The Die and Post Extrusion Equipment

DIE DESIGN CRITERIA

The die is the assembly, located at the end of an extruder, which contains an orifice used to shape a plastics melt (Figure 1.). Basically the die is a block of metal containing an internal flow channel that can be divided into three parts:

1. The adapter section that connects with the output channel of the extruder
2. The distribution section that spreads the melt into the correct shape
3. The land, which maintains a constant cross section to the flow channel until it reaches the die exit lips

General Design Criteria

When designing or evaluating dies there are certain general criteria that can be applied. The prime requirement is to produce the correct extrudate shape or cross-section. This often involves producing an extrudate of constant thickness (film, sheet, pipe, cable coating etc.). To do this the die must:

- Provide a uniform flow rate of material through its exit gap
- Maintain a uniform melt temperature over the whole of the exit gap
- Produce melt that has the same shear history for all parts of the exit gap

Failure to meet any one of these criteria may result in poor thickness distribution in the extrudate. Regions of the extrudate that are hotter than the bulk will deform more readily and thus become thinner than average. The viscoelastic nature of molten plastic means that it can “remember” how much it has been deformed. This “memory” is short term (generally, a few seconds at processing temperatures), but the shear history within this time frame may alter the stiffness of the melt and its die swell behavior.

Polymer Degradation

Degradation within the die must be avoided. This requires smooth flow channels without step changes in size. Steps in the flow channel provide places where the melt can hold up for long periods and degrade. Specks of black degraded polymer are then carried into the melt stream and hence to the extrudate. Any leakage into the die that provides a source for air to enter will also cause degradation of the melt. The residence time of the melt in the die also will determine how much degradation will occur. The average time in the die is the ratio of the weight of molten polymer held in the die to the output rate. For example, a 15 inch (380 mm) pipe die holds about 200 lb (91 kg) of molten unplasticized polyvinyl chloride (UPVC). If the output rate is 1100 lb/hr (18.3 Ib/minute or 8.3 kg/min) then the average residence time in the die is 200/18.3 = 10.9 minutes (91/8.3 = 10.9 min). The weight of material in the die can be determined by experiment or by calculation. In the latter case the volume of the die must be calculated and then multiplied by the density of the molten polymer (in the case of PVC, its molten density is about 1020 kg/m3 (1.02 g/cm3) as compared to a solid density of 1400 kg/m3 (1.4 g/cm3) at room temperature). Minimizing the size of the internal die channels thus reduces the possibility of degradation. (Note that the above calculation only gives average residence time in the die. Material in the center of the flow channel travels through the die faster than material next to the walls of the die; this material takes much longer to pass through).

Material Changes

Polymer grade changes are frequently made during production and the time for the changeover depends on how rapidly the composition of the extrudate changes to the new material. The die design affects this rate of change. Dies with short residence times, and no areas where polymer can ‘hangup’, are preferred. Because of the nature of the flow pattern in the die channels, the new material will appear first at the center of the extrudate and the old material will remain the longest in the outer skin layer.

Surface Finish

The surface finish of the extrudate is affected by the die design. For the best surface finish, the land should be reasonably long and the lead in angle to the land should be low (Note: If the lead in angle is too low, the length of the die is increased. This is usually not an advantage). Blocking, or partial blocking, of flow channels by contamination or degraded melt, which leads to the formation of die lines, can occur if the flow channels are too narrow. For this reason the minimum dimension of a channel should usually not be less than 0.03 inch (0.762 mm).

Back Pressure

Back-pressure, from the resistance to flow through the die, is an important consideration. If the pressure needed to force material through the die, at the correct output rate, is too high, it will:

- Tend to stretch and distort die bolts
- Cause leakage from joints
- Increase the power requirements of the extruder possibly causing it to stall
- Increase the working of and amount of shear heat generated in the resin
- Increase wear of the screw and extruder

On the other hand too low a pressure can give:

- Poor thickness distribution
- Weld line effects in the extrudate
- Poor mixing of the material in the extruder

Calculations of the estimated pressure drops in a die are very useful in design and evaluation procedures. A simple method to do this is given in the section Estimation of Pressure Drops in Extrusion Dies.

