

# The Screw and Barrel System

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## MATERIALS HANDLING

The subject of materials and component handling is one that appears to be ignored in many extrusion shops. Thus, material and component contamination is common. The most common source of resin contamination is water. Generally oil, grease and dust are observed in the contamination of products as well.

### Material Feed

The feed to machines involved in processing thermoplastics is very often a mixture of virgin (new) material, regrind, and colorant (often in the form of a master batch). All of these materials must be kept clean and dry. A controlled ratio of the materials must also be used if consistent machine operation and component quality (such as surface appearance) are to be maintained. The extruder can be fed with plastics (resins) or compounds in various forms. The feed may be fine powder, regrind material or virgin pellets. If the material is available in more than one form, feeding problems will probably occur if a mixture of forms is used. In terms of feeding efficiency, spherical granules (of approximately 3 mm/0.125 in diameter) are the most efficient, while fine powders are usually the worst. Frequently, regrind material can be almost as difficult as fine powder. Cube-cut granules are better and lace-cut (or face-cut) granules are better still. As a result of feeding differences, machines must be fed with a consistent raw material mix or a pre-blended masterbatch. The use of a masterbatch mixture can produce significant cost savings as a compounding step may be eliminated. However, the use of such a mixture can sometimes cause problems. There may be a color shade differences between the same material processed on different machines. Another problem is the separation of the components of the masterbatch in the hopper.

### Stock Control

All storage and unloading areas must be kept clean and dry to minimize fire hazards. Storerooms should be separated from the processing area by fire resistant doors. The materials should be stored away from direct sunlight and on properly constructed racks. Usually, the use of unheated storage areas, with natural ventilation, is sufficient. To ensure that the material does not stagnate in the stores a strict first-in, first-out policy (Fi-Fo) policy is wise. Strict stock control is important. Within a shipment of material there can be several different batches and one of these may be faulty. By adopting a strict stock control system, a faulty batch can be readily identified and isolated, thus preventing defective products from being produced.

### Condensation Minimization

Many thermoplastic materials are supplied in pellet or granular form in sacks or bags. Before use, it is important that the granules inside the sack reach the temperature of the workshop to prevent condensation from forming on the surface of the granules. Even if a material is said not to absorb water, it is recommended that the material be stored in the extrusion shop for at least 8 hours prior to opening the sack. This advice applies particularly during the colder months and at times of high



humidity. At such times, it is advisable to store the day's requirements in the shop. Before opening the bag, wipe it clean to avoid dust being transferred with the material when the bag is tipped or inverted. After the bag has been opened and the required amount of polymer removed, reseal it immediately and label the bag with the amount remaining, the date and your signature. Only put sufficient material into the hopper for about 1 hour of operation and keep the hopper covered. Wherever possible use dried material and a hopper heater or a direct feed loader.

## Hygroscopic Behavior

If a polymer or compound contains water or another low boiling point material, the temperatures seen in many extrusion processes will be above its boiling point. Visible bubbles will then form within the thermoplastic as the external pressure falls when the material emerges from the die of an extruder. Generally speaking, the higher the processing temperatures, the lower the amount of water (or other volatiles) that can be tolerated. This is because the higher temperatures will generate larger volumes of steam from the same quantity of water. The water may be introduced into the compound by additives that contain excessive water. Usually commodity thermoplastics do not suffer from water-related problems. Engineering thermoplastics, however, do often absorb water; that is, they are hygroscopic.

## Drying

While many processors have drying facilities, they rarely check the moisture content of the material, but dry it for a set number of hours at a particular temperature. Such a drying procedure may not always be satisfactory, as many factors affect the drying process. It is a given that the higher the initial moisture content, the longer the time needed to reach the required low moisture content or limit. Therefore, there is a need to measure the moisture content of the material at various stages in the cycle; for example, as supplied and after drying. A generally standard measure of how much water a material will absorb is given by the amount it will absorb in 24 hours at room temperature. If the value is greater than approximately 0.1%, drying is usually necessary before extrusion. If it is lower, drying is not normally required. Drying should be done in a hot air oven, desiccant drier or in a vacuum drier. The last two methods are the more efficient as they are faster and reduce the water content to lower values. They take approximately half the time required by a hot air drier and, for some resins, they are the only way of getting the material dry.

## Consistent Drying

Many virgin thermoplastic materials do not require drying before processing; that is, they are supplied dry and are ready to use. However, hygroscopic materials need to be dried before melt processing. To reduce problems, in general, it is suggested that all materials be dried to predetermined moisture content levels as a matter of course. After drying, the material should not be placed into an open hopper for extended periods, as it will reabsorb moisture. Ideally, material usage should be calculated to determine how much should be loaded into the hopper to prevent storage for an extended length of time. Where space is at a premium and storage in the hopper is necessary, then a hopper heater should



be used to prevent re-absorption of water. The region of the barrel under the hopper (zone 0) should also be held at a known, elevated temperature.

**Table 14.**

**Suggested Drying Conditions for Extrusion Materials**

(Based on drying conditions for Injection molding materials)

| Abbrev.     | Water Abs.<br>(%) | Hot Air Drying |              | Desiccant Drying |              |
|-------------|-------------------|----------------|--------------|------------------|--------------|
|             |                   | (°C)           | (# of hours) | (°C)             | (# of hours) |
| ABS         | 0.2-0.35          | 70-80          | 2-4          | 70-80            | 2            |
| HIPS        | 0.08              | 70             | 2-3          | 70               | 1-2          |
| LDPE        | <0.2              | 65             | 3            | 80               | 1-1.5        |
| HDPE        | <0.01             | 65             | 3            | 80               | 1-1.5        |
| LLDPE       | <0.2              | 65             | 3            | 85               | 1-1.5        |
| PP (H + CO) | <0.2              | 65             | 3            | 85               | 1-1.5        |
| PA 6        | 1.6               | 80             | 16           | 105              | 12           |
| PA 66       | 1.5               | 85             | 16           | 105              | 12           |
| PMMA        | 0.3               | 75             | 2-4          | 90               | 3-4          |
| PPVC        | -                 | -              | -            | -                | -            |
| UPVC        | <0.2              | 65             | 3            | 80               | 1-1.5        |

**Materials Management**

Material provides the biggest single cost of producing an extrudate. We do not want to waste time and material by producing rejects. Even if the material can be reclaimed, we will have lost production capability and wasted money. Machine manufacturers produce machines that can be started up quickly and which maintain consistently the preset operating conditions. The die and haul off have been designed and manufactured so that they produce extrudate at the required rate producing the minimum amount of regrind. Such efforts will be wasted unless you play your part by looking after the material. What does this mean? It basically means that one should keep the material clean, dry and free from contamination. Remember and apply the following:

- Only open sacks when they have reached workshop temperature
- Only use material when you have double-checked that it is the correct type and grade
- Check to see that the machine has been set correctly for that material
- Reseal containers immediately after use and check that the material is labeled correctly
- Ensure that regrind is kept clean, dry and used in the correct proportions



## THE HOPPER

The hopper is the material holding unit attached to the barrel at the feed port. It is used to hold and feed plastic material into the extruder (See Figure 1).

### Conical Hopper

Usually the hopper is shaped like a tapered cone, the smaller end of which is attached to the hopper block on the barrel. The larger end, through which it is filled, is closed by a lid. At the base of the hopper is the hopper slide (throat gate) which can be used to block the material feed into the machine. The taper angle of the hopper (usually between 20° and 45°) must be greater than the angle of repose of the material being extruded to reduce the risk of bridging. The inner surface of the hopper must be smooth and highly polished to minimize material stagnation and to prevent any material from adhering to the metal surface. Often the hopper is made from aluminum although stainless steel is preferable. Simple gravity feed is most often used with a conical hopper, unless the material does not flow uniformly. To avoid material feed problems, such as bridging, the hopper may be vibrated and/or the material may be stirred by means of a rotating arm. It is desirable to keep the level of material in the hopper as constant as possible to assure a constant output from the die. The material temperature should also be kept as constant as possible using a heated hopper assembly.

### Hopper Block

The hopper block is that part of an extruder that supports the feed hopper and contains the throat. To ensure that material freely enters the feed section of the screw, cooling water is generally passed around the hopper throat assembly. The flow rate and temperature of the cooling water is important, as these variables affect how the material is converted from solid to melt (plasticized) within the barrel. Usually, the water passing around the hopper throat is from the local supply and is, therefore, subject to a seasonal temperature variation. This variation can affect the melt temperature and cause product variation. To overcome this problem a temperature control system (similar to a mold temperature controller) can be installed with the flow rate and temperature of coolant standardized for each machine. Alternatively, a solenoid-actuated valve fit into the coolant supply can be used to provide water flow when the temperature exceeds a preset value.

