EXTRUSION

Introduction

The main function of an extruder is to develop sufficient pressure in the material so as to force the material through the die. The pressure necessary to force a material through the die depends on the geometry of the die, the flow properties of the material, and the flow rate. Basically, an *extruder* is a machine capable of developing pressure. In other words, an extruder is a pump. A *plastics extruder* is a pump for plastic materials. However, this is not to be confused with a *plasticating extruder*, which is a machine that not only extrudes but also plasticates, or melts, the material. A plasticating extruder is fed with solid plastic particles and delivers a completely molten plastic to the die. On the other hand, a machine that extrudes molten plastic without melting it is called a *melt-fed extruder*.

Extruders Types

Extruders are the most common machines in the plastics processing industry. Extruders are used not only in extrusion operations, but also in most molding operations, for instance injection molding and blow molding. Essentially every plastic part has gone through an extruder at one point or another; in many cases, more than once.

Single Screw Extruders. In the plastics industry, there are three main extruder types: the screw extruder, which is the most common; the ram extruder; and the drum or disk extruder, which is the least common. In a screw extruder a screw rotates in a cylinder; the rotation of the screw creates a pumping action (see Fig. 1).

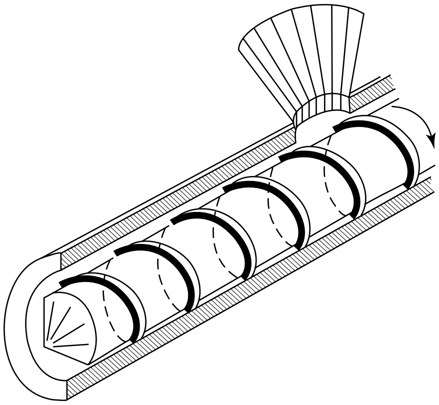


Fig. 1. A single screw extruder.

Twin Screw Extruders. A screw extruder can have one screw or more than one screw. An extruder with one screw is called a single screw extruder; it is the most common machine in the plastics processing industry. An extruder with more than one screw is called a multiscrew extruder. The most common multiscrew extruder is the twin screw extruder; it has two screws.

Co-Rotating Twin Screw Extruders. There are several types of twin screw extruders. In most twin screw extruders, the screws are located side by side. If both screws rotate in the same direction, the extruder is called a *co-rotating twin screw extruder* (see Fig. 2).

Co-rotating twin screw extruders used for compounding run at high screw speed, typically between 200 and 500 rpm. Some of the newer very high speed twin screw extruders are capable of running at speeds over 1000 rpm, as high as 1600 rpm.

Counter-Rotating Twin Screw Extruders. If the screws of a twin screw extruder rotate in opposite direction, it is called a *counter-rotating twin screw*

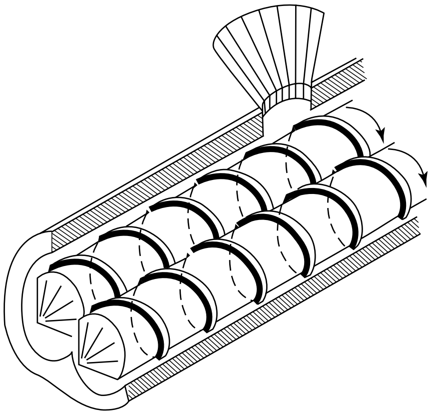


Fig. 2. A co-rotating twin screw extruder.

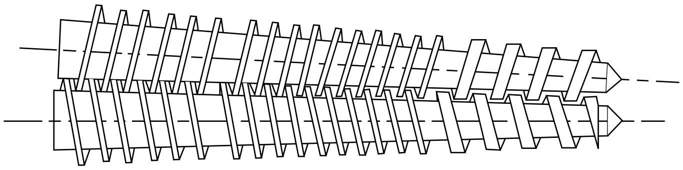


Fig. 3. Conical twin screw extruder.

extruder. Twin screw extruders can run at high or low speed, depending on the application. High speed extruders run at around 200–500 rpm and even higher; they are primarily used in compounding. Low speed extruders run at about 10–40 rpm and are used mostly in profile extrusion applications.

Most twin screw extruders for profile extrusion are counter-rotating extruders. This is because counter-rotating extruders tend to have better conveying characteristics than co-rotating extruders. Most twin screw extruders have parallel screws, but some extruders have conical screws where the screws are not parallel (see Fig. 3). Another distinguishing feature of twin screw extruders is the extent that the screws intermesh. The screws can be fully intermeshing (Fig. 4a), partially intermeshing (Fig. 4b), and nonintermeshing (Fig. 4c).

Most twin screw extruders are intermeshing. The advantage of nonintermeshing twin screw extruders is that they can have a very long length without problems with metal-to-metal contact between the screws. The *L*/*D* ratio can be 100:1 and higher. The *L*/*D* of intermeshing twin screw extruders is generally limited to values less than 60:1. A disadvantage of current nonintermeshing twin screws is that they have limited dispersive mixing capability; however, newer dispersive mixing technologies may negate this limitation (see section on The CRD Mixer and Figs. 63, 64, 65).

Ram Extruders. In a ram extruder a piston forces the material through the die (see Fig. 5). Ram extruders have very good conveying characteristics and can develop very high pressures. The drawback of ram extruders is that they have low melting capacity. Therefore, they are not used very often for normal plastics. There are some unusual plastics, however, that are often processed on a ram extruder, such as the so-called *intractable plastics* that cannot be processed on normal extruders. Examples of such plastics are PTFE and ultrahigh molecular weight (UHMW) PE. These plastics do not melt like normal plastics and are formed by sintering. Continuous products can be made on a ram extruder; the line speeds are quite low though, in the range of 25–75 cm/h (10–30 in./h).

Components of an Extruder

The Extruder Screw. The heart of the extruder is the extruder screw. This is a long cylinder with a helical flight wrapped around it (see Fig. 6). The screw is so important because conveying, heating, melting, and mixing of the plastic are mostly determined by the screw. The stability of the process and the quality of the extruded product are very much dependent on the design of the screw. The screw rotates in a cylinder that fits closely around it.

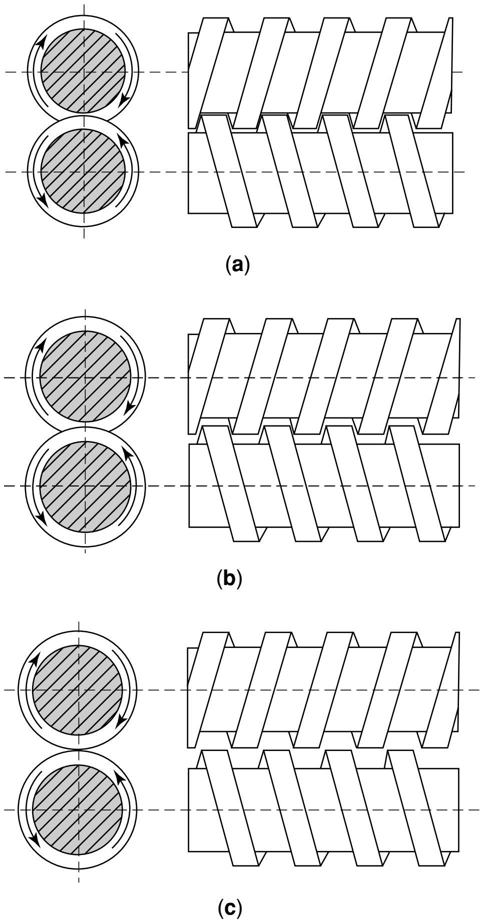


Fig. 4. Counter-rotating screws: (**a**) fully intermeshing; (**b**) partially intermeshing; and (**c**) nonintermeshing (tangential).t

The Extruder Barrel. The cylinder is called the extruder barrel. The barrel is a straight cylinder usually equipped with a bimetallic liner; this liner is a hard, integral layer with high wear resistance. In most cases, the wear resistance of the barrel should be better than that of the screw. The reason is that the screw is much easier to rebuild and replace than the barrel. Bimetallic barrels usually cannot be rebuilt.

The barrel may have a vent opening through which volatiles can be removed from the plastic (see Fig. 7), a process called *devolatilization*. An example is the removal of moisture from a hygroscopic plastic. An extruder with a vent port should use a special screw geometry to keep the plastic melt from coming out of the vent port; such a screw is called a two-stage screw (see Fig. 7).

The Feed Housing. The feed housing is connected to the barrel; it contains the feed opening through which the plastic material is introduced to the extruder. The feed throat usually has water-cooling capability because the feed

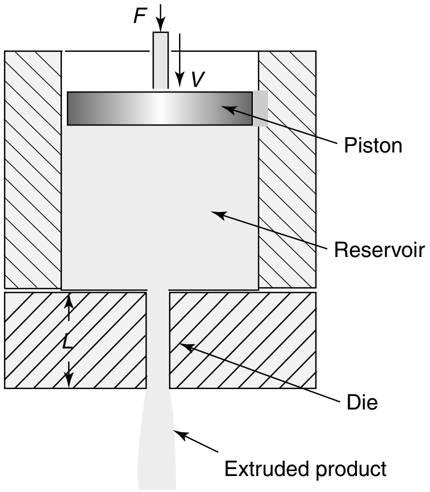


Fig. 5. Schematic of a ram extruder.

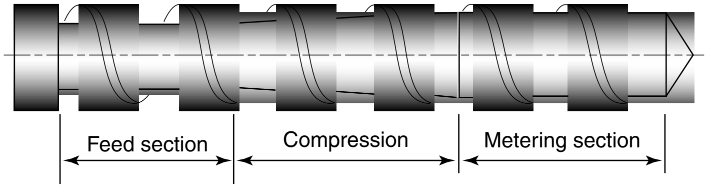


Fig. 6. A single flighted extruder screw.

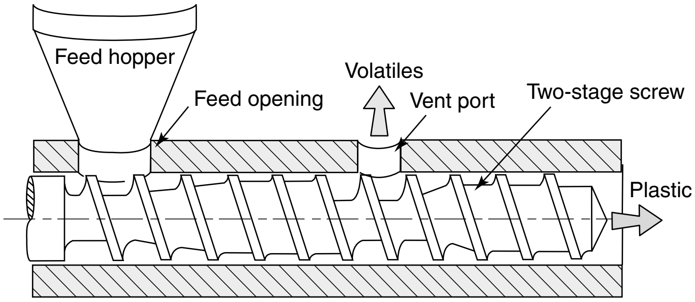


Fig. 7. A vented extruder barrel with a two-stage screw.

throat temperature is kept low enough to keep the plastic particles from sticking to the wall. To improve the intake capability of the feed throat, the feed opening can be offset as shown and have an elongated shape. The length of the feed opening should be about 1.5 times the diameter of the barrel and the width about 3/4 times the diameter, as shown in Figure 8.

Some extruders do not have a separate feed throat, but the feed opening is machined right into the extruder barrel. There are both advantages and

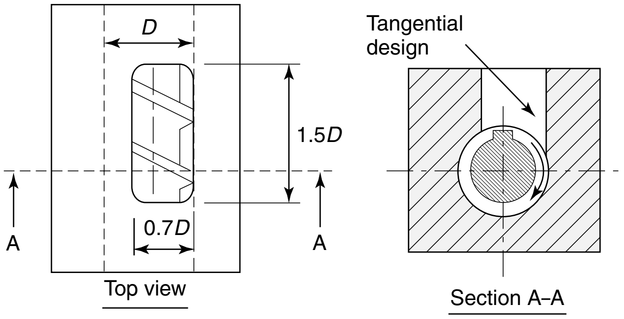


Fig. 8. Preferred geometry for feed opening in the feed throat.

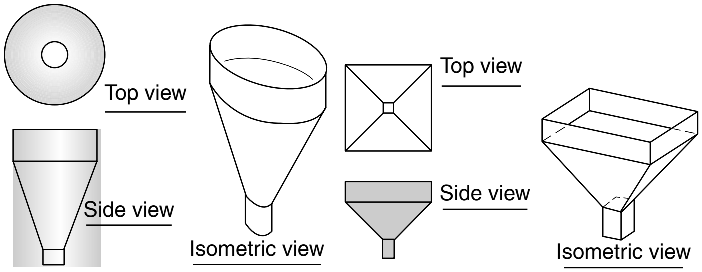


Fig. 9. Good hopper design (left) and poor hopper design (right).

disadvantages to such a setup. The advantages are lower cost, fewer parts, and no problems with alignment of the barrel to the feed throat. Disadvantages are that it is more difficult to create a thermal barrier between the hot barrel and the cold feed throat region, and good cooling of the feed throat region is more difficult.

The Feed Hopper. The feed throat is connected to the feed hopper and the extruder barrel. The feed hopper holds the plastic pellets or powder and discharges the material into the feed throat. The hopper should be designed to allow a steady flow of material through the hopper. Steady flow is best achieved with a circular hopper with a gradual transition in the conical section of the hopper (see Fig. 9). For difficult bulk materials, special devices, such as vibrating pads, stirrers, wipers, and even crammer screws, can be used to promote steady flow through the hopper so as to force the material to the discharge (see Fig. 10).

Barrel Heating and Cooling. The extruder barrel typically has both heating and cooling capability. Heating is usually done with electrical band heaters located along the length of the extruder. Induction and radiation heating are not commonly used; fluid heating is used in some rubber extrusion operations and on some older plastic extruders.

Most extruders have at least three temperature zones along the length of the barrel. Long extruders may have eight temperature zones or more. Each zone has its own heating and cooling capability and at least one temperature sensor to measure the zone temperature. The temperature is usually measured in the barrel. The die may have one or several temperature zones depending on its complexity.

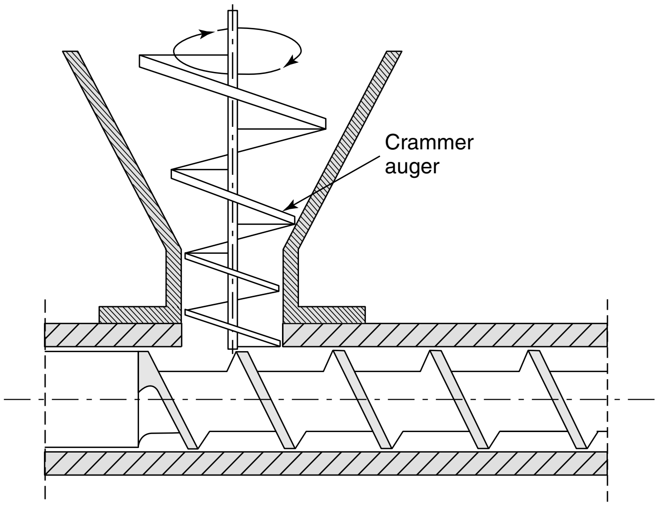


Fig. 10. Example of crammer feeder.

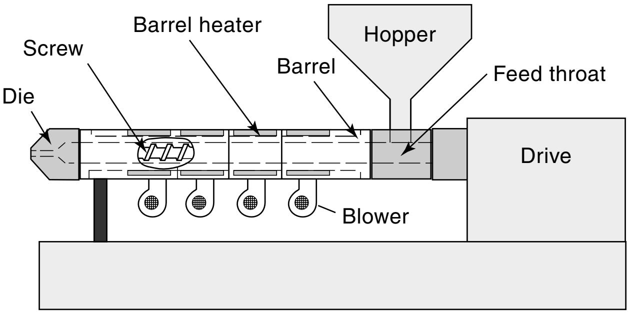


Fig. 11. Extruder with barrel heaters and blowers for cooling.

Some dies have more then 10 temperature zones. Dies have heating capability, but usually do not have cooling.

The barrel has to be cooled if the internal heat generation in the plastic raises the barrel temperatures above the set point. This is likely to occur when extruding high viscosity plastics and when running at high screw speeds. Cooling on single screw extruders is usually done with air. Blowers are placed under the extruder barrel and temperature zones are partitioned, so that one blower cools only one temperature zone (see Fig. 11).

Water cooling can be used as well, particularly if large amounts of heat must be removed. The extrusion process normally runs best when the screw supplies most of the energy needed in the process, so that little additional heating or cooling needs to be done through the barrel. As a result, air cooling is sufficient for most extrusion operations using single screw extruders. Since water cooling removes heat more quickly, it can be more difficult to maintain good temperature control

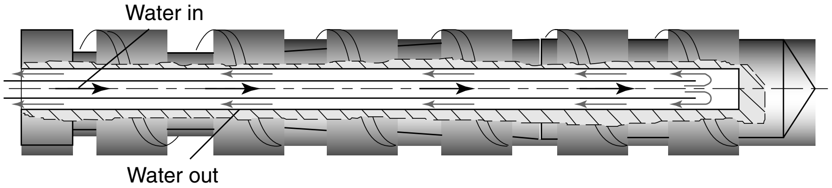


Fig. 12. Circulating a heat transfer fluid through the screw.

with water cooling. Oil cooling can be used as well; in fact, oil can be used both for heating and cooling.

With barrel cooling active, it is important to realize that even if the temperature is at its one word, the actual melt temperature is above the one word. With barrel cooling on, the heat flows from the plastic through the barrel to the outside. In this situation, the highest temperature occurs in the plastic. Even if the barrel temperature is at one word, the plastic temperature can be substantially higher. When a large amount of cooling is done in a particular part of the extruder the actual plastic temperature will be substantially above the barrel temperature set point. Therefore, barrel cooling should be minimized as much as possible.

Screw Heating and Cooling. The screw of an extruder is usually neither heated nor cooled; such a screw is called a *neutral screw*. However, it is possible to either heat or cool the screw by coring the screw (making it hollow) and circulating a heat transfer fluid through the hollow section (see Fig. 12). The screw can also be heated by a cartridge heater. The heater's electrical power has to be supplied through a slip ring assembly at the drive end of the screw. If the cartridge heater is equipped with a temperature sensor, the power to the heater can be controlled to maintain a constant temperature.

The Breaker Plate. The breaker plate is located at the end of the barrel. It is a thick metal disk with closely spaced holes.

The main purpose of the breaker plate is to support a number of screens located just ahead of the breaker plate. The other function of the breaker plate is to stop the spiraling motion of the melt as it comes off the screw. The breaker plate forces the melt to flow in a straight-line fashion into the die. It is possible to incorporate mixing capability into the breaker plate; this allows the breaker plate to act as a static mixer. Such a mixer was developed by The Madison Group in cooperation with Rauwendaal Extrusion Engineering. This mixing breaker plate (MBP) has many tapered channels that split the flow and expose the plastic melt to elongational flow. This promotes both distributive and dispersive mixing. An example of the MBP is shown in Figure 13. Different pattern can be machined into the MBP and several MBPs can be stacked together to enhance the mixing action.

The screens are used to trap contaminants so that they do not end up in the extruded product. Usually, several screens are stacked together, starting with a coarse screen, followed by increasingly finer screens, and then a coarse screen again right up against the breaker plate. The plastic melt thus flows through screens with increasingly smaller openings. The last coarse screen acts merely as a support for the finer screen. The collection of screens is called the *screen pack*.

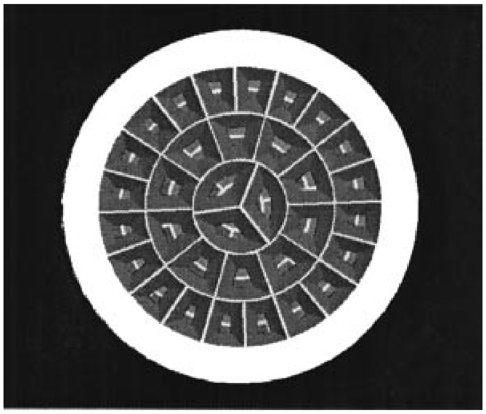


Fig. 13. Example of a mixing breaker plate.

The Screen Pack. The screen pack is not only used to trap contaminants, but in some cases the restriction of the screen pack is increased to increase mixing in the extruder. This works to some degree; however, the mixing can be improved more efficiently by adding mixing sections to the extruder screw. The most common filters are wire mesh screens. The mesh number of the screen represents the number of wires per inch (25 mm). The higher the mesh, the more wires per inch and the smaller the openings of the screen.

