2 + 2R_2^2}$$

(A refers to the area of the relevant runner).

Using equation (4.22) we can write

$$\text{Pressure loss in runner 1} = \frac{8\eta L_1 x q}{\pi R_1^4}$$

$$\text{Pressure loss in runner 2} = \frac{8\eta L_2(1-x)q}{2\pi R_2^4}$$

$$\text{Pressure loss in runner 3} = \frac{8\eta L_3 x q}{2\pi R_3^4}$$

Thus, equating pressure losses after point J

$$\frac{8\eta L_2(1-x)q}{2\pi R_2^4} = \frac{8\eta L_1 x q}{\pi R_1^4} + \frac{8\eta L_3 x q}{2\pi R_3^4}$$

Substituting for x and rearranging to get R_2

$$R_2 = \frac{R_1 R_3 \sqrt{2L_2}}{\sqrt{2L_1 R_3^4 + L_3 R_1^4}}$$

For the dimensions given:

$$R_2 = 3.8 \text{ mm}$$

In practice there are a number of other factors to be taken into account. For example, the above analysis assumes that this plastic is Newtonian, ie that it has a constant viscosity, η . In reality the plastic melt is non-Newtonian so that the viscosity will change with the different shear rates in each of the three runner sections analysed. In addition, the melt flow into the mould will not be isothermal – the plastic melt immediately in contact with the mould will solidify. This will continuously reduce the effective runner cross-section for the melt coming along behind. The effects of non-Newtonian and non-isothermal behaviour are dealt with in Chapter 5.

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 (see Fig. 4.38). 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. Unfortunately, it is not economically viable to discard them so they must be re-ground for subsequent reprocessing. Regrinding is expensive and can introduce contamination into the material so that any system which avoids the accumulation of runners and sprues is attractive. 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

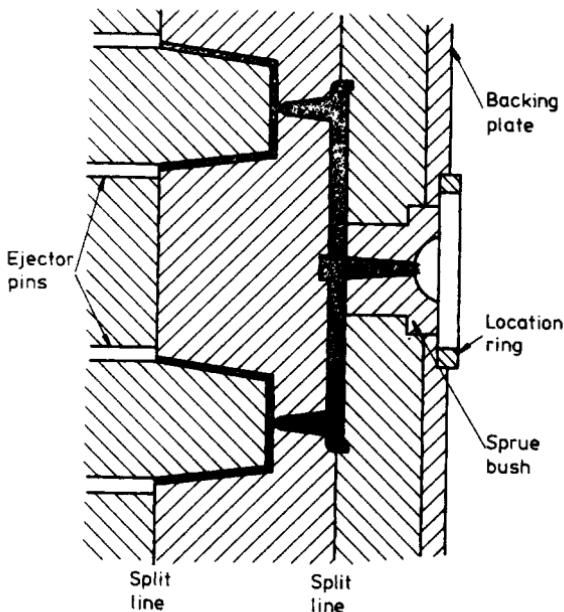


Fig. 4.38 Typical 3-plate mould

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. A typical mould layout is shown in Fig. 4.39.

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. Also there are many areas in the hot runner manifold where material can get trapped. This means that problems can be experienced during colour or grade changes because it is difficult to remove all of the previous material. As a practical point it should also be realised that the system only works as long as the runner remains molten. If the runner system freezes off then the hot runner manifold needs to be dismantled to remove the runners. Note also that hot runner system are not suitable for heat sensitive materials such as PVC.

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

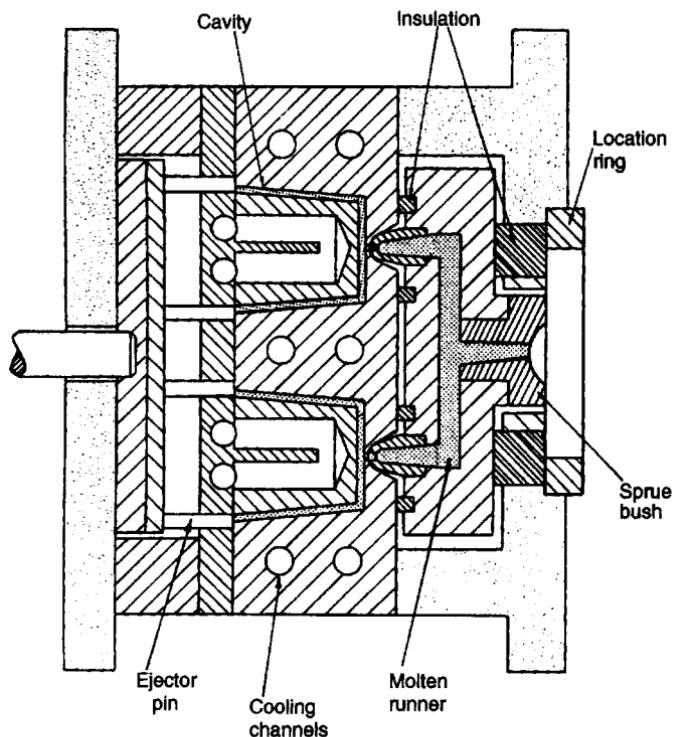


Fig. 4.39 Layout of hot runner mould

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. If an undue delay causes the whole runner to freeze off then it may be ejected and when moulding is restarted the insulation layer soon forms again. 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.

A recent development of the insulated runner principle is the *distribution tube system*. This overcomes the possibility of freezing-off by insertion of heated tubes into the runners. However, this system still relies on a thick layer of polymer forming an insulation layer on the wall of the runner and so this system is not suitable for heat sensitive materials.

Note that both the insulated runner and the distribution tube systems rely on a cartridge heater in the gate area to prevent premature freezing off at the gate (see Fig. 4.40).

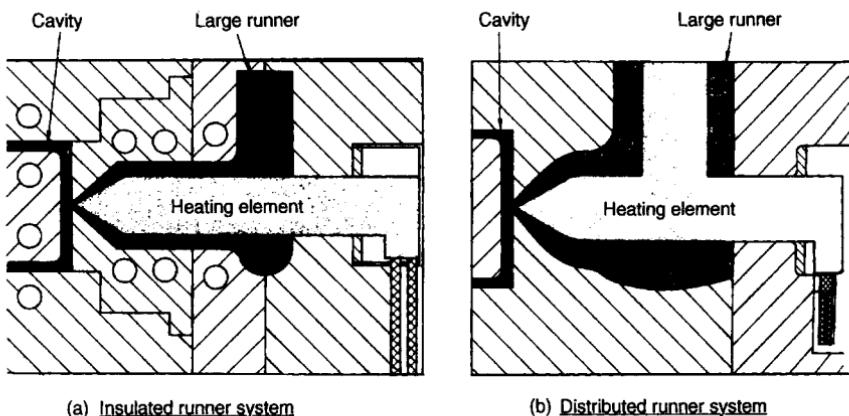


Fig. 4.40 Insulated and distributed runner systems

Mould Clamping Force

In order to prevent 'flashing', i.e. a thin film of plastic escaping out of the mould cavity at the parting line, it is necessary to keep the mould tightly closed during injection of the molten plastic. Before setting up a mould on a machine it is always worthwhile to check that there is sufficient clamping force available on the machine. To do this it is necessary to be able to estimate what clamping force will be needed. The relationship between mould area and clamp requirements has occupied the minds of moulders for many years. Practical experience suggests that the clamping pressure over the projected area of the moulding should be between 10 and 50 MN/m² depending on factors such as shape, thickness, and type of material. The mould clamping force may also be estimated in the following way. Consider the moulding of a disc which is centre gated as shown in Fig. 4.41(a). The force on the shaded element is given by

$$\text{Force, } F = \int_0^R P_r 2\pi r dr \quad (4.23)$$

The cavity pressure will vary across the disc and it is necessary to make some assumption about this variation. Experimental studies have suggested that an empirical relation of the form

$$P_r = P_0 \left(1 - \left(\frac{r}{R} \right)^m \right) \quad (4.24)$$

is most satisfactory. P_0 is the pressure at the gate and m is a constant which is usually between 0.3 and 0.75. It will be shown later (Chapter 5) that ' m ' is in fact equal to $(1-n)$ where ' n ' is the index in the Power Law expression for polymer melt flow.

Substituting (4.24) in (4.23) then

$$F = \int_0^R P_0 \left(1 - \left(\frac{r}{R} \right)^m \right) 2\pi r dr$$

$$F = \pi R^2 P_0 \left(\frac{m}{m+2} \right) \quad (4.25)$$

This is a simple convenient expression for estimating the clamping force required for the disc. The same expression may also be used for more complex shapes where the projected area may be approximated as a circle. It will also give sufficiently accurate estimates for a square plate when the radius, R , in Fig. 4.41(a) is taken as half of the diagonal.

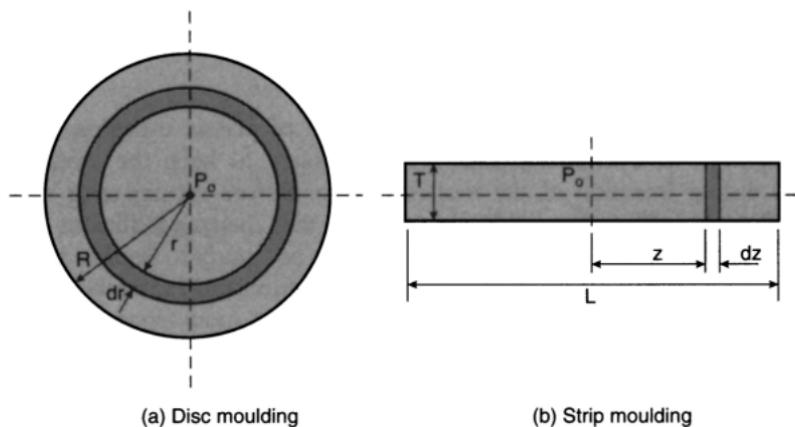


Fig. 4.41 Clamp force analysis

An alternative way of looking at this equation is that the clamping pressure, based on the projected area of the moulding, is given by

$$\text{Clamping pressure} = \left(\frac{m}{m+2} \right) \times \text{Injection pressure}$$

For any particular material the ratio ($m/(m + 2)$) may be determined from the flow curves and it will be temperature and (to some extent) pressure dependent.

In practice the clamping pressure will also depend on the geometry of the cavity. In particular the flow ratio (flow length/channel lateral dimension) is important. Fig. 4.42 illustrates typical variations in the Mean Effective Pressure in the cavity for different thicknesses and flow ratios. The data used here is typical for easy flow materials such as polyethylene, polypropylene and polystyrene. To calculate the clamp force, simply multiply the appropriate Mean Effective Pressure by the projected area of the moulding. In practice it is

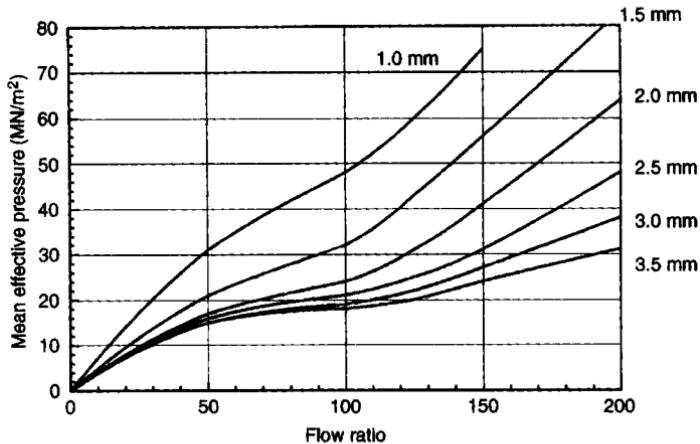


Fig. 4.42 Clamping pressures for different cavity geometries (typical values for easy flow materials)

prudent to increase this value by 10–20% due to the uncertainties associated with specific moulds.

For plastics other than the easy flow materials referred to above, it would be normal to apply a factor to allow for the higher viscosity. Typical viscosity factors are given below.

Material	Viscosity Factor
Polyethylene, polypropylene, polystyrene	1
Nylon 66	1.2 → 1.4
ABS	1.3 → 1.4
Acrylic	1.5 → 1.7
PVC	1.6 → 1.8
Polycarbonate	1.7 → 2.0

Example 4.6 The mould shown in Fig. 4.35 produces four cup shaped ABS mouldings. The depth of the cups is 60 mm, the diameter at the base is 90 mm and the wall thickness is 1.0 mm. The distance from the sprue to the cavity is 40 mm and the runner diameter is 6 mm. Calculate the clamp force necessary on the moulding machine and estimate how the clamp force would change if the mould was designed so as to feed the cups through a pin gate in the centre of the base (as illustrated in Fig. 4.38). The clamp pressure data in Fig. 4.42 should be used and the taper on the side of the cups may be ignored.