### Hopper Heater and Drier

A hopper drier is used for drying a material, (for example, an engineering thermoplastic) before, melt processing. Heated air is blown through the base of the hopper and filters through the material. Part of this air is bled-off during the drying process to prevent it from becoming saturated with moisture. With such a system, drying times are measured in hours (See Table 6.), but this can be reduced by the use of a desiccant drier or vacuum drier. Because of the relative inefficiency of many hopper dryers it is best to refer to them as hopper heaters. Such hopper heaters should be used to keep a material hot before melt processing. The material may have been dried in another system and the heated hopper simply acts to prevent the regain of moisture and to maintain material temperature.



## Hopper Loading

Although a hopper may be loaded with material manually, it is easier, safer and more efficient to use one of the commonly available alternatives such as a negative pressure (or vacuum) hopper loader. This may be connected to a floor-mounted material bin via a conveying tube through which the applied vacuum draws up the material to the receiver. Once the receiver is filled, the vacuum application is stopped and the material discharges by gravity. Some negative pressure hopper loaders have a reverse flow feature to pressurize the vacuum receiver and break up potential bridging. Some of these hopper loaders, designed to handle dusty materials such as regrind, are known as powder loaders. The hopper may be loaded using timed loading cycles or filled to a predetermined level by means of a level control which senses a full receiver and switches off the conveying action to save energy. When materials are conveyed in automatic systems, the dangers of dust generation, and dust inhalation, should be recognized and all equipment must be properly grounded. It should be noted that individual machines may also be fed from a centralized supply (a bulk handling loading system). An auger conveyor (flexible worm hopper loader) is used to convey dusty or difficult-flow materials over short distances. Such conveyors can require considerable cleaning between material changes.

## Material Measurement and Blending

The blending of materials is now common, as many machines run on a mixture of virgin material and regrind. Most systems use volumetric blending where the ingredients of a blend are measured by volume and then fed either to a separate blender or to a blender hopper on the machine (in a blender hopper the material may fall through a series of baffles to cause blending). An accuracy of approximately 0.1% is achievable by volumetric measurement. Alternatively gravimetric blending may be used. With this type of system the ingredients of a blend are measured by weight. For example, a receiving vacuum hopper may be mounted over a blender supply hopper that is mounted on load cells. As material is metered away from the supply hopper, the amount being fed to the extruder can be weighed by difference. Gravimetric measurement can provide a guaranteed accuracy of 0.05% to 0.005%.

## THE BARREL

The barrel of an extruder is a hollow chamber in which the screw (or screws) operates (See Figure 1.). If one screw is used the barrel has a cylindrical cross-section: if two screws are used, the barrel has a figure eight (8) crosssection. It is the screw and the barrel, which interact to melt, convey, and generate pressure on a polymeric material within an extruder. It is essential that this be done under controlled conditions since the extruder must produce a uniformly plasticized material, of constant composition, at the required rate. To achieve this, the barrel must be made very accurately. The total out-of-alignment error, after machining, must be less than one half of the screw/barrel clearance. A barrel is generally rated in terms of its diameter (D) in inches or millimeters.



## Barrel Construction

Because the pressures generated within an extruder can reach very high values (up to 10,000 psi or 70 Mpa), the barrel is constructed to withstand these high pressures without distortion. The barrel, therefore, is made from thick walled alloy steel tubing or pipe and is usually designed to operate safely at twice the estimated operating pressures. Wear and corrosion resistance are often provided by ion nitriding, although a bimetallic barrel is preferred for wear resistance. The feed throat, cut through the barrel wall, is approximately the same size as the barrel diameter. It is very important that adequate provision is made to cool the barrel in this region, as otherwise the extruder will not feed properly. Provision is made to attach the adapter and die at the discharge end of the barrel.

## Barrel Wear

Frequently, there is an increase in the clearance of the screw/barrel system, especially in the hopper region, over time of operation. The screw and barrel assembly operates in a very aggressive environment that may cause severe wear problems. As material modification becomes more common with abrasive materials, like flame retardants and fillers (such as glass), being added to more plastic materials, wear has become a major problem. As it is preferable to replace a screw than a barrel, the barrel must be harder than the screw. To improve the wear resistance of the barrel (which is required mostly in the transition zone) it may be modified or lined. Modification may be by processes such as nitriding or ion implantation, but these treatments are not as good as lining (which gives a bimetallic barrel). This produces a barrel that is based on two different metallic materials, in which one metallic material surrounds the other. The inner layer, in contact with the melt, possesses good wear and/or corrosion resistance characteristics and is about 1.5 mm thick (the thickness is approximately 2 mm thick for a grooved barrel). This layer may be based on one of a number of materials or alloys such as a nickel alloy matrix reinforced with particles of 25% iron boride or of tungsten carbide. The inner liner is cast inside a flanged steel backing cylinder of a high quality tensile steel (AISI 4140), which resists crushing and distortion. An outer assembly, generally a cast aluminum housing, contains heating elements, cooling channels and pockets for the temperature sensors. The barrel may be made in sections, the number of which corresponds to the number of barrel zones.

## Barrel Heating and Cooling

Most extruders are electrically heated and use resistance coils, bands, or cuffs that are strapped or bolted around the barrel. Upon demand, initiated by a thermocouple, electrical current is passed through the resistance wire, inside the coil. The resistance produces heat that causes the temperature to rise. If a PID controller is used, as the set point temperature is approached the power is progressively reduced and then finally turned off completely at the set point. For a given machine, the actual barrel settings required to achieve a desired melt temperature will depend on the screw rotational speed, the pressure within the system and the polymer throughput. As it is very easy to exceed the extrusion set point temperature, many machines are equipped with cooling systems. Air cooling systems are the simplest to install and consist of fans that circulate air around the barrel on demand. These are not as



efficient as liquid cooling systems. A popular system is based on a closed loop, heat exchanger that uses distilled water contained inside a sealed coil surrounding the barrel. When the set point is exceeded, the vapor from this water is cooled by water flow so that the distilled water vapor condenses to absorb more heat.

## Zoned Heating

A zone is a part or section of an extruder barrel. For ease of control, the barrel is divided into zones or regions. Zoned heating is the separate heating, and temperature control, of each zone of a machine. The smallest machines usually have three zones while larger machines may have as many as twelve. A temperature sensor and its associated electronics, (such as a microprocessorbased, three term (PID) controller), controls each of these zones.

## Barrel Temperature Settings

These are the temperatures set on the control instruments. It is the melt temperature, however, that is important and any barrel temperatures quoted (in the literature) are only guidelines. When there is no experience in the processing a particular grade of material, it is best to start with the lowest settings recommended. Usually the first zone temperature is set at the lowest value as this helps prevent premature melting and bridging of the resin in the feed throat. The temperatures of the other zones are gradually increased until the die is reached. In extrusion processes the die temperature is sometimes set slightly higher to put a higher gloss on the product. As it is easier to heat a barrel than to cool it, it makes sense to approach the final operating temperatures slowly to minimize the risk of temperature over-shoot. Setting the temperatures 20°C/30°F below the run settings during initial barrel heating most easily does this.

## Barrel Residence Time

This is the average time during which a material resides within the extruder barrel. It is important because time at temperature controls of the rate of decomposition of plastics. A plastic may be degraded by a short exposure to a high temperature or by a longer exposure to a lower temperature. How long the plastic is in the barrel is therefore important. The actual residence time may be determined experimentally by measuring the time taken for colored plastic to pass through the extruder.

## Vented Extruder

The barrel of a vented extruder contains a vent or port that is used to reduce the water (moisture) and/or volatile content of a plastic material. The melt is decompressed partway along the barrel by reducing the screw root diameter. At this point in the barrel a vent is located to allow the vapor to escape (the vent may be plugged when venting is not required). The vapor-free melt is then conveyed towards the die and re-compressed by increasing the screw root diameter. To ensure that melt does not escape through the vent, a dam or torpedo section is incorporated on the screw just before the vent. As a result





of the way that vented machines are constructed (high L/D ratio and variable screw geometry) and operated they produce very good mixing. It must be remembered, however, that the action of heating some plastics in contact with water can cause decomposition, or degradation. In some cases a vent may be used to add something to the barrel. For example, a relatively high loading of filler may be added to a plastic material if it is first softened in the screw/barrel assembly. Thus the filler may be added partway down the barrel via a vent or vents.

### **Grooved Barrel Extruder**

This is an extruder that contains grooves in the feed section of the barrel. It may also be referred to as an axial grooved barrel extruder as the barrel contains axial grooves. The barrel contains a number of grooves running parallel to the screw that improve the feeding characteristics of the system. The grooved section is of the order of 3 to 4 D in length and tapers out as it progresses along the barrel. Temperature control of the grooved section is important. It is generally held at a temperature of 70°C by intensive circulation of water. To decrease heat generation, a zero compression screw may be used. By using a grooved feed throat, the output of the extruder is increased (compared to a machine with a plain barrel), but there is an increase in power consumption (approximately 10% more). The output, however, is virtually independent of the back-pressure. The peak pressure within the barrel often occurs at the end of the grooved section. A grooved barrel extruder is said to be driven from the back – as compared to an extruder fitted with a gear pump that is said to be driven from the front. The use of axial grooves and a barrier screw produces a machine that can uniformly plasticize plastics at high outputs and comparatively low melt temperatures. A lower melt temperature improves the capacity of the downstream cooling equipment and thus allows an increase in the output.