Figure 14 shows the relationship between the mesh value of the screen and the micron rating. The micron rating indicates what size particles the screen is able to trap. The higher the mesh, the lower the micron rating and, therefore, the

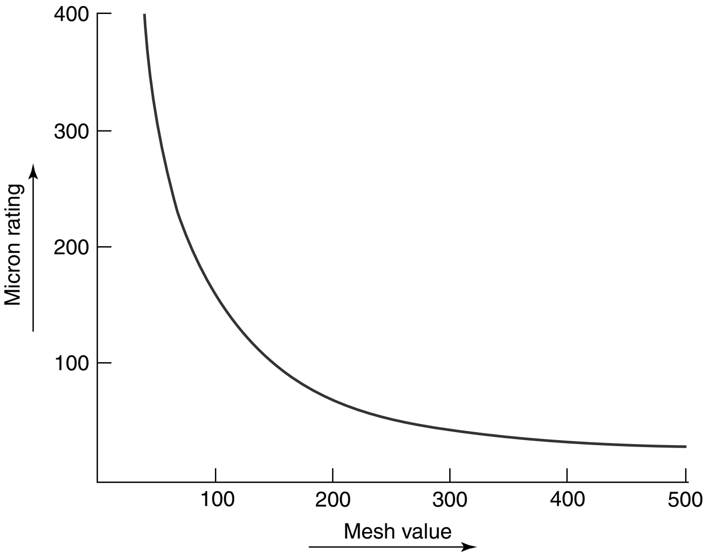


Fig. 14. The micron rating vs the mesh value for wire mesh screens.

Table 1. Comparison of Different Filter Media

	Wire mesh square weave	Wire mesh Dutch twill	Sintered metal powder	Random metal fibers
Gel capture	Poor	Fair	Good	Very good
Contaminant capacity	Fair	Good	Fair	Very good
Permeability	Very good	Poor	Fair	Good
Price	Low	Fair	High	High

finer the screen. A typical screen pack can consist of a 20-mesh screen, followed by a 40-, 60-, and 80-mesh screens, with a final 20-mesh screen for support against the breaker plate.

There are a number of different filter materials. Wire screens are the most common. Several types of wire screens are available, such as the square mesh with plain weave and the square mesh with Dutch twill. There are also depth filtration media, such as sintered metal powder and random metal fibers. Advantages and disadvantages of different filter materials are shown in Table 1.

Other filter materials used in some cases are plates with small holes and filters made up of sand. Plates with small holes are useful in filtering out coarse contaminants and, for that reason, are used for prefiltration. Sand is inexpensive and because of the large volume, sand filters can operate for long periods before they have to be changed. A drawback of sand is that the filtration action is not uniform. Also, the run-in period for sand filters can be long and the installation is complicated.

Screen Changers. In some cases, screens have to be replaced at short intervals, for instance, every 2 h. This may happen when the plastic contains a substantial level of contaminants. In such a situation, it can be advantageous to use a *screen changer*, which is a device that allows a quick change of the screens. Some screen changers allow the extruder to keep running while the screens are changed; these are called *continuous screen changers*. Screen changers are useful when pressure increases rapidly at the screens. Screen changers can be manual or automatic. In many automatic screen changers, the screens are changed when the pressure drop across the screens reaches a preset value.

There are various types of screen changers, including manual screen changers, hydraulic screen changers, semicontinuous screen changers, screen changers with a continuous moving screen, and rotary-type screen changers. Manual screen changers are used on smaller extruders, up to about 120 mm or 4.5 in. They use a slide plate design with two circular screen blocks; one is in the melt flow at all times. When the pressure builds up to a certain level, the operator uses a hand lever to insert a new screen into position. At the same time, the dirty screen is pushed out of position so that it can be removed and replaced with a clean screen pack.

Hydraulic screen changers use a hydraulic ram to push the block containing a new screen into the melt stream (see Fig. 15). They can be used with larger extruders. Semicontinuous screen changers allow the screen to be changed without stopping the melt flow. In most units, trapped air is prevented from going into the melt stream by a bleed valve. Even if the entrapped air can be eliminated

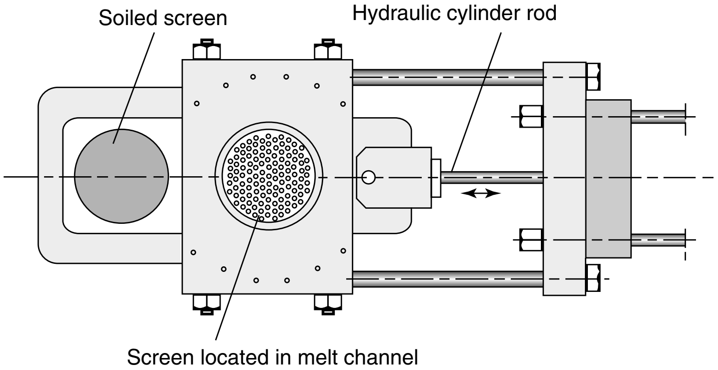


Fig. 15. Typical slide plate screen changer.

completely, there may still a pressure spike when a new screen is moved into position.

In screen changers with a continuously moving screen, a continuous band of screen material passes across the melt flow at a speed determined by the pressure difference across the screen. The rotary screen changer uses a moving wheel with 10–16 kidney-shaped cavities containing the screens. Each cavity moves slowly through the melt stream. This is similar to the continuously moving screen, except that in the rotary screen, the screen itself is not continuous because of the webs between the cavities. The webs, however, are relatively thin, so that at all times at least 90% of the channel is occupied by the screen. Rotary screen changers use separate screen inserts that are changed by the operator. The advantage of the screen changer with the continuously moving screen and the rotary screen is that pressure disturbances during screen changes are minimized.

The Extrusion Die. The die is placed at the discharge end of the extruder. Its function is to form the flowing plastic into the desired shape of the extruded product. Dies can be categorized by the shape of the product that they produce. Annular dies are used to make tubing, pipe, and wire coating. Slit dies are used to make flat film and sheet. Circular dies are used to make fiber and rod. Profile dies are used to make shapes other than annular, circular, or rectangular. Dies are also named by the product that they produce. So, we talk about tubing dies, flat film dies, blown film dies, etc.

The inlet channel of the die is usually designed to match the exit of the extruder. If the die entrance does not match the extruder exit, an adapter can be used between the extruder and the die. The three main elements of the die flow channel are the inlet channel, the manifold, and the land region (see Fig. 16).

The flow channel of the die should be designed such that the plastic melt achieves a uniform velocity across the die exit. The shape of the land region of the die corresponds to the shape of the extruded product. An example of an in-line tube or pipe die is shown in Figure 17. The material flows into the die from the extruder; then it flows around a torpedo.

The torpedo is supported by spider legs that have a streamlined shape to achieve smooth flow around the support legs. From the torpedo, the plastic melt

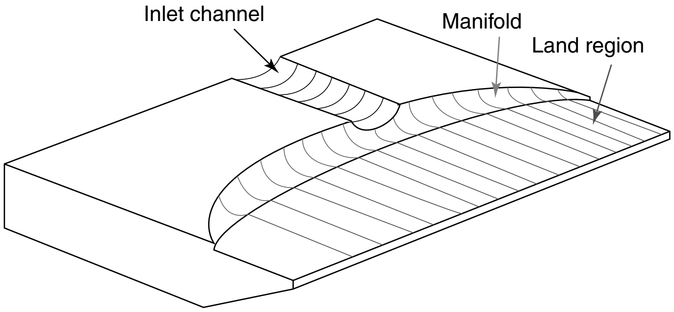


Fig. 16. The three main elements of an extrusion die.

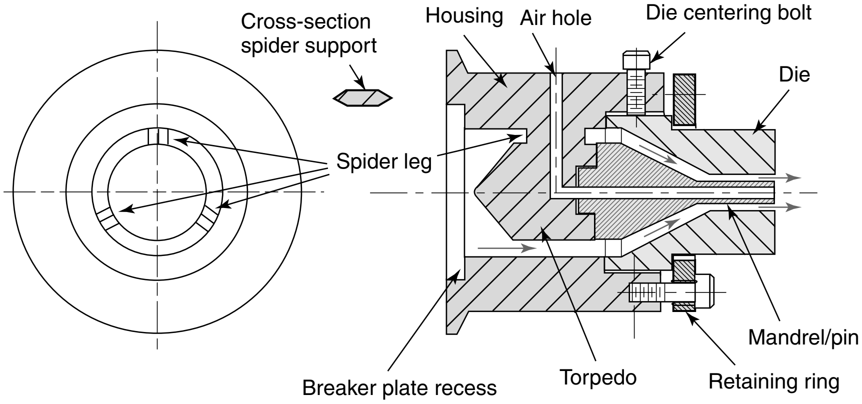


Fig. 17. Example of in-line tubing or pipe die.

flows to the tip and die where it is shaped into an annulus, so that a tube-shaped product emerges.

The size and shape of the land region are not exactly the same as the extruded product. There are several reasons for this: draw down, cooling, swelling, and relaxation. Because of the several variables affecting the size and the shape of the extruded plastic, it is often difficult to predict how exactly the size and shape of the plastic changes as it leaves the die. As a result, it is also difficult to predict how the die flow channel should be shaped to achieve the desired shape of the extruded product. This is an important reason why die design is sometimes still largely based on experience rather than on engineering calculations. With the advent of improved numerical techniques and commercial die flow analysis software, this situation is improving; however, die design is still often a trial and error process.

Coextrusion Dies. Another type of die used in the extrusion industry is the coextrusion die. This type of die is used to make a multilayered product in one step. There are two main coextrusion systems: the feed block system and the multimanifold system. In the feed block system, the different plastic melt streams are combined in a feed block and then fed into a regular single manifold extrusion die (see Fig. 18).

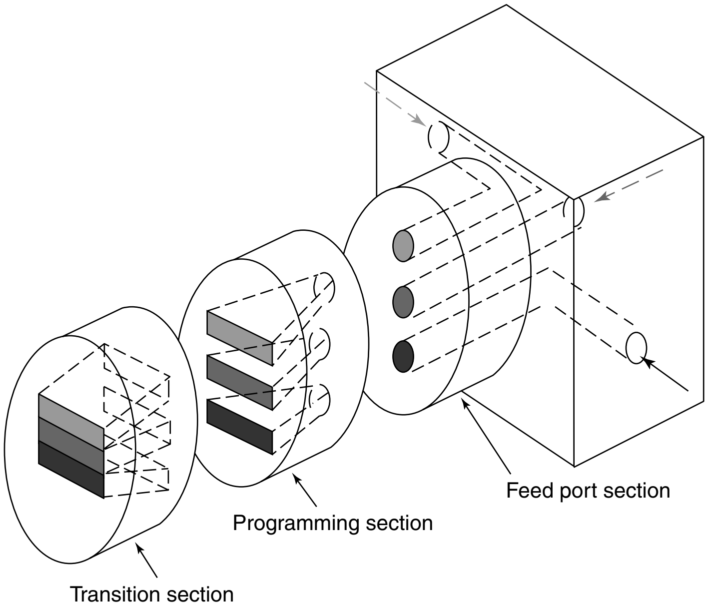


Fig. 18. Example of a feed block system.

In the multimanifold system, the different plastic melt streams enter the die separately and each material has its own manifold. The different melt streams combine close to the die exit to make the multilayered product (see Coextrusion).

The Extruder Drive. The screw drive is usually an electric motor that supplies the power to turn the screw. The nominal speed of the motor is typically around 1800 rpm, while a typical maximum screw speed is about 100 rpm. As a result, a speed reducer is needed between the motor and the screw. Various motors can be used for extruders. DC motors are most common up to the 1990s; nowadays, AC motors are starting to be used more frequently. Older extruders often use a DC brush motor with tachometer feed back. This yields a speed regulation of about 1% of full speed. One-percent regulation may be acceptable for some products, but it may not be good enough for high precision operations, such as medical tubing, particularly when the extruder operates at low speed. For example, if an extruder has a maximum screw speed of 100 rpm and a DC brush motor with tachometer feed back, the screw speed can vary as much as 1 rpm (see Table 2).

However, if the screw speed is reduced to 10 rpm, the screw speed can still vary as much as 1 rpm. This 1-rpm variation now represents 10%. Obviously, this

Table 2. Screw Speed Variation at Different Screw Speeds

Screw speed, rpm	Screw speed variation, rpm	Screw speed variation, %
100	1	1
10	1	10

would be too much for a high precision extruded product. Fortunately, nowadays we have drives with better speed control. For example, there are brushless DC drives with a speed regulation of about 0.01% of full speed. Drives with similar speed control are digital DC brush drives and variable frequency AC vector drives. Servo drives can achieve speed regulation that is considerably better than 0.001% of full speed.

Coupling between Motor and Gearbox. When we have a direct coupling between the motor and the gear reducer, we call this a *direct drive* (see Fig. 19). Some extruders have a belt transmission between the motor and the gear reducer; these are called *indirect drives* (see Fig. 20). Advantages of direct drives are no chance of slippage, energy efficiency, and fewer parts. The disadvantage of a direct drive is that it may be more difficult to change the reduction ratio. Advantages

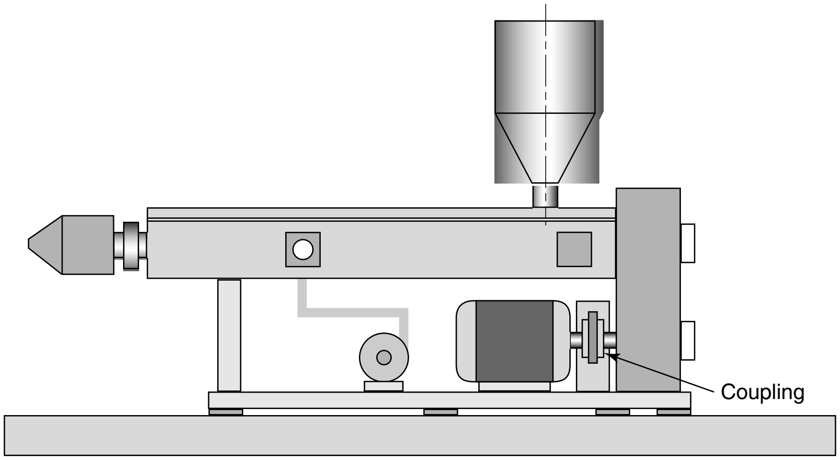


Fig. 19. Example of extruder with direct drive.

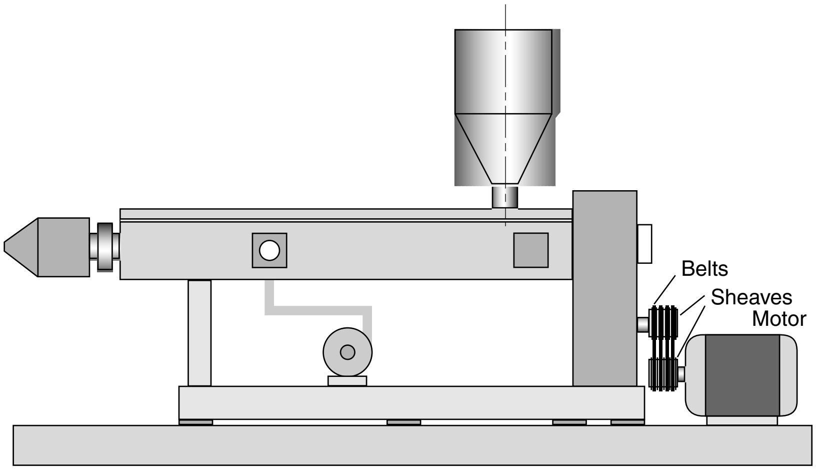


Fig. 20. Example of an extruder with indirect drive.

of indirect drives are ease of changing the reduction ratio and more freedom to position the motor. Disadvantages of indirect drives are chance of slippage, energy loss in the belts, and more parts that can wear out and fail.

Even though direct drives appear to be more attractive, many extruders are made with indirect drives. An example of an extruder with an indirect drive is shown in Figure 20.

The Speed Reducer. A speed reducer is necessary because the speed of the motor is much higher than the speed of the screw. Typical reduction ratios range from 15:1 to 20:1; they can be as low as 5:1 and as high as 40:1. The most common reducers with extruders are gear reducers using spur gears. A popular spur gear is the herringbone gear. The V-shaped tooth design practically eliminates axial loads on the gears.

Important issues with gear reducers are the reduction ratio, energy efficiency, power transmission capability, cost, and backlash of the gearbox. Backlash is basically the slop in the gears. If the screw speed is maintained at a constant value, backlash is not a big issue. However, if the screw speed is changed quickly, as is done in some advanced control schemes, then the backlash should be minimal to maintain good speed control and to avoid rapid wear of the gears.

Gear boxes can be made with a quick-change gear provision. This allows a quick and easy change of the gear ratio. A quick-change gear provision can improve the flexibility and versatility of an extruder. Changing the gear ratio on a regular gearbox is a precision job and is quite time consuming. Most gear boxes in the industry are not quick-change gear boxes.

Thrust Bearing Assembly. Thrust bearings are necessary because the extruder screw has to develop substantial pressure to overcome the flow resistance of the die. Typical diehead pressures range from 7 to 28 MPa (about 1000 to 4000 psi). The melt pressure at the end of the screw causes a thrust force on the screw, pushing it in the direction of the drive. The thrust bearings are necessary to take up the thrust load acting on the screw. A 150-mm (6-in.) extruder running at a head pressure of 35 MPa (about 5000 psi) experiences an axial thrust of about 620 kN (about 140,000 lbf). The thrust bearing assembly may be connected to the gear reducer or it may also be part of the gearbox itself.

The ability of the thrust bearings to handle the thrust load on the screw is reflected in the *B-10 life* of the thrust bearings. The B-10 life is the number of hours that 9 out of 10 identical bearings last at a certain load and speed. The B-10 life for the extruder thrust bearings is usually given at a head pressure of 35 MPa (5000 psi) and a screw speed of 100 rpm. If an extruder is operated 24 h a day, the B-10 life should be at least 100,000 h to get a useful life of more than 10 years out of the thrust bearing.

The Gear Pump. Extruders have some limitations, including the fact that high output stability is difficult to achieve. This is important in high precision extrusion operations such as fiber spinning or medical tubing extrusion. The best output variation that can be obtained in a regular extruder is about 1%. To improve the output stability, a gear pump can be added to the extruder; it is placed between the extruder and the die. The gear pump consists of two intermeshing counter-rotating gears.

Material entering the gear pump is trapped in the space between two teeth and moves forward in a circular path with the gears. At the point where the gears start to intermesh, the plastic melt is forced out of the gears and to the discharge of the pump. The action of a gear pump is similar to that of a bucket brigade. The "buckets" are filled at one end and emptied at the other end. If each bucket has the same volume and is filled completely, precise control of the flow rate can be achieved.

The conveying of plastic melt in the gear pump is by forced conveying rather than by drag as is the case in the extruder. As a result, good output stability is easier to achieve with a gear pump than without one. Another advantage of the gear pump over the extruder is that it generates pressure more efficiently. As a result, gear pumps make sense in the following applications:

(1) high precision extrusion where the output variability must remain less than 1%
(2) operations where the extruder does not have sufficient pressure generating capability, for instance, a vented extruder that has to operate at high barrel pressure

There are some operations where the use of gear pumps can create problems. One is when a plastic containing abrasive fillers or other abrasive ingredients is extruded. This causes wears of the gear pump and reduces its pumping accuracy. Another potential problem can occur when a gear pump is used with a plastic that is susceptible to degradation. In many gear pumps, the plastic melt is used to lubricate the gears. This means that a small fraction of the plastic spends a long time in the gear pump, as much as 15 min or longer. The long residence time in the gear pump combined with the high temperatures can cause degradation.

Complete Extrusion Lines

In addition to the extruder, upstream and downstream equipment is needed to produce a useful product. The main elements of an extrusion line are resin handling system, drying system, extruder, post-shaping or calibrating device, cooling device, take-up device, and cutter or saw. The main types of extrusion lines are tubing and pipe extrusion lines, film and sheet extrusion lines, extrusion compounding lines, and profile extrusion lines. Besides these four main types there are quite a few more, such as fiber spinning lines, extrusion blow molding machines, and integrated sheet and thermoforming lines.

Tubing and Pipe Extrusion Lines. Dies for tubing and pipe were discussed earlier. Small diameter tubing (less than 10 mm) is usually made with a free extrusion process; this is a process without a sizing or calibrating unit. Large diameter tubing and pipe is made with a sizing device just downstream of the die. The purpose of the sizer or calibrator is to solidify the plastic to a thickness sufficient to transfer the stresses acting on the product while maintaining the desired shape and dimensions. The main components of a typical tubing extrusion line are shown in Figure 21.

This line does not use a sizing unit and thus, would be used for small diameter tubing. The gear pump may or may not be used depending on the precision

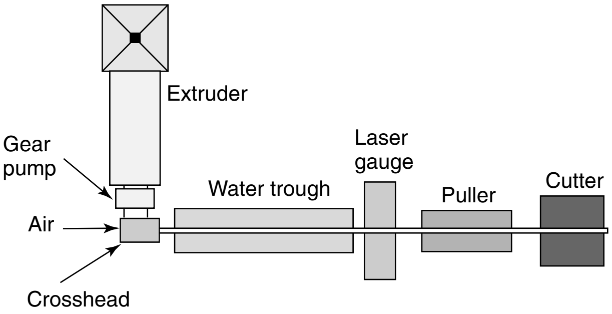


Fig. 21. Components of a typical tubing extrusion line.