Solution

(a) Within the cavity, the maximum flow length for the plastic melt will be from the gate, along the side of the cup and across the base of the cup, ie

$$\text{Flow length} = 60 + 90 = 150 \text{ mm}$$

The thickness of the moulding is 1 mm, hence the flow ratio = $150/1 = 150$. From Fig. 4.42 at this thickness and flow ratio, the mean effective pressure is 75 MN/m^2 .

Allowing an extra 15% for uncertainties and applying the viscosity factor of 1.4 for ABS, then the appropriate mean effective pressure is $75 \times 1.15 \times 1.4 = 120 \text{ MN/m}^2$. For each cavity, the projected area is $(\pi/4)(90)^2 = 6360 \text{ mm}^2 = 6.36 \times 10^{-3} \text{ m}^2$.

Hence, clamp force per cavity = $120 \times 6.36 \times 10^{-3} = 763 \text{ kN}$.

The projected area of the runners is $4 \times 40 \times 6 = 960 \text{ mm}^2$.

Assuming that the mean effective pressure also applies to the runner system, then

$$\text{clamp force for runners} = 120 \times 0.96 \times 10^{-3} = 115 \text{ kN}$$

Hence total clamp force for 4 cavities and 1 runner system is given by

$$\text{Total clamp force} = (4 \times 763) + 115 = 3167 \text{ kN}$$

The required clamp force is therefore 317 tonnes.

(b) If a pin gate in the middle of the base is used instead of an edge gate, then the flow ratio will be different. In this case

$$\text{flow length} = \frac{1}{2}(90) + 60 = 105$$

This is also the flow ratio, so from Fig. 4.42 the mean effective pressure is 50 MN/m^2 . Applying the viscosity factor, etc as above, then

$$\text{Clamp force per cavity} = 50 \times 1.15 \times 1.4 \times \left(\frac{\pi}{4}\right)(90)^2 \times 10^{-6} = 512 \text{ kN}$$

In this case the runner system will be almost totally in the 'shadow' of the projected area of the cavities and so they can be ignored.

Hence, total clamp force = $4 \times 512 = 2048 \text{ kN} = 205 \text{ tonnes}$.

Another common shape which is moulded is a thin rectangular strip. Consider the centre gated strip as shown in Fig. 4.41(b). In the same way as before the clamping force, F , is given by

$$F = 2 \int_0^{L/2} P_z T dz \quad (4.26)$$

$$F = 2 \int_0^{L/2} P_0 \left(1 - \left(\frac{z}{L/2}\right)^m\right) T dz$$

i.e.

$$F = TP_0 L \left(\frac{m}{m+1} \right) \quad (4.27)$$

The calculation of clamp force is considered in more detail in Chapter 5.

4.3.4 Structural Foam Injection Moulding

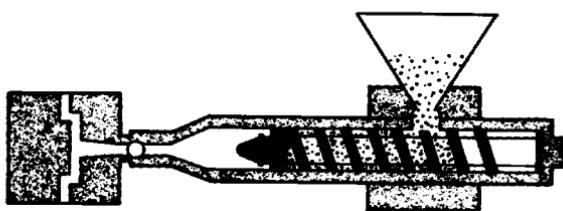
Foamed thermoplastic articles have a cellular core with a relatively dense (solid) skin. The foam effect is achieved by the dispersion of inert gas throughout the molten resin directly before moulding. Introduction of the gas is usually carried out either by pre-blending the resin with a chemical blowing agent which releases gas when heated or by direct injection of the gas (usually nitrogen).

When the compressed gas/resin mixture is rapidly injected into the mould cavity, the gas expands explosively and forces the material into all parts of the mould.

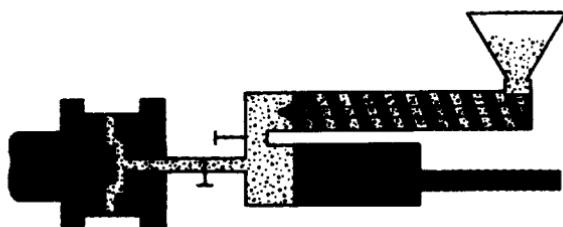
The advantages of these types of foam moulding are

- (a) for a given weight they are many times more rigid than a solid moulding
- (b) they are almost completely free from orientation effects and the shrinkage is uniform
- (c) very thick sections can be moulded without sink marks.

Foamed plastic articles may be produced with good results using normal screw-type injection moulding machines (see Fig. 4.43(a)). However, the limitations on shot size, injection speed and platen area imposed by conventional



(a) Standard injection moulding press



(b) Specialised foam moulding press

Fig. 4.43 Structural foam moulding equipment

injection equipment prevent the full large-part capabilities of structural foam from being realised. Specialised foam moulding machines currently in use can produce parts weighing in excess of 50 kg (see Fig. 4.43(b)).

Wall sections in foam moulding are thicker than in solid material. Longer cycle times can therefore be expected due to both the wall thickness and the low thermal conductivity of the cellular material. In contrast, however, the injection pressures in foam moulding are low when compared with conventional injection moulding. This means that less clamping force is needed per unit area of moulding and mould costs are less because lower strength mould materials may be used.

4.3.5 Sandwich Moulding

This is an injection moulding method which permits material costs to be reduced in large mouldings. In most mouldings it is the outer surface of an article which is important in terms of performance in service. If an article has to be thick in order that it will have adequate flexural stiffness then the material within the core of the article is wasted because its only function is to keep the outer surfaces apart. The philosophy of sandwich moulding is that two different materials (or two forms of the same material) should be used for the core and skin. That is, an expensive high performance material is used for the skin and a low-cost commodity or recycled plastic is used for the core. The way that this can be achieved is illustrated in Fig. 4.44.

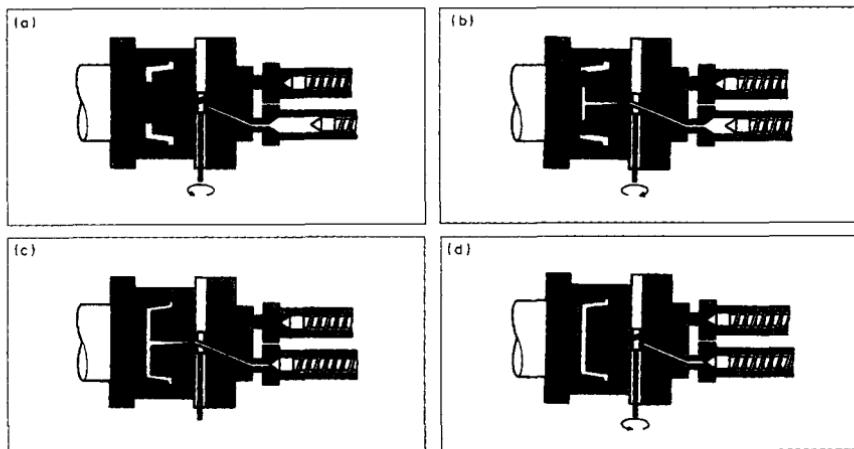


Fig. 4.44 Stages in sandwich moulding process

Initially the skin material is injected but not sufficient to fill the mould. The core material is then injected and it flows laminarly into the interior of the core. This continues until the cavity is filled as shown in Fig. 4.44(c). Finally the

nozzle valve rotates so that the skin material is injected into the sprue thereby clearing the valve of core material in preparation for the next shot. In a number of cases the core material is foamed to produce a sandwich section with a thin solid skin and a cellular core.

It is interesting that in the latest applications of sandwich moulding it is the core material which is being regarded as the critical component. This is to meet design requirements for computers, electronic equipment and some automotive parts. In these applications there is a growing demand for covers and housings with electromagnetic interference (EMI) shielding. The necessity of using a plastic with a high loading of conductive filler (usually carbon black) means that surface finish is poor and unattractive. To overcome this the sandwich moulding technique can be used in that a good quality surface can be moulded using a different plastic.

4.3.6 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 pressure at the polymer gate remains high and, therefore, the gas chooses a natural path through the hotter and less viscous parts of the polymer melt towards the lower pressure areas. 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

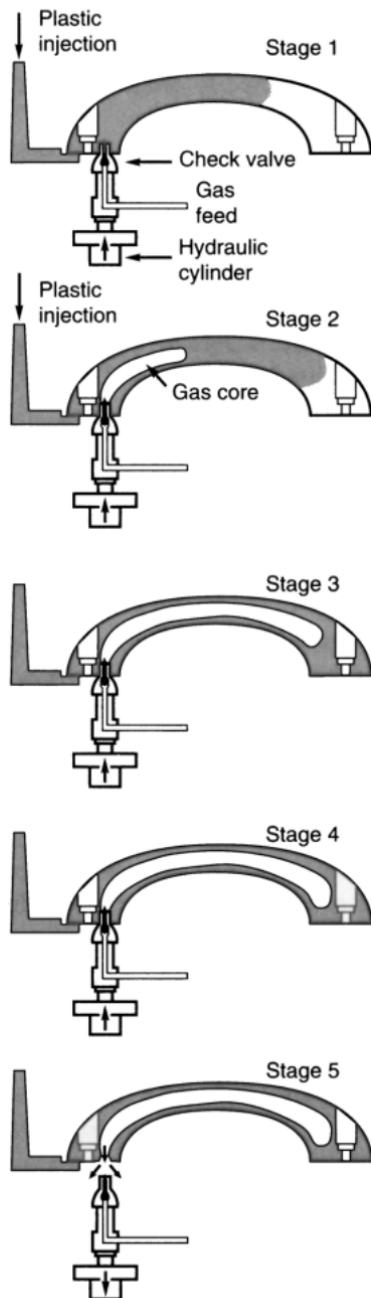


Fig. 4.45 Stages in the gas injection moulding of an automotive handle (courtesy of Cinpress Ltd)

(caused by escaping gas bubbles in structural foam moulding) and cycle times are lower because thinner sections are being cooled.

4.3.7 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.

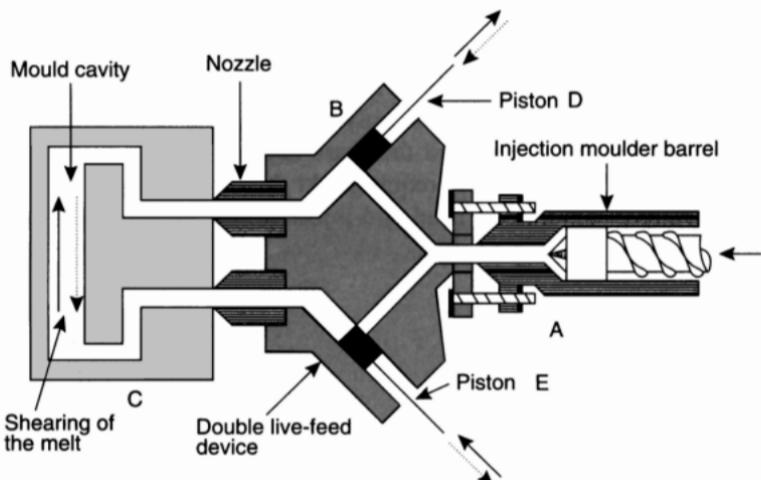


Fig. 4.46 One embodiment of SCORIM where the device (B) for producing shear during solidification, by the action of pistons (D) and (E), is placed between the injection moulding machine barrel (A) and the mould (C) (Courtesy of Brunel University)

Shear controlled orientation in injection moulding (SCORIM) is based on the progressive application of macroscopic shears at the melt-solid interface during solidification in the moulding of a polymer matrix.

Macroscopic shears of specified magnitude and direction, applied at the melt-solid interface provide several advantages:

- Enhanced polymer matrix or fibre alignment by design in moulded polymers or fibre reinforced polymers.
- Elimination of mechanical discontinuities that result from the initial mould filling process, including internal weld lines.
- Reduction in the detrimental effects of a change in moulded section thickness.
- Elimination or reduction in defects resulting from the moulding of thick sectioned components.

4.3.8 Reaction Injection Moulding

Although there have been for many years a number of moulding methods (such as hand lay-up of glass fibres in polyester and compression moulding of thermosets or rubber) in which the plastic material is manufactured at the same time as it is being shaped into the final article, it is only recently that this concept has been applied in an injection moulding type process. In Reaction Injection Moulding (RIM), 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).

The basic RIM process is illustrated in Fig. 4.47. A range of plastics lend themselves to the type of fast polymerisation reaction which is required in this process – polyesters, epoxies, nylons and vinyl monomers. However, by far the most commonly used material is polyurethane. The components A and B are an isocyanate and a polyol and these are kept circulating in their separate systems until an injection shot is required. At this point the two reactants are brought together in the mixing head and injected into the mould.