## **THE SCREW**

The most popular type of extruder is the single-screw type machine. In this extruder it is the screw and the barrel that interact to convey, melt and generate pressure with a plastic material. It is required that this be done in a controlled way, since the die must be supplied with uniformly plasticized material, of constant composition, at a constant and controllable rate. For this reason, many single screw machines are fitted with mixing sections and/or a gear pump.

### **Flow Mechanism**

The screw consists of a cylinder of steel with a helical channel cut into it. This screw rotates inside the extrusion barrel and conveys the plastic material from the hopper to the die along the screw channel (the open section between the flights of the screw) (Figure 13.). In the ideal case, as the screw rotates, the material slips on the screw and adheres to the inside the barrel, producing a purely axial (forward) movement of the polymer. If the material sticks to the screw and slips on the barrel then there will be zero output, as the material and the screw rotate together. In practice, the flow behavior lies between these two extremes since the material adheres to both the screw and the barrel.

## Extruder Output

As the polymer moves along the screw a thin film of the material initially forms on the barrel wall. The screw rotation scrapes this thin film of melted polymer away from the barrel wall and it flows down the front face of the screw flight. It is then forced (or dragged) along the core of the screw and up the rear face of the flight giving what is called drag flow. Drag flow, which is due to the interaction of the screw and the barrel, produces a circulatory flow in which the melt surrounds un-melted granules. Ideally the

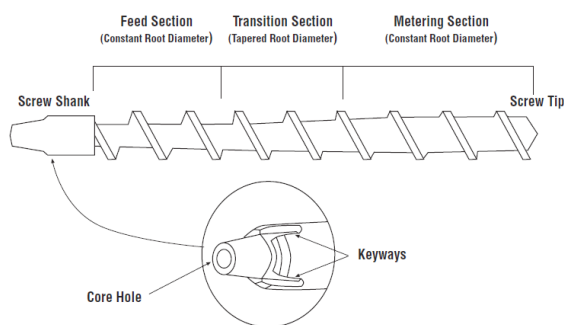


Figure 13. The Basic Extrusion Screw

melt pool then expands until there are no granules left. The generation of uniform melt is promoted because the material flow is not purely axial. The material also rotates with the screw producing rotary flow and melt leaks over the screw flights (Figure 14). The output from an extruder is the result of drag flow minus the sum of the pressure flow plus the leakage flow. Pressure flow, which opposes output, occurs because of the pressure built up at the die and leakage flow reduces output as melt leaks over the screw flight (Figure 15)

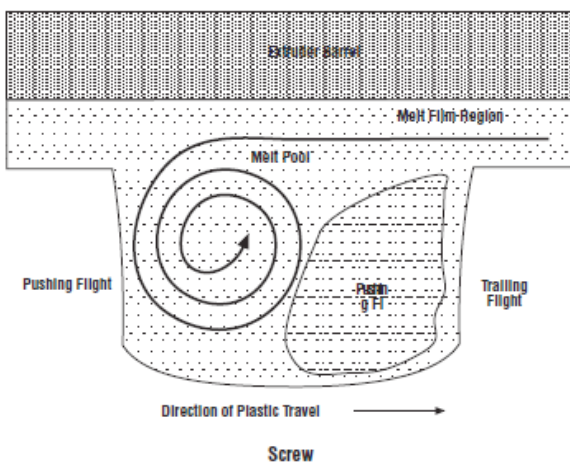


Figure 14. Polymer Melting on the Extrusion Screw

## Length and Diameter

Screws are usually rated in terms of their diameter (D), measured in inches or millimeters. In order to allow rotation there must be a clearance between the screw and the barrel. There is, therefore, a difference in radius between the screw and the barrel. To illustrate, a 100 mm diameter extruder may be fitted with a screw of radius 49.9 mm or, 99.8 mm diameter. The screw clearance is the difference between the radii of the screw and the barrel. To obtain the desired melt properties of uniform high temperature and a stable output the screw length (L) is, generally, relatively long (L is measured from the rear of the hopper to the front of the screw). Screw length is usually expressed as a ratio of its length to the diameter: the L/D ratio. The use of a long screw (an L/D ratio of, say, 28:1) gives a stable output, improves mixing and gives scope for the use of mixing elements.

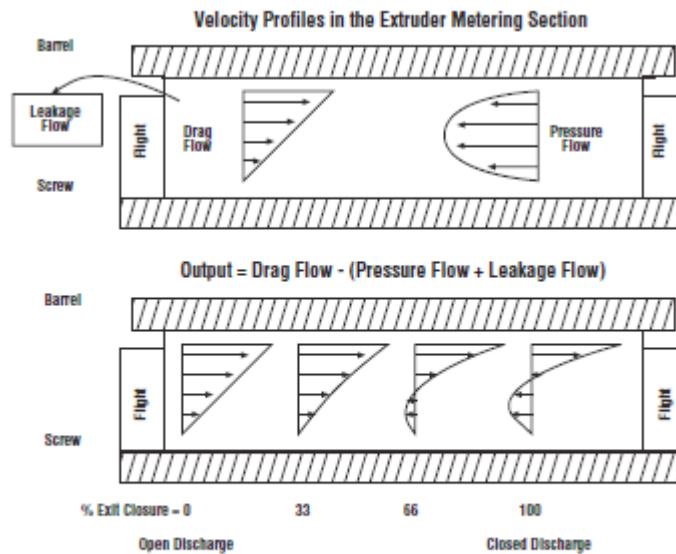


Figure 15. Flow Profiles in the Extruder

## Screw Zones

A screw may be divided into zones or regions. Typically a general-purpose screw has three distinct zones: the feed zone, the compression (plasticating) zone, and the metering (pumping) zone. The feed section, which conveys the material from the hopper, starts at the rear of the hopper and usually has a constant depth. In the transition zone, the root diameter of the screw increases as compression is applied. In the metering section the depth becomes constant again. The feed section, is generally about 50% of the length (50% L), the transition section is about 30% L and the metering section is 20% L.

## Compression Ratio

The ratio of the volume of the flight in the feed zone to that in the metering zone gives the compression ratio. This reduction in volume compensates for the reduction in volume of the feed (solid material + air) which occurs as the plastic melts and fuses together. Compression ratio is related to channel depth

so if the depth is 0.373” at the hopper and 0.125” at the screw tip, then the compression ratio is said to be 3:1. A typical compression ratio is 2.0/1 (or 2.5/1) and the length to diameter ratio (L/D) is about 20:1. The terms used to describe a screw are shown in Figure 16. When a three-zone screw is used to process a material, a large amount of heat may be generated as a result of the compression ratio. To avoid this heat generation, extruders are now being built that have screws with zero compression, that is, the depth of the screw flight is the same along its entire length. Such screws give very little mixing but they do prevent the generation of excessively high melt temperatures (melt temperature override). Mixing can be improved by the use of mixing sections, fluted sections, or mixing elements located near the screw tip. Such screws are widely used in extrusion blow molding where high melt temperatures must be avoided if high production rates are to be achieved.

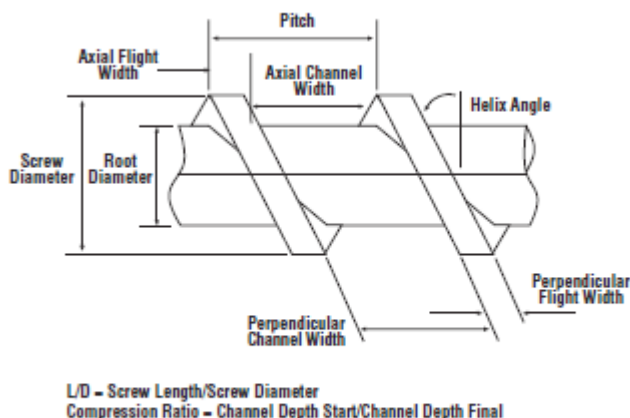


Figure 16. Elements of an Extrusion Screw

### Helix Angle and Volumetric Efficiency

In extrusion, the helix angle ( $\phi$ ) is the angle between the screw thread and the transverse plane of the screw. For most screws the pitch of the screw equals the screw diameter and  $\phi = 17^{\circ}40'$ . The volumetric efficiency of the screw is dependent on the helix angle. If volumetric output rate is designated Q then, the volumetric efficiency of the screw may be expressed as  $Q_{max}/Q_{ideal} = 0.5\cos 2\phi$  (Eqn. 18) Where  $Q_{max}$  is the maximum volumetric output rate,  $Q_{ideal}$  is the ideal volumetric output rate and  $\phi$  is the helix angle of the extrusion screw. The volumetric efficiency depends on the helix angle only and in cases where the pitch equals the screw diameter ( $\phi = 17^{\circ}40'$ ) then the volumetric efficiency is 45.4%.