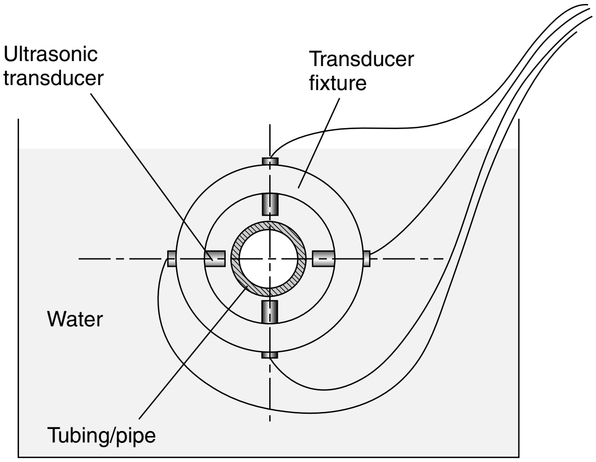


Fig. 22. Ultrasonic wall thickness gauge.

required in the extrusion process. The internal air pressure of the tubing is controlled to achieve the correct values for the outside diameter and wall thickness. The diameter is often measured with a laser gauge to allow close monitoring and control. The diameter and the wall thickness are primarily determined by the extruder output, the puller speed, and the internal air pressure. Closed loop control systems are available that automatically set the appropriate screw or gear pump speed, the puller speed, and internal air pressure. After the puller, the tubing may be cut or reeled up on a spool. In some lines, the wall thickness is measured directly; this can be done with ultrasonic sensors positioned around the circumference of the tubing or pipe as shown in Figure 22.

Film and Sheet Lines Using the Roll Stack Process. There are no significant differences between the extrusion of flat film and sheet. The main components of a sheet line are the extruder, the roll stack, the cooling section, the nip roll section, and the winder (see Fig. 23). The roll stack contains three rolls that are often referred to as polishing rolls. They are used to exert pressure on the sheet and to impart the surface conditions of the rolls to the plastic sheet. If a smooth surface is required, smooth rolls are used. If a textured surface is needed,

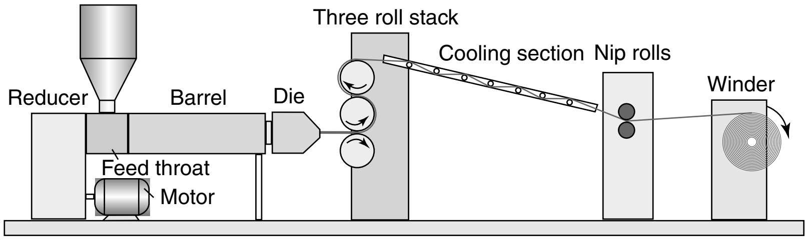


Fig. 23. Components of a sheet or flat film extrusion line.

a textured surface is used on the roll. The roll texture is the negative of the texture required on the sheet. It is possible to produce a sheet with one textured surface and the other smooth by using a smooth and textured roll next to each other.

Figure 23 shows the plastic sheet going up along the center roll and making an S-wrap around the center roll and top roll; this is called "upstack" operation. Sheet lines can also run in the "downstack" mode, where the material makes an S-wrap around the center roll and bottom roll. The rolls do not have to be in the vertical position; they can be in a horizontal position or any angle between vertical and horizontal. In fact, in some roll stacks, the angle is adjustable.

The rolls are normally cored so that the temperature of the rolls can be controlled. This is usually done with circulating hot oil. It should be possible to adjust the temperature of each roll separately. The cooling section consists of a number of rolls positioned in a frame; the sheet runs over and under the rolls to keep the sheet flat. At the end of the cooling section are the pull rolls or nip rolls; these are rubber rolls that pull the sheet from the roll stack to maintain a certain tension in the sheet. After the nip rolls, the sheet is led to the winder that rolls the sheet on a core. Many different winders are available; some winders automatically transfer the sheet to a new core when one package is full.

Film Lines Using Chill Roll Casting. Thin films are often cast on a chill roll rather than extruded into a roll stack. The main components of a cast film line are the extruder, the film die, the chill roll unit, the thickness gauging system, the surface treatment unit, and the winder.

The film is extruded downward onto the chill roll. The initial contact between the film and the chill roll is established by the use of an air knife. The air knife produces a thin stream of high velocity air across the width of the chill roll, and the air stream pushes the film against the roll surface, as shown in Figure 24.

From the chill roll unit the film is led to a thickness-gauging unit where the thickness of the sheet is measured across the width of the film. Most thickness gauges for film and sheet have a scanning measuring head that traverses across the film back and forth to measure thickness both along the length and across the width of the film.

After the thickness-gauging unit, the film passes through a surface treatment unit. Such a unit is incorporated if surface treatment of the film is required. This is usually done to improve adhesion, for instance, for a subsequent printing or laminating operation. The most important adhesion promoters are flame treatment, corona-discharge treatment, ozone treatment, and primers. From the

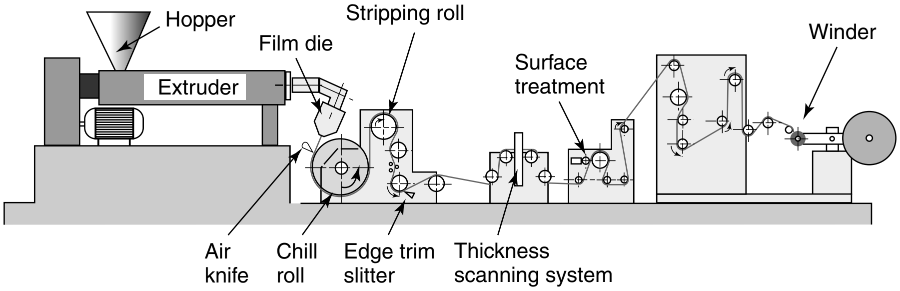


Fig. 24. Components of a cast film extrusion line

treatment unit, the film is led to the winder unit. Just as with sheet extrusion, many different types of winders are available.

Combination of Materials. The requirements of many products, particularly in packaging applications, are such that a single plastic cannot meet all of them. To meet the requirements, often two or more materials have to be combined. There are a number of techniques to combine different materials; some of the more important ones are coextrusion, coating, and lamination.

Coextrusion. *Coextrusion* is a commonly used technique to combine two or more plastics passing through a single extrusion die. There are two major coextrusion techniques: the feed block system and the multimanifold system. In the feed block system the different plastics are combined in the feed block module (see Fig. 18) and then enter into a regular extrusion die with a single inlet, manifold, and outlet.

The advantage of the feed block system is that it is simple, inexpensive, and allows many layers to be combined. The main drawback is that the flow properties of the different plastics have to be quite close to avoid interface distortion. This limits the choice of materials that can be combined through feed block coextrusion.

In the multimanifold system each plastic has its own entrance and manifold in the coextrusion die. The different melt streams are combined just before they exit the die, so that minimum interface distortion can occur. The advantage of the multimanifold system is that plastics with widely different flow properties can be combined. As a result, there is a wide choice of materials that can be combined through this extrusion technique. The disadvantage is that the design of the die is more complicated and therefore more expensive.

Figure 25 shows a multimanifold sheet or film die. This die has two inlets, two manifolds, and a single outlet. The flow of the upper layer can be adjusted by flexing the choker bar, using the adjustment nuts. The two plastics combine at the entrance to the land region; this is the last parallel section of the die flow channel. The flow in the land region can be adjusted with the flex lip adjustment bolts. These bolts are located along the width of the die exit with a spacing of about 25–40 mm (1.0–1.5 in.) and allow local adjustment of the die gap. Some newer sheet and film dies have a flexible membrane to allow adjustment of the flow. Many multimanifold dies are possible, including flat film and sheet dies, tubing and pipe dies, blown film dies, and profile dies.

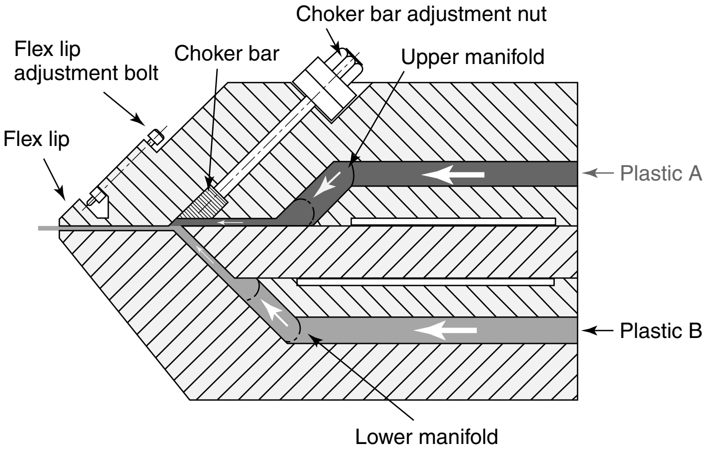


Fig. 25. Example of a multimanifold sheet die.

Extrusion Coating. In extrusion coating, a molten layer of plastic film is combined with a moving solid web or substrate. The substrate can be paper, paperboard, foil, plastic film, or fabric; the substrate can also be a multilayer product. A schematic of an extrusion coating operation is shown in Figure 26.

Extrusion Lamination. Extrusion lamination involves two or more substrates, such as paper and aluminum foil, combined by using a plastic film as the adhesive between the two substrates (see Fig. 27). The webs may be preheated or surface treated to improve bonding with the plastic film.

The extruded sheet or film can be laminated with a film on one side or both sides. The laminate can be paper, foil, mesh, or a number of other materials. With lamination many different structures of sheet or film products can be made. The laminate is unrolled from a payoff, combined with the film, and

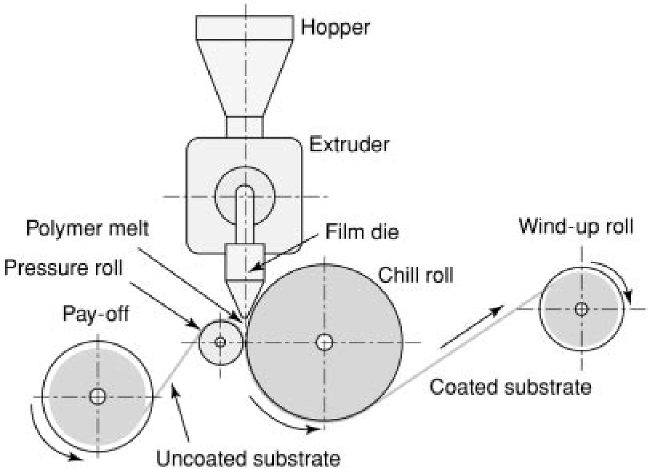


Fig. 26. Schematic of extrusion coating operation.

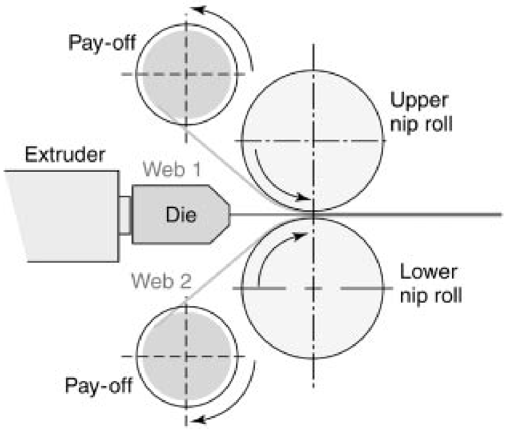


Fig. 27. Schematic of extrusion lamination.

immediately led into a set of nip rolls. After lamination, the film is handled as a regular film.

Blown Film Lines. A blown film line is quite different from a flat film line. In a blown film line, a tubular film is extruded vertically upwards as shown in Figure 28. Air is introduced to the inside of the tube; as a result, the tube expands to a bubble with a diameter larger than the diameter of the die. The ratio of the bubble diameter to the die diameter is called the *blow-up ratio*. Typical blow-up ratios used in LDPE film extrusion for packaging are in the range of 2.0–2.5:1.

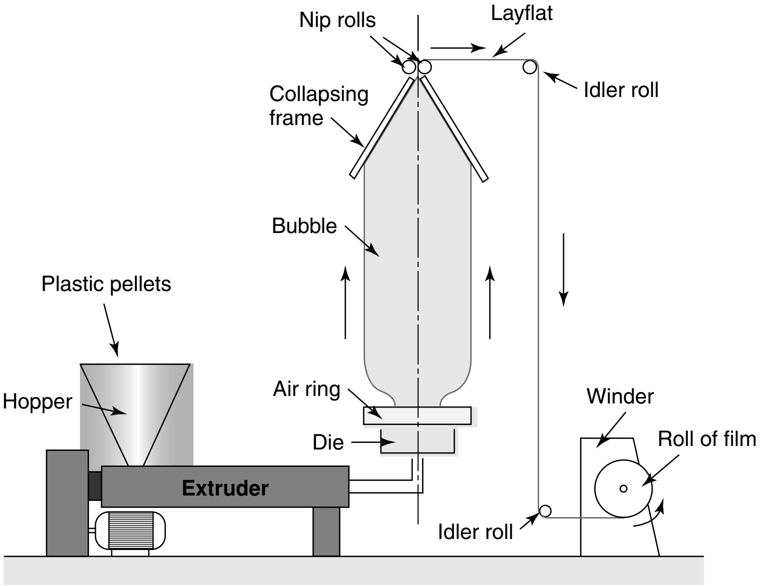


Fig. 28. Schematic of blown film line.

When the bubble has cooled sufficiently, it is flattened in a collapsing frame and pulled through a set of nip rolls to its top. From there, the layflat film is guided over several idler rollers to the winder where it is rolled up over a core.

One advantage of the blown film process is that it can produce not only tubular products (bags) but also flat film, simply by slitting open the tube. In some blown film processes the plastic is extruded downwards to produce films with special properties.

Extrusion Compounding Lines. Compounding lines come in many shapes and sizes. Compounding can be done on single screw extruders, twin screw extruders, reciprocating single screw compounders, batch internal mixers, and continuous internal mixers. The configuration of the line is determined, among other things, by the ingredients to be combined in the compounding extruder. The downstream equipment typically consists of a pelletizing system (see Fig. 29). The polymeric components are usually added through the first feed port. Fillers are often added to a downstream feed port at a point where the plastic has melted already; this arrangement reduces wear on the extruder that might be caused by the filler. High levels of filler are often added by a twin screw stuffer, particularly when the filler has a low bulk density. With high levels of filler, there is often a substantial amount of entrained air; this is removed through the vent port. The vent port is often connected to a vacuum pump; a high level of vacuum improves the removal of volatiles from the plastic.

Some pelletizers cut extruded strands cooled in a water bath; these are called strand pelletizers. Dicers cut extruded sheet rather than strands. The pellets from a dicer have a uniform cubic or octahedral shape. Other pelletizers cut the material right at the die exit; these are called die face pelletizers. These cutting systems can be dry die face pelletizers, water ring pelletizers, and under water pelletizers.

In dry die face pelletizers, the molten plastic is cut at the die face. The pellets are hurled away from the die face by the rapid motion of the cutter knives usually into a water slurry. In water ring pelletizers, the centrifugal action of the cutter hurls the pellets into a snail's cage of water whirling around the perimeter of the cutter housing. The slurry flows to a centrifugal dryer. In underwater pelletizers, the molten plastic is extruded directly into water and cut immediately by a multiple knife cutter. The die may need special heating capability to avoid die plate freeze-off. The start-up procedure for underwater pelletizers often requires careful sequencing of plastic flow, cutter rotation, and inlet water flow rate to avoid die freeze-off or agglomeration.

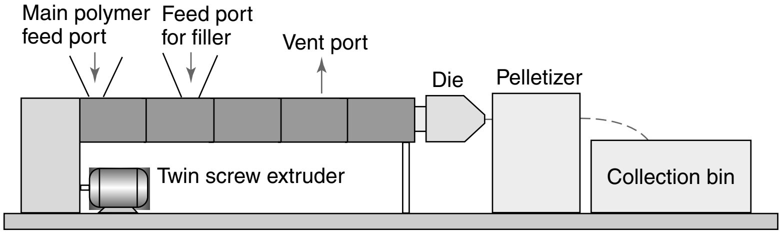


Fig. 29. Typical extrusion compounding line.

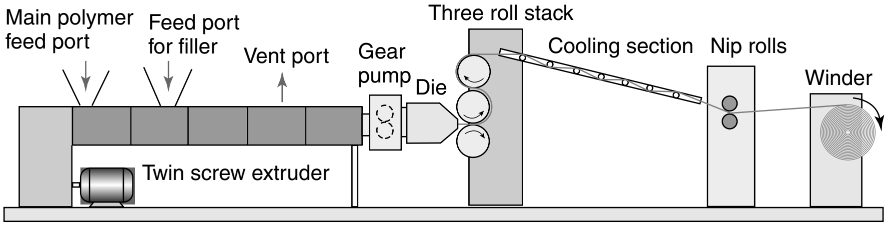


Fig. 30. Extrusion compounding line with in-line shaping.

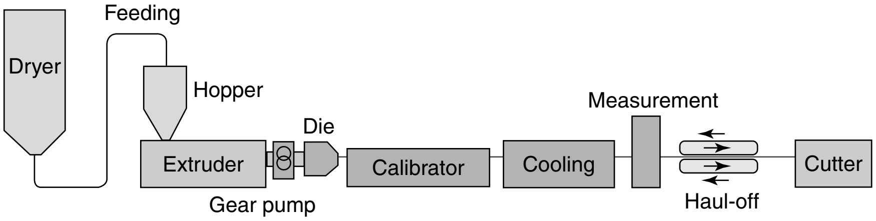


Fig. 31. Components of a profile extrusion line.

Compounding extruders can also be combined with direct forming systems downstream. In many cases, a gear pump is placed at the discharge end of the extruder to generate the diehead pressure and to control the throughput. An example of a combination compounding/sheet extrusion line is shown in Figure 30.

The plastic is introduced to the first feed port of the compounding extruder, the filler is introduced to the second feed port, and the volatiles and air entrapment are removed from the vent port. A gear pump is placed between the compounding extruder and the sheet die. The sheet is fed to a roll stack and from there it is handled as in a normal sheet line, as discussed earlier.

Profile Extrusion Lines. Many extrusion lines are used for the production of profiles. Profile lines also come in many shapes and forms. A typical extrusion line consists of an extruder, a die, a calibrating unit, a cooling unit, a measurement device, a haul-off, and a coiler or cutter or saw (see Fig. 31). A gear pump may be used if the dimensional tolerance of the extruded product is quite small. On some profile lines a film or foil is laminated to the extruded profile. Extruded profiles have an enormous range of shapes and sizes.

Extrusion Tasks: Inner Workings of an Extruder

In a plasticating extruder, a number of tasks are performed that are each critical to the proper functioning of the extruder. These tasks or functions are solids conveying, melting or plasticating, mixing, melt conveying, degassing, and shaping or forming.

Degassing is not done on all extruders; some extruders are equipped with a vent port. The vent port allows volatiles or gasses to escape from the plastic melt. Degassing is also referred to as devolatilization. The functions listed above are interdependent. For instance, a change in the forming region affects the other functions. The forming region is the extrusion die. So, if the die temperature in lowered, this affects melt conveying, melting, mixing, solids conveying, and degassing if a vented extruder is being used.

To understand how an extruder works, it is important to know what happens in the different functional zones in an extruder. The starting and end points of each functional zone depend on the machine geometry, the plastic properties, and the operating conditions. For instance, melting starts where the plastic temperature first exceeds the melting point. This point can shift when barrel temperatures or screw speed are changed.

On the other hand, the geometrical sections of the screw are fixed by the screw geometry. The feed section is the first deep flighted section of the screw and this is where solids conveying occurs. However, the solids conveying zone may end before or after the end of the feed section. The same is true for the melting in the transition section of the screw and the melt conveying in the metering section of the screw. The boundaries of the screw sections are fixed, but the boundaries of the functional zones can shift with plastic properties and operating conditions.

Solids Conveying

Solids conveying occurs both in the feed hopper and along the first several diameters of the screw. The solids conveying in the feed hopper results from the weight of the material. The conveying mechanism at work in the hopper is called *gravity induced conveying*. The material flows down the feed hopper into the feed throat and from there, into the screw channel. The conveying along the screw results from frictional forces acting on the plastic. This conveying mechanism is called *drag induced conveying*, and is the mechanism in the solids conveying zone, the melting zone, and melt conveying zone.

Gravity Induced Conveying. The flow in the feed hopper can be quite complicated. A number of things can go wrong in this section of the machine. For instance, if the bulk material consists of small and large particles, the small particles can separate from the larger particles, causing nonuniform flow from the hopper. This, in turn, causes instabilities in the extruder resulting in output variation.