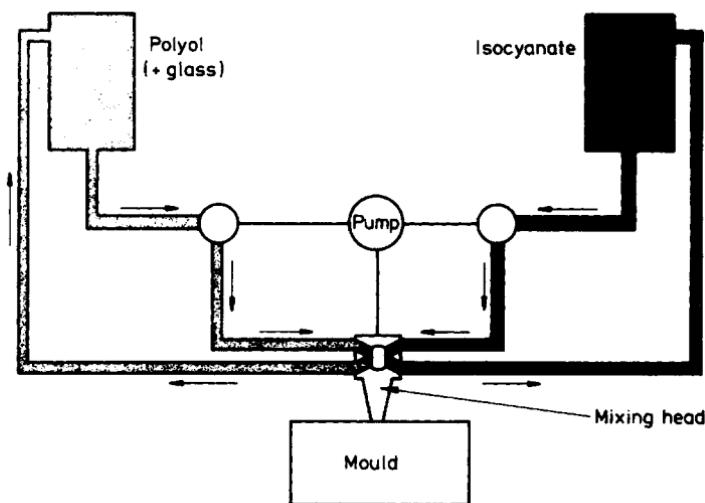


Fig. 4.47 Schematic view of reaction injection moulding

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). Therefore the RIM process is particularly suitable for large

area mouldings such as car bumpers and body panels. Another consequence of the low injection pressures is that 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 but they must not be regarded as cheap. RIM moulds require careful design and, in particular, a good surface finish because the expansion of the material in the mould during polymerisation causes every detail on the surface of the mould to be reproduced on the moulding.

4.3.9 Injection Blow Moulding

In Section 4.2.7 we considered the process of extrusion blow moulding which is used to produce hollow articles such as bottles. At that time it was mentioned that if molecular orientation can be introduced to the moulding then the properties are significantly improved. In recent years the process of injection blow moulding has been developed to achieve this objective. It is now very widely used for the manufacture of bottles for soft drinks.

The steps in the process are illustrated in Fig. 4.48. Initially a preform is injection moulded. This is subsequently inflated in a blow mould in order to produce the bottle shape. In most cases the second stage inflation step occurs immediately after the injection moulding step but in some cases the preforms are removed from the injection moulding machine and subsequently re-heated for inflation.

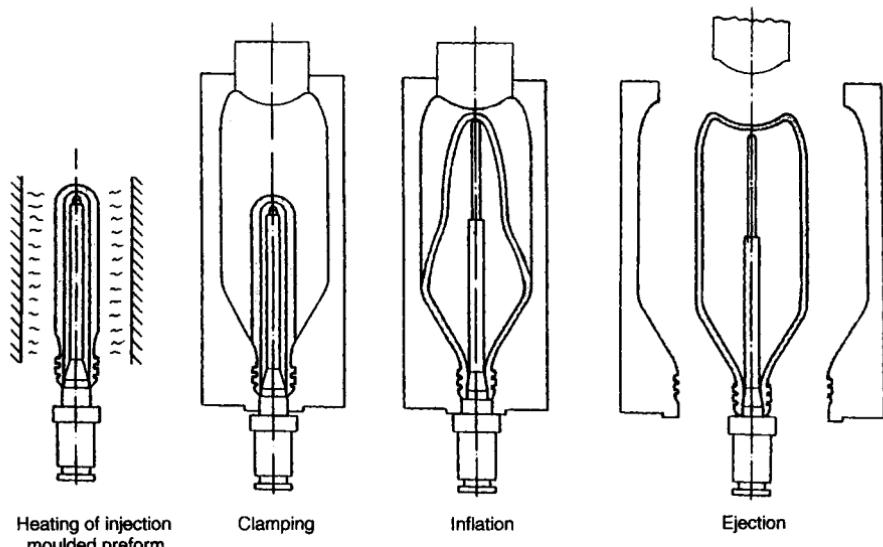


Fig. 4.48 Injection blow moulding process

The advantages of injection blow moulding are that

- (i) the injection moulded parison may have a carefully controlled wall thickness profile to ensure a uniform wall thickness in the inflated bottle.
- (ii) it is possible to have intricate detail in the bottle neck.
- (iii) there is no trimming or flash (compare with extrusion blow moulding).

A variation of this basic concept is the *Injection Orientation Blow Moulding* technique developed in the 1960s in the USA but upgraded for commercial use in the 1980s by AOKI in Japan. The principle is very similar to that described above and is illustrated in Fig. 4.49. It may be seen that the method essentially combines injection moulding, blow moulding and thermoforming to manufacture high quality containers.

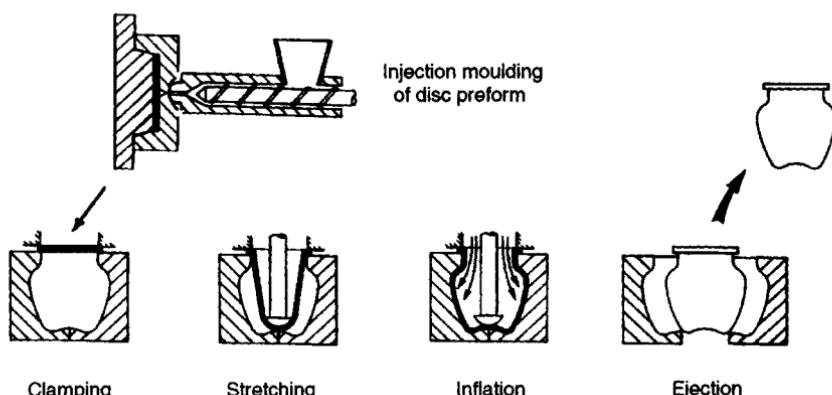


Fig. 4.49 Injection orientation stretch blow moulding

4.3.10 Injection Moulding of Thermosetting Materials

In the past the thought of injection moulding thermosets was not very attractive. This was because early trials had shown that the feed-stock was not of a consistent quality which meant that continual alterations to the machine settings were necessary. Also, any undue delays could cause premature curing of the resin and consequent blockages in the system could be difficult to remove. However, in recent years the processing characteristics of thermosets have been improved considerably so that injection moulding is likely to become one of the major production methods for these materials. The injection moulding of fibre reinforced thermosets, such as DMC (Section 4.10.2), is also becoming very common.

Nowadays, the injection moulder can be supplied with uniform quality granules which consist of partially polymerised resin, fillers and additives. The formulation of the material is such that it will flow easily in the barrel with a slow rate of polymerisation. The curing is then completed rapidly in the mould.

In most respects the process is similar to the injection moulding of thermoplastics and the sequence of operations in a single cycle is as described earlier. For thermosets a special barrel and screw are used. The screw is of approximately constant depth over its whole length and there is no check value which might cause material blockages (see Fig. 4.50). The barrel is only kept warm ($80\text{--}110^{\circ}\text{C}$) rather than very hot as with thermoplastics because the material must not cure in this section of the machine. Also, the increased viscosity of the thermosetting materials means that higher screw torques and injection pressures (up to 200 MN/m^2 are needed).

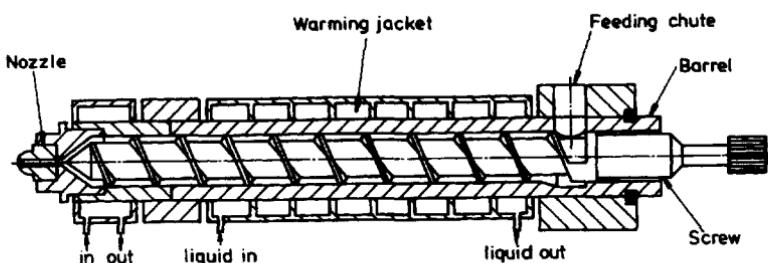


Fig. 4.50 Injection moulding of thermosets and rubbers

On the mould side of the machine the major difference is that the mould is maintained very hot ($150\text{--}200^{\circ}\text{C}$) rather than being cooled as is the case with thermoplastics. This is to accelerate the curing of the material once it has taken up the shape of the cavity. Another difference is that, as thermosetting materials are abrasive and require higher injection pressures, harder steels with extra wear resistance should be used for mould manufacture. As a result of the abrasive nature of the thermosets, hydraulic mould clamping is preferred to a toggle system because the inevitable dust from the moulding powder increases the wear in the linkages of the latter.

When moulding thermosetting articles, the problem of material wastage in sprues and runners is much more severe because these cannot be reused. It is desirable therefore to keep the sprue and runner sections of the mould cool so that these do not cure with the moulding. They can then be retained in the mould during the ejection stage and then injected into the cavity to form the next moulding. This is analogous to the hot runner system described earlier for thermoplastics.

The advantages of injection moulding thermosets are as follows:

- fast cyclic times (see Table 4.4)
- efficient metering of material
- efficient pre-heating of material
- thinner flash – easier finishing
- lower mould costs (fewer impressions).

Table 4.4

For the same part, injection moulding of thermosets can offer up to 25% production increase and lower part-costs than compression.

<i>Compression moulding</i>	<i>Minutes</i>
Open mould, unload piece	0.105
Mould cleaning	0.140
Close machine, start pressure	0.100
Moulding cycle time	2.230
Total compression cycle	2.575

<i>Injection moulding</i>	<i>Minutes</i>
Unload piece, open/close machine	0.100
Moulding cycle time	1.900
Total injection cycle	2.000

4.4 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, motor-bike fairings etc.

The term 'thermoforming' incorporates 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 corners which is considerably less than that close to the clamp. If this was not acceptable then

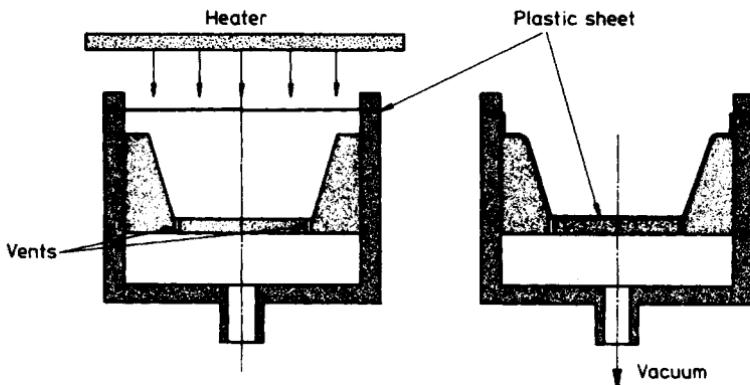


Fig. 4.51 Vacuum forming process

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 *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 tight, 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/m². 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 crystallisable 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.

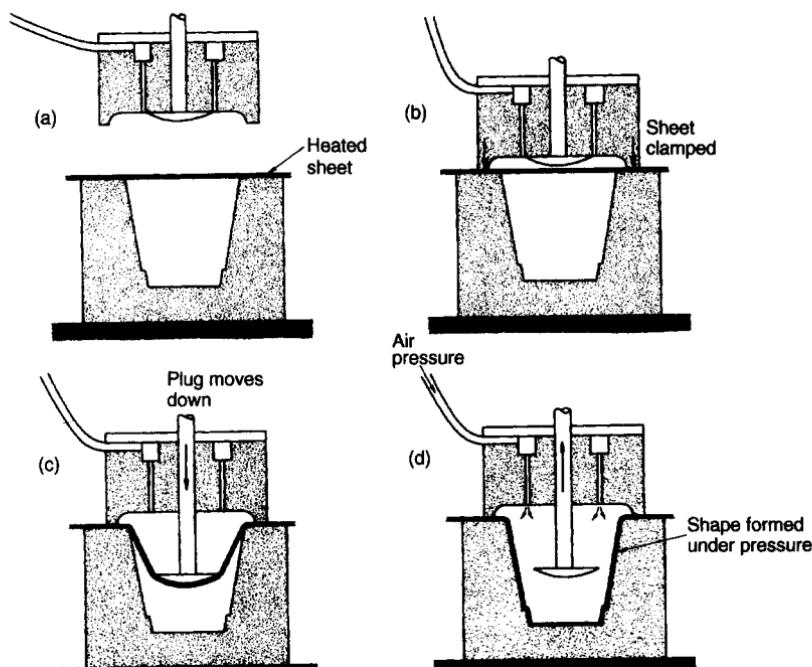


Fig. 4.52 Pressure forming process

(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.