### Shear Heat

The energy expended in turning the screw and pumping the material forward is turned into heat. Because the material is being sheared, the heat generated is known as shear heat. The shear heat is not spread uniformly throughout the material, but is greatest where the shear rate is the highest. It can be high enough that it can cause localized overheating and material decomposition, or degradation at the tips of the screw flights.

For a given material, the amount of shear heat depends on the screw speed and on the screw diameter. If possible, the machine size should be matched to the anticipated output. It may be possible to achieve the required output with a small diameter machine running fast or with a larger diameter machine running more slowly. It is generally found that the larger machine will produce a melt of significantly lower temperature and higher outputs are achieved. A higher screw/barrel L/D is another answer, as this will give the same throughput as a lower one, but at a lower screw speed.

## SCREW TYPES

Over the years many different types of screws have evolved for the processing of thermoplastics materials (Figure 17). Some are designed to improve mixing whereas others may be designed to suit a particular material or process. With the advent of cheap computing power, and a greater knowledge of the extrusion process, computer design of extrusion screws is now extensively used.

### Tapered and Parallel Extruders (Figure 17.)

A very popular type of extruder contains a tapered parallel screw. A tapered parallel screw has a gradually tapering screw root (the channel depth gradually changes) in the compression zone. The feed zone and the metering zone are parallel and of constant depth. Unlike the double parallel screw, the velocity of the un-melted portion of the melting material bed is maintained and there is less risk of polymer stagnation. The double parallel screw has a “step” that is, a rapid decrease in channel depth (over one screw turn or less), between the parallel feed and metering sections. In the “stepped” screw (a double parallel screw or nylon screw), it is claimed, that the rapid decrease in channel depth acts as a barrier to forward flow of un-melted granules and therefore fixes the melting point at the step.

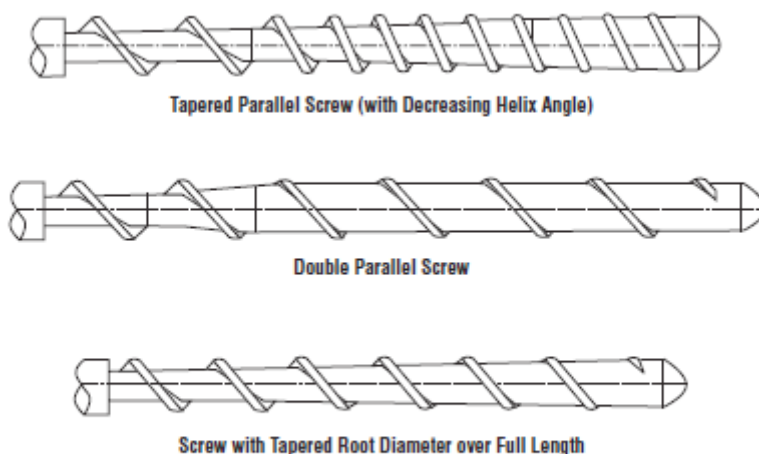


Figure 17. Tapered and Parallel Screws



A tapered screw may be selected for heat sensitive materials (UPVC). This is a screw which has a gradually tapering screw root, that is, the channel depth gradually changes – usually the diameter of the screw root increases steadily from the hopper end to the die end of the extruder so as to gradually compress the material.

### Poor Mixing

A conventional screw does not provide very good mixing. This is because of the way that the material flows, or is transported, along the screw. Since the material towards the center of the flight can easily remain undisturbed, the output from the machine will not be of uniform quality. It will be inhomogeneous as it has a non-uniform shear history (even if nothing else happens, the melt temperature will be non-uniform). Ideally the system should break up agglomerates (provide dispersive mixing) and then produce a random spatial distribution of any dispersed material (provide distributive mixing) (See Screen Packs Section and Mixing Section).

### High L/D Ratio Screws

There is a tendency towards the use of longer extrusion screws with length to diameter ratios (L/D ratio) exceeding 24/1. Such long assemblies are used where high melt flow rates and excellent melt homogeneity are required, since they will produce the same throughput as a shorter screws but, at lower speeds. This is particularly important when high frictional heat generation must be avoided. The use of a longer screw/barrel assembly gives increased operating flexibility, as there is more opportunity for the use of shearing and mixing elements. Some extrusion screws are now as much as 32 D long.

### Screw Cooling

When screw cooling is used, the temperature of part or all of the screw is reduced or maintained, during machine operation, by circulating water from the rear end of the screw through a bore in the center of the screw. Screw cooling is done to resolve feeding problems (to improve operating consistency), to improve mixing and/or to minimize material decomposition. In some cases it may only be necessary to cool the screw in the feed section, while in other cases it may be necessary to bore out the whole length of the screw (almost as far as the screw tip). In the second case, the cooling water freezes a layer of material at the screw tip that effectively increases the compression ratio of the screw. Mixing efficiency is improved, but the output rate goes down and the power consumption goes up. A big disadvantage in both cases is that the actual temperature of the screw is not known. Screw cooling should be turned off before shutdown to minimize material adhering to the screw.

### Dedicated Screw

A dedicated screw is a screw that is designed to suit one type of material, for instance, nylon (PA 66) or polyvinyl chloride (PVC). A general-purpose (GP) screw is designed to suit as wide a range of plastics as possible and is not the ideal answer for the processing of any specific material. For example, a screw designed for a semi-crystalline, thermoplastics material, such as PA 66, must provide a greater heat input than one designed for an amorphous, thermoplastic material. If a machine will be dedicated to

one plastic for a long time, then it is worthwhile considering the purchase of a specially designed, or dedicated, screw.

### Barrier Design Screw

This type of screw (Figure 18.) contains a barrier to hold back un-melted material. The flights of a conventional screw are often filled with a mixture of solid and molten plastic. It is difficult for the screw to grip the solid resin

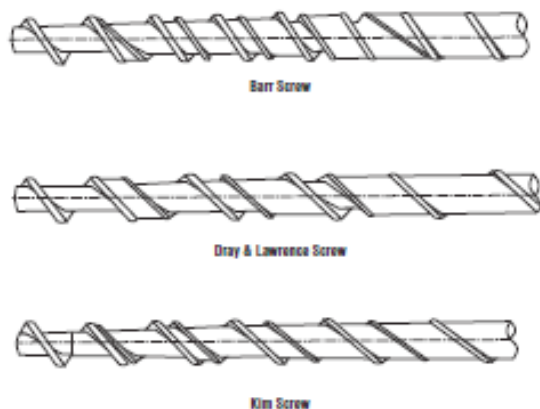


Figure 18. Barrier Design Screws

since it floats or ‘swims’ in a pool of melt. Barrier design screws are used to improve the ability of the machine to produce melt, and to give more uniform melt. The barrier screw has two separate flights that are separated by the flight land. These two separate flights may only run for part of the screw length. For example, it may run for 13 diameters (13 D), in place of the compression zone, on a 24 D screw. As the resin melts it is transferred from one flight to the other over the narrow land. Thus the screw separates the melt pool and solid bed. This produces improved output per rpm and a lowering of melt temperature.

### Zero Compression Screw

A large amount of heat will be generated, when a conventional screw is used to extrude a plastic material, because of the compression ratio on the screw. To avoid this heat generation, machines are now built which have screws where the depth of the screw flight is the same along its entire length (zero compression)(Figure 19). Such screws give very little mixing, but this can be improved by the use of mixing sections located near the screw tip. Such zero compression screws are commonly used with barrels that have longitudinal grooves in the feed section. These grooved barrel assemblies are now considered essential for the processing of high molecular weight PE, and PP, at high throughput rates. These assemblies give consistent outputs even if the diehead resistance alters due to the use of parison programming in blow molding operations. For blow molding machines, such barrels are available in diameters of up to 90 mm (3.5”) with L/Ds of 20/1 or greater (See The Barrel Section).