Die Maintenance

Die maintenance is another important consideration. The ideal die is low in size and weight, made from very few components, easily lifted, disassembled and easily reassembled. Simplicity is a virtue here as well as use of designs that allow the die to be rebuilt in one way only. The use of both conventional and wire electro-discharge techniques enable complex extruder dies to be machined in one or two component assemblies. This prevents problems of leakage during production and damage during disassembly and assembly.

MATERIALS OF DIE CONSTRUCTION

The properties required of a die material are as follows:

- High modulus to prevent the die channels from deforming under pressure or under its own weight
- Toughness and robustness to withstand constant use
- Wear and corrosion resistance to give a long production life.
- Good machinability characteristics so that a high surface finish may be maintained throughout the working life of the die (this is especially important near the die exit. For this reason the die land, or sections of the die lands are made interchangeable).
- High thermal conductivity and low density to provide a uniformity of temperature

Low Carbon Steels (Mild Steel)

Untreated low carbon steels are easily machined, but are far too soft for extrusion dies due to their inability to be through hardened. In their natural soft state the wear characteristics are poor and the die will not last. Processors who need to manufacture simply shaped extrudates at low output rates with relatively low production requirements often use mild steel. A considerable number of prototype dies are made from low carbon steels. To improve its wear resistance and dimensional stability the surface of the steel is frequently ion implanted or titanium nitrided.

Pre-toughened Steels

The main advantage of quenched and tempered, or pre-toughened, steels, is that they can be used to manufacture dies that include intricate shapes. Its inherent hardness is sufficient (42 Rockwell C) to resist deformation during use and, therefore, no subsequent heat treatment is needed. Elimination of this second heat treatment means the die does not need to be re-machined to remove deformation incurred from the first heat treatment process. Therefore, savings in die manufacturing times and costs are realized. If the internal surface of the die requires a higher hardness, then surface treatments such as titanium nitriding, ion implantation, flame hardening and chromium plating are used. Since many dies are manufactured by electro-discharge machining (EDM), care should be taken in selecting the correct type of pre-toughened steel. Sulfur containing types are not recommended when using EDM. The designation given to the pre-toughened steel is AISI P20, or DIN 40 CrMnMo7.

Brass

This material, though poor in wear, is easily machined and does not require heat treatment. It is, therefore, sometimes used to make prototype dies to evaluate their performance, before going to the expense of building the final die. Changes to the flow channels are relatively easy to make and the die will last long enough for trials to be carried out. However, certain polymer melts are attacked by the constituents of brass which initiate degradation of the polymer in the molten state. This causes a reduction in the physical properties of the resultant extrudate. The polymers most reactive with brass are PP, PE and ABS.

Case Hardening Steels

These steels, also called low carbon or mild steels, (with a carbon content of less than 0.2%) are heat treated after the die shapes have been manufactured. The die parts are heated to a temperature of 1,470˚F to 1,650˚F (800˚C to 900˚C) and then quenched. High hardening temperatures and fast quenching give harder steel surfaces, but with a greater dimensional change after hardening. The surface structure of these case hardened steels will differ from the structure in their interior due to different thermal histories. The softer interior is tougher than the hard skin. The hardened skin, depending upon the grade of steel, can reach as high as 62 Rockwell C. For extruder dies, an oil quench bath at about 390˚F (199˚C) gives the most suitable combination of hardness and minimal dimensional change. Carburizing of the steel to increase the carbon content of the surface will produce an increase in surface hardness. The thickness of the hardened skin ranges from 0.008 to 0.0394 inch (0.2 to 1.00 mm). The major drawback to case hardened steel is the change in dimensions upon heat treatment. This is especially problematic for wide sheet or complex profile dies. Modification of the die sometimes requires a further re-hardening operation since the machining operation may remove the hardened skin. Hence the surface hardening and quenching processes must be carried out correctly to give the proper properties to the steel and the required die dimensions.

Nitrided Steels

These materials contain additives such as chromium or molybdenum that form hard nitrides when heated to 1100˚F (600˚C) in an atmosphere of ammonia. Quench cooling is unnecessary and distortion of the die is less likely. Excellent surface finishes can be achieved when using these types of steels.