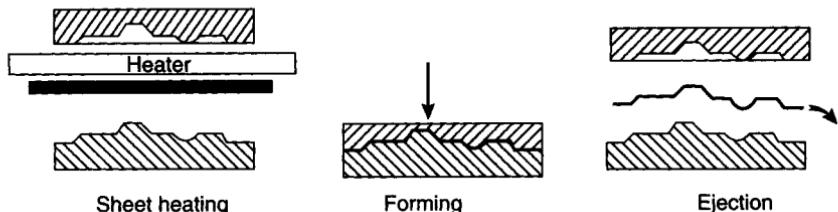


Fig. 4.53 Thermoforming between matched dies

(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.

4.4.1 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.

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

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

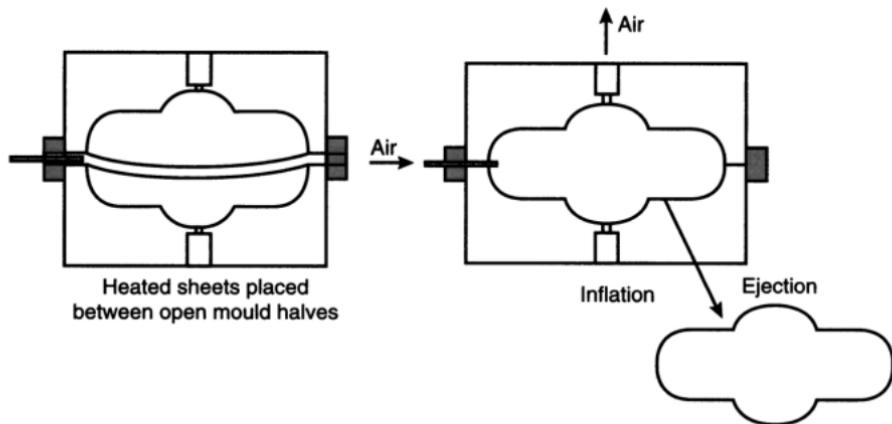


Fig. 4.54 Dual sheet forming

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 × 100 mm × 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 × 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.

Consider the thermoforming of a plastic sheet of thickness, h_0 , into a conical mould as shown in Fig. 4.55(a). At this moment in time, t , the plastic is in contact with the mould for a distance, S , and the remainder of the sheet is in the form of a spherical dome of radius, R , and thickness, h . From the geometry of the mould the radius is given by

$$R = \frac{H - S \sin \alpha}{\sin \alpha \tan \alpha} \quad (4.29)$$

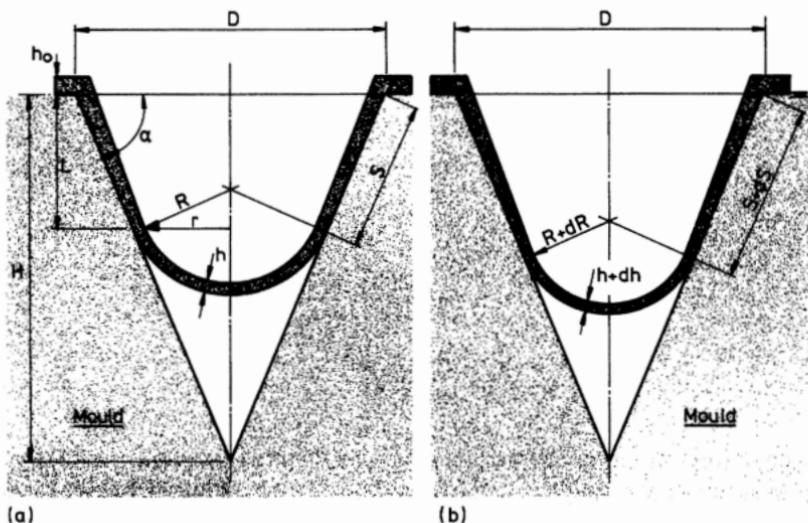


Fig. 4.55 Analysis of thermo forming

Also the surface area, A , of the spherical bubble is given by

$$A = 2\pi R^2 (1 - \cos \alpha) \quad (4.30)$$

At a subsequent time, $(t + dt)$, the sheet will be formed to the shape shown in Fig. 4.55(b). The change in thickness of the sheet in this period of time may

be estimated by assuming that the volume remains constant.

$$2\pi R^2(1 - \cos \alpha)h = 2\pi(R + dR)^2(1 - \cos \alpha)(h + dh) + 2\pi rh dS \sin \alpha$$

Substituting for $r (= R \sin \alpha)$ and for R from (4.29) this equation may be reduced to the form

$$\frac{dh}{h} = \left[2 - \left(\frac{\sin^2 \alpha \tan \alpha}{1 - \cos \alpha} \right) \right] \cdot \frac{\sin \alpha dS}{(H - S \sin \alpha)} \quad (4.31)$$

This equation may be integrated with the boundary condition that $h = h_1$ at $S = 0$. As a result the thickness, h , at a distance, S , along the side of the conical mould is given by

$$h = h_1 \left(\frac{H - S \sin \alpha}{H} \right)^{\sec \alpha - 1} \quad (4.32)$$

Now consider again the boundary condition referred to above. At the point when the softened sheet first enters the mould it forms part of a spherical bubble which does not touch the sides of the cone. The volume balance is therefore

$$\left(\frac{D^2}{4} \right) h_0 = \frac{2(D/2)^2(1 - \cos \alpha)h_1}{\sin^2 \alpha}$$

$$\text{So, } h_1 = \frac{\sin^2 \alpha}{2(1 - \cos \alpha)} \cdot h_0$$

Making the substitution for h_1 in (4.32)

$$h = \frac{\sin^2 \alpha}{2(1 - \cos \alpha)} \left[\frac{H - S \cdot \sin \alpha}{H} \right]^{\sec \alpha - 1} \cdot h_0$$

or

$$h/h_0 = \left(\frac{1 + \cos \alpha}{2} \right) \left[\frac{H - L}{H} \right]^{\sec \alpha - 1} \quad (4.33)$$

This equation may also be used to calculate the wall thickness distribution in deep truncated cone shapes but note that its derivation is only valid up to the point when the spherical bubble touches the centre of the base. Thereafter the analysis involves a volume balance with freezing-off on the base and sides of the cone.

Example 4.8 A small flower pot as shown in Fig. 4.56 is to be thermoformed using negative forming from a flat plastic sheet 2.5 mm thick. If the diameter of the top of the pot is 70 mm, the diameter of the base is 45 mm and the depth is 67 mm estimate the wall thickness of the pot at a point 40 mm from the top. Calculate also the draw ratio for this moulding.

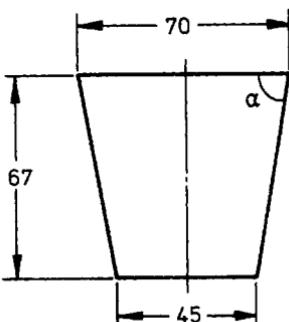


Fig. 4.56 Thermoformed flower pot

Solution

$$(a) \quad \alpha = \tan^{-1} \left(\frac{67}{12.5} \right) = 79.4^\circ$$

Using the terminology from Fig. 4.39(b)

$$H = 35 \tan \alpha = 187.6 \text{ mm}$$

From equation (4.33)

$$\frac{h}{h_0} = \left(\frac{1 + \cos 79.4^\circ}{2} \right) \left(\frac{187.6 - 40}{187.6} \right)^{(\sec 79.4)-1} = 0.203$$

$$h = 0.203 \times 2.5 = 0.51 \text{ mm}$$

(b) The *draw-ratio* for a thermoformed moulding is the ratio of the area of the product to the initial area of the sheet. In this case therefore

$$\begin{aligned} \text{Draw ratio} &= \frac{\pi \sqrt{[(R - r)^2 + h^2](R + r)} + \pi r^2}{\pi R^2} \\ &= \frac{\pi \sqrt{[(35 - 22.5)^2 + 67^2](35 + 22.5)} + \pi(22.5)^2}{\pi(35)^2} \\ &= 3.6 \end{aligned}$$

4.5 Calendering

Calendering is a method of producing plastic film and sheet by squeezing the plastic through the gap (or 'nip') between two counter-rotating cylinders. The art of forming a sheet in this way can be traced to the paper, textile and metal industries. The first development of the technique for polymeric materials was in the middle 19th century when it was used for mixing additives into rubber. The subsequent application to plastics was not a complete success because the

early machines did not have sufficient accuracy or control over such things as cylinder temperature and the gap between the rolls. Therefore acceptance of the technique as a viable production method was slow until the 1930s when special equipment was developed specifically for the new plastic materials. As well as being able to maintain accurately roll temperature in the region of 200°C these new machines had power assisted nip adjustment and the facility to adjust the rotational speed of each roll independently. These developments are still the main features of modern calendering equipment.

Calenders vary in respect of the number of rolls and of the arrangement of the rolls relative to one another. One typical arrangement is shown in Fig. 4.57 – the inverted L-type. Although the calendering operation as illustrated here looks very straightforward it is not quite as simple as that. In the production plant a lot of ancillary equipment is needed in order to prepare the plastic material for the calender rolls and to handle the sheet after the calendering operation. A typical sheet production unit would start with premixing of the polymer, plasticiser, pigment, etc in a ribbon mixer followed by gelation of the premix in a Banbury Mixer and/or a short screw extruder. At various stages, strainers and metal detectors are used to remove any foreign matter. These preliminary operations result in a material with a dough-like consistency which is then supplied to the calender rolls for shaping into sheets.

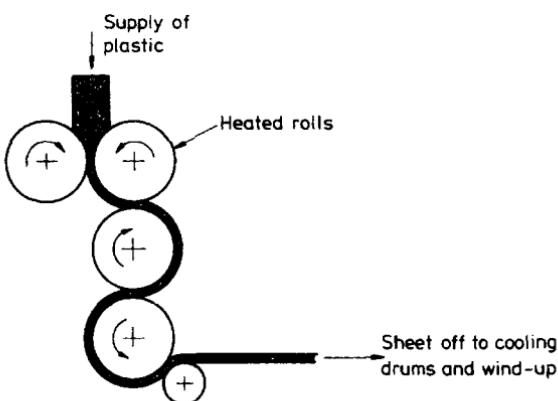


Fig. 4.57 Typical arrangement of calender rolls

However, even then the process is not complete. Since the hot plastic tends to cling to the calender rolls it is necessary to peel it off using a high speed roll of smaller diameter located as shown in Fig. 4.57. When the sheet leaves the calender it passes between embossing rolls and then on to cooling drums before being trimmed and stored on drums. For thin sheets the speed of the winding drum can be adjusted to control the drawdown. Outputs vary in the range 0.1–2 m/s depending on the sheet thickness.

Calendering can achieve surprising accuracy on the thickness of a sheet. Typically the tolerance is ± 0.005 mm but to achieve this it is essential to have very close control over roll temperatures, speeds and proximity. In addition, the dimensions of the rolls must be very precise. The production of the rolls is akin to the manufacture of an injection moulding tool in the sense that very high machining skills are required. The particular features of a calender roll are a uniform specified surface finish, minimal eccentricity and a special barrel profile ('crown') to compensate for roll deflection under the very high pressures developed between the rolls.

Since calendering is a method of producing sheet/film it must be considered to be in direct competition with extrusion based processes. In general, film blowing and die extrusion methods are preferred for materials such as polyethylene, polypropylene and polystyrene but calendering has the major advantage of causing very little thermal degradation and so it is widely used for heat sensitive materials such as PVC.

4.5.1 Analysis of Calendering

A detailed analysis of the flow of molten plastic between two rotating rolls is very complex but fortunately sufficient accuracy for many purposes can be achieved by using a simple Newtonian model. The assumptions made are that

- (a) the flow is steady and laminar
- (b) the flow is isothermal
- (c) the fluid is incompressible
- (d) there is no slip between the fluid and the rolls.

If the clearance between the rolls is small in relation to their radius then at any section x the problem may be analysed as the flow between parallel plates at a distance h apart. The velocity profile at any section is thus made up of a drag flow component and a pressure flow component.

For a fluid between two parallel plates, each moving at a velocity V_d , the drag flow velocity is equal to V_d . In the case of a calender with rolls of radius, R , rotating at a speed, N , the drag velocity will thus be given by $2\pi RN$.

The velocity component due to pressure flow between two parallel plates has already been determined in Section 4.2.3(b).

$$V_p = \frac{1}{2\eta} \frac{dP}{dx} (y^2 - (h/2)^2)$$

Therefore the total velocity at any section is given by

$$V = V_d + \frac{1}{2\eta} \frac{dP}{dx} [y^2 - (h/2)^2]$$

Considering unit width of the calender rolls the total throughput, Q , is given by

$$\begin{aligned} Q &= 2 \int_0^{h/2} V dy \\ &= 2 \int_0^{h/2} \left[V_d + \frac{1}{2\eta} \frac{dP}{dx} (y^2 - (h/2)^2) \right] dy \\ &= h \left(V_d - \frac{h^2}{12\eta} \frac{dP}{dx} \right) \end{aligned} \quad (4.34)$$

Since the output is given by V_dH

$$\text{then } V_dH = h \left(V_d - \frac{h^2}{12\eta} \frac{dP}{dx} \right) \quad (4.35)$$

From this it may be seen that $\frac{dP}{dx} = 0$ at $h = H$.