## Vented Systems

Vented extruders were developed in order to allow gas or vapor to be removed from a molten polymer. In some cases this gas is simply air, but it may also be a vapor given off by the plastics compound (water vapor, residual monomer, or gaseous degradation products). If this vapor is prevented from escaping it will be compressed by the incoming melt and carried to the die,



Figure 19. Zero Compression Screw (Variable Pitch)

where it will expand to produce bubbles in the product. To remove the gas before it reaches the die, the melt is decompressed partway along the extrusion barrel by reducing the screw root diameter partway along its length. A vent or port, through which the gas escapes, is located at this point in the barrel (Figure 20.) (The vent may be plugged when venting is not required). The vapor-free melt is then re-compressed, by increasing the screw root diameter, and conveyed to the die. To ensure that melt does not escape through the vent, a dam or torpedo section may be incorporated on the screw just before the vent

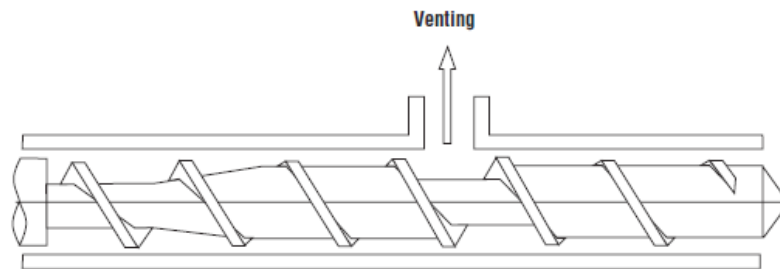


Figure 20. Standard Two Stage Screw for Venting





## Wear Resistant Screws

Screw and barrel assemblies frequently operate in very aggressive environments that can cause severe wear problems. If the clearance between the flight and the barrel increases, then the pumping efficiency of the screw will decrease and temperature differences in the screw channel will increase. Usually the screw is made from a good quality tensile steel such as AISI 4140, which resists torque and distortion, and is oil quenched and tempered or hardened by induction heating. It is easier to replace a screw than a barrel. Thus the barrel must be harder than the screw. The wear resistance of the screw may be improved in various ways. If the screw is deep nitrided to 67 Rockwell C, this will improve wear and give protection against chemical attack. It will also stop plastic from adhering, and then decomposing, on the screw. The screw need not be of the same composition over its entire length, as those parts that are subject to the severest use can be given extra protection. For example, the screw may be constructed from 4140 heat-treated steel and the flights may be surfaced with a wear resistant alloy such as Colmonoy 56. Ion nitrided screws are also used, as are hard chromium plated screws. If the thermoplastic material evolves corrosive gases, as in the case of UPVC, then a stainless steel screw (AISI 316) may be specified.

## Computer Software

Computer simulation software is available, which allows many different designs of screws and changes in operating conditions to be tested quickly, without the high cost of machining and running extrusion trials. Software is available which deals with solids transport, material melting, and melt pumping performance within a single screw extruder: These programs predict the presence of un-melted material and variations of temperature, pressure and energy along the screw. Such predictions can be used for screw design and to determine the effect of changes in material properties, screw speed and barrel temperature profile on the performance of the system.

## SCREW MIXING SECTIONS

Unless the screw in the single screw extruder is fitted with special mixing sections, it is unlikely that it will do a very good job of mixing. It is essential that mixing is done under controlled conditions, as production of uniformly plasticized material, of constant composition, delivered at a constant and controllable rate, is essential.

## Uniform Feed

The extruder must be fed with a uniform feedstock if a uniform product is to be obtained. This means that all of the ingredients must be accurately dispensed and well dispersed throughout the plastic material before the feedstock reaches the screw. For most materials this simply means emptying known weights of material into a conical blender and then adding a color masterbatch. A simple tumbling operation is then performed. This may be done continuously, on the machine, if the output is sufficient. For PVC, high-speed dryblending is usually used and the uniformly blended materials are then fed to the screw of the extruder for melt mixing.



## Poor Melt Mixing

A conventional screw (for example, a three zone screw) does not give very good melt mixing because of the way that the material is transported along the screw. The material in the center of the flight can easily remain undisturbed, while the material at the edges is circulated and repeatedly sheared. This means that the output from the machine will not be of uniform quality, that is, it will be inhomogeneous, as it has a non-uniform shear history. Even if no mixing is required, the melt temperature will be non-uniform and this non-uniformity can cause product distortion and alterations in output due to viscosity variations.

## Cooling and Mixing

The viscosity of plastic materials is higher at lower temperatures. In fact, for some materials, a slight variation in the melt temperature will have a very large effect on the viscosity. If the melt viscosity is low, then agglomerates can escape the mixing action. Improved dispersive mixing is obtained if the melt temperature can be kept low and uniform. This means that barrel cooling must be very efficient and heat transfer must be good: particularly in those regions where dispersive mixing is being performed. A great deal of shear heat is generated in those regions.

## Improving Melt Mixing

A simple way to improve mixing in a single screw extruder is to increase the density of the screen pack by adding fine screens (See the section on Screen Packs). However, the use of mixing sections, offers a more efficient way of improving mixing. Barrier design screws improve the ability of the extruder to produce a more uniform melt, as the screw has two separate flights separated by the flight land. As the resin melts, it is transferred from one flight to the other. That is, the screw separates the melt from the solid bed and produces an improved output per rpm and lower melt temperature. Mixing sections may also use this principle. For example the Egan mixing section uses barrier flights. Longer screws give improved mixing, but, perhaps, more importantly, they give scope for the use of mixing sections.

## Dispersive and Distributive Mixing

Ideally the extrusion system should reduce additive agglomerates such as pigment or impact modifier agglomerates. That is, it should provide dispersive mixing (Figure 21a.). Once the solid agglomerates have been broken up, then uniform distribution (random spatial orientation) of the dispersed additive is required. This is known as distributive mixing. The two mixing processes are not totally separated. When dispersive mixing is performed, there always is some distributive mixing, (Figure 21b.) but the converse is not always true. One could have a uniform distribution of agglomerated pigment particles. If, in a subsequent process, stresses acting on the agglomerates become too high, the agglomerates may break up, producing color streaks.

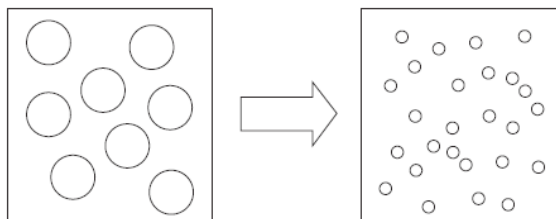


Figure 21a. Dispersive Mixing

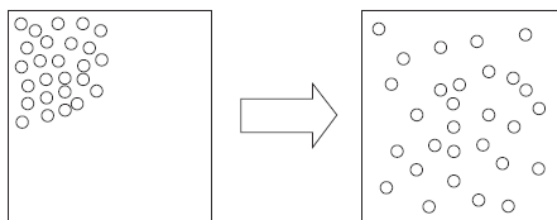


Figure 21b. Distributive Mixing

### Mixing Section Requirements

A system should first provide dispersive mixing and then produce distributive mixing. These two mixing processes may be repeated more than once. Ideally, any mixing section should:

- Not cause a pressure drop and, ideally, should have a positive pumping action.
- Not possess dead spots or material hang-up regions. Flow through the section should be streamlined.
- Completely wipe the barrel surface.
- Be easy to strip, clean and re-assemble.
- Be cheap to purchase, install and maintain.

### Dispersive Mixing Sections

A large number of dispersive mixing sections are now available (Figure 22a.). They may be classified into four main groups (1) shear or blister rings, (2) fluted mixers (such as the Egan, Maddock or Zorro mixing sections), (3) cross barrier mixers (such as the EVK and the straight cross-channel barrier mixing sections) and, (4) planetary-gear (PG) extruder mixers. When judged by the criteria outlined above, the planetary gear extruder (PGE) mixers are probably the best all round single screw machines. The excellent heat transfer obtained, as a result of the large surface areas in contact with the melt, make them well suited for processing heat sensitive materials, such as UPVC. Good distributive and dispersive mixing are obtained. However, it should be possible to obtain slightly better dispersive mixing by the use of relatively simple, fluted mixing sections, such as the Egan, Maddock or Zorro mixing sections,

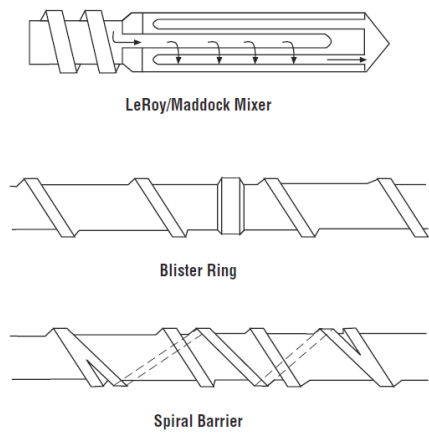


Figure 22a. Dispersive Mixing Sections

## Distributive Mixing Sections

Many distributive mixing sections are now available. They may be classified into four main groups (1) slotted flight mixers, (2) pin mixers, (3) cavity mixers and (4) variable depth mixers (Figure 22b.). If judged by the criteria outlined above, slotted flight mixers are probably the best. The Dulmage mixing section (Dow) is probably the best known. It has several, shallow-angled, multi-flighted sections separated by tangential grooves. The section is formed by machining several flights over approximately 3 D in length and then making three cuts completely across (around) the flights. Because these grooves do not overlap, the barrel surface is not completely wiped by the rotating screw. A Saxton mixing section (DuPont) overcomes this problem by using helical grooves. It gives good distributive mixing with a low pressure drop as the mixing section has some forward conveying action.