Some bulk materials are very difficult to handle; for instance, post consumer reclaim (PCR) usually has a wide particle size distribution and a low bulk density. As a result, special extruders have been developed to handle this bulk material efficiently. These machines can have larger diameters in the feed section than in the metering section; they may also use crammer feeders to achieve steady flow of material into the extruder. In some cases, a grooved feed section is used to improve the feeding of low bulk density material.

Important bulk properties are bulk density, compressibility, internal coefficient of friction, external coefficient of friction, particle size and particle size distribution, and particle shape and particle shape distribution.

The bulk density is the density of the material, including the air voids between the particles. The density of a material is the mass per unit volume. The bulk density of pelletized material is usually around 60% of the regular density.

If the bulk density is less than about 30% of the actual density, conveying the bulk solid can become quite problematic and special design features may be necessary to ensure consistent flow. The compressibility is the change in bulk density when pressure is applied. A high compressibility indicates a bulk material that compacts readily under pressure. Highly compressible materials are difficult to handle and susceptible to various flow problems in feed hoppers.

The *internal coefficient of friction* is the friction between the plastic particles themselves. The *external coefficient of friction* is the friction between the plastic particles and another surface, such as the barrel surface. For efficient conveying in the feed hopper, it is required that both the internal and external frictions should be low. For efficient conveying along the extruder screw, it is required that the barrel friction to be high and the screw friction should be low; this is discussed later.

The design of the feed hopper can have a strong effect on the flow in the hopper. This is particularly true for difficult bulk flow materials. Stagnation should be avoided in the flow through the hopper. As a result, a circular hopper is better than a hopper with a square or rectangular cross section (see under The Feed Hopper). Also, the converging region of the hopper should expose the material to a gradual compression; otherwise, unstable flow results. If the compression of the material is too rapid, the flow may stop altogether. This can happen when the bulk material is susceptible to *bridging*. This is a condition where a natural bridge is formed in the material strong enough to support the material above it. When bridging occurs, the flow can stop completely.

Various devices can be used in the feed hopper to promote steady flow. Sometimes stirrers are used to gently mix the material. The stirrer may be equipped with a blade to wipe the material off the hopper wall. This can be beneficial if the material has a tendency to stick to the wall. When the material is susceptible to bridging, vibrating pads may placed against the hopper to create a vibrating action to dislodge any bridges that could form. When the bulk material is very difficult to handle, a crammer feeder may be used. This is a conveying screw placed in the hopper that forces the material to the discharge by the rotation of the screw (see under The Feed Hopper).

A special feed hopper design to minimize flow problems was developed by Johanson (1). The geometry of this hopper transitions from a circular cross section to an oval cross section and back to a circular cross section; it is called the diamondback hopper (see Fig. 32).

The solids conveying into the extruder is also affected by the design of the feed opening. For difficult bulk flow materials, it has been found that an elongated feed opening improves feeding (see also under The Feed Housing). Also, feeding can be improved by offsetting the opening in the direction of the movement of the screw flight in the top position, as shown in the figure. By offsetting the feed opening, a more or less tangential feed opening is created that increases the action of the screw flight in pushing the feed material into the extruder barrel.

Drag Induced Conveying. Once the bulk material drops into the screw channel, it starts moving along its length as a result of frictional forces acting on the plastic. To understand conveying in screw extruders, it is important to know which frictional force is responsible for the forward movement of material and which force is holding the material back. Since the material moves forward as a

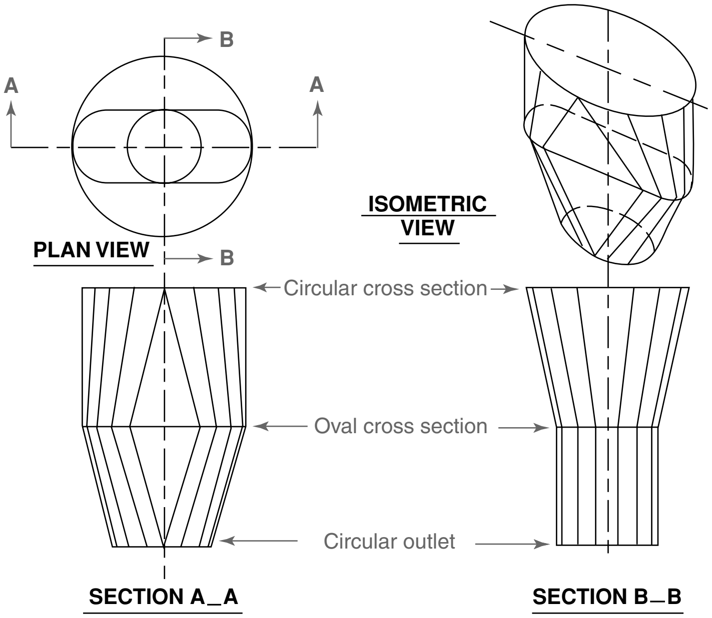


Fig. 32. The diamondback feed hopper (U.S. Pat. 4958741).

result of the rotation of the screw, it would seem that the friction between the plastic and the screw moves the material forward.

Even though this seems like a plausible argument, this is not what really happens. It is the frictional force at the barrel that is responsible for moving the material forward. To understand this, consider an extruder with a barrel coated with a zero friction material. In this case, the material drops down into the screw channel and, once in there, only moves with the screw, around and around. Without friction at the barrel, there is no forward movement of the material.

Another analogy is a rotating threaded shaft with a nut on the shaft that is free to rotate with the shaft. In this situation, the nut stays in the same position on the shaft rotating with the shaft, but not moving forward. If the nut is kept from rotating with the shaft, the nut starts to move along the length of the shaft. If the extruder screw is considered as being the threaded shaft and the plastic as being the nut on the shaft, then it becomes clear why the friction at the barrel is responsible for moving the material forward (see Fig. 33). In fact, barrel friction is a necessary condition for forward transport. If there is no barrel friction, then there can be *no* forward conveying.

Starve Feeding. Starve feeding is a method of feeding the extruder where the plastic is metered directly into the extruder at a rate below the flood feed rate. This means that the plastic drops directly into the screw channel without any buildup of plastic in the feed hopper. With starve feeding, the screw channel is partially empty in the first few diameters of the extruder. Thus, if one looks into the feed opening, one should be able to see the screw flight and part of the root of the screw.

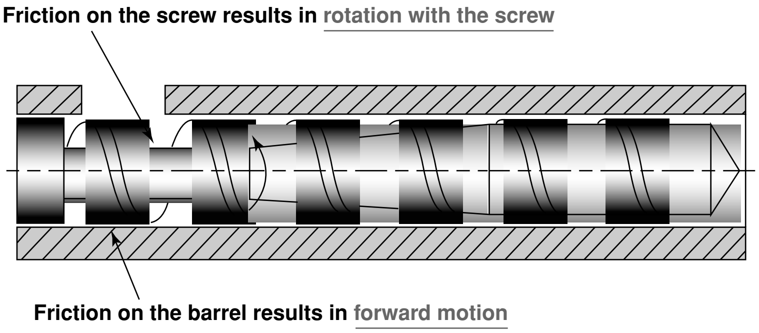


Fig. 33. Driving force and retarding force in conveying along the extruder screw.

When the screw channel is partially filled, there is no pressure development in the plastic. Without pressure development, there is very little frictional heating and mixing. In effect, starve feeding reduces the effective length of the extruder. Thus, a 25 *L*/*D* extruder might have an effective length of only 21*D* with the first four diameters partially filled with material. Starve feeding may be beneficial if the extruder is longer than necessary for the plastic being processed. However, if the length of the extruder is marginal, starve feeding most likely results in poor extruder performance.

Starve feeding is commonly used on high speed twin screw extruders; in fact, most high speed twin screw extruders run starved. Starve feeding is less commonly used with single screw extruders, because it is beneficial only in some cases. Starve feeding can be useful to reduce the motor load of the extruder, to reduce the temperature buildup in the plastic melt, and to add several ingredients simultaneously through one feed port using several feeders.

In mixing and compounding starve feeding can be very useful because it reduces the chance of agglomeration of the filler. As a result, mixing and compounding operations frequently use starve fed extruders. A number of workers have reported dramatic improvement in dispersive mixing when comparing flood fed to starve fed extruders.

Grooved Feed Extruders. The driving force for the conveying process is the frictional force at the barrel surface, as discussed earlier. The frictional force can be affected by adjusting the barrel temperature in the first one or two temperature zones. However, the effect of barrel temperature is usually small. Another method of increasing barrel friction is to machine grooves into the barrel surface; this has a strong effect on the feeding characteristics of the extruder. The grooves typically run in the axial direction, with a length of several screw diameters. The barrel around the grooved section has to be cooled to avoid plastic from melting in the grooved section; the plastic can degrade if melt collects in the grooves.

A relatively new development is the adjustable grooved feed extruder (AGFE). This extruder has a grooved feed section with a mechanism that allows adjustment of the groove depth (2). This makes it possible to adjust the solids conveying efficiency to match the characteristics of the plastic and the screw geometry. The adjustment to the grooves can be made while the extruder is running.

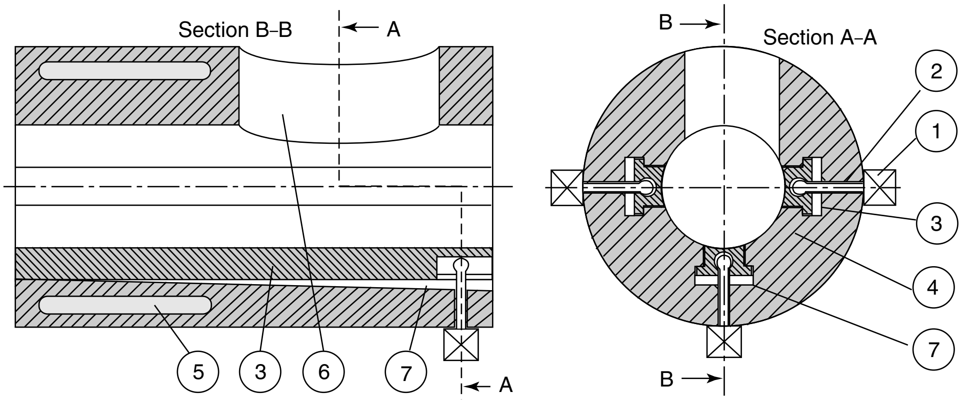


Fig. 34. Grooved feed section with adjustable groove depth.

As a result, it is possible to set the groove depth to achieve the minimum pressure fluctuation at the discharge end of the extruder. The AGFE allows a level of control and versatility not possible with conventional extruders. Figure 34 shows a schematic representation of the AGFE with the grooves shown in the zero depth position. Actuators can pull the keys into the housing to increase the groove depth. This allows continuous adjustment of the grooved depth between zero and maximum depth.

There are a number of advantages associated with grooved feed extruders, including

(1) The output of grooved feed extruders is less dependent on discharge pressure (see Fig. 35); as a result, the stability of the extrusion process tends to improve.

(2) The output of grooved feed extruders tends to be higher than that of smooth bore extruders.

(3) Grooved feed extruders allow extrusion of some very high molecular weight plastics, such as very high molecular weight PE. These materials cannot be processed on conventional smooth bore extruders.

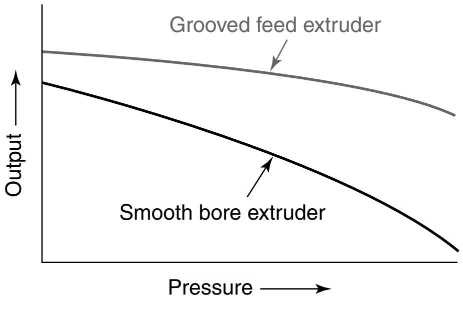


Fig. 35. Output vs discharge pressure for grooved feed vs smooth bore extruder.

With the conventional grooved feed extruder there are some disadvantages as well, such as

(1) The grooved barrel section has to be cooled well enough to avoid premature melting of the plastic in the grooves; this reduces energy efficiency and adds to the complexity of the extruder.
(2) The stresses that occur in the grooved region can be quite high, making the grooves susceptible to wear. The grooves have to be made out of a wear-resistant material to avoid high rates of wear.
(3) The pressures that occur in the grooved section can be quite high, in the range of 70–140 MPa (10,000–20,000 psi). The barrel has to be designed to withstand these high pressures.
(4) The screw design rules for grooved feed extruders are quite different from the rules for smooth bore extruders. Thus, grooved feed extruders require special screw designs. The use of conventional screw designs in grooved feed extruder can lead to a number of problems, such as overheating of the plastic and screw wear.
(5) With a grooved barrel section, the motor load increases and with it, the torsional load on the extruder screw.

It should be remembered that conveying can be improved not only by increasing the barrel friction, but also by reducing the by screw friction. This can be done by screw design, by screw temperature, and by the screw material. Screw design features that reduce screw friction are single flighted geometry (avoid multiple flights), large flight flank radius, and large helix angle. These features are illustrated in Figure 36.

Reducing screw friction can often be achieved by internal screw heating. This can be done by coring the screw and circulating a heat transfer fluid inside the screw, usually oil. Another method of heating the screw is to put a cartridge

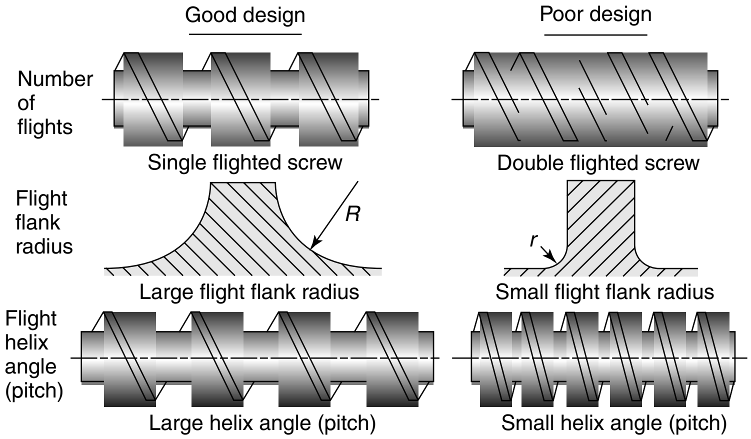


Fig. 36. Measures to reduce screw friction by screw design.

heater inside the screw. Power to the heater can be supplied through a slip-ring assembly at the shank of the screw. Finally, the surface friction of the screw can be reduced by applying a coating to the screw or a surface treatment. The following coatings and surface treatments have been used PTFE impregnated nickel plating, PTFE/chrome plating, titanium nitride, boron nitride, tungsten disulfide (WS2), and catalytic surface conversion (eg J-Tex). The advantage of a low friction coating extends beyond improved conveying along the screw. It reduces the tendency of the plastic to hang up or build up on the screw surface and makes it easier to clean the screw. These coatings can also be used for extrusion dies, particularly the inside surfaces of the die channel in contact with the plastic melt. The advantages here are reduced pressure drop in the die, improved surface quality of the extruded product, and reduced tendency of material to build up at the die exit. The last problem is often referred to as *die drool* or *beard formation*.

Melting

Melting in the extruder starts when the plastic temperature reaches the melting point. There are two types of melting that occur in screw extruders.

Contiguous Solids Melting. In the first type of melting, the solid particles are compacted and form a solid plug that spirals along the length of the screw channel. Between the solid bed and the barrel a thin melt film is located. Most of the melting occurs at the interface between the solid bed and the melt film. The newly melted material collects in the melt film, but is dragged away to the melt pool that is pushed against the active flight flank (see Fig. 37). This type of melting is called contiguous solids melting (CSM) and is most often observed in single screw extruders.

Dispersed Solids Melting. In the second type of melting, the solid particles are dispersed in a melt matrix (see Fig. 38). The solid particles decrease in size until they have melted completely. This type of melting is called dispersed solids melting (DSM) and is observed in high-speed twin screw extruders and reciprocating single screw compounding extruders. The melting in DSM is substantially more efficient than in CSM. The axial length from the start to end of melting in

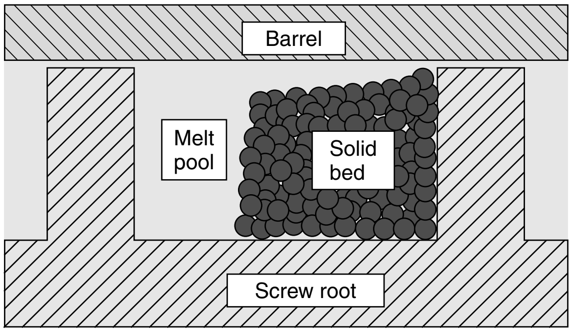


Fig. 37. Contiguous solids melting in single screw extruders.

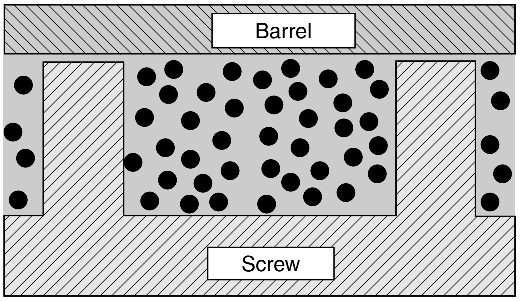


Fig. 38. Dispersed solids melting in single screw extruders.

twin screw extruders is usually about 1–2 screw diameters. On the other hand, in single screw extruders, the melting length is usually 10–15 diameters.

This is an important difference between single and twin screw extruders. In single screw extruders the solids conveying and melting zones extend about 15–20 diameters. This means in a 25 *L*/*D* extruder, there is not much length left for melt conveying, mixing, and degassing. In fact, if degassing is to be done, the extruder length is generally increased to 30–35 diameters. In a twin screw extruder, the solids conveying and melting zones may extend only 5–6 screw diameters. If the twin screw extruder is 30*D* long, it means that most of the length of the extruder is still available to do mixing, degassing, chemical reactions, etc. This makes the twin screw extruder a more versatile machine than the single screw extruder. As a result, the twin screw extruder is often the machine of choice for demanding processing tasks.

The theory of CSM melting was developed by Tadmor (3) in the early 1960s. The theory of DSM was not developed until much later (4). From the quantitative description of the CSM melting, we can determine how plastic properties, processing conditions, and screw geometry affect melting. There are two important sources of heat in the melting process. One is the heat from the barrel heaters conducted through the barrel, then through the melt film into the solid bed. The other source of heat is the viscous heating in the melt film. The amount of viscous heating is determined by the viscosity of the material and the shear rate in the melt film.

The melting mechanism in contiguous solids metting is called *drag induced melt removal*. This refers to the action in the melt film. The melted material added to the melt film is dragged away to the melt pool by the rotation of the screw. As a result, the melt film can remain thin, which is critical to maintaining a high melting rate. If the newly melted material is not dragged away, the melt film thickness will increase as melting progresses and the melting efficiency will drop off rapidly. This is why single screw extruders melt much more efficiently than ram extruders and this is why larger injection molding machines use screw extruders rather than ram extruders.

From this description of melting it is clear that the thickness of the melt film is an important parameter in the melting process. A thin melt film is important in maintaining high melting efficiency. With a thin melt film, there is high viscous heat generation in the melt film and the barrel heat has to travel only a short distance through the melt film to reach the solid bed. The initial melt film thickness is primarily determined by the flight clearance. The larger the flight clearance, the thicker the melt film. As a result, to achieve efficient melting, it is important to keep the flight clearance small. A worn screw or barrel results in a large flight clearance, and this generally has a negative effect on melting and therefore on the overall extruder performance.

Clearly, when we increase the barrel temperature, more heat is available from the barrel heaters to melt the plastic. On the other hand, a higher barrel temperature increases the melt temperature in the melt film. This, in turn, reduces the viscosity of the melt film and the viscous heat generation. Therefore, a higher barrel temperature increases the barrel heat, but reduces viscous heat generation. If the reduction in viscous heat generation is larger than the increase in barrel heat, then the net effect is a reduction in the melting rate. This may seem somewhat counter intuitive; however, this is certainly possible when one considers that at high screw speeds, most of the heat introduced to the plastic is by viscous heating.

The helix angle of the screw flight can have a considerable effect on the melting efficiency, as shown in Figure 39. We see that the axial length required to complete melting decreases when the helix angle increases. It is interesting to see that the highest melting efficiency occurs at a helix angle of 90°. Such a helix angle may be good for melting, but it certainly would not be good for efficient conveying. Remember that a 90° helix angle means that the screw flight is parallel to the axis of the screw. Clearly, the forward conveying capability of the screw is zero when the helix angle is 90°. To achieve both good conveying and good melting we should select a helix angle that gives us not only good melting but also good conveying. Usually a helix angle in the range of 20–30° satisfies both demands.