To determine the shape of the pressure profile it is necessary to express h as a function of x . From the equation of a circle it may be seen that

$$h = H_0 + 2(R - (R^2 - x^2)^{1/2}) \quad (4.36)$$

However, in the analysis of calendering this equation is found to be difficult to work with and a useful approximation is obtained by expanding $(R^2 - x^2)^{1/2}$ using the binomial series and retaining only the first two terms. This gives

$$h = H_0 \left(1 + \frac{x^2}{H_0 R} \right) \quad (4.37)$$

Therefore as shown earlier dP/dx will be zero at

$$\begin{aligned} H &= H_0 \left(1 + \frac{x^2}{H_0 R} \right) \\ x &= \pm \sqrt{(H - H_0)R} \end{aligned} \quad (4.38)$$

This gives a pressure profile of the general shape shown in Fig. 4.58. The value of the maximum pressure may be obtained by rearranging (4.35) and substituting for h from (4.37)

$$\frac{dP}{dx} = \frac{12\eta V_d \left(H_0 - H + \frac{x^2}{R} \right)}{\left(H_0 + \frac{x^2}{R} \right)^3} \quad (4.39)$$

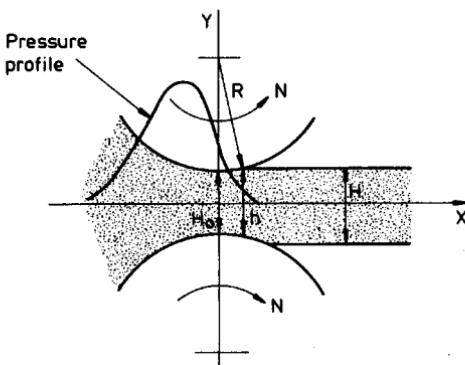


Fig. 4.58 Melt flow between calender rolls

If this equation is integrated and the value of x from (4.38) substituted then the maximum pressure may be obtained as

$$P_{\max} = \frac{3\eta V_d}{H_0} \left(2\omega - \frac{(4H_0 - 3H)}{H_0} \left(\omega + \sqrt{\frac{R}{H_0}} \tan^{-1} \sqrt{\left(\frac{H - H_0}{H} \right)} \right) \right) \quad (4.40)$$

where

$$\omega = \frac{\sqrt{(H - H_0)R}}{H} \quad (4.41)$$

Example 4.9 A calender having rolls of diameter 0.4 m produces plastic sheet 2 m wide at the rate of 1300 kg/hour. If the nip between rolls is 10 mm and the exit velocity of the sheet is 0.01 m/s estimate the position and magnitude of the maximum pressure. The density of the material is 1400 kg/m^3 and its viscosity is 10^4 Ns/m^2 .

Solution Flow rate, $Q = 1300 \text{ kg/hour} = 0.258 \times 10^{-3} \text{ m}^3/\text{s}$

but $Q = HWV_d$ where W = width of sheet

$$\text{So } H = \frac{0.258 \times 10^{-3}}{2 \times 0.01} = 12.9 \text{ mm}$$

The distance upstream of the nip at which the pressure is a maximum is given by equation (4.38)

$$x = \sqrt{(12.9 - 10)200} = 24.08 \text{ mm}$$

Also from (4.37)

$$\begin{aligned} P_{\max} &= \frac{3 \times 10^4 \times 0.01}{10 \times 10^{-3}} \{ (2 \times 1.865) - 0.13[1.865 + (4.45)(0.494)] \} \\ &= 96 \text{ kN/m}^2 \end{aligned}$$

4.6 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 right 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 modern 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).

$$hA(T_0 - T) = \rho C_p V \left(\frac{dT}{dt} \right) \quad (4.42)$$

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

$$\begin{aligned} hA \int_0^t dt &= \rho C_p V \int_{T_i}^{T_t} \frac{dT}{(T_0 - T)} \\ hAt &= -\rho C_p V \log_e \left(\frac{T_0 - T_t}{T_0 - T_i} \right) \\ \left(\frac{T_0 - T_t}{T_0 - T_i} \right) &= e^{-h\beta t/\rho C_p} \end{aligned} \quad (4.43)$$

where T_i 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.

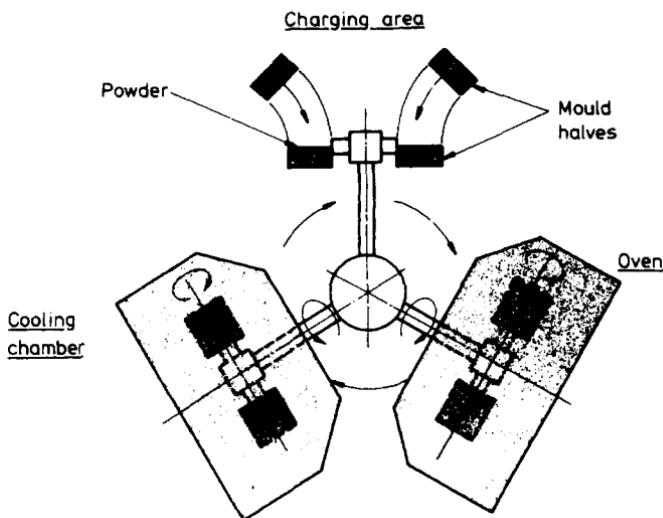


Fig. 4.59 Typical rotational moulding process

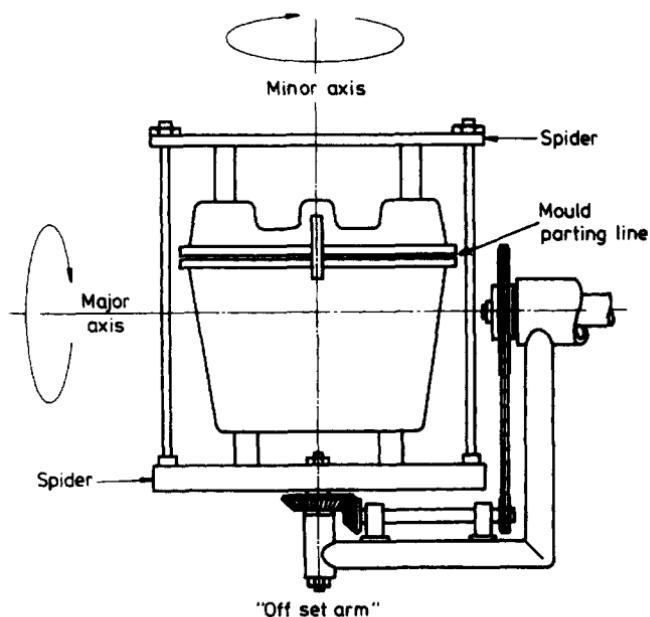


Fig. 4.60 Typical 'off-set arm' rotation

Fig. 4.61 illustrates typical temperature profiles during the rotational moulding of polyethylene. With typical values of oven temperatures and data for an aluminium mould

$$T_0 = 300^\circ\text{C}, \quad T_i = 30^\circ\text{C}, \quad T_t = 20^\circ\text{C}$$

$$h = 22 \text{ W/m}^2\text{K} \quad C_p = 917 \text{ J/kg K}, \quad \rho = 2700 \text{ kg/m}^3$$

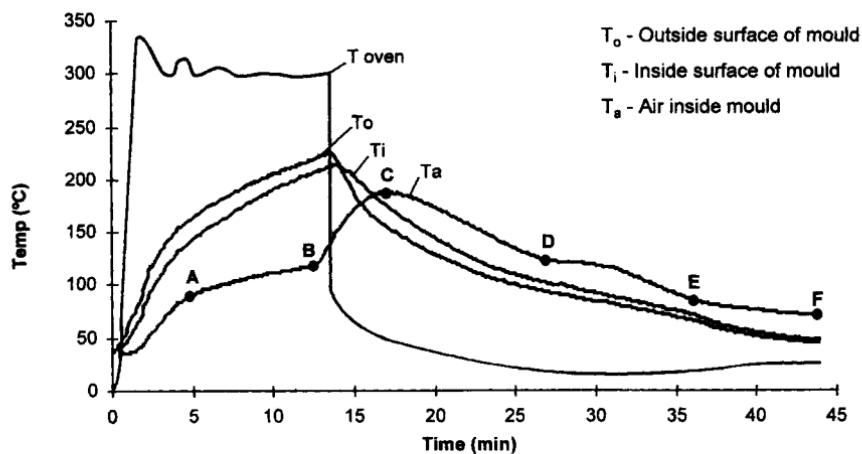


Fig. 4.61 Temperature profiles during rotational moulding

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 ($h = 11 \text{ W/m}^2\text{K}$, $C_p = 480 \text{ J/kg K}$ and $\rho = 7850 \text{ kg/m}^3$) 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 bonded together whereas at C it has become a uniform melt. The value of temperature 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 $200^{\circ}\text{C} \pm 5^{\circ}\text{C}$.

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 an 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.

4.6.1 Slush Moulding

This is a method for making hollow articles using liquid plastics, particularly PVC plastisols. A shell-like mould is heated to a pre-determined temperature (typically 130°C for plastisols) and the liquid is then poured into the mould to completely fill it. A period of time is allowed to elapse until the required thickness of plastic gels. The excess liquid is then poured out and the plastic skin remaining in the mould is cured in an oven. The moulding is then taken from the mould.

It should be noted that when the plastisol liquid gels it has sufficient strength to remain in position on the inside surface of the mould. However, it has insufficient tear strength to be useful and so it has to go through the higher temperature curing stage to provide the necessary toughness and strength in the end-product. The mould is not rotated during slush moulding.

4.7 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

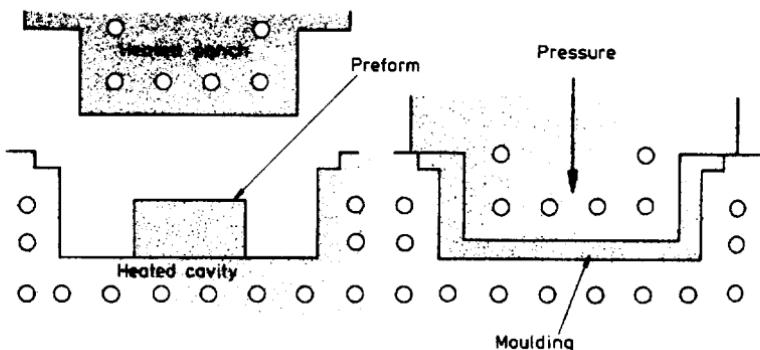


Fig. 4.62 Principle of compression moulding

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/m² cavity pressure needed. It should also be noted that compression moulding is also used for Dough Moulding Compounds (DMC) – these will be considered in Section 4.10.2

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

$$\text{flow rate, } Q_p = \frac{1}{12\eta} \left(\frac{dP}{dz} \right) TH^3 \quad (4.6)$$

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

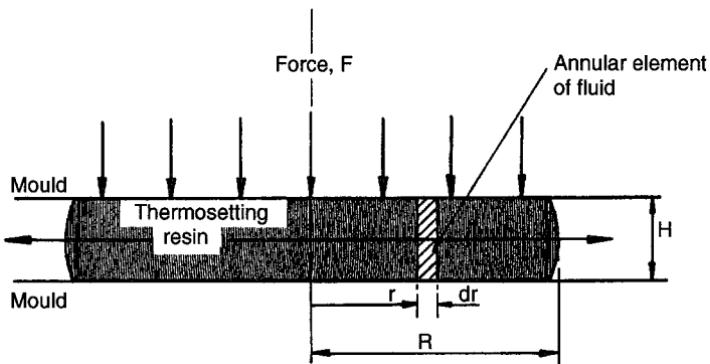


Fig. 4.63 Analysis of compression moulding

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

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

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

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

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

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

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

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 10^3 Ns/m².

Solution

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

So $H = 1 \text{ mm}$

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

4.8 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.

The success of transfer moulding prompted further developments in this area and clearly it was only a relatively small step to an injection moulding process for thermosets as described in Section 4.3.10.