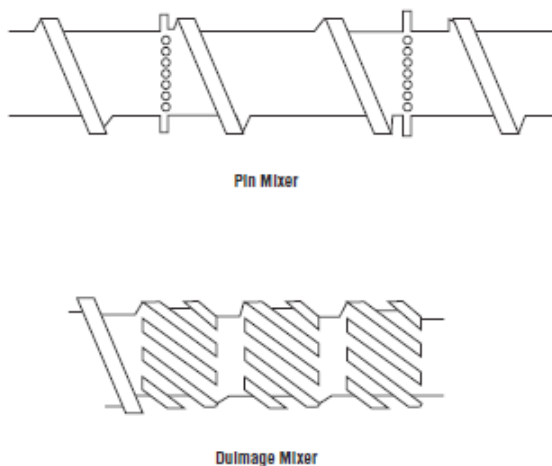


Figure 22b. Distributive Mixing Sections

## Mixing Pins and Sections

Pins, which protrude from the root of the screw into the plastic, are sometimes used to improve mixing, by breaking up laminar flow. The screw may also be fitted with mixing sections or elements. Typically, for a blow molding machine running a high molecular weight PE (HMWPE), the zero compression screw used is lengthened so that a fluted barrier section may be fitted, followed by a section which contains mixing pins. The fluted barrier section (also known as a Maddock mixing section or element) is a cylindrical shearing section, of approximately 2 to 3 D in length, which forms the screw tip. It has inlet passages from which melt can only reach the outlet passages via the land of the mixing section. Thus the melt must pass over a narrow gap before it can escape. This produces dispersive mixing (Figures 22a. & 22b.). However, at high output rates, this type of mixing section often cannot homogenize high molecular weight melts satisfactorily. So, use is also made of a mixing pin section after the Maddock mixing section. This arrangement also allows the melt to become thermally homogenized after it has been sheared. Thus it provides distributive mixing. Other arrangements are possible. For example, two mixing pin sections may sandwich a Maddock mixing section (see Dispersive Mixing Sections).

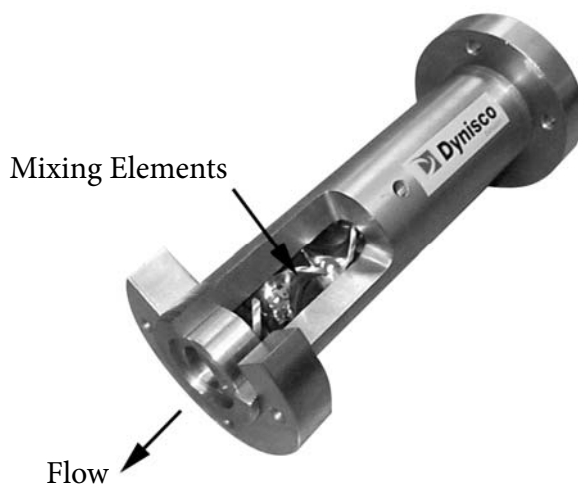


Figure 23. Static Mixer

## Static Mixers

In addition to using the extruder screw to mix the polymer, one can use a “static” or “motionless” mixer (Figure 23.). These mixers typically consist of a number of metal “blades” or “ribbons”, inserted in an adapter pipe between the end of the extruder and the die. As it flows through this section, the extrudate is continuously divided and re-combined by the blades or ribbons to thoroughly mix its components.

## Vented Machines and Mixing

It has been found that vented machines give very good mixing because of the way they are constructed (high L/D ratio and variable screw geometry) and operated.



## Material Changes

During the material handling, shaping and post-extrusion processes there should be little or no change in a plastic material. Any change is usually undesirable. Some of the changes that can occur are:

- Water contamination caused by the material absorbing water or by condensation. This will affect the material flow.
- Volatiles loss when the material is contaminated with volatile materials like water. During melt processing the volatile material (e.g., water) will turn to vapor and on exiting from the die will cause foaming or surface marking.
- Oxidation, that occurs when plastics are heated in contact with oxygen. The first sign of this may be a change in color that will be followed by changes in other properties.
- Degradation or decomposition will occur if plastics are overheated, even if there is no air present. Dangerous gases may be produced.
- Surface property changes such dust contamination can easily cause product rejection. It is easy to generate static electricity on plastics and this attracts dust, or dirt, very quickly.

## Thermal Considerations

The large amounts of heat, carried from the extrusion process by thermoplastics, causes post extrusion heat removal problems. Heat removal is made difficult by the very low thermal conductivity of the thermoplastic material. This means that diffusion of heat from the center of the product to the outside and along the length of a product is slow and difficult. Thus, local temperature variations are extremely difficult to eliminate. Shear heating (induced when the molten material passes through a restricted gap or section, or the long chain polymer molecules create friction as they pass over each other) may cause some areas to become hotter than others. This may alter the flow properties of the material. Different rates of cooling will then occur in different areas of the extrudate. The stresses introduced within the product, as a result of different heat removal rates, may affect its properties.

## BREAKER PLATES, SCREEN PACKS, AND GEAR PUMPS

In order to get good quality melt from an extruder, it is important that the material be uniformly heated/melted and well mixed. Proper melting and mixing require that the correct screw be used and sufficient pressure (or backpressure) in the barrel to obtain mixing and thermal uniformity. Screen packs, supported by a breaker plate, are often used to build up pressure within a conventional machine.

### Breaker Plate

A breaker plate is a disc, or plate, that has a series of uniform holes (approximately 3 mm/0.125") machined through the thickness which are aligned in the flow direction (Figure 24.). As the holes are there to permit the plastic material to flow they should offer minimum restriction. The holes should be polished in the line of flow and the entrances, and exits, should be tapered. The breaker plate fits in the die-end of the barrel and is used to support one or more fine metal screens (the screen pack). These screens remove contamination from the melt and build up pressure within the system, thus improving mixing.

## Screens

A screen may be a metal plate with holes of a specified size and shape or a woven metal sieve with a specified number of holes per unit area. A screen may be classified by mesh number and by open area. The mesh number is used to classify a screen. The higher the mesh-number, the finer the screen and the better the screen pack is at contamination removal. Open area is the percentage of the total area of a screen that is open. It does not change significantly going from a coarse screen (40 mesh) to a fine screen (200 mesh). For example, the open area of a 40 mesh screen may be 38% while that of a 200 mesh screen is 34%. The fine screen, however, will block more quickly. Sintered powder and metal fiber screens have been used for gel removal in polyolefin extrusion and polymer fiber production.

## Screen Pack

Combining more than one screen or gauze makes a screen pack, also called a filter pack. A screen pack may be made from an assembly of a 40 mesh, 60 mesh, 100 mesh, 60 mesh and 40-mesh gauze, that is, 40/60/100/60/40. The finer mesh gauze removes the fine contamination while the coarser mesh materials are there to provide support and to minimize fine mesh blocking.

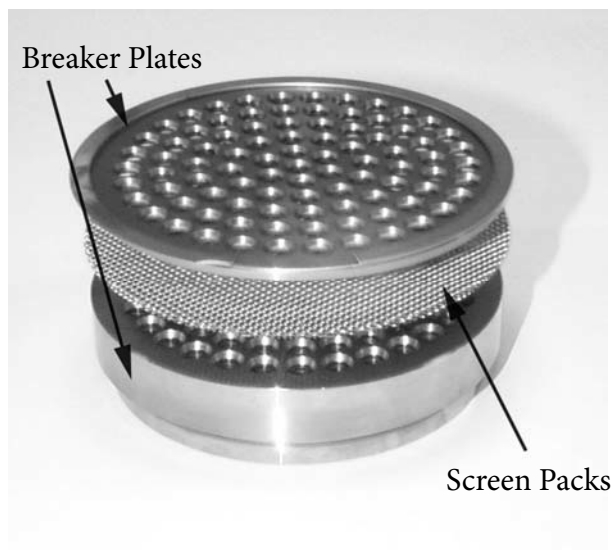


Figure 24. Breaker Plate and Screen Pack

Therefore, a screen pack supported by the breaker plate, is used not only to remove contamination from the melt, but also to build up pressure within a conventional extruder. Two pressure transducers, one on either side of the screen pack, are used to indicate when the screen pack is becoming blocked and needs to be changed. The signals from the transducers may also be used to increase the screw speed to keep the output steady as the screen pack becomes blocked.



## Ready Made Packs

It is possible to buy commercial screen packs with a binding made of a soft metal. This soft metal edge helps the pack to make a good seal in the head assembly and minimizes gauze movement. One should be careful to ensure that the screen pack is used in the correct orientation, that is, with the fine gauze supported by the coarser gauze.