The use of multiple flights can also improve melting, as shown in Figure 39, because the average melt film is thinner than in a single flighted screw (see Fig. 40). A drawback of multiple flights is that it reduces solids conveying and melt conveying. So, a double flighted screw may improve melting, but at the same time may cause problem in solids conveying and melt conveying. As a result,

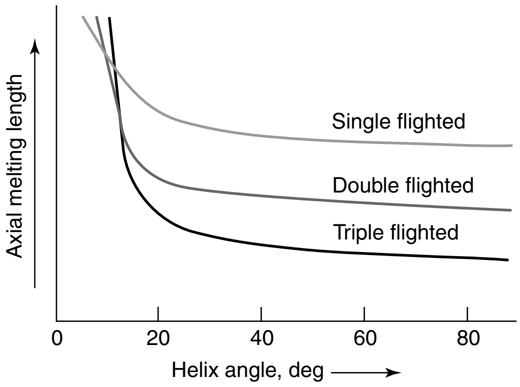


Fig. 39. The effect of the number of flights on the melting length.

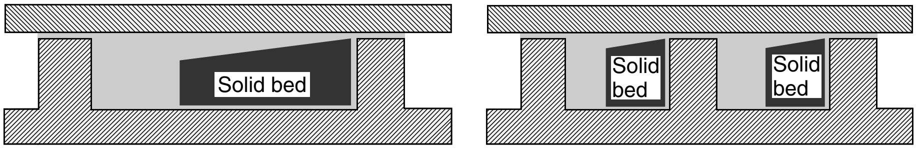


Fig. 40. Melting in a single flighted screw (left) and double flighted screw (right).

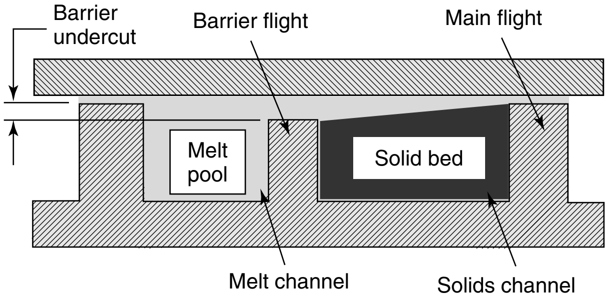


Fig. 41. Cross section of a barrier screw.

a multiflighted screw makes sense if the extrusion is clearly limited by melting capacity.

It is also important to realize that the advantage of a multiflighted screw to melting does not apply to a barrier screw. A barrier screw has two flights: a main flight and a barrier flight. The purpose of the main flight is to separate the solid material from the melted material (see Fig. 41). Thus, the barrier flight effectively separates the solid bed from the melt pool. Because the barrier screw has only one solid bed, its melting capability is about the same as a single flighted screw without a barrier flight.

One variable that affects the melting in an extruder is the temperature at which the plastic is introduced to the extruder. By preheating the plastic in the feed hopper or before, the amount of heat that has to be added to melt the plastic in the extruder is reduced and as a result, melting occurs earlier in the extruder. When it is suspected that an extrusion problem is related to melting, preheating is a method of diagnosing the problem.

The barrier screw has the following advantages:

(1) The barrier screw achieves more stable extrusion than a simple conveying screw.
(2) With a barrier screw, there is virtually no chance of unmelted material beyond the barrier section. However, this is not true for all barrier screw designs.
(3) There is a certain amount of dispersive mixing that occurs as the plastic melt flow over the barrier flight into the melt channel.

Next to these advantages, there are the following disadvantages:

(1) Barrier screws are no better in performance than nonbarrier screws designed with mixing sections.
(2) Barrier screws are more expensive than nonbarrier screws, particularly when purchased from an original equipment manufacturer (OEM).
(3) Because the solid material is restricted to the solids channel, the barrier screw is inherently more susceptible to plugging. This occurs when melting cannot keep up with the reduction in the size of the channel in the compression section of the screw, resulting in the solid material getting stuck in the screw channel. This creates a momentary obstruction to flow and leads to surging. Surging is a variation in extruder output.

Melt Conveying

Melt conveying starts when the melting is completed in the extruder. Strictly speaking, melt conveying starts when melting starts, because it is the melting zone where both solids conveying and melt conveying take place, with the amount of solid material gradually decreasing and, at the same time, the amount of melted material gradually increasing. However, the *melt conveying zone* is defined as the region where all the plastic is completely melted.

The mechanism of melt conveying is viscous drag. In other words, the viscous forces acting on the plastic melt are responsible for the forward conveying of the melt. In the melt conveying zone, the viscous force at the barrel is responsible for forward conveying, while the viscous force at the screw is a retarding force. As a result, melt conveying is improved by reducing the barrel temperature and increasing the screw temperature. Interestingly, screw heating in the melt conveying zone makes more sense than barrel heating. Internal screw heating is not used much in the extrusion industry; the obvious reason is that barrel heating is much easier than internal screw heating.

The optimum screw geometry for melt conveying can be determined from extrusion theory. The optimum helix angle is dependent only on the degree of non-Newtonian behavior of the plastic melt; it can be determined from the following expression:

$$\text{optimumhelixangle[degrees]} = 13.5 + 16.5(\text{powerlawindex})(1) \tag{1}$$

The optimum helix angle for melt conveying decreases as the power law index decreases; in other words, when the plastic is more shear thinning. A similar expression can be derived for the optimum depth of the channel in the melt conveying zone. The optimum depth depends on the viscosity, the pressure gradient, and the power law index. When the plastic becomes more shear thinning, the channel depth should be reduced to maintain good melt conveying.

Melt Temperatures. Because of the low thermal conductivity of the plastic melts, the temperatures in the melt conveying zone can vary substantially. Local temperatures are difficult to measure because it hard to put a probe in the screw channel while the screw is rotating. Melt temperatures can be predicted from extrusion theory using numerical techniques. A popular technique for this purpose is finite element analysis (FEA). With this technique the flow patterns and temperature distribution can be predicted.

In Figure 42 we show the temperature distribution in the screw channel by looking at a cross section of the screw channel. The temperatures are shown in colors; different colors represent different temperatures, just like the weather map on the back page of USA Today. The temperature scale is shown on the right-hand side of the figure. The lower surface of the picture is the root of the screw; the upper surface is the extruder barrel. The barrel is maintained at 175°C and the screw surface is considered insulated (adiabatic). It can be seen in the figure that the highest melt temperatures occur in the mid-region of the channel, while the outside region of the channel remains at a lower temperature.

The reason for this temperature distribution is the way the plastic melt flows along the screw channel. This flow can be illustrated by unrolling the screw channel and by looking it as a straight trough see Fig. 43 and the barrel as a flat plate.

If the flow is viewed relative to the screw, then the barrel moves in tangential direction, v_b, making an angle ϕ with the channel. Angle ϕ is the helix angle of the screw flight. A fluid element close to the barrel surface flows in the direction of the channel until it gets to the pushing side of the flight. At this point, the element moves downward and then crosses the screw channel. When the element gets to the trailing side of the flight, the element moves up again close to the barrel surface and the element starts moving in the direction of the barrel again. This pattern repeats itself numerous times as long as the regular flight geometry is maintained.

If the flow is viewed in the cross section of the screw channel (see Fig. 44), then the material moves to the pushing side of the flight at the top of the channel. This flow results from drag flow. At the bottom of the channel, the material moves toward the trailing side of the channel. This is a pressure flow resulting from the fact that the pressure at the pushing side of the flight is higher than at the trailing side of the flight. If the leakage flow through the flight clearance is negligible, the

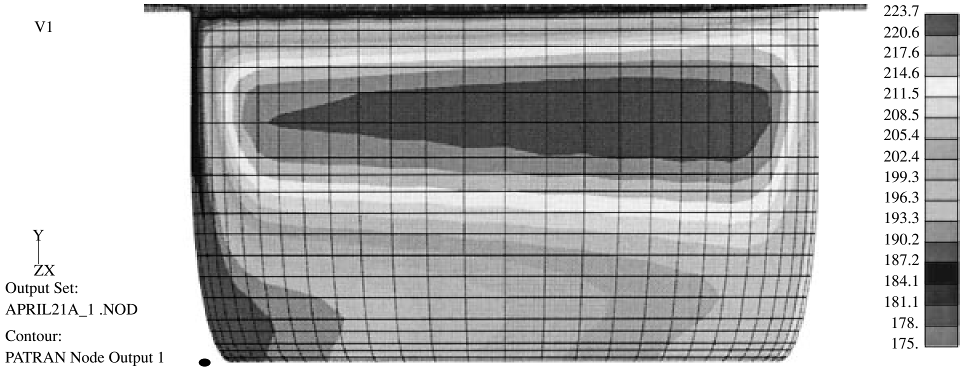


Fig. 42. Predicted melt temperatures in the screw channel.

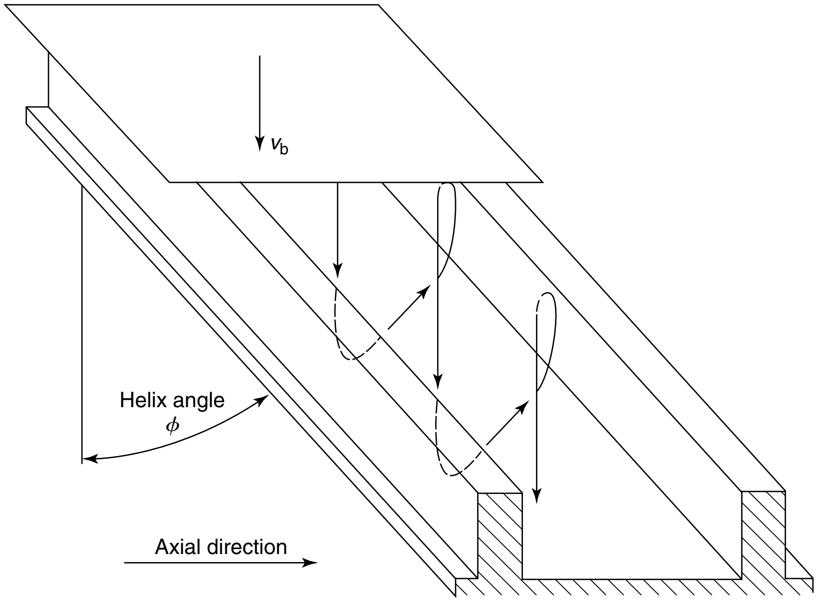


Fig. 43. Flow along the unrolled screw channel.

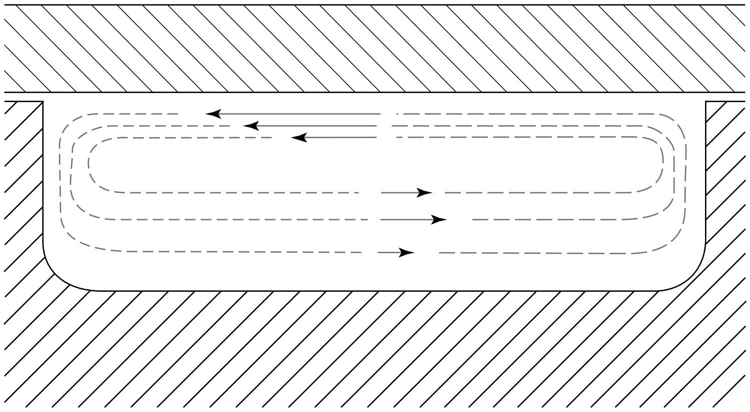


Fig. 44. Recirculating flow in the cross section of the screw channel.

amount of material flowing to the pushing flight flank is the same as the amount of material flowing to the trailing flight flank. Thus, a recirculating flow is obtained as shown in Figure 44. There are also small velocity components in the normal direction close to the flight flanks. At the pushing flight flank, the normal flow is downward, toward the root of the screw; at the trailing flight flank, the normal flow is upward, toward the barrel. The normal flow also results from pressure differences. For instance, the pressure at the top of the pushing flight flank is higher than at the bottom of the flight flank, which is why the flow is downward in this region.

The fluid is sheared as it flows along the screw channel and as a result, there is viscous heat generation in the plastic melt. The actual temperatures that occur at different points in the screw channel are determined not only by viscous heating, but also by how efficiently this heat can be removed. If the barrel is cooled, the melt flowing close to the barrel surface can exchange heat efficiently and hence cool down efficiently. When this outer layer moves along the screw surface, it remains relatively cool even if the screw is insulated.

However, the situation is quite different for the inner layer. Because this layer is trapped in the inner recirculating region, it never gets close to the barrel. As a result, this layer has very limited opportunity for removed of its heat; the outer layer of plastic melt essentially insulates the inner layer. This explains why the temperature in the inner region of the screw channel tends to be higher than in the outer region. In Figure 42, the temperature in the center region is about 60°C higher than the barrel temperature. Thus, it is clear that considerable melt temperature differences can occur in the screw channel.

If these temperature differences are carried to the end of the screw, the melt discharged into the die is not thermally homogeneous. This leads to flow problems in the die and distortion of the extruded product. It is important, therefore, to try to keep these nonuniform melt temperatures from reaching the end of the screw. The most efficient method to do this is by incorporating mixing elements into the design of the screw. Mixing sections are not only important when different plastics are mixed, but also when a single plastic is extruded so that a thermally homogeneous melt at the end of the screw is achieved.

Mixing

Mixing takes place both in the melting zone as well as the melt conveying zone of the extruder. The solid plastic typically moves in plug flow, which means that there is no relative motion between the solid plastic particles. As a result, there is little or no mixing in solids conveying. This means that complete mixing does not start until all the plastic has melted. For this reason, mixing is to be viewed only in the melt conveying zone of the extruder.

Distributive Mixing. The extent of distributive mixing can be determined from the total shear deformation of the plastic melt in the melt conveying zone. The total shear deformation is also called the *total shear strain*; it is determined by the product of the shear rate and the length of time that the fluid is exposed to the shear rate. For instance, if the plastic melt is exposed to a shear rate of $100\ \mathrm{s}^{-1}$ for 15 s, the resulting shear strain is $100 \times 15 = 1500$. The units of shear strain are dimensionless. The shear rate is determined by the velocity profiles in the extruder.

Mixing in single screw extruders is determined mostly by the two main velocity components in the screw channel. These are the velocity in the direction of the channel (z-direction) and the velocity in the cross-channel direction (x-direction) (see Fig. 45).

There is also a velocity component in the third direction (y-direction) parallel to the flight flank. This velocity component is usually very small and therefore, can usually be neglected. The velocities in down-channel direction depend on the

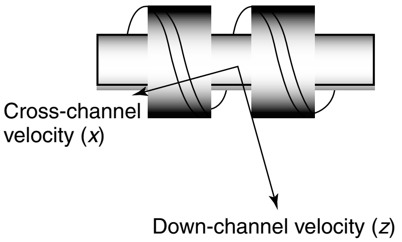


Fig. 45. The two main flow components in a single screw extruder.

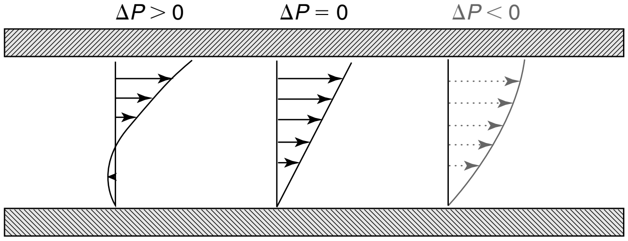


Fig. 46. Down-channel velocity profiles for three pressure conditions.

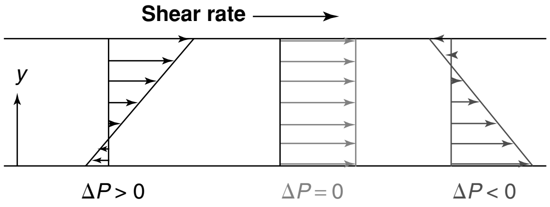


Fig. 47. Down-channel shear rates for three pressure conditions.

pressure gradient; this can be positive, zero, or negative. When the pressure gradient is positive, pressure is increasing along the melt conveying zone; when the pressure gradient is negative, pressure is decreasing along the melt conveying zone. Down-channel velocity profiles for different values of the pressure gradient are shown in Figure 46.

The cross-channel flow is shown in Figure 44. At the top of the channel, the material flows to the left by drag flow and at the bottom of the channel, the material flows to the right by pressure flow. The shear rate can be determined from the velocity profile; the shear rate is equal to the slope of the velocity profile. This slope of the velocity profile is also called the velocity gradient. From the down-channel velocities, we can determine the down-channel shear rates; these are shown in Figure 47.

When the pressure gradient is positive, the shear rates increase toward the barrel surface, when the pressure gradient is zero the shear rate is constant, and when the pressure gradient is negative the shear rates decrease toward the barrel surface. The same approach can be used to determine the cross-channel shear rate

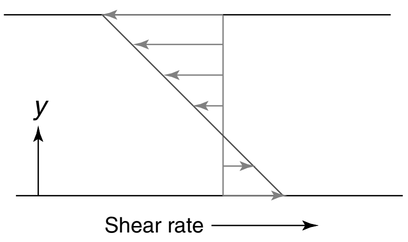


Fig. 48. Cross-channel shear rate vs normal distance.

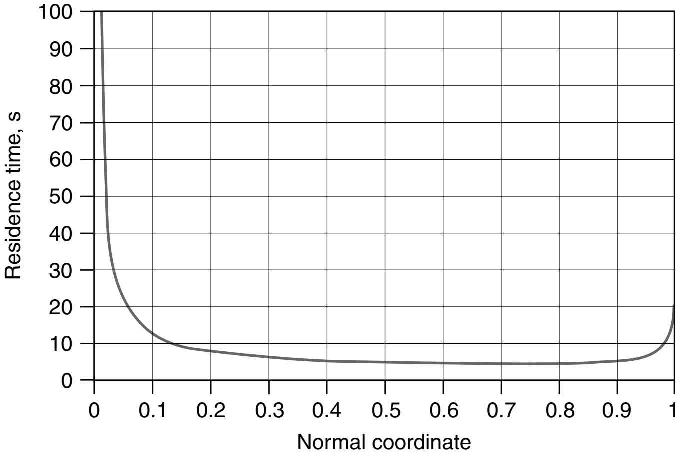


Fig. 49. Residence time vs normal distance (dimensionless).

from the cross-channel velocities. The cross-channel shear rate profile is shown in Figure 48.

In the bottom of the channel, the fluid is exposed to positive shear rates and in the top of the channel, the fluid is exposed to negative shear rates. This has important consequences for the mixing that occurs in screw extruders.

The residence time as a function of the normal distance is shown in Figure 49. The vertical axis shows the residence time $t(y)$ and the horizontal axis shows the normal distance y. The screw surface corresponds to $y=0$ and the barrel surface corresponds to $y=1$.

It is clear from this figure that fluid elements in the center region of the channel have the shortest residence time. The residence time increases toward the screw and barrel surfaces and becomes very long at the barrel and screw surfaces. From Figure 49 it is clear that particularly on the screw there is a relatively thick layer of plastic melt that has a very long residence time relative to the material in the center of the channel. Unfortunately, this increases the chance of material building up on the screw surface and causing problems with degradation.

The total cross-channel shear strain can be determined by adding the shear strain in the upper portion of the channel to that in the lower portion of the

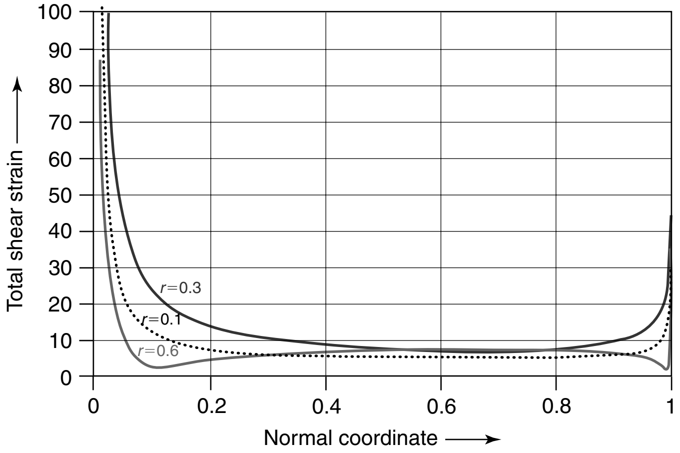


Fig. 50. Total shear strain vs normal distance (dimensionless) at various r_d values.

channel. The total down-channel shear strain can be found the same way. The total shear strain is obtained by adding the cross- and down-channel shear strains. The total shear vs normal distance for several values of the throttle ratio r_d is shown in Figure 50. The *throttle ratio* is the ratio of the pressure flow to drag flow. When $r_d = 0$, we have pure drag flow (pressure flow is zero). When $r_d = 1/3$, the drag flow is three times the pressure flow; this is a fairly common situation in single screw extruders.