Corrosion Resistant Steels

For dies used to process polyvinyl chloride (PVC), steels with a content of up to 16% chromium will give excellent corrosion resistance. This type of steel is able to hold temperature during processing (it has a low thermal conductivity), is readily machined to complex shapes and heat treated to relatively high hardness values (54 Rockwell C) while possessing a very high surface finish and minimal dimensional changes. This material is inherently corrosion resistant and hence the production life of a die is often increased three fold when compared to other types of steels. The two corrosion resistant steels that are most commonly used are classified as AISI 414 and AISI 420. AISI 420 steel can contain either 13% or 16% chromium. The higher the amount of chromium the more corrosion resistant the steel becomes. Both types of steel are supplied in a pretoughened condition (similar to the hardness of the P20 type steel). However, the lower the percentage of chromium the higher the hardness value that can be achieved. For PVC dies, the 16% chromium grade is preferred, whereas for general use the 13% grade tends to be selected.

Anodized Aluminum

Anodized aluminum alloy is now used for extrusion dies due to its ability to resist wear, its overall dimensional stability and the fact that it can be polished to a mirror finish. Special grades of anodized aluminum, that need to be machined by the EDM process, have been produced for extruder dies. Such grades now provide the die maker with the opportunity to obtain a high gloss surface finish of the internal flow channels of the die.

Chromium Plating

During the plating of a die, a layer of chromium about of 100 microns in thickness is deposited electrolytically. The electrodes must be shaped for the die to give a uniformly thick layer. The chromium protects against corrosive attack from PVC decomposition products. Re-plating is necessary in time, due to wear and chipping of the chrome laminate; particularly at the entrance edges of the flow channels/die lands. Chrome plating, although still used, has been largely replaced by a process called titanium nitriding (TiN). This is due to the non-stick properties associated with TiN and the use of corrosion resistant steels.

DIE HEATING

The temperature of the die should not be used to control the melt temperature of the polymer, but should present the melt with a channel whose walls are at the same temperature as the molten material (melt). Electrical heating elements, with thermocouples as sensors and PID (three-term) controllers (with cascade feedback control) are used. In some cases, where a glossy finish on the extrudate is required, the die temperature may, in fact, be hotter than the extrudate itself.

Zoning

The die should be divided into as many zones as necessary to maintain the desired temperatures across the die, each having a temperature feed back device and control function. This allows the overall temperature profile of the die to be set globally or individually. Control of the temperature can then be programmed to be global, in zones, or as individual portions (areas) of the die. This provides better temperature control especially during heating of the cold die and during production, particularly when a heating element fails.

Cartridge Heaters

These tubular heaters consist of a nickel chrome resistance element wound onto a magnesium oxide former and contained in a brass or stainless steel outer sheath. The heating element is electrically insulated from the sheath by magnesium oxide powder or paste. Positioning of the heating elements inside of the die gives them protection and places the heat source close to the channel. However, care must be taken not to place the heaters too close to the channel. Apart from mechanical considerations, there is a non-uniform temperature distribution in the immediate vicinity of each element. The temperature, however, becomes more uniform as the distance from the cartridge heater increases. When fitting the heaters into the die, there should be a close fit (maximum gap 0.012 inch (0.3 mm) between the cartridge sheath and the die material. Poor contact gives rise to cold spots next to the gap and hot spots on the other part of the heater, leading to reduced life. To prevent premature failure, the cartridge heater is often covered with a polytetraflouroethylene (PTFE) paste so that all the inherent air gaps are filled with the paste. Tapered outer sheaths are preferred nowadays due to the ease with which a failed cartridge heater can be extracted from the die body.

Band and Plate Heaters

These heaters are clamped onto the outside of the die body and provide a cheaper heating system than internal heaters. Because of their position they are prone to damage and less efficient in the use of power than internal heaters. They should be used with deeply imbedded thermocouples and PID type controllers. When fitting, care must be taken to get good thermal contact between the heater and the surface of the die over the whole area of the heater. Any contamination will lead to a hot spot on the heater and a reduction in heater life. If a number of band heaters are used their clamping bolts should be staggered in position as a neat line will lead to a cold band on the die.

Cast Heaters

Aluminum alloy cast heaters with internal sheathed heating elements can be manufactured to give a close fit to the outside of the die. Though more expensive than band heaters, their life expectancy is considerably greater, they give better temperature uniformity and the heat energy density or watt density, can be higher (up to 50 watts per square inch, or 7.73 watts per square cm).