## Screen Changers

In addition to breaker plates, which are built into the extruder barrel or adapter, there are also screen changers, which are devices that allow one to change screens without disassembling the extrusion line. There are three basic types of screen changers (Figure 25.):

1. Manual screen changers
2. Hydraulic screen changers
3. Continuous screen changers

The manual screen changer is the simplest and least costly of the three. It consists of a slide plate with two cavities, each designed to accept a breaker plate with screen packs. The spacing of these cavities is such that one breaker plate will be in line with the extruder flow, while the other is clear of the machine. This allows for the insertion of a clean breaker plate and screen pack combination. When it is time to make a screen change, the extruder pressure is reduced to zero and the operator moves the clean breaker plate/screen pack assembly into the line by moving a handle attached to the side plate. The dirty breaker plate and screen pack are then removed and replaced with clean units for the next change. The hydraulic screen changer consists of a slide-plate with two cavities to accept breaker plates with screen packs. They are spaced so that one is in-line with the extruder flow and the other is in a position clear of the machine, which allows insertion of a clean breaker plate and screen pack. The slide plate is attached to a hydraulic cylinder, which moves it back and forth to remove a clogged screen pack and insert a clean one. The shifting procedure typically takes less than one second and causes only minimal interruption of the extrudate flow. The major advantage of the hydraulic screen changer is that the screen pack can be changed with the extruder running at full speed. However, it may cause an interruption in the finished extrudate due to the introduction of air from the clean breaker plate/screen changer combination. The continuous screen changer is designed to insert clean screens without disturbing the extrudate flow. Of the various designs available, the most common are the dual bolt or dual slide-plate, continuous screen, and the rotary disc. The dual bolt or dual slide-plate design uses two bolts or slideplates that hold the screens. During a screen change, one bolt or slide-plate is removed from the line by diverting the flow through the remaining bolt or slide-plate. Continuous type screen changers use a roll of filter screen that is continuously moved across the flow of melt in the extruder to provide new filtration area. The rotary disc type uses a wheel with multiple breaker plates. This system slowly indexes a clean screen pack into the extrudate flow, while the old, clogged, screen pack is indexed out.



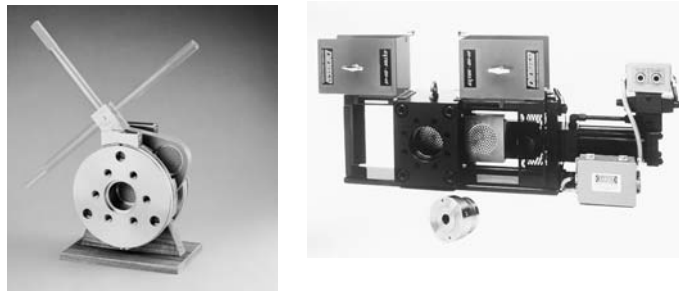


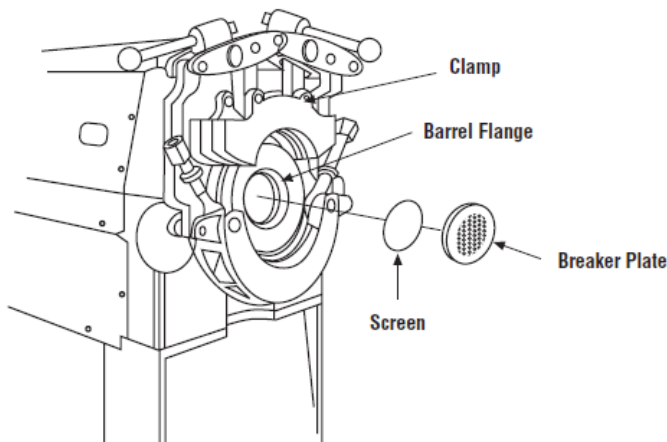
Figure 25. Screen Changers

### Disadvantages of Screen Packs

A simple way to improve mixing in a single screw extruder is to increase the density of the screen pack by using finer screens. However, the improvement in mixing may not justify the loss in output, increases in material residence time and residence time distribution, melt temperatures and the chances of stagnation and degradation. There will also be an increased risk of variability as the screen pack will suffer more chances of becoming blocked as the extrusion run continues. The use of screw mixing sections offers a more efficient way of improving mixing. The use of longer screws gives improved mixing, but perhaps, more importantly, gives more scope for the use of mixing elements.

### The Adapter

The heated adapter holds the breaker plate assembly and directs the melt flow to the extruder die. Streamlined flow must be attained to minimize pressure losses and reduce material stagnation. If cross-head extrusion is being performed, then the adapter must turn the melt through the required angle (for example, 90°). The extruder head is hinged for access so that the screw and the breaker plate can be removed for cleaning when required. When closed, the head must be sealed against the barrel so that material cannot escape, even at maximum extrusion pressure (Figure 26.).

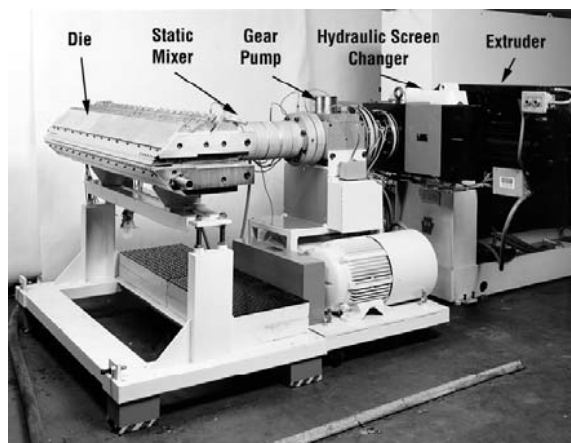


## Rupture Disc

A rupture disc is a hollow, threaded plug with a thin metal diaphragm welded to the plug housing. The diaphragm is exposed to the melt on one side. If the melt pressure exceeds the strength of the diaphragm it will burst and reduce the extrusion pressure by venting material from the machine. Such a plug is generally located between the screw tip and the breaker plate.

## Gear Pumps

A gear pump (See Figure 3.) is frequently installed between the breaker plate or screen pack (or changer) and the die (Figure 27.). Its function is to build pressure and maintain precise flow of material to the die. As mentioned in Section 1 the gear pump is a very simple form of the twin-screw extruder, in which the screws are replaced by intermeshing gears that accurately pump the extrudate. The precise control of pressure and flow, provided by the gear pump, allows one to reduce the gauge variation in the extrudate and to minimize the amount of material required to produce a given product. By building the required die pressure more efficiently, a gear pump will also reduce the load on the extruder, resulting in lower extrudate temperature and increased extruder output.



## SCREW DRIVE SYSTEM

An extruder drive system consists of an electric motor, gearbox, linkage, and thrust bearings. An appropriate power supply is also required. The electric motor (usually a DC motor) is mounted in the base of the machine and is connected via a system of pulleys to a reduction gearbox. This arrangement reduces the (screw) speed and increases the torque. A flexible coupling connects the gearbox to the screw. The backwards thrust generated by the screw in pumping the material through the die is absorbed by a thrust bearing assembly. The total drive system is designed to support the screw in the barrel and to efficiently rotate it at a selected speed.



## AC and DC

The drive motor can be either AC or DC. A common type of AC motor is the cage induction motor that is very popular because it is simple in construction, rugged and has low maintenance requirements. It is recommended for all applications (such as driving hydraulic pumps) where a single speed is acceptable. However, an extruder requires a drive system that gives step-less speed control with minimum speed variation in response to torque requirements. The big advantage of a direct current (DC) motor is that its speed can be readily varied so that the speed can be corrected very quickly if necessary. Such a motor will also run under conditions that would stall an AC motor. However, DC power does not lend itself to efficient transmission and distribution over more than a short distance (couple of hundred yards/meters at most). For this reason electricity is nearly always generated and distributed as alternating current (AC). Electricity is transmitted over long distances at high voltages (V) to take advantage of the lower current (I) needed (as power  $P = VI$ ). This means that smaller diameter wires are needed and power losses are low as  $P = I^2R$  (where  $R =$  resistance). AC voltage can be readily changed, by means of a transformer and may be converted by means of a rectifier into DC.

## DC Motor

A direct current (DC) motor is the most popular type of motor for the modern extruder. The motor speed is regulated by solid state systems based on thyristors. Such a drive may operate on 460 V three phase AC with a fixed field of 300 V, a variable armature of 0 to 500 V, and a base speed of 1750 rpm. As the armature voltage is reduced the speed decrease linearly, while the full load torque capacity is maintained. A plot of power available versus speed produces a straight line through the origin. Thus, a motor speed of 1500 rpm gives a screw speed of 90 rpm while at a motor speed of 500 rpm the screw speed will be 30 rpm. At either speed, the full load torque is maintained. Motors are usually found in a packaged drive (with a solid state, electronic rectifier and a speed controller) ready for connection to an AC supply. The transformer and rectifier are designed as a unit and employ solid state, power devices that can be turned off and on for voltage and current control. Starting speed, running speed and torque can be very closely regulated to give efficient operation and screw protection. This is necessary, as the weakest point in the drive system is the screw because the screw root is thinnest (weakest) in the hopper area and can be snapped by over-loading.