The total strain depends strongly both on the normal distance and on the throttle ratio. Fluid elements close to the barrel wall experience a high level of shear strain and thus, will be well mixed. Elements further away from the wall, as well as elements close to the wall, experience a lower level of strain and will not be well mixed.

The shear strain in the center region increases with the throttle ratio. When the throttle ratio is one-third or greater, the shear strain reaches a minimum when close to the wall; this corresponds to the location where the down-channel shear strain approaches zero. Mixing is improved by increasing the throttle ratio or choking the extruder. This can be done by increasing the restriction at the end of the screw, for instance, by increasing the number of screens in the screen pack. Such an increase in mixing, however, is at the expense of output. Since reduced output increases residence time and plastic melt temperatures, there is an increased chance of degradation. Therefore, increasing the restriction of the screen pack is often not the most efficient way of improving mixing.

The nonuniform cross- and down-channel shear strains result in nonuniform mixing in the screw channel. Unfortunately, poor mixing ability is typical of single screw extruders with straight conveying screws, ie without mixing sections. The best method to really improve mixing in single screw extruders is to incorporate mixing sections. Mixing sections are also useful in reducing the large variations in melt temperature that can occur in screw extruders. If a melt with nonuniform melt temperatures is discharged into an extrusion die, several problems can occur, when affects the quality of the extruded product.

There are certain characteristics that are desirable for mixing sections in general. These are

(1) The mixing section should have minimum pressure drop, preferably by having forward pumping capability.
(2) The mixing section should have streamlined flow; dead spots should be avoided.
(3) The mixing section should wipe the barrel surface completely; thus, circumferential grooves should be avoided.
(4) The mixing section should be operator friendly; it should be easy to assemble, install, run, clean, and disassemble.
(5) The mixing section should be easy to manufacture and reasonably priced.

In addition to the general characteristics desirable for mixing sections, there are some specific characteristics important for distributive mixing:

(1) The plastic melt should be subjected to significant shear strain, and
(2) The flow should be split frequently with reorientation of the fluid elements.

Splitting and reorientation is critical to achieving efficient distributive mixing, because mixing can improve exponentially by splitting and reorientation. Distributive mixers can be divided into some main groups: cavity mixers, pin mixers, slotted flight mixers, variable channel depth mixers, and variable channel width mixers.

Based on the important characteristics of mixers we can compile the various distributive mixers and list how they perform with respect to different criteria. This is shown in Table 3; the ranking is based on a five-point system: 5 is very good, 1 is very bad.

The last column in Table 3 is the most important when it comes to distributive mixing effectiveness. The Dulmage, Saxton, CTM, TMR, and CRD all do very well in this category. The Saxton and CRD mixers combine good mixing with low cost,

Table 3. Comparison of Various Distributive Mixers[a]

Mixers	Pressure drop	Dead spots	Barrel wiped	Operator friendly	Machining cost	Shear strain	Splitting, reorientión
Pins	2	2	3	4	5	2	4
Dulmage	4	4	2	4	4	4	5
Saxton	4	4	5	4	4	4	5
CTM	1	3	2	1	1	4	5
TMR	1	3	4	3	2	4	5
CRD	4	4	5	4	3	4	5
Axon	4	4	4	4	5	4	3
Double wave	4	4	4	4	2	4	2
Pulsar	4	4	4	4	3	3	2
Strata-blend	4	3	4	4	3	3	2

[a] The ranking is based on a five-point system: 5 is very good, 1 is very bad.

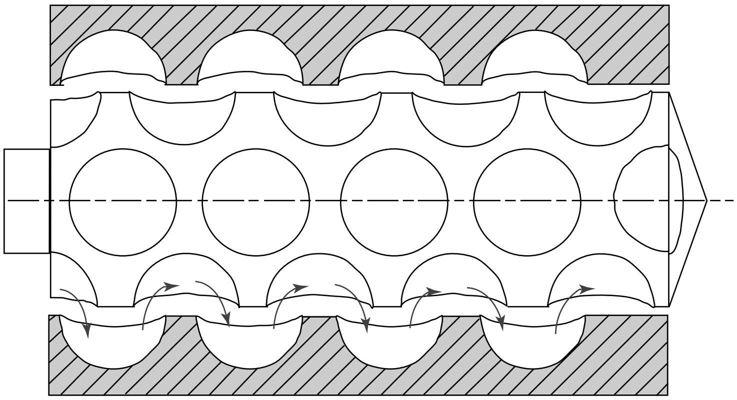


Fig. 51. Cavity transfer mixer.

good streamlining, ease of use, and low pressure drop. The CRD mixer also has dispersive mixing capability; it will be discussed in the next section.

Cavity Mixers. One of the well-known cavity mixers is the cavity transfer mixer (CTM). It consists of a screw section and a barrel section, both containing hemispherical cavities (see Fig. 51).

As the plastic melt travels through the mixer, the material is frequently cut and reoriented. This action gives the mixer good mixing capability. There are a few practical issues, however, that make the CTM a less than ideal mixer. It has no forward pumping capability; thus, the CTM is a pressure consuming mixing device that will reduce the extruder output and increase the temperature buildup in the plastic melt. With the hemispherical cavities, the streamlining is not very good; this can be a problem in product changeover and with thermally sensitive materials. Other drawbacks of the CTM are high cost, difficult installation and cleaning, and the fact that the barrel is not completely wiped during processing.

Another cavity mixer is the Twente mixing ring (TMR) developed by Semmekrot at Twente University in Enschede, the Netherlands. It is similar to the CTM, but it has a freely moving mixing ring with circular holes instead of a barrel with cavities (see Fig. 52). This removes a number of the disadvantages of the CTM; the TMR is easier to install, easier to clean, and the barrel is completely wiped.

Pin Mixers. Pin mixers have been in use for many years and come in many shapes and sizes. Often the pins are circular, but other shapes can be used as well, eg, square, rectangular, and diamond-shaped. Two examples of pin mixing sections are shown in Figure 53.

Pins achieve a moderate level of splitting and reorientation, and as a result, give a moderate improvement in mixing. One drawback of pins is that they create a restriction to flow and, thus, reduce extruder output. The greater the number of pins, the more the output goes down. Another drawback of pins is that they tend to create regions of stagnation, particularly at the corner of the pin and at the root of the screw.

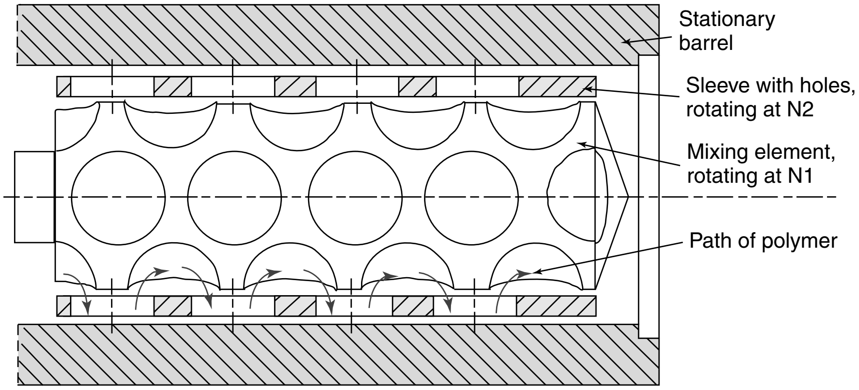


Fig. 52. Twente mixing ring, N1 > N2.

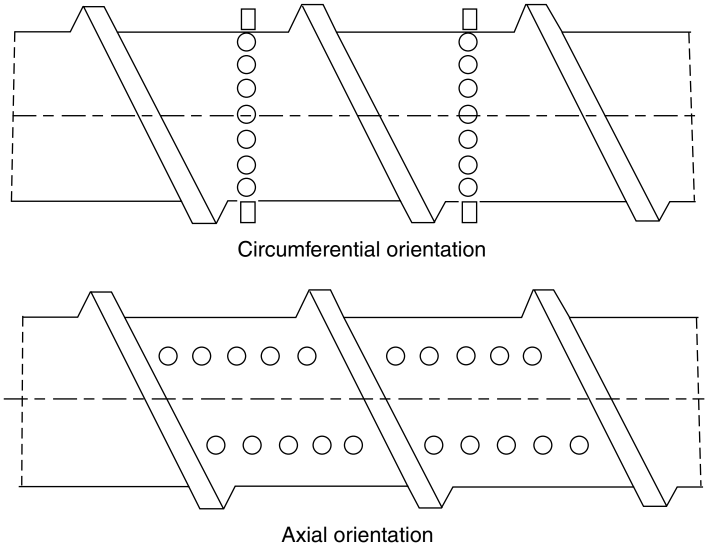


Fig. 53. Examples of pin mixing sections.

Slotted Flight Mixers. There are a great number of slotted flight mixers. Examples of slotted mixers are the Dulmage (Fig. 54) and the Saxton mixing sections (Fig. 55).

Both these mixers have frequent splitting and reorientation, resulting in effective mixing action. Because of the forward orientation of the flights, there is some forward pumping capability. Thus, good mixing can be combined with high output capability. The drawback of the Dulmage mixer is that it has circumferential slots, which means that the barrel is not completely wiped by the mixing section.

Variable Depth Mixers. In these mixers, the channel depth of the mixer is varied to obtain improved mixing. One variable depth mixer is the double wave screw (see Fig. 56).

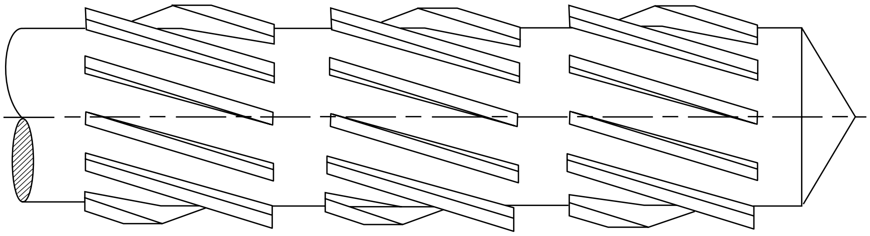


Fig. 54. The Dulmage mixing section.

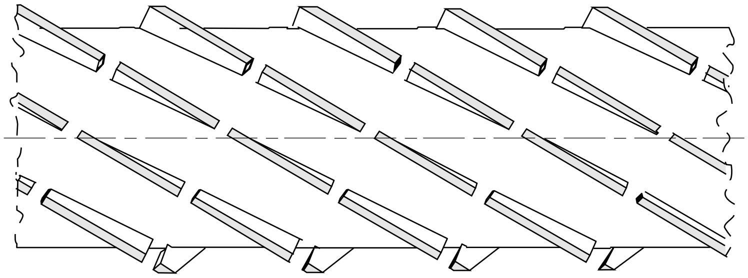


Fig. 55. The Saxton mixing section.

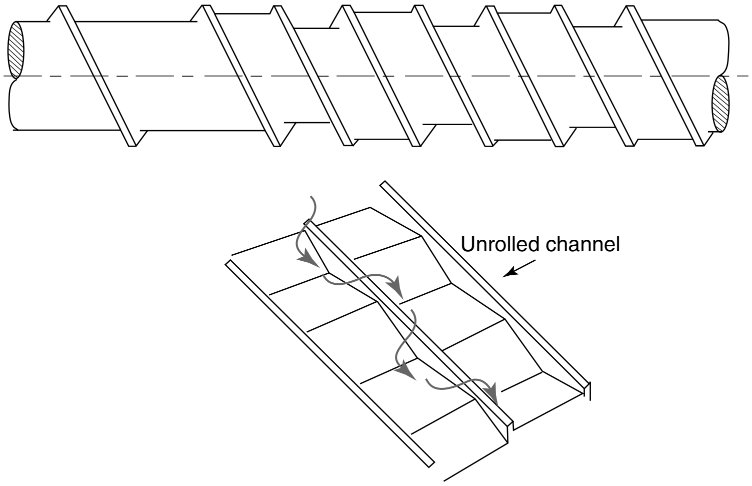
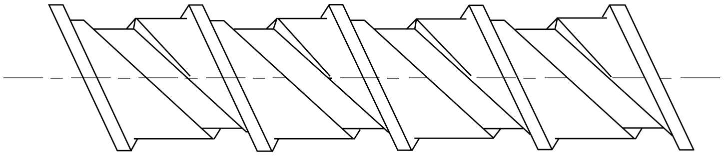
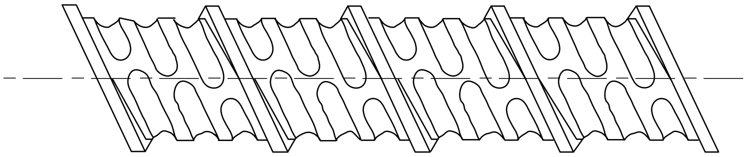


Fig. 56. Double wave screw.

The channel depth varies periodically in each channel in such a way that when one channel decreases in depth, the other increases and vice versa. In this mixer there is no strong mechanism for flow splitting and reorientation. Thus, the mixing capability of this mixer is moderate. Other variable depth mixers are the Pulsar and Strata-blend mixing sections (see Fig. 57). These do not achieve efficient flow splitting and reorientation.



Pulsar mixing section



Strata-blend mixing section

Fig. 57. Pulsar mixer and Strata-blend mixer.

Dispersive Mixing. For dispersive mixing the following characteristics are desirable:

(1) The mixing section should have a region where the material is subjected to high stresses, preferably elongational stresses.
(2) The high stress region should be designed such that the exposure to high shear stresses occurs only for a short time, while exposure to elongational stresses is maximized.
(3) All fluid elements should pass through the high stress regions many times to achieve efficient dispersive mixing action.
(4) All fluid elements should pass through the high stress regions the same number of times for uniform mixing.

A comparison of dispersive mixers is shown in Table 4; the ranking is based on a five-point system: 5 is very good, 1 is very bad.

There are several types of dispersive mixing sections: blister rings, fluted mixing sections, and planetary gear extruders.

Table 4. Comparison of Dispersive Mixers for Single Screw Extruders[a]

Mixer	Pressure drop	Dead spots	Barrel wiped	Cost	Number passes	Type of flow
Blister	1	3	2	5	1	Shear
Egan	2	5	5	4	1	Shear
LeRoy/Maddock	2	2	5	4	1	Shear
Zorro	5	5	5	3	1	Shear
Helical LeRoy	5	5	5	4	1	Shear
Planetary gear	3	5	5	2	Multiple	Shear
CRD	5	5	5	4	Multiple	Elongation

[a] The ranking is based on a five-point system: 5 is very good, 1 is very bad.

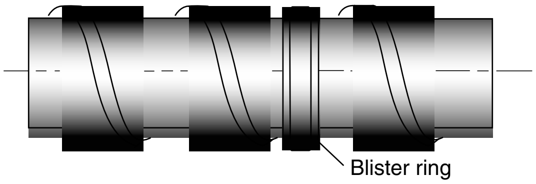


Fig. 58. Blister ring.

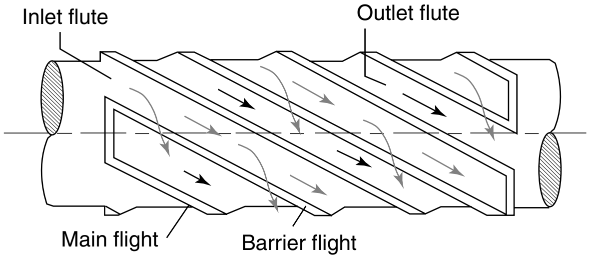


Fig. 59. Egan mixing section.

Blister Ring. The blister ring is simply a circumferential shoulder on the screw with a small clearance between the ring and the barrel (see Fig. 58). All material must flow through this small gap where it is exposed to high shear stresses. Since no forward drag flow occurs in the blister ring, relatively high pressure drops occur across the blister ring. The stress level in the gap is not uniform; therefore, the mixing action is not uniform.

Fluted Mixing Sections. These mixers have inlet and outlet flutes separated by barrier flights. For the material to exit the mixer it has to pass through the narrow gap of the barrier flights; this is where the mixing action takes place. One of the earliest fluted mixers was the Egan mixing section developed by Gregory and Street. The flutes in this mixer have a helical orientation (see Fig. 59).

Another fluted mixer is the Union Carbide mixer (UC mixer) developed by LeRoy and popularized by Maddock. It has straight flutes as shown in Figure 60. Because of the straight flutes, the LeRoy mixer has no forward pumping capability and thus, tends to have high pressure drop. It is typically machined with a ball mill; as a result, the flutes have a semicircular cross section. This tends to result in inefficient streamlining at the entry and exit of the flutes. Despite these shortcomings, the LeRoy mixer is probably the most commonly used mixer in single screw extruders.

It is important to design mixing sections to have a low pressure drop; this is particularly true for dispersive mixers. High pressure drop reduces output, increases melt temperatures, increases residence time, and increases the chance of degradation. Higher melt temperatures reduce the melt viscosity and the stresses in the melt in the mixing section. As a result, higher temperatures reduce dispersive mixing. Since high pressure drop causes high temperatures, high pressure drop should be avoided. For this reason a helical LeRoy mixer is better than the straight LeRoy mixer.

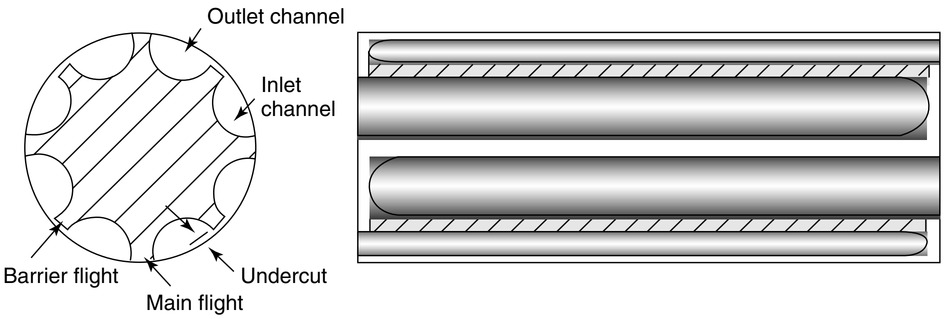


Fig. 60. LeRoy mixing section.

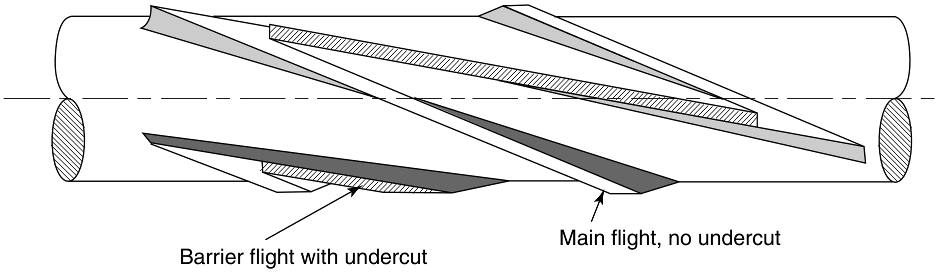


Fig. 61. Zorro mixing section.

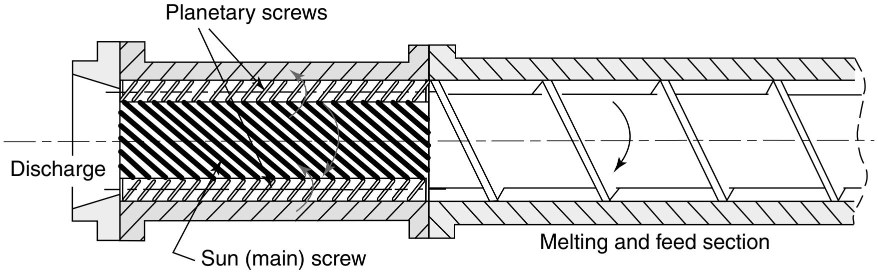


Fig. 62. Schematic of planetary gear mixer.

To promote good streamlining, the helix angle of the barrier flight can be made larger than that of the main flight. This makes the entry channel wide at the entrance and the exit channel wide at the exit. To minimize hang-up, the channels should taper to zero depth at the end of the entry channels and the start of the exit channels. A commercial version of this mixer is the Zorro mixing section (see Fig. 61).

Planetary Gear Mixers. Planetary gear mixers have six or more planetary screws that revolve around the circumference of the main screw. The planetary barrel section must have helical grooves corresponding to the helical flights on the planetary screws. The planetary barrel section is generally separate, with a flange-type connection to the other barrel section (see Fig. 62).

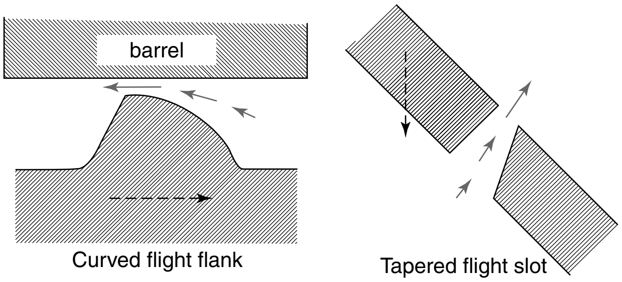


Fig. 63. Various flight geometries that form a wedge-shaped lobal region.