Sizing of Heating Elements

The selection of the correct power rating for heating elements is very important to ensure that the die heats up to temperature in a reasonable time and that different parts of the die and extrusion system heat up to temperature uniformly. This reduces the risks involved in heating a system when it contains solidified polymer. One method is to calculate the actual power requirements for each individual extrusion die. The weight of metal to be heated by each separately controlled heating zone, is first determined and the target time to reach temperature is selected. The heater power is calculated from knowledge of the specific heat of the steel and the temperature rise required. For example, suppose a die part to be heated weighs 350 Lbs. (159 kilos) and is required to raise its temperature from 70˚F to 400˚F (20˚C to 204˚C) in 30 minutes. To calculate the heater power, multiply the weight by the temperature rise by the specific heat of steel and divide by the time in seconds. The specific heat of steel is 119 Joules (J)/lb/˚F (470 J/kg.K).

Heater Power =
[Wt. x Csp]/ t (sec) = (350 x 330 x 119)/30 x 60 = 7,640 watts (Eqn. 21.)

This calculation ignores any heat losses from the surface of the die. To allow for such losses, a 10 kW heater would be recommended.

FLAT FILM AND SHEET DIES

The main characteristic of these dies is the presence of a manifold that distributes the melt across the width of the die (Figure 28.). Melt flows out from the manifold through a slit channel. These dies are normally made in two halves. In symmetrical dies the flow channel is cut equally from each half of the die. Asymmetric dies have one half with a flat plane surface and the flow channel cut in the other half. Asymmetric dies are cheaper, but exhibit an inferior flow distribution across their surfaces.

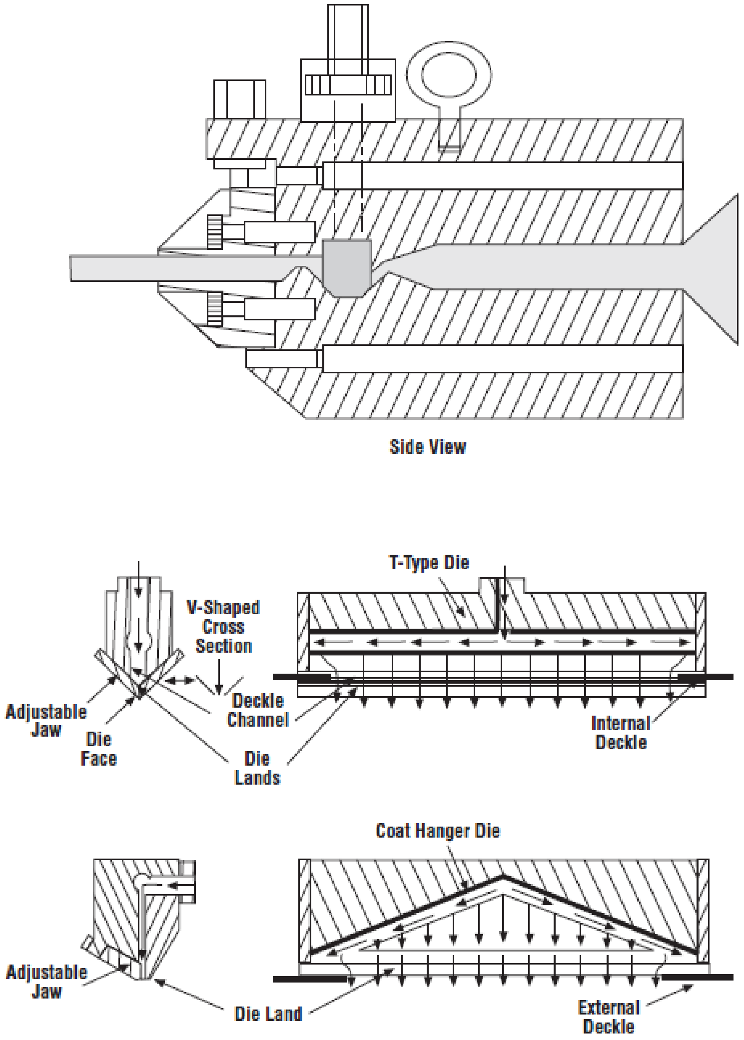


Figure 28. Flat Film and Sheet Dies (“T”, Coathanger)

‘T’ and Fishtail Designs

The simplest manifold is in the ‘T’ die. The melt enters the center of a cylindrical channel, of uniform cross section, which goes from one side of the die to the other. This is the manifold. Its axis is at right angles to the machine direction. The material escapes from the manifold through a slit running the length of the manifold. Because the size of the manifold cross-section is much greater than the slit, the pressure drop along the manifold is very small and there is nearly uniform output from the manifold across the entire width of the die. There are problems with the ‘T’ manifold design resulting from ‘hang-up’ of polymer at the ends of the manifold and a small but finite pressure drop across the manifold. Fishtail designs are better in that the manifold is angled and opens gradually like a fish tail. Though suffering less from polymer ‘hang-up’, fish-tail designs do not give a perfect flow distribution over the die width for a system where the polymer or the production conditions are changing (Figure 28.).