## AC Flux Vector Motor

AC Vector drives are a relatively new method of controlling AC induction motors. The first commercial applications of AC Vector drives only became possible after high speed micro processor electronics were developed. These drives control the field orientation of the induction motor by synthesizing the motor flux current and the torque current, permitting control from full speed to nearly zero shaft speed with full torque. The high speed electronics are necessary because the control scheme requires that the motor be mathematically modeled and updated continuously. As with all variable speed AC drives, Vector controllers vary the frequency to the induction motor to control the speed. Usually, a pulse width modulated (PWM) drive takes the incoming AC line voltage, where a diode bridge converts it to a stable DC supply. This DC voltage is then fed to the inverter section - usually an insulated gate bipolar



transistor (IGBT). The IGBTs regulate the voltage and frequency to the motor and produce a sine like wave output that can vary from 2 to 400hz. The drives are called PWM because the sine wave is actually the sum of a series of pulses that a shaped and timed to “look” like a true seamless sine wave. Two variations of Vector drives have evolved. The first uses a sensor, usually an encoder, to provide phase feedback. This type of Vector drives can provide nearly full torque down to zero shaft speed. The second type of Vector drive is sensor-less (no encoder!) and only recently became possible. This family of Vector drives employs the relatively new high speed digital signal processors (DSP) electronics to permit even faster processing of the complex motor simulation algorithms required for sensor-less control of induction motors. The DSP’s also permit for “on the fly” adjustments to the motor simulations to compensate for changes to the induction motor due to temperature and age. This type of Vector drive requires a minimum signal to maintain control of the motor, thus control down to zero shaft speed is not possible. Control down to very slow shaft speeds, even 2 to 4 Hz, are still attainable though, and because most applications do not require control down to zero shaft speed, the sensor-less vector drives are gaining in popularity. The control accuracy of the vector drives is approaching and in some application surpassing that of DC motor and drives. This fact coupled with the efficiency advantages of AC motors has led to the increased use of AC Vector drives.

## Gearbox

If the motor speed is 1500 rpm and the required screw speed is 90 rpm then a reduction gearbox with a ratio of 16.67:1 is required. Often the exact gearbox ratio required is not available. Then different sized pulleys, connected by a system of belts, are used to make the final adjustments. For example, the speed of the motor may be reduced, at the input to the gearbox, by using a larger pulley on the gearbox shaft and a smaller pulley on the drive shaft. A belt drive provides some safety against sudden overloads, but power losses can be as high as 10%. All belts and pulleys must be guarded. A change of pulleys can be useful if the extruder is used for another application whose power requirements are different. Pulleys whose size can be altered during running (by using expanding pulleys) can provide a non-electrical method for changing screw speed. Because extruder motors deliver approximately constant torque over their entire speed range, the power available increases linearly with speed. For maximum power therefore, the motor should be run at its top rated speed and the power transmission capability of the gearbox must be matched to the maximum motor power. If herringbone style gears are used (usually in a two stage process) the efficiency of the gearbox is high (96 to 98%). The gearbox is connected to the screw through a flexible coupling. The flexible coupling accommodates any slight errors in alignment that exist between the output shaft of the gearbox and the thrust assembly and helps to isolate thrust loads (generated by the screw) from the gearbox. Regular maintenance of the gearbox is essential.

## Screw Support Bearings

The shank of the screw is fitted into a driving sleeve in the bearing housing. Normally a single slotted key is used, but a splined fitting is better at distributing the torque around the shaft. The bearing must support the screw horizontally, so that it does not contact the barrel wall. It must transmit the motor torque to the screw and withstand the considerable thrust loads generated by the screw. For example, a



4 inch (100 mm) diameter extruder will have a back thrust of 28 tons (30.8 tonnes) if the pressure at the end of the screw is 4000 psi (276 bar). Although ball bearings allow high rotation speeds, their load bearing capacity is not as high as roller bearings and so these are employed to withstand the high thrust loads. Programmed lubrication of the screw support bearings is important. Bearings do wear out and damaged bearings will affect the performance of the extruder by producing increased motor current and reduced output (because of increased wear of the screw and barrel). Bearings are sold with a predicted life under prescribed loading conditions.

### Screw Surface Speed and RPM

In extrusion screw speed means screw rotational speed which is usually measured in revolutions per minute (RPM or sec<sup>-1</sup>). However, it is the screw surface speed that determines the amount of shear heat generated. The faster the screw is rotated, the higher is the temperature of the melt (due to the amount of shear being increased). This means that to obtain the same amount of shear, the screw on a larger machine should be rotated more slowly than the screw on a smaller machine. This will keep the shear rate down and prevent localized overheating. The speed of rotation will also differ from material to material. UPVC is limited to a maximum, screw surface speed of 0.25 ms<sup>-1</sup> (15 m/min or, 50 ft/min), whereas with other more shear resistant materials, higher speeds can be employed. To convert from rpm to ms<sup>-1</sup>, multiply the rpm by the screw diameter in mm and then by 0.0000524. Screw Surface Speed = ms<sup>-1</sup> = 0.0000524 [RPM x Ds(mm)] (Eqn. 19)

### MOTOR SIZE AND THRUST BEARING LIFE

The drive system is designed to support the screw in the barrel and to rotate it at a selected speed. Once the speed is set it must remain constant, despite changes in the load on the screw or in the temperature of the drive system. It is very important that the screw speed selected is held constant during operation as it controls the amount of material fed to the die, the shear history of that material, and the melt temperature. The torque supplied must overcome the resistance of the screw to turning, even at low speeds, such as those seen during start-up. It is the torque and speed desired which determine the power requirements of the system.

### Torque and Horsepower

Torque is a measure of rotary force or the turning effort of a motor. It is a product of the length of a lever arm and the force applied to the end of the lever arm that is measured in Newton meters (Nm). In North America, motors are rated in horsepower whereas in Europe, motors are rated in kilowatts (kW). Horsepower (HP or hp) is a unit for measuring the rate of work which is equivalent to 550 ft lbs/s or 0.746 kW. **HP = 6.28 x rpm x torque/33,000 = rpm x torque/5255. (Eqn. 20)** This means that in order to obtain the same HP from a slow speed motor, more torque must be developed. As torque is what produces stress on the mechanical parts of a motor, a slow speed requires a motor that is larger than a high-speed motor. A 1 hp motor running at 1750 rpm is approximately twice the size of a 1 hp motor that runs at 3500 rpm.



## Motor Size

The size of the motor required to drive a screw can be estimated from the experience based “rule of thumb” that approximately 10 lbs/hr of polymer can be extruded per horsepower (HP) on a single screw machine. Some typical power requirements for various sizes of single screw extruders (24/1 L/D ratio) are given below. This assumes a smooth barrel, no vents and an L/D ratio of 24/1. If a grooved barrel or a vent is used, then extra power will be required.

| Diameter |      | Power |      |
|----------|------|-------|------|
| (in.)    | (mm) | (kW)  | (HP) |
| 1.5      | 38   | 12    | 16   |
| 2.5      | 50   | 40    | 50   |
| 3.5      | 90   | 85    | 115  |
| 4.5      | 100  | 130   | 175  |
| 6.0      | 150  | 230   | 310  |
| 8.0      | 200  | 400   | 530  |

The motor must be sized to match the workload and this depends not only upon the diameter of the extruder, but also on the application. For example, with a 6” (150 mm) extruder, the motor power can vary from 160 kW to 280 kW according to what is being processed, as shown below.

|                 | Application | Polymer Output |         | Power |      |
|-----------------|-------------|----------------|---------|-------|------|
|                 |             | (lb/hr)        | (kg/hr) | (kW)  | (HP) |
| Sheet           | PMMA        | 1260           | 573     | 160   | 215  |
| Pipe coating    | HDPE        | 1150           | 523     | 230   | 310  |
| Blown film      | LDPE        | 2000           | 909     | 280   | 375  |
| Multi-filaments | PP          | 1750           | 795     | 280   | 375  |

## Life of a Thrust Bearing

The B10 life of a thrust bearing is the length of time in hours when 10 out of 100 bearings are expected to fail if run continuously under the specified conditions. Many manufacturers quote B10 life assuming that the extruder will run at 100 rpm with a 5000 psi (345 bar) head pressure. If the extruder is run faster or at a higher head pressure, there is a reduction in the expected bearing life. The following tables indicate the B10 multiplying factor for a range of conditions other than the standard conditions. For example, if a ball thrust bearing has a predicted life of 100,000 hours at 100 rpm, then its expected life at a screw speed of 125 rpm and head pressure of 7,000 psi (483 bar) is only 30,000 hours. (0.3 x 100,000). (Note: 100,000 hours is about 12 years of 7 day per week 24 hour per day operation.)



**Multiplying Factor for Thrust Ball Bearings**

| Head Pressure |     | Screw Speed (RPM) |      |      |      |
|---------------|-----|-------------------|------|------|------|
| psi           | bar | 75                | 100  | 125  | 150  |
| 3000          | 207 | 6.45              | 4.84 | 3.87 | 3.23 |
| 4000          | 276 | 2.72              | 2.04 | 1.63 | 1.36 |
| 5000          | 345 | 1.33              | 1.00 | 0.80 | 0.67 |
| 6000          | 414 | 0.80              | 0.60 | 0.48 | 0.40 |
| 7000          | 483 | 0.51              | 0.38 | 0.30 | 0.25 |
| 8000          | 552 | 0.35              | 0.26 | 0.21 | 0.17 |