These machines are commonly used in Europe; they are used less in the United States. Some of the benefits of planetary gear mixers are, good homogeneity of the melt at low temperature level, uniform shear exposure, high output per screw revolution, low production cost per unit throughput, self-cleaning action for easy material change, and good dispersive and distributive mixing of various additives.

These characteristics make the planetary gear extruders well suited for processing heat-sensitive materials such as rigid and flexible PVC. They are also used to process blends (eg, PVC and ABS), plastic foams, powder coatings, epoxy, polyester, acrylic, polyurethane, chlorinated polyethylene, etc.

The CRD Mixer. Current dispersive mixers have two important drawbacks. One, they rely mostly on shear stresses to disperse materials rather than elongational stresses; dispersion is more effective in elongational flow than in shear flow. Two, the material passes over the high stress region only once. Advantages of elongational flow over shear flow are

(1) Lower viscous dissipation resulting in lower melt temperatures;
(2) Action of greater forces on agglomerates and droplets;
(3) More efficient deformation of agglomerates and droplets;
(4) Dispersion of gels in elongational flow but not in shear flow.

New mixing technology developed by Rauwendaal eliminates these disadvantages of existing dispersive mixers (5). The CRD mixer uses a slanted pushing flight flank to create a wedge-shaped lobal region, as shown in Figure 63. To create effective distributive mixing, multiple flights are used with many slots. The slots are tapered so that material flowing through the slot is accelerated and exposed to elongational deformation.

The wedge shapes create strong elongational flow. The CRD (6) mixer uses multiple mixing flights with a relatively large flight clearance to ensure that all fluid elements pass through the high stress region several times. There are also a large number of tapered slots to make sure that all fluid elements pass through the slots several times. In addition, there are two wiping flights with slots to make sure that the barrel surface is completely wiped by the mixer and to keep the mixer centered within the barrel. A picture of an actual CRD8 mixer is shown in Figure 64.

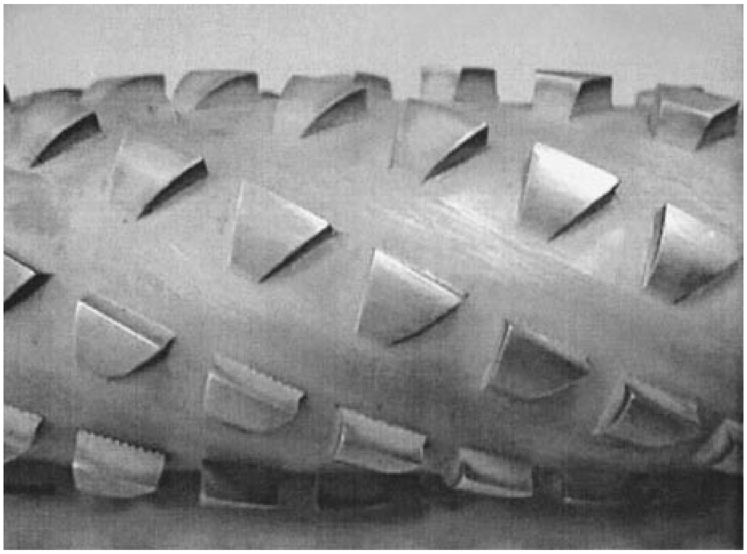


Fig. 64. CRD8 mixer with separate wiping flights. Copyright Rauwendaal Extrusion Engineering, Inc.

The mixing and wiping flights have a positive helix angle; this gives the mixing forward pumping capability. As a result, the mixer does not compromise extruder output. It also allows the mixer to be quite long. A typical length of the CRD mixer is six to eight screw diameters; this results in excellent mixing. Because of the large clearance of the mixing flights, it is necessary to use wiping flights to avoid a stagnant film at the barrel surface and improve pumping. The slots generate efficient distributive mixing in the CRD mixer to randomize the fluid elements and ensure that all elements pass through the high stress regions several times. Separate wiping flights can be avoided by incorporating wiping segments along the dispersive mixing flights.

The CRD mixer has also been applied to twin screw extruders, blow molding, and injection molding machines. A special version of the CRD mixer has been developed that combines a nonreturn valve (NRV) at the end of an injection molding screw with a CRD mixer. This CRD–NRV takes up the same space as a regular NRV, and as a result, offers a quick and convenient method to improve the mixing capability of injection molding machines. Figure 65 shows a slide-ring-type CRD–NRV; the slide ring has internal mixing pins that split the flow and accelerate the plastic melt. The conical nosepiece has tapered circular holes that cause splitting and acceleration as well. As a result, the plastic melt is exposed to three splitting, acceleration, and reorientation events as it passes through the CRD–NRV.

Even though the CRD–NRV is designed for injection molding machines the same principle can be used in conventional extruders. In this case there is no axial motion of the slide ring; however, there will still be a difference in rotational speed between the slide ring and the rest of the screw. The velocity difference will enhance the mixing action.

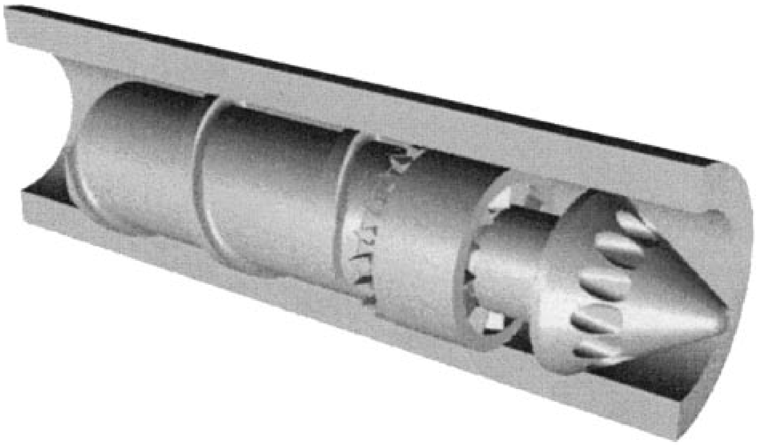


Fig. 65. CRD–NRV used in injection molding.

The following are the benefits of the CRD mixer:

(1) Better dispersive and distributive mixing than existing mixers;
(2) Reduced barrel pressure and melt temperature fluctuation resulting in better output stability and dimensional control;
(3) Reduced die lip buildup, and better and more consistent product appearance;
(4) Lower viscous dissipation and reduced power consumption resulting in lower melt temperatures (less degradation);
(5) Higher extruder output because of pumping action of the mixer; and
(6) The CRD mixer can disperse gels; shear-based mixers cannot disperse gels.

Degassing

Degassing is done on a vented extruder; this is an extruder with a vent port in the barrel. A special screw design has to be used in a vented extruder to make sure that there is a zero pressure region under the vent port. Degassing is needed when the plastic contains volatile components at a level high enough to cause problems. Generally, volatiles cause voids or surface defects in the extruded product.

Degassing is often used in extrusion of hygroscopic materials; these materials have an equilibrium moisture content higher than the level that can be tolerated in extrusion, which is about 0.1% for most plastics. For some plastics, this level is quite a bit lower. Table 5 lists hygroscopic plastics with their equilibrium moisture contents and the allowed moisture content.

With such materials we have two choices: predry the plastic or remove the moisture at the vent port. Drying plastics is usually a very slow process; it can take from 4 to 40 h. Devolatilization in the extruder is much more rapid because of the high temperatures involved. As a result, it can be advantageous to remove the moisture by venting rather than by predrying. In some cases drying and venting

Table 5. Equilibrium and Allowable Moisture Content for Various Plastics

Plastic	Equilibrium moisture content, %	Allowable moisture content, %
CA	2.2	<0.05
CAB	1.3	<0.05
ABS	1.5	<0.10
PA6	3.0	<0.10
PA66	2.8	<0.10
PC	0.19	<0.015
PBTP	0.2	<0.03
PMMA	0.8	<0.10
PAN	0.4	<0.10

are done at the same time, particulary in high output extrusion operations. Many hygroscopic plastics contain too much moisture to remove the required amount of moisture through a single vent port. In this case some predrying has to be done or an extruder can be used with two vent ports rather than one.

It should be noted that there are some hygroscopic plastics that are not good candidates for venting. Some plastics degrade rapidly when the plastic is exposed to high temperatures in the presence of moisture; an example is polyester. This moisture-induced degradation is called hydrolysis. Venting such material to remove moisture invariably results in considerable degradation of the plastic. As a result, polyester is usually dried before extrusion, rather than having the moisture removed during extrusion through the vent port. Other plastics susceptible to hydrolysis are polyamide (nylon), polycarbonate, and polyurethane.

Vented extruders require a special screw design to keep the vent port region at zero pressure; such a screw is called a two-stage screw. The zero pressure region is achieved by following a shallow metering section before the vent port with a deep flighted extraction section underneath the vent port. A short compression section and a second metering section or pump section follow this extraction section. Figure 66 shows the geometry of a two-stage extruder screw.

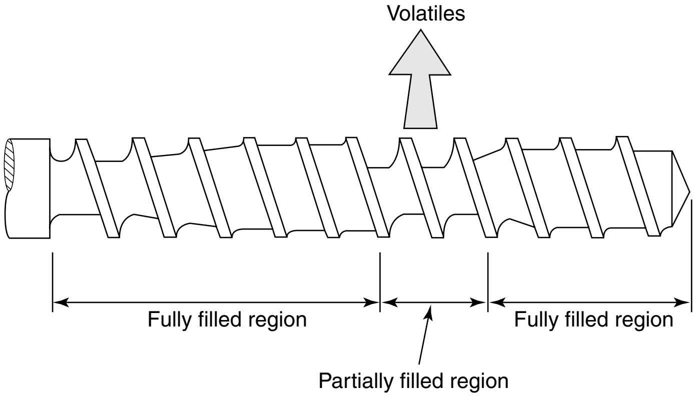


Fig. 66. A two-stage extruder screw used for devolatilization.

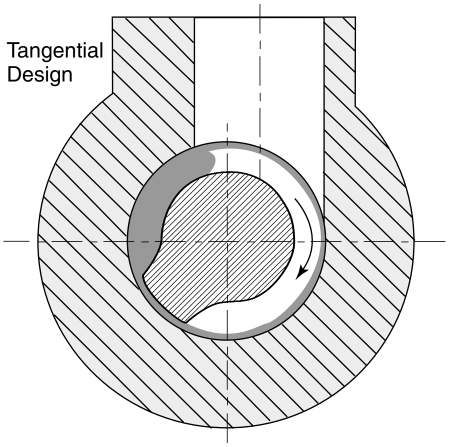


Fig. 67. Cross section of a tangential vent port region showing the rolling bank.

The feed section, the first compression section, and the first metering section make up the first stage of the screw. The extraction section, the second compression section, and the pump section make up the second stage of the screw. For the proper functioning of the screw, it is important that the conveying ability of the pump section be greater than the metering section. The metering section should be the rate controlling part of the screw; it should act as a dynamic choke. If this is the case, the extraction section of the screw is only partially filled and venting occurs properly. If this is not the case, the extraction section completely fills and molten plastic escapes through the vent port; this is referred to as vent flow.

It is critically important that the screw channel under the vent port is only partially filled with plastic; this is true for single as well as twin screw extruders. Figure 67 shows a cross section of a partially filled screw channel. The vent opening has a tangential design; this is beneficial in minimizing accumulation of plastic melt in the vent port.

There is a rolling bank of plastic melt at the leading side of the screw flight. Only when this condition is fulfilled can one be sure that no pressure is generated in the vent port region. If pressure does build up in the vent port region, the plastic melt flows out through the vent port, causing vent flow. This is a common problem in vented extruders.

Vent flow occurs when the conveying rate of the second stage cannot keep up with the first stage. This happens when the first stage is supplying more material than the second stage can handle. This condition can result from incorrect screw design. Vent flow can also occur when a high restriction die is used at the end of the extruder. The diehead pressure is generated only in the second stage of the screw because the extraction section is pressureless. As a result, a higher diehead pressure reduces the pumping capacity of the second stage while the pumping capacity of the first stage is not affected. As the diehead pressure increases, it will reach a point where the pumping capacity of the second stage decreases to that of the first stage. This is the critical diehead pressure for vent flow. If the diehead pressure increases above this value, vent flow occurs. The critical diehead pressure for vent flow depends on the screw design, the flow properties of the plastic, and the operating conditions.

Die Forming

The shaping of the molten plastic occurs in the extrusion die. As the plastic flows through the die, it adopts the shape of the flow channel. Thus, the exit geometry of the die flow channel is shaped like the required shape of the extruded product. The exit region of the die flow channel is called the *land region*. The land region for a pipe or tubing die has an annular shape; for a flat film or sheet die, it has the shape of a slit. One of the most important objectives in die design is to distribute the melt in the flow channel such that the material exits from the die with a uniform velocity. With certain extruded shapes, it can be quite difficult to achieve a uniform exit velocity across the die.

Size and Shape Changes. The land region of the die does not have exactly the same shape and dimensions as the extruded product because there are a number of factors that change the shape and dimensions of the plastic as it emerges from the die. The main factors are drawdown, extrudate swell, cooling, and relaxation. Drawdown occurs because the take-up speed has to be higher than the velocity of the plastic at the die exit to maintain a tension in the plastic between the die and the take-up. This tension is necessary to keep the plastic from sagging. In some operations, the drawdown only reduces the size of the extrudate a few percent; in other cases, the size change can be quite large, as much as a factor of 2 or 3. Drawdown can change the shape of the product if the product has a noncircular shape.

Extrudate swell is the expansion of the plastic as it leaves the die; it is often called die swell, even though this term is not accurate; it is the material coming out of the die that swells, not the die itself! The swelling of the extrudate occurs primarily because of the elastic nature of the plastic melt. Even though plastic melts are usually considered viscous materials, they are not purely viscous but actually visco-elastic. This means that plastic melts behave both in a viscous and an elastic manner. The elastic component is responsible for most of the swelling of the extrudate. The swelling is the result of the relaxation of the strain imparted to the plastic in the die and perhaps even upstream of the die.

The swelling of the melt is determined by the die design, the flow properties of the plastic, the flow rate, the temperatures, and the drawdown between the die and the take-up. If the drawdown is large enough, there may not be any visible expansion of the material coming out of the die. In this case, the size reduction resulting from drawdown overrides the swelling of the extrudate. A problem with the swelling is that it is generally not uniform; this is illustrated in Figure 68.

With a square flow channel, swelling occurs more at the centers of the sides than in the corners. This nonuniform swelling results from the fact that the shear rates in the corners are lower than at the centers of the sides. Another reason for the distortion of the extruded product is that the flow velocities in the corners are lower than along the sides. This is illustrated in Figure 69; since the velocity field is symmetrical, only the upper left quadrant is shown.

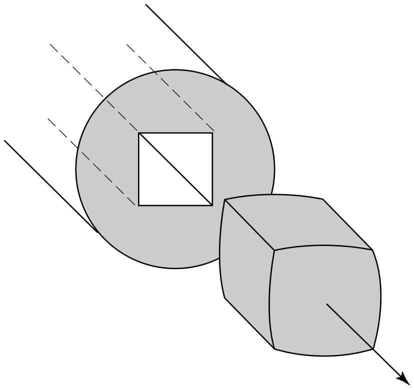


Fig. 68. Swelling of the melt coming out of a die with a square flow channel.

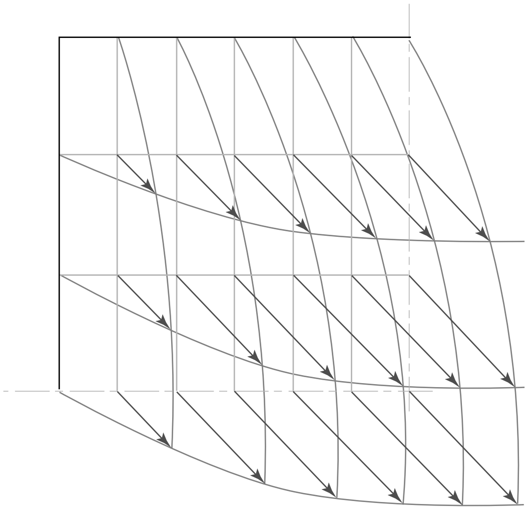


Fig. 69. Velocities in a square flow channel.

As a result, the material in the corners is drawn down more than the material along the sides. Reducing the land length in the corners can enhance flow in the corners; this is typically done by back relieving the die. An example of back relieving the corners is shown in Figure 70.

Cooling increases the density of the plastic and therefore reduces the size of the extruded product. Semicrystalline plastics shrink more upon cooling than amorphous plastics because crystalline regions have a higher density than amorphous regions. Cooling usually does not result in a uniform size reduction. In thick parts, shrink voids can form upon cooling because the outer wall cools and solidifies first. Later the inner layers cool, but they are restrained from shrinking because of the solidified outer wall. As a result, the plastic tends to shrink to the outside, leaving a shrink void in the center, as shown in Figure 71.

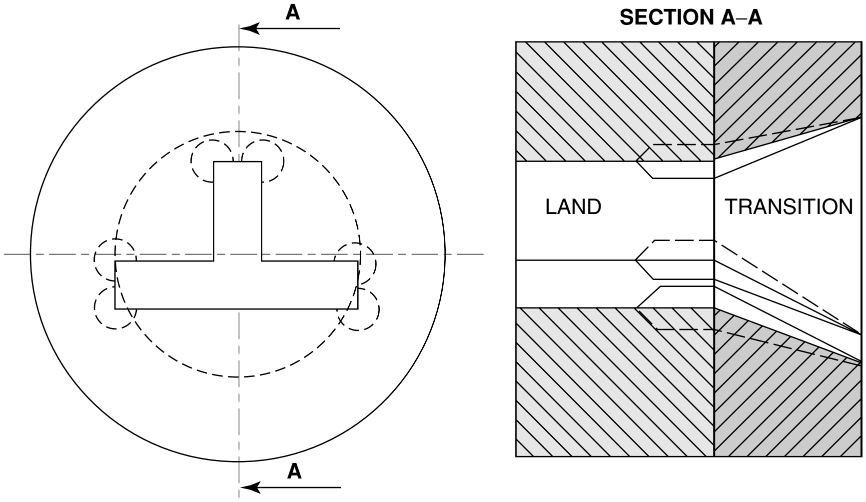


Fig. 70. An example of back relieving the corners of a T-shaped profile.

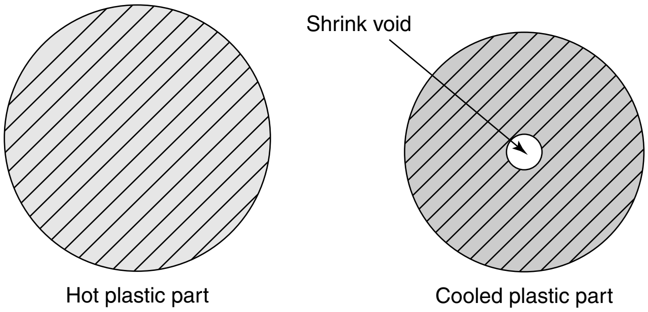


Fig. 71. Formation of a shrink void upon cooling.

Relaxation is the gradual reduction of internal stresses resulting from changes within the material. The stresses can result from the flow in and before the die. Die swell is the result of these stresses. Stresses are also induced after the die exit. The stresses resulting from drawdown are often the dominant stresses induced in the extrusion process. The relaxation processes are strongly temperature-dependent and occur rapidly at high temperatures, particularly above the melting point. At low temperatures however, relaxation occurs only slowly. If drawdown occurs at sufficiently low temperatures, the orientation can relax only partially and a high level of orientation remains in the extruded product. Several commercial processes take advantage of this, such as cold drawing of synthetic fibers.

If nonuniform stresses occur within an extruded product, relaxation of these stresses can lead to warping of the product. An example is shown in Figure 72.