Coat-Hanger Dies

The most satisfactory design is the coat-hanger manifold. It is based on the ‘T’ manifold, but it slopes towards the die exit at the edges of the die, like the shape of a coat-hanger. Usually the slit downstream of the coat-hanger manifold has a constant channel thickness. In a correctly designed coat-hanger die, the flow rate per unit width is constant from the exit of the slit. This means that the flow rate in the manifold should decrease linearly from the center to the edge of the die. The pressure drop between the entrance to the manifold and the end of the slit should be equal for all flow paths. Ideally the shear rates in the manifold should be the same along the whole width of the manifold. Dies designed to fulfill these requirements have a manifold whose radius decreases as the 1/3 power of the distance from the center and a slit whose length in the machine direction varies as the 2/3 power of the distance from the center.

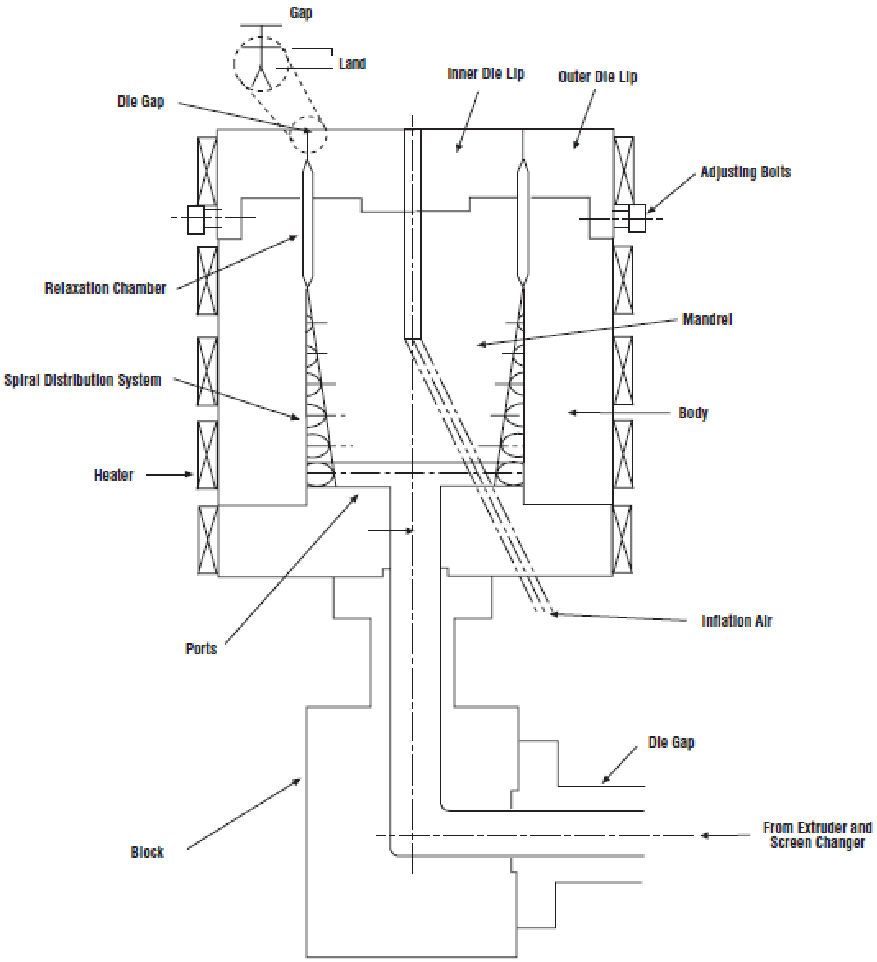
Die Adjustment

Following the manifold, the melt passes under a choker bar. The height of the flow channel under the choker bar can be adjusted by moving the choker bar normal to the flow channel. Tension and compression bolts are provided for this purpose at about 1 inch (25.4 mm) intervals. This gives some adjustment to the overall die resistance and can correct differences between one side of the die and the other. These bolts may be adjusted automatically by means of built in heaters and associated controllers on some machines. The use of heat pipes help to longitudinally distribute the excess heat in the center of the die to the outer edges. Monitoring of this temperature dissipation and using the thermal die resistance control technique can suitably optimize the corresponding output rates across the die length. In the common “Flex-Lip” flat die design, one side of the exit lips is adjustable. There are a number of closely spaced adjusting bolts that can be used to alter the die gap at the exit. Since each part of the extrudate width can be separately adjusted with a bolt, the system allows for a more even exit pressure across the die, and as a result, the production of close tolerance sheeting. The width of an extrudate can be reduced, by up to a third, by blocking the edges of the die exit gap with deckels. How-

However, the use of these deckels creates a dead-space on each side of the die where material will stagnate and eventually degrade. Thus deckeling can only be used with very heat stable polymers at low temperatures. They will also alter the flow balance for the die and so thickness tolerances will be more difficult to maintain.

BLOWN FILM DIES

There are three basic die designs used in the manufacture of blown film. These are the sidefed, bottomfed and spiral mandrel types. All three designs aim to produce a uniform melt around the circumference of the die exit lips. A uniform melt temperature, shear history, and flow rate are required to achieve this. A typical blown film die is shown in Figure 29.



Outer Ring

All three basic die designs can be fitted with an adjustable outer ring that forms the outer boundary of the die exit gap. It can be moved relative to the inner mandrel to correct for variations in the thickness distribution around the circumference of the film (that is, in the transverse direction). However, movement of the outer ring alters the die gap on both sides of the die. So, if the thickness of one side of the die is increased, that on the opposite side will be reduced. The outer ring must be bolted to the body of the die, at the correct torque, to allow movement when the gap is adjusted, while preventing leakage.