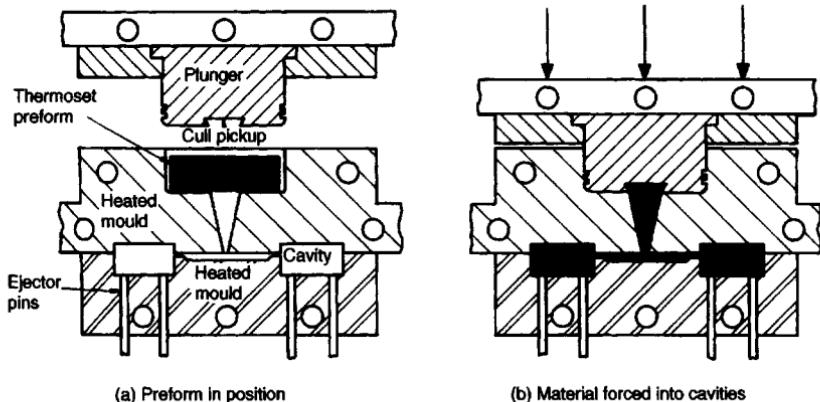


Fig. 4.64 Transfer moulding of thermosetting materials

4.9 Processing Reinforced Thermoplastics

Fibre reinforced thermoplastics can be processed using most of the conventional thermoplastic processing methods described earlier. Extrusion, rotational moulding, blow moulding and thermoforming of short fibre reinforced thermoplastics are all possible, but the most important commercial technique is injection moulding. In most respects this process is similar to the moulding of un-reinforced thermoplastics but there are a number of important differences. For example the melt viscosity of a reinforced plastic is generally higher than the unreinforced material. As a result the injection pressures need to be higher, by up to 80% in some cases. In addition the cycle times are generally lower because the greater stiffness of the material allows it to be ejected from the mould at a higher temperature than normal. However, the increased stiffness can also hamper ejection from the mould so it is important to have adequate taper on side walls of the cavity and a sufficient number of strategically placed ejector pins. Where possible a reciprocating screw machine is preferred to a plunger machine because of the better mixing, homogenisation, metering and temperature control of the melt. However, particular attention needs to be paid to such things as screw speed and back pressure because these will tend to break up the fibres and thus affect the mechanical properties of the mouldings.

A practical difficulty which arises during injection moulding of reinforced plastics is the increased wear of the moulding machine and mould due to the abrasive nature of the fibres. However, if hardened tool steels are used in the manufacture of screws, barrels and mould cavities then the problem may be negligible.

An inherent problem with all of the above moulding methods is that they must, by their nature, use short fibres (typically 0.2–0.4 mm long). As a result the full potential of the reinforcing fibres is not realised (see Section 2.8.5). In recent years therefore, there have been a number of developments in reinforced

thermoplastics to try to overcome these problems. One approach has been to produce continuous fibre tapes or mats which can be embedded in a thermoplastic matrix. The best known materials of this type are the Aromatic Polymer Composites (APC) and the glass mat reinforced thermoplastics (GMT). One of the most interesting of these consists of unidirectional carbon fibres in a matrix of polyetheretherketone (PEEK). The material comes in the form of a wide tape which may be arranged in layers in one half of a mould to align the unidirectional fibres in the desired directions. The assembly is then pressurised between the two matched halves of the heated mould. The result is a laminated thermoplastic composite containing continuous fibres aligned to give maximum strength and stiffness in the desired directions.

Another recent development has been the arrival of special injection moulding grades of thermoplastics containing long fibres. At the granule production stage the thermoplastic lace contains continuous fibres and to achieve this it is produced by pultrusion (see Section 4.10.3) rather than the conventional compounding extruder. The result is that the granules contain fibres of the same length as the granule (≈ 10 mm).

These long fibres give better product performance although injection moulding machine modifications may be necessary to prevent fibre damage and reduce undesirable fibre orientation effects in the mould.

4.10 Processing Reinforced Thermosets

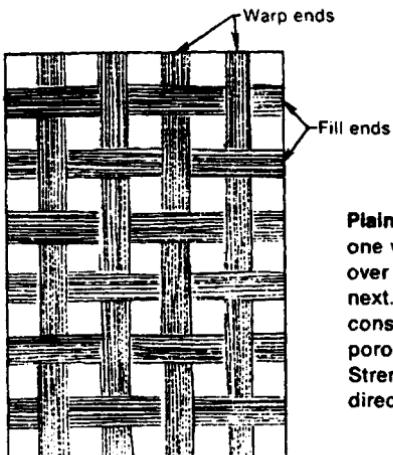
There is a variety of ways in which fibre reinforcement may be introduced into thermosetting materials and as a result there is a range of different methods used to process these materials. In many cases the reinforcement is introduced during the fabrication process so that its extent can be controlled by the moulder. Before looking at the possible manufacturing methods for fibre reinforced thermosetting articles it is worth considering the semantics of fibre technology. Because of their fibre form, reinforcing materials have borrowed some of their terminology from the textile industry.

Filament This is a single fibre which is continuous or at least very long compared with its diameter.

Yarn or Roving Continuous bundle of filaments generally fewer than 10,000 in number.

Tow A large bundle of fibres generally 10,000 or more, not twisted.

Fabric, Cloth or Mat Woven strands of filament. The weave pattern used depends on the flexibility and balance of strength properties required in the warp and fill directions. Fig. 4.65 shows a plain weave in which the strength is uniform in both directions. The warp direction refers to the direction parallel to



Plain Weave—In this construction, one warp end is repetitively woven over one fill yarn and under the next. It is the firmest, most stable construction, which provides for porosity and minimum slippage. Strength is uniform in both directions.

Fig. 4.65 Plain weave fibre fabric

the length of the fabric. Fabrics are usually designated in terms of the number of yarns of filament per unit length of warp and fill direction.

Chopped Fibres These may be subdivided as follows

Milled Fibres: These are finely ground or milled fibres. Lengths range from 30 to 3000 microns and the fibre (L/D) ratio is typically about 30. Fibres in this form are popular for closed mould manufacturing methods such as injection moulding.

Short Chopped Fibres: These are fibres with lengths up to about 6 mm. The fibre (L/D) ratio is typically about 800. They are more expensive than milled fibres but provide better strength and stiffness enhancement.

Long Chopped Fibres: These are chopped fibres with lengths up to 50 mm. They are used mainly in the manufacture of SMC and DMC (see Section 4.10.2).

Chopped Strand Mat This consists of strands of long chopped fibres deposited randomly in the form of a mat. The strands are held together by a resinous binder.

Manufacturing Methods

The methods used for manufacturing articles using fibre reinforced thermosets are almost as varied as the number of material variations that exist. They can, however, be divided into three main categories. These are manual, semi-automatic and automatic.

The *Manual* processes cover methods such as hand lay-up, spray-up, pressure bag and autoclave moulding.

The *Semi-Automatic* processes include processes such as cold pressing, hot pressing, compression moulding of SMC and DMC, resin injection.

The *Automatic* processes are those such as pultrusion, filament winding, centrifugal casting and injection moulding.

Typical market shares for the different methods are shown in Fig. 4.66.

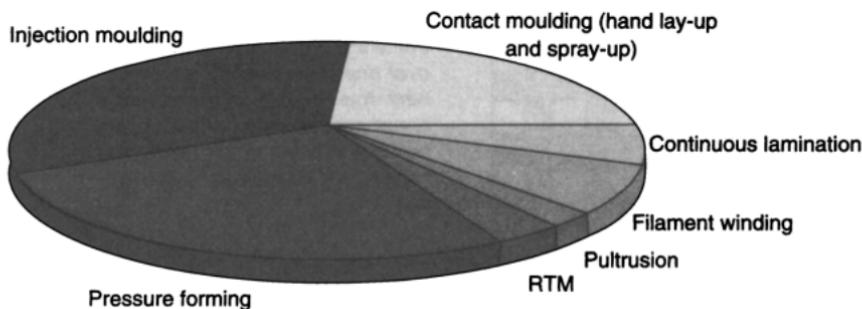
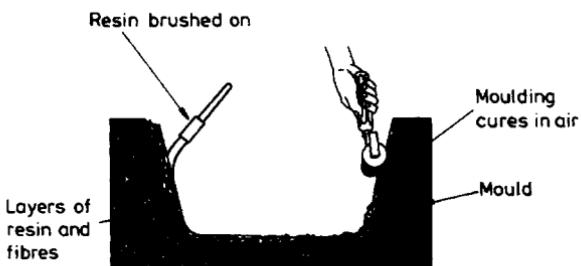


Fig. 4.66 Typical market shares for composite moulding methods in Europe

4.10.1 Manual Processing Methods

(a) **Hand Lay-Up:** This method is by far the most widely used processing method for fibre reinforced materials. In the UK it takes up about 40% of the FRP market. Its major advantage is that it is a very simple process so that very little special equipment is needed and the moulds may be made from plaster, wood, sheet metal or even FRP. The first step is to coat the mould with a release agent to prevent the moulding sticking to it. This is followed by a thin layer (approximately 0.3–0.4 mm) of pure resin (called a gelcoat) which has a number of functions. Firstly it conceals the irregular mesh pattern of the fibres and this improves the appearance of the product when it is taken from the mould. Secondly, and probably most important, it protects the reinforcement from attack by moisture which would tend to break down the fibre/resin interface. A tissue mat may be used on occasions to back up the gelcoat. This improves the impact resistance of the surface and also conceals the coarse texture of the reinforcement. However, it is relatively expensive and is only used if considered absolutely necessary.

When the gelcoat has been given time to partially cure the main reinforcement is applied. Initially a coat of resin (unsaturated polyester is the most common) is brushed on and this is followed by layers of tailored glass mat positioned by hand. As shown in Fig. 4.67 a roller is then used to consolidate the mat and remove any trapped air. The advantage of this technique is that the strength and stiffness of the composite can be controlled by building up the thickness with further layers of mat and resin as desired. Curing takes place at room temperature but heat is sometimes applied to accelerate this. Ideally any trimming should be carried out before the curing is complete because the



(a) Basic hand lay-up method

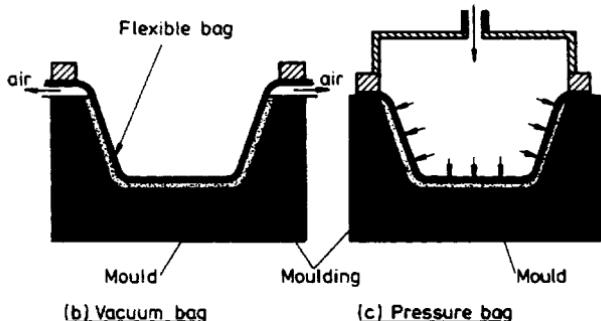


Fig. 4.67 Hand lay-up techniques

material will still be sufficiently soft for knives or shears to be used. After curing, special cutting wheels may be needed.

Variations on this basic process are (i) *vacuum bag moulding* and (ii) *pressure bag moulding*. In the former process a flexible bag (frequently rubber) is clamped over the lay-up in the mould and a vacuum is applied between the moulding and the bag. This sucks the bag on to the moulding to consolidate the layers of reinforcement and resin. It also squeezes out trapped air and excess resin. The latter process is similar in principle except that pressure is applied above the bag instead of a vacuum below it. The techniques are illustrated in Fig. 4.67(b) and (c).

(b) **Spray-Up:** In this process, the preparatory stages are similar to the previous method but instead of using glass mats the reinforcement is applied using a spray gun. Roving is fed to a chopper unit and the chopped strands are sprayed on to the mould simultaneously with the resin (see Fig. 4.68). The thickness of the moulding (and hence the strength) can easily be built up in sections likely to be highly stressed. However, the success of the method depends to a large extent on the skill of the operator since he controls the overall thickness of the composite and also the glass/resin ratio.

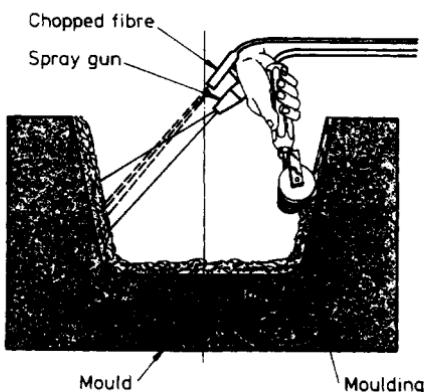


Fig. 4.68 Spray-up technique

(c) **Autoclave Moulding:** In order to produce high quality, high precision mouldings for the aerospace industries, for example, it is necessary to have strict control over fibre alignment and consolidation of the fibres in the matrix. To achieve this, fabric 'pre-pregs' (i.e. a fabric consisting of woven fibre yarns pre-impregnated with the matrix material) are carefully arranged in layers in an open mould. The arrangement of the layers will determine the degree of anisotropy in the moulded article. A typical layer arrangement is shown in Fig. 4.69(a). The pre-preg stack is then covered with a series of bleeder and breather sheets, as shown in Fig. 4.69(b) and finally with a flexible vacuum bag. When the air is extracted from between the flexible bag and the pre-preg stack, the latter will be squeezed tightly on to the mould. The whole assembly is then transferred to a very large oven (autoclave) for curing.