The orientation in the thin legs of the profile tends to be higher than in the thick section. As a result, relaxation in the thin legs is higher than in the thick section, with a correspondingly larger reduction in length. With more length

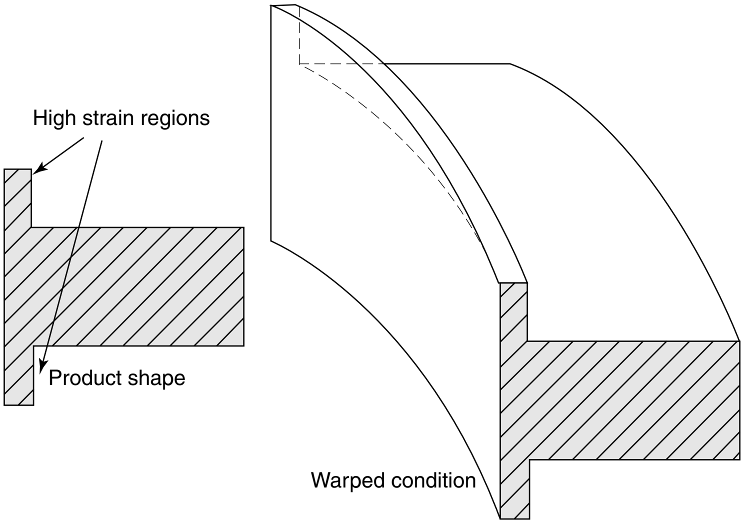


Fig. 72. Warp as a result of nonuniform relaxation in a T-profile.

reduction on the side of the legs (left side), the profile bows with the legs at the concave side as shown. The results of relaxation may not be immediately noticeable. Often the extruded profile appears perfectly straight when first produced. Warpage may not be seen until after the product has spent several days in the warehouse or worse, after it has been sitting in a customer's plant for some time.

Tubing and Pipe Dies. Extrusion dies can be categorized based on the shape of the product produced. Thus, we can distinguish annular dies, slit dies, rod dies, and profile dies. Annular dies are used to make tubing, pipe, blown film, and wire coating. Tubing is a small diameter (less than about 25-mm outside diameter) annular product; it is usually flexible. Pipe is a large diameter annular product (usually with a diameter greater than 25 mm) and is rigid in most cases. Both tubing and pipe are most often used to transport fluids; as a result, they can be exposed to substantial internal pressures. Blown film can have a very large diameter, up to 10 m (30 ft), but the wall thickness is quite small, in the range of 5–250 μm (0.002–0.010 in.). Wire coating and cable jacketing is the extrusion of a layer of plastic over a core. In wire coating, the core is conducting wire; in cable jacketing, the core is a bundle of coated wires.

Annular dies can be either in-line or crosshead. As the name implies, the entrance channel of the in-line die is in-line with the exit channel. This geometry is preferred if it is important to have uniform stresses in the extruded product. A schematic of an in-line die is shown in Figure 73.

Looking at the cross section, the melt enters from the left, then flows around the torpedo, and then though the annular space between the tip and the die. The torpedo is supported by a number of spider legs with a streamlined cross section to minimize hang-up of material. The tip is attached to the torpedo and the die is pressed against the housing by a retaining ring that is bolted against the housing.

A crosshead die is shown in Figure 74. The melt is split around the flow splitter or helicoid, then flows over a shoulder to the tip and the die. The tip is

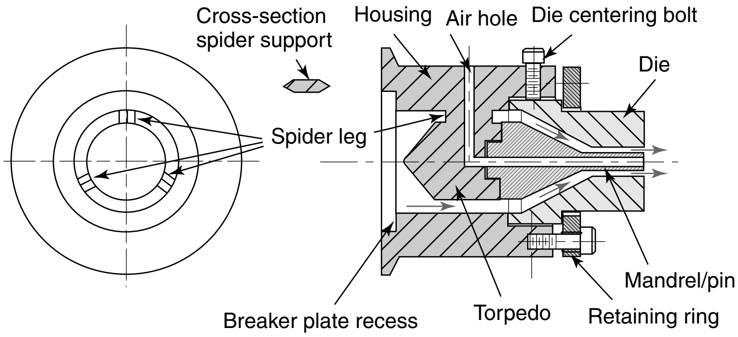


Fig. 73. Schematic of an in-line annular die.

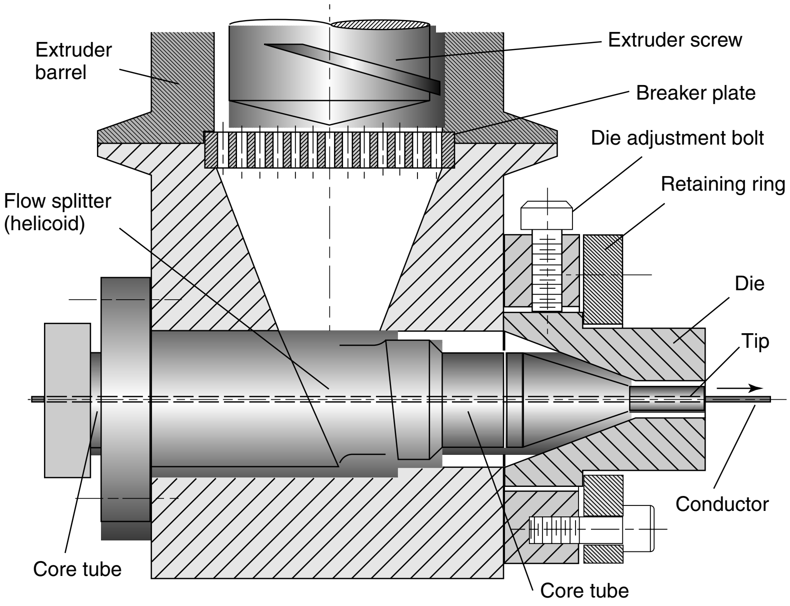


Fig. 74. Example of a crosshead die.

attached to the core tube that can be moved axially. This allows axial adjustment of the tip relative to the die. The die can be adjusted vertically and horizontally by two sets of die adjustment bolts; this allows adjustment of the concentricity of the extruded tube.

Crosshead dies are also used for wire coating. In this case, a conductor moves through the core tube and tip, often at high speed. As the conductor exits from the tip, it is coated with molten plastic in a continuous fashion. Very high line speeds can be achieved in wire coating, as high as 3000 m/min (about 10,000 ft/min).

It should be noted that the dies shown here are some simple examples of annular dies. There is an enormous variety of designs; however, at this point only the main types and features are covered. For instance, in the die assemblies shown, the die can be moved relative to a fixed tip to adjust concentricity. It is also possible to design the die assembly such that the tip can move relative to a

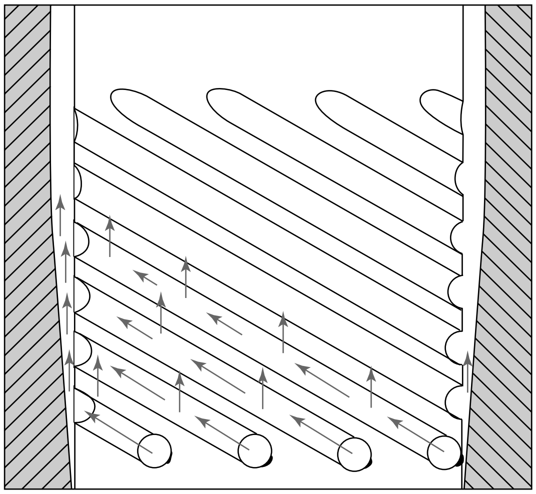


Fig. 75. Spiral mandrel die.

fixed die to adjust concentricity, for instance, by moving the core tube in the back section of the die assembly.

In some annular dies the concentricity adjustment is done automatically. In order to do this, the wall thickness has to be measured downstream of the die along the circumference of the product or in at least four positions. In most cases, the wall thickness is measured using ultrasound. Automatic adjustment is done in some pipe extrusion operations where excess material usage because of poor concentricity could be quite costly.

A special die geometry that was developed for blown film extrusion is the spiral mandrel die, shown in Figure 75. The plastic melt is usually fed through a central channel, then led through radial channels that come out in helical channels in the mandrel. The helical channels are deep initially but they gradually become shallower. At the same time the clearance between the mandrel and the housing increases. As a result, the initial flow is largely a helical flow; however, there is a gradual increase in annular leakage flow with a corresponding reduction in helical flow. At the end of the spiral mandrel section, the flow is a pure annular leakage flow.

The following are the advantages of the spiral mandrel die:

1. Weld lines are largely eliminated.
2. Good flow distribution is eliminated.
3. The helical flow induces some circumferential orientation which increases the hoop strength of the extruded product.
4. The flow through the spiral mandrel section can be readily modeled, which is helpful in design and optimization.

Even though spiral mandrel dies are primarily used in blown film, they have obvious advantages in tubing and pipe extrusion. Both tube and pipe are often

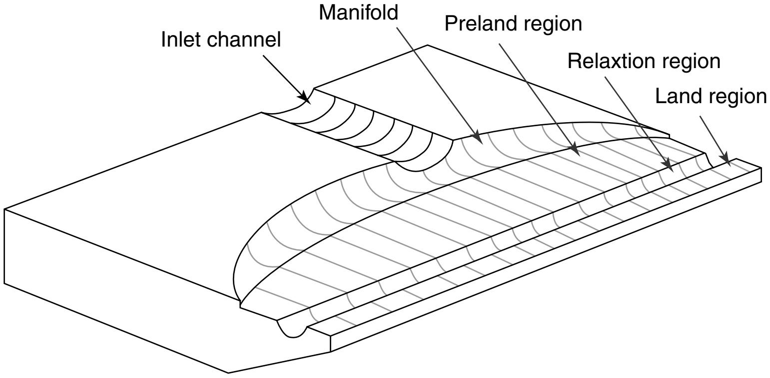


Fig. 76. Main sections of the flow channel of a flat film or sheet die.

pressurized internally in normal product use. With internal pressurization, it is important to have high hoop strength and make sure that weld lines are avoided as much as possible. Since spiral mandrel dies increase hoop strength and reduce weld line problems, they are an attractive option for almost any annular product exposed to a high internal pressure during its end-product use.

Flat Film and Sheet Dies. Dies for flat film and sheet have the same general shape, although there are many differences in the geometrical details. The main sections of the flow channel of a sheet die are the inlet channel, the manifold, the preland section, the relaxation section, and the land section. The main sections of the flow channel are shown in Figure 76.

The inlet channel connects with the discharge of the extruder on one end; on the other end it connects with the manifold section. The function of the manifold is to evenly distribute the flow from the inlet across the manifold outlet. From the manifold, the melt flows to the pre-land, through the relaxation section, and then to the land section. There are a number of different manifold designs, such as the T-die, the coat hanger die, and the horse shoe die. The T-shaped manifold of the T-die does not yield well-streamlined flow; however, the geometry works for low viscosity plastics that are not susceptible to degradation. Another advantage of the T-die is that it is not susceptible to clam shelling, which is the separation of the die lips resulting from the internal pressure of the plastic melt in the die (see Fig. 77).

The coat hanger die has a manifold shaped like a coat hanger (see Fig. 76). The manifold has a complicated shape and is not easy to design or machine. The advantage of the coat hanger manifold is that it produces streamlined flow and it is not susceptible to clam shelling. Coat hanger dies have been made in widths as large as 10 m (30 ft).

The horseshoe die has a manifold with a rectangular cross section (see Fig. 78). It can be designed such that the distribution of flow is independent of the degree of shear thinning of the plastic melt. In fact, it is the only manifold geometry that has this characteristic. The drawback is that the horseshoe die is susceptible to clam shelling. As a result, this die is not typically used for dies wider than 1 m (40 in.).

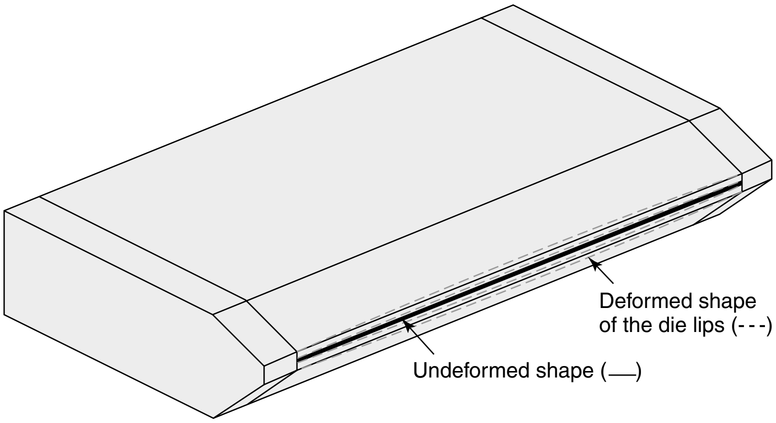


Fig. 77. Illustration of clam shelling.

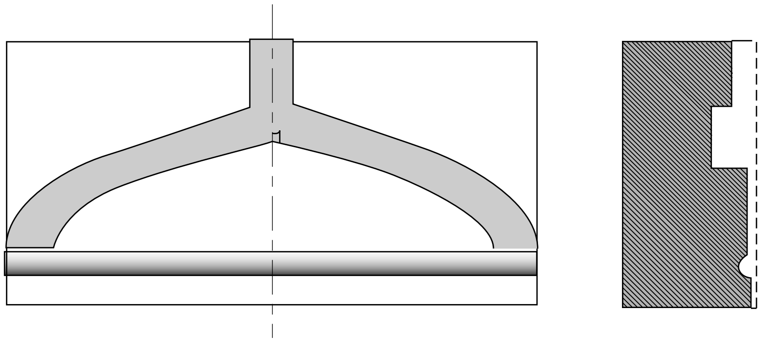


Fig. 78. Horse shoe manifold.

Profile Dies. Profile dies come in many different shapes and sizes. The term profile die is used for dies that extrude shapes other than rectangular, annular, or circular. There are two main types of profile dies: the plate die and the fully streamlined die. The plate die, shown in Figure 79, uses a plate with a cavity shaped to produce the required extruded product. This plate is attached to the end of a section with a large flow channel. The advantage of the plate die is that it is easy to make. On the other hand, the flow is not streamlined and dead spots are likely to occur.

The streamlined die, shown in Figure 80, has a flow channel that gradually changes to the exit geometry of the die. As a result, the velocities gradually increase as the plastic melt moves through the die. There is little chance of hang-up in this geometry. Therefore, the streamlined die is more appropriate for long runs and for plastics with limited thermal stability. The disadvantage of the streamlined die is that it is more difficult to manufacture and therefore more expensive.

There are many profile dies that have a geometry between the plate die and the fully streamlined die; these could be called partially streamlined dies. Because of the enormous variety of profile dies, it is not possible to cover this subject

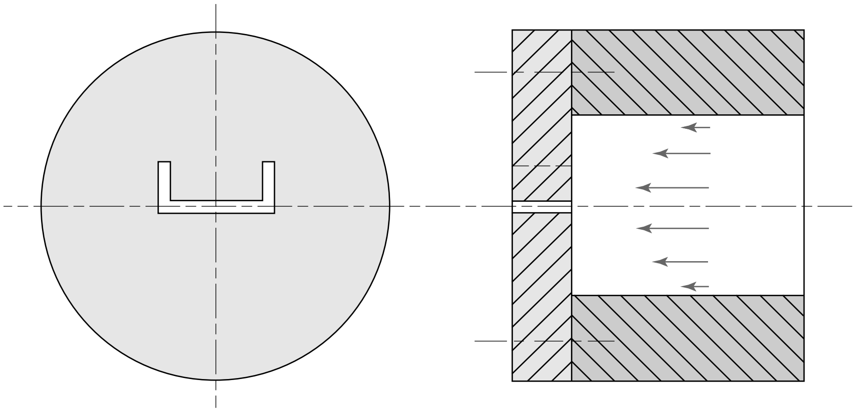


Fig. 79. Example of plate die.

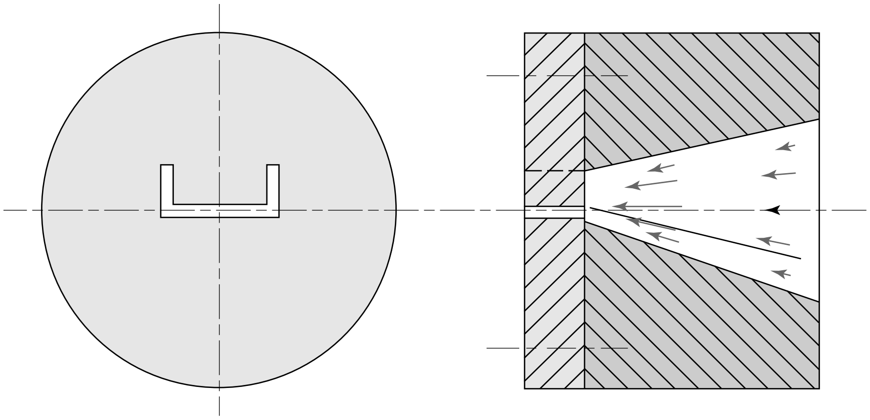


Fig. 80. Example of streamlined die.

comprehensively. For more information, the reader is referred to Michaeli's book on die design (7).

BIBLIOGRAPHY

"Melt Extrusion" in *EPST* 1st ed., Vol. 8, pp. 533–587, by R. F. Westover, Bell Telephone Laboratories, Inc.; "Extrusion" in *EPSE* 2nd ed., Vol. 6, pp. 571–631, by G. A. Kruder, Consultant.

1. J. R. Johanson, in *Pacific Paper '95*, Vancouver, B.C., Oct. 16, 1995.
2. C. Rauwendaal and J. Sikora, *Int. Polym. Process.* **XV**, 1–4 (2000).
3. Z. Tadmor, *Polym. Eng. Sci.* **6**, 185–191 (1966).
4. C. Rauwendaal, *Adv. Polym. Technol.* **15**(2), 135–144 (1996).
5. C. Rauwendaal, T. Osswald, P. Gramann, and B. Davis, in *SPE ANTEC*, 1998, pp. 277–283.

6. U.S. Pat. 5932159 (Aug. 3, 1999), C. Rauwendaal (to Rauwendaal Extrusion Engineering, Inc.).
7. W. Michaeli, *Extrusion Dies*, Hanser Verlag, Munich, 1984.

GENERAL REFERENCES

G. Schenkel, *Kunststoff Extruder-Technik*, Carl Hanser Verlag, Munich, 1963.

Z. Tadmor and I. Klein, *Engineering Principles of Plasticating Extrusion*, Van Nostrand Reinhold, New York, 1970.

H. Hermann, *Schneckenmaschinen in der Verfahrenstechnik*, Springer Verlag, Berlin, 1972.

E. Harms, *Kautschuk-Extruder*, Krausskopf Verlag, Mainz, 1974.

S. Middleman, *Fundamentals of Polymer Processing*, McGraw-Hill, New York, 1977.

Z. Tadmor and C. Cogos, *Principles of Polymer Processing*, John Wiley & Sons, Inc., New York, 1979.

W. Michaeli, *Extrusion Dies, Design and Engineering Computations*, Carl Hanser Verlag, Munich, 1984.

F. Hensen, W. Knappe, and H. Potente, eds., *Plastics Extrusion Technology*, Carl Hanser Verlag, Munich, 1988.

F. Hensen, W. Knappe, and H. Potente, eds., *Handbuch der Kunststoff-Extrusions-technik I Grundlagen*, Carl Hanser Verlag, Munich, 1989.

F. Hensen, W. Knappe, and H. Potente, eds., *Handbuch der Kunststoff-Extrusions-technik II Extrusionsanlagen*, Carl Hanser Verlag, Munich, 1989.

A. Limper, P. Barth, and F. Grajewski, *Technologie der Kautschuk-verarbeitung*, Carl Hanser Verlag, Munich, 1989.

J. White, *Twin Screw Extrusion*, Carl Hanser Verlag, Munich, 1991.

J.-F. Agassant, P. Avenas, J.-Ph. Sergent, and P. J. Carreau, *Polymer Processing, Principles and Modeling*, Carl Hanser Verlag, Munich, 1991.

M. Xanthos, ed., *Reactive Extrusion*, Carl Hanser Verlag, Munich, 1992.

C. Rauwendaal, *Polymer Extrusion*, 4th ed., Carl Hanser Verlag, Munich, 2001.

J. White, *Rubber Processing*, Carl Hanser Verlag, Munich, 1995.

A. Grefenstein, *Reaktive Extrusion und Aufbereitung*, Carl Hanser Verlag, Munich, 1996.

T. Osswald and G. Menges, *Materials Science of Polymers for Engineers*, Carl Hanser Verlag, Munich, 1996.

C. Rauwendaal, *Polymer Mixing, A Self-Study Guide*, Carl Hanser Verlag, Munich, 1998.

C. Rauwendaal, *Understanding Extrusion*, Carl Hanser Verlag, Munich, 1998.

C. Rauwendaal, *Statistical Process Control in Injection Molding and Extrusion*, Carl Hanser Verlag, Munich, 2000.

C. Rauwendaal and M. Pilar Noriega, *Troubleshooting the Extrusion Process*, Carl Hanser Verlag, Munich, 2001.

C. Rauwendaal and K. Cantor, *Extrusion Handbook*, Carl Hanser Verlag, Munich, 2001.

CHRIS RAUWENDAAL
Rauwendaal Extrusion Engineering, Inc.