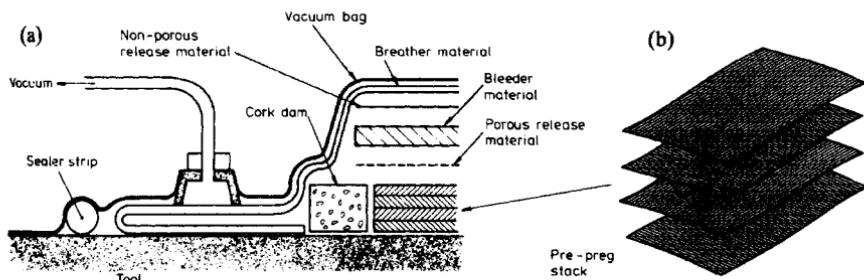


Fig. 4.69 Diagrammatic cross section of a bagged lay-up

4.10.2 Semi-Automatic Processing Methods

(a) **Cold Press Moulding:** The basis of this process is to utilise pressure applied to two unheated halves of a mould to disperse resin throughout a

prepared fabric stack placed in the mould. The typical procedure is as follows. Release agent and gelcoat are applied to the mould surfaces and the fibre fabric is laid into the lower part of the open mould. The activated resin is then poured on top of the mat and when the mould is closed the resin spreads throughout the reinforcement. High pressures are not necessary as the process relies on squeezing the resin through the reinforcement rather than forcing the composite into shape. A typical value of cycle time is about 10–15 minutes compared with several hours for hand lay-up methods. The process is illustrated in Fig. 4.70.

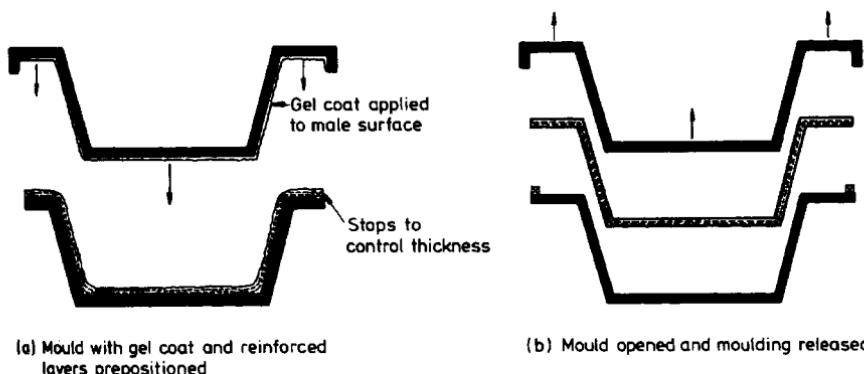


Fig. 4.70 Basic cold press moulding process

(b) Hot Press Mouldings: In this type of moulding the curing of the reinforced plastic is accelerated by the use of heat ($\approx 180^\circ\text{C}$) and pressure ($\approx 15 \text{ MN/m}^2$). The general heading of Hot Press Moulding includes both preform moulding and compression moulding.

(i) *Pre-form Moulding:* This technique is particularly suitable for mass production and/or more complex shapes. There are two distinct stages. In the first a preform is made by, for example, spraying chopped fibres on to a perforated metal screen which has the general shape of the article to be moulded. The fibres are held on the screen by suction applied behind it (see Fig. 4.71). A resin binder is then sprayed on the mat and the resulting preform is taken from the screen and cured in an oven at about 150°C for several minutes. Other methods by which the preform can be made include tailoring a continuous fibre fabric to shape and using tape to hold it together. The preform is then transferred to the lower half of the heated mould and the activated resin poured on top. The upper half of the mould is then brought into position to press the composite into shape. The cure time in the mould depends on the temperature, varying typically from 1 minute at 150°C to 10 minutes at 80°C . If the mould was suitably prepared with release agent the moulding can then

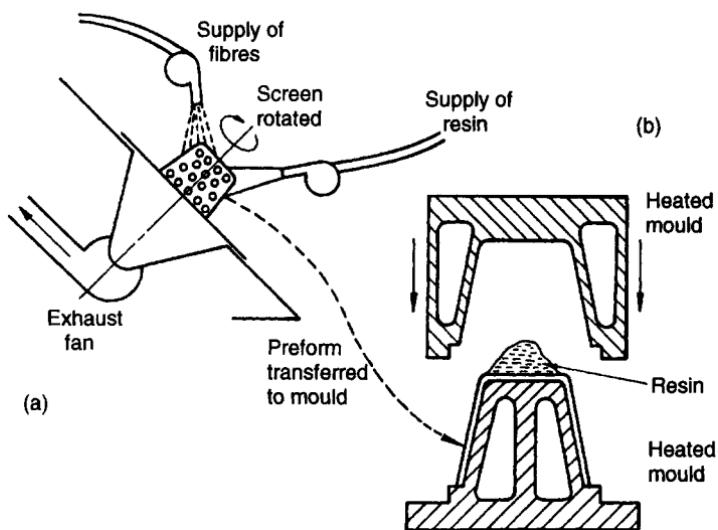


Fig. 4.71 Pre-form moulding of GFRP

be ejected easily. This method would not normally be considered for short production runs because the mould costs are high.

(ii) *Compression Moulding* (see also Section 4.7): Sheet Moulding Compounds: SMC is supplied as a pliable sheet which consists of a mixture of chopped strand mat or chopped fibres (25% by weight) pre-impregnated with resin, fillers, catalyst and pigment. It is ready for moulding and so is simply placed between the halves of the heated mould. The application of pressure then forces the sheet to take up the contours of the mould. The beauty of the method is that the moulding is done 'dry' i.e. it is not necessary to pour on resins. Fig. 4.72 illustrates a typical method used to manufacture SMC material.

Dough Moulding Compounds: DMC (also known as BMC – Bulk Moulding Compound) is supplied as a dough or rope and is a mixture of chopped strands (20% by weight) with resin, catalyst and pigment. It flows readily and so may be formed into shape by compression or transfer moulding techniques. In compression moulding the charge of dough may be placed in the lower half of the heated mould, in a similar fashion to that illustrated in Fig. 4.50(b) although it is generally wise to preform it to the approximate shape of the cavity. When the mould is closed, pressure is applied causing the DMC to flow in all sections of the cavity. Curing generally takes a couple of minutes for mould temperatures in the region of 120°–160°C although clearly this also depends on the section thickness.

In general, SMC moulds less well than DMC on intricate shapes but it is particularly suitable for large shell-like mouldings – automotive parts such as

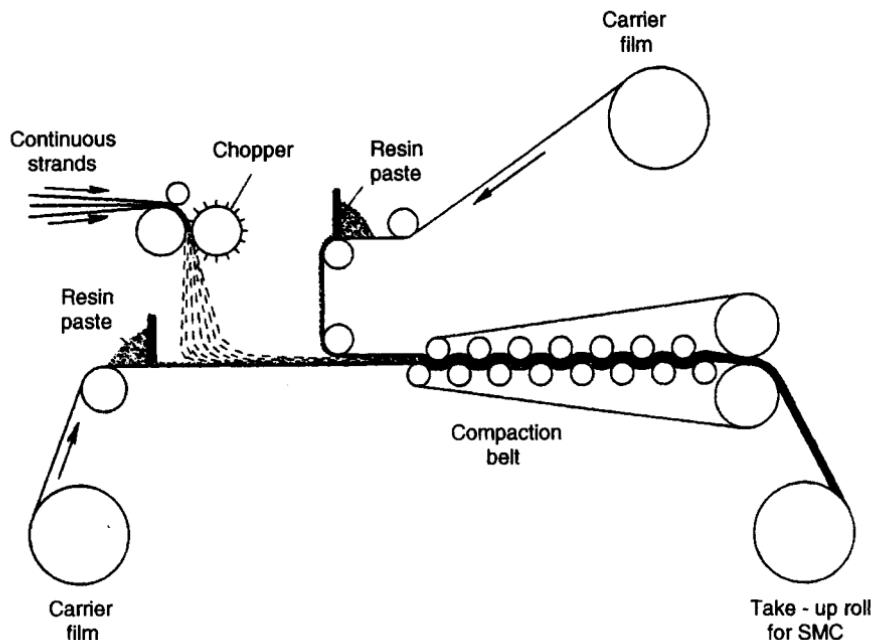


Fig. 4.72 Manufacture of SMC material

body panels and fascia panels are ideal application areas. An engine inlet manifold manufactured from SMC has recently been developed in the UK. DMC finds its applications in the more complicated shapes such as business machine housings, electric drill bodies, etc. In France, a special moulding method, called ZMC, but based on DMC moulding concepts has been developed. Its most famous application to date is the rear door of the Citroen BX saloon and the process is currently under active consideration for the rear door of a VW saloon car. Injection moulding of DMC is also becoming common for intricately shaped articles (see Section 4.3.10).

Other types of compression moulding and stamp forming used for continuous fibre reinforced composites are illustrated in Fig. 4.73.

(c) **Resin Injection:** This is a cold mould process using relatively low pressures (approximately 450 kN/m^2). The mould surfaces are prepared with release agent and gelcoat before the reinforcing mat is arranged in the lower half of the mould. The upper half is then clamped in position and the activated resin is injected under pressure into the mould cavity. The advantage of this type of production method is that it reduces the level of skill needed by the operator because the quality of the mould will determine the thickness distribution in the moulded article (see Fig. 4.74). In recent times there has been a growing use of pre-formed fabric shells in the resin injection process. The pre-form is produced

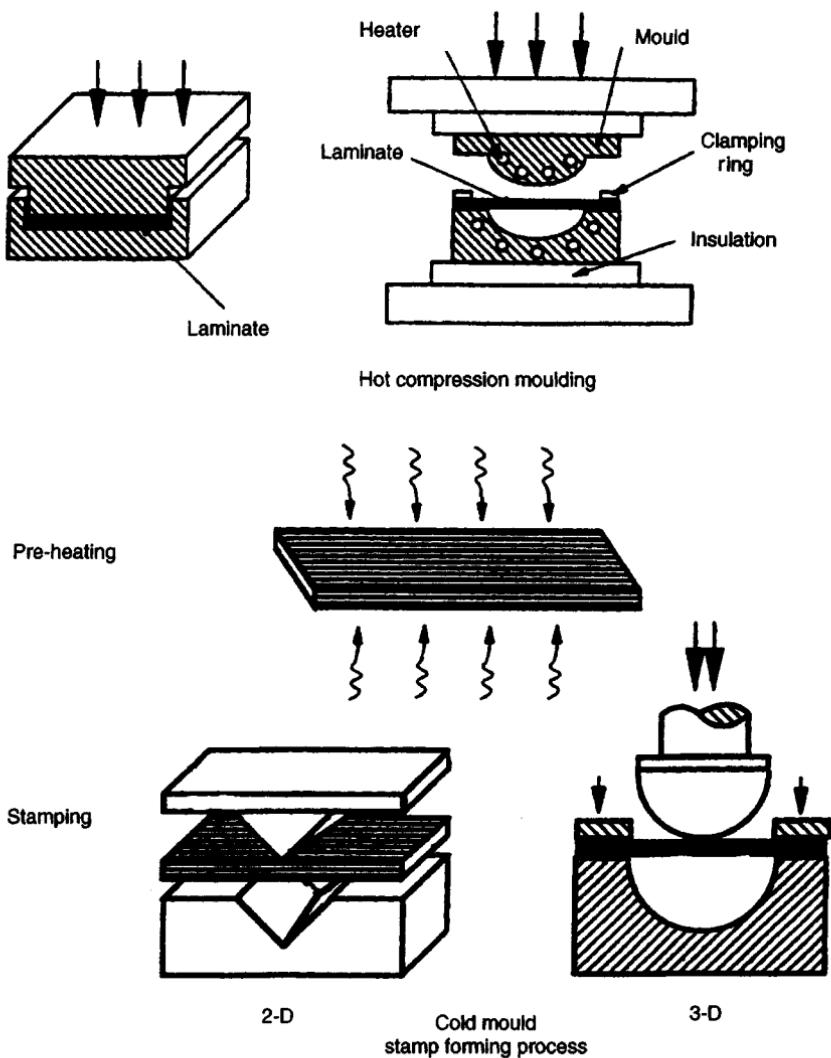


Fig. 4.73 Other types of compression moulding and stamp forming

using one of the methods described above and this is placed in the mould. This improves the quality and consistency of the product and reinforcements varying from chopped strand mat to close weave fabric in glass, aramid, carbon or hybrids of these may be used. It is possible, with care, to achieve reinforcement loadings in the order of 65%.

(d) **Vacuum Injection:** This is a development of resin injection in which a vacuum is used to draw resin throughout the reinforcement. It overcomes the

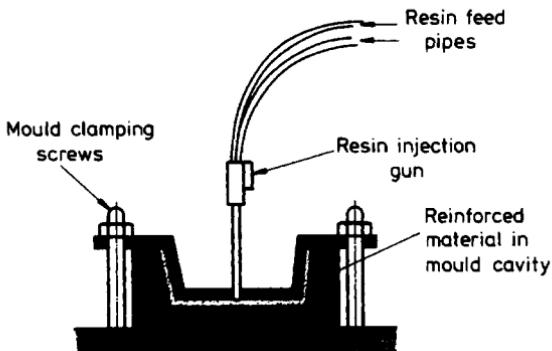


Fig. 4.74 Resin injection process

problem of voids in the resin/fibre laminate and offers faster cycle times with greater uniformity of product.

4.10.3 Automatic Processes

(a) **Filament Winding:** In this method, continuous strands of reinforcement are used to gain maximum benefit from the fibre strength. In a typical process rovings or single strands are passed through a resin bath and then wound on to a rotating mandrel. By arranging for the fibres to traverse the mandrel at a controlled and/or programmed manner, as illustrated in Fig. 4.75, it is possible to lay down the reinforcement in any desired fashion. This enables very high strengths to be achieved and is particularly suited to pressure vessels where reinforcement in the highly stressed hoop direction is important.

In the past a limitation on this process was that it tended to be restricted to shapes which were symmetrical about an axis of rotation and from which the mandrel could be easily extracted. However, in recent years there have been major advances through the use of collapsible or expendable cores and in particular through the development of computer-controlled winding equipment. The latter has opened the door to a whole new range of products which can be filament wound – for example, space-frame structures. Braiding machines for complex shapes are shown in Fig. 4.76.

(b) **Centrifugal Casting:** This method is used for cylindrical products which can be rotated about their longitudinal axis. Resin and fibres are introduced into the rotating mould/mandrel and are thrown out against the mould surface. The method is particularly suited to long tubular structures which can have a slight taper e.g. street light columns, telegraph poles, pylons, etc.

(c) **Pultrusion:** This is a continuous production method similar in concept to extrusion. Woven fibre mats and/or rovings are drawn through a resin bath and then through a die to form some desired shape (for example a 'plank'

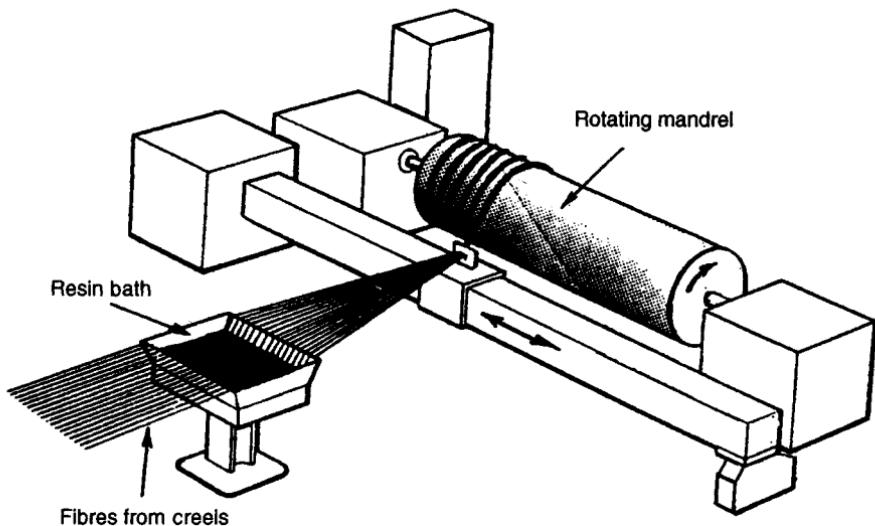


Fig. 4.75 Filament winding of fibre composites

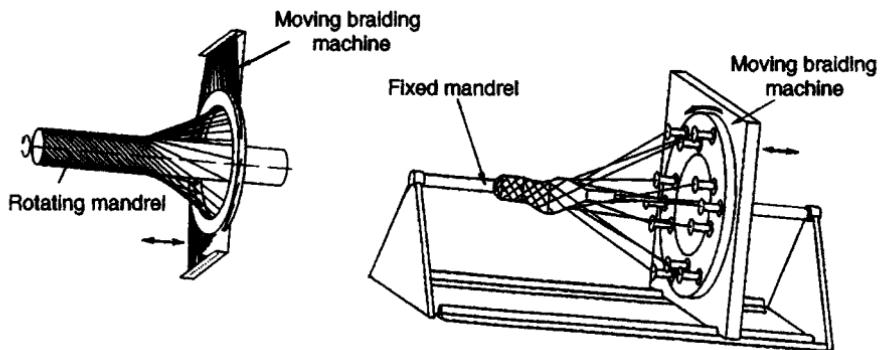


Fig. 4.76 Two types of filament winding

as illustrated in Fig. 4.77). The profiled shape emerges from the die and then passes through a tunnel oven to accelerate the curing of the resin. The pultruded composite is eventually cut to length for storage. A wide range of pultruded shapes may be produced – U channels, I beams, aerofoil shapes, etc.

(d) Injection Moulding: The injection moulding process can also be used for fibre reinforced thermoplastics and thermosets, for example DMC materials. This offers considerable advantages over compression moulding due to the higher production speeds, more accurate metering and lower product costs which can be achieved. The injection moulding process for thermosets has

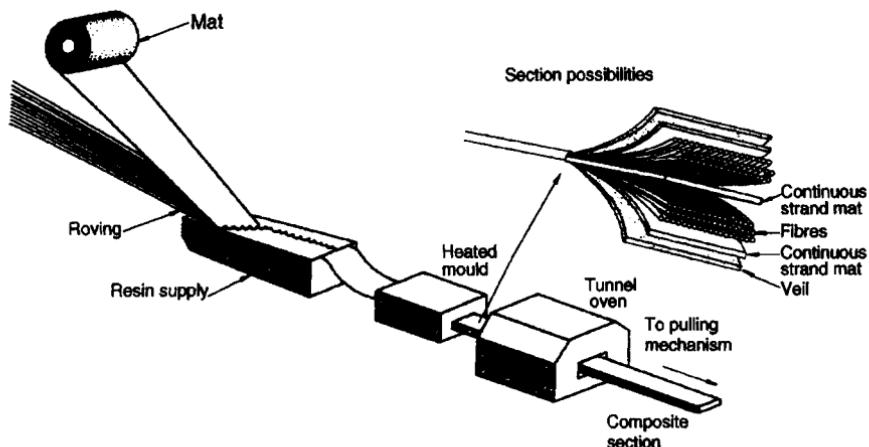


Fig. 4.77 Pultrusion process

already been dealt with in Section 4.3.8. See also the section on Reaction Injection Moulding (RIM) since this offers the opportunity to incorporate fibres.

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Questions

4.1 In a particular extruder screw the channel depth is 2.4 mm, the screw diameter is 50 mm, the screw speed is 100 rev/min, the flight angle is $17^\circ 42'$ and the pressure varies linearly over the screw length of 1000 mm from zero at entry to 20 MN/m^2 at the die entry. Estimate

- the drag flow
- the pressure flow
- the total flow.

The plastic has a viscosity of 200 Ns/m^2 . Calculate also the shear rate in the metering zone.

4.2 Find the operating point for the above extruder when it is combined with a die of length 40 mm and diameter 3 mm. What would be the effect on pressure and output if a plastic with viscosity 400 Ns/m^2 was used.

4.3 A single screw extruder has the following dimensions:

screw length = 500 mm
 screw diameter = 25 mm
 flight angle = $17^\circ 42'$
 channel depth = 2 mm
 channel width = 22 mm

If the extruder is coupled to a die which is used to produce two laces for subsequent granulation, calculate the output from the extruder/die combination when the screw speed is 100 rev/min. Each of the holes in the lace die is 1.5 mm diameter and 10 mm long and the viscosity of the melt may be taken as 400 Ns/m^2 .

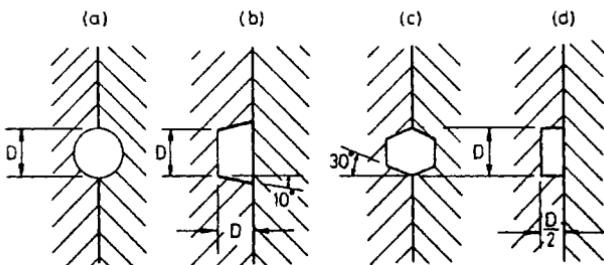
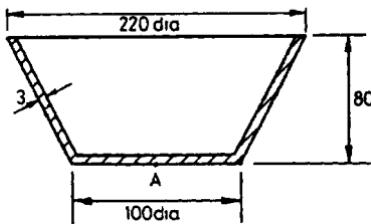
4.4 An extruder is coupled to a die, the output of which is given by (KP/η) where P is the pressure drop across the die, η is the viscosity of the plastic and K is a constant. What are the optimum values of screw helix angle and channel depth to give maximum output from the extruder.

4.5 A circular plate of diameter 0.5 m is to be moulded using a sprue gate in its centre. If the melt pressure is 50 MN/m^2 and the pressure loss coefficient is 0.6 estimate the clamping force required.

4.6 The container shown at the top of p. 341 is injection moulded using a gate at point A. If the injection pressure at the nozzle is 140 MN/m^2 and the pressure loss coefficient, m , is 0.5, estimate (i) the flow ratio and (ii) the clamping force needed.

4.7 Compare the efficiencies of the runners shown on p. 341.

4.8 A calender having rolls of diameter 0.3 m produces plastic sheet 1 m wide at the rate of 2000 kg/hour. If the roll speed is 5 rev/minute and the nip between the rolls is 4.5 mm, estimate



the position and magnitude of the maximum pressure. The density of the material is 1400 kg/m^3 and its viscosity is $1.5 \times 10^4 \text{ Ns/m}^2$.

4.9 A calender having rolls of 0.2 m diameter produces 2 mm thick plastic sheet at a linear velocity of 0.1 m/s. Investigate the effect of nips in the range 0.8 to 1.9 mm on the pressure profile. The viscosity is 10^3 Ns/m^2 .

4.10 A hemispherical dome of 200 mm diameter has been vacuum formed from a flat sheet 4 mm thick. What is the thickness of the dome at the point furthest away from its diameter.

4.11 A disposable tumbler which has the shape of a frustum of a cone is to be vacuum formed from a flat plastic sheet 3 mm thick. If the diameter of the mouth of the tumbler is 60 mm, the diameter of the base is 40 mm and the depth is 60 mm estimate the wall thickness at (a) a point 35 mm from the top and (b) in the centre of the base.

4.12 A blow moulding die which has an outside diameter of 40 mm and a die gap of 2 mm is used to produce a plastic bottle with a diameter of 70 mm. If the swelling ratio of the melt in the thickness direction is 1.8 estimate

- the parison dimensions
- the thickness of the bottle and
- a suitable inflation pressure if melt fracture occurs at a stress of 10 MN/m^2 .

4.13 A plastic film, 0.1 mm thick, is required to have its orientation in the transverse direction twice that in the machine direction. If the film blowing die has an outer diameter of 100 mm and an inner diameter of 98 mm estimate the blow-up ratio which will be required and the lay flat film width. Neglect extrusion induced effects and assume there is no draw-down.

4.14 A molten polymer is to be coated on a cable at a speed of 0.5 m/s. The cable diameter is 15 mm and the coating thickness required is 0.3 mm. The die used has a length of 60 mm and an internal diameter of 16 mm. What pressure must be developed at the die entry if the viscosity of the polymer under these operating conditions is 100 Ns/m^2 .

4.15 During a rotational moulding operation an aluminium mould with a uniform thickness of 3 mm is put into an oven at 300°C . If the initial temperature of the mould is 23°C , estimate the time taken for it to reach 250°C . The natural convection heat transfer coefficient is $28.4 \text{ J/m}^2\text{s}$.

K and the thermal diffusivity and conductivity of aluminium may be taken as $8.6 \times 10^{-5} \text{ m}^2/\text{s}$ and 230.1 J/m.s.K respectively.

4.16 A billet of PVC weighing 150 g is to be compression moulded into a long playing record of diameter 300 mm. If the maximum force which the press can apply is 100 kN estimate the time needed to fill the mould. The density and viscosity of the the PVC may be taken as 1200 kg/m^3 and 10 Ns/m^2 respectively.