Side-Fed Film Dies

The oldest design is the side-fed type. Melt is directed at the side of the mandrel and flows around it before joining on the side opposite the feed. Because of this, there is an inherent difference between the two sides of the die. Careful design of the thickness of the flow channel and the provision of flow restrictors on the feed side of the die will produce a reasonably uniform flow. However, any change in operating conditions, the plastic, or the melt viscosity of the material being used will invalidate the design balance. Hence, the film produced will become non-uniform.

Bottom-Fed Film Dies

A more axially symmetric design is found in the bottom-fed type of die in which the melt is directed at the center of the base of the mandrel. Streamlined spider arms are used to support the mandrel in the die body. The flow of the melt around the spider arms will produce a disturbance in the flow path at each spider arm producing potential flaw in the film. One advantage of the bottom-fed design is that the flow channels in the die have a low total volume. This leads to short residence times and the design is used extensively for manufacturing soft PVC films and other easily degraded polymers.

Spiral Mandrel Film Dies

The most common blown film die design is the spiral mandrel type. The melt stream is divided into four or more equal flows, each of which passes through its own port at the base of the mandrel. Each port connects with a flow channel cut into the mandrel that takes the melt in a spiral path up the outer surface of the mandrel. The depth of the spiral channel decreases as it spirals up the mandrel, while, at the same time, the gap between the mandrel and the outer die body increases. This design geometry aims to allow plastic melt from a port to flow increasingly upwards in the gap between the mandrel and outer die body as the melt moves away from the port. In a correctly designed die, the rate of flow in the spiral channel decreases uniformly to give an even transfer of flow to the upward direction. Melt from each port is spread evenly over about three-quarters of the die circumference. Since there are a number of ports, typically six or eight in the best dies, the combined flows give a very even output around the circumference of the die exit gap.

Blown Film Die Land Design

The are a number of factors to be considered in the design of the land section of a blown film die.

- Sufficient back-pressure must be generated to ensure good performance of the die distribution section
- The film must be drawn down to its final thickness after it has left the die
- The wider the die land the greater the necessary draw-down
- The die gap must be large enough to prevent blockage by any contaminants in the melt
- It is necessary to operate in the land area at a melt shear stress below that at which melt fracture will occur.

Widening the land gap will reduce the shear stress in the land. Increasing melt temperature or reducing output has the same effect. The critical stress above which melt fracture occurs depends on the plastic material. For LDPE a die gap between 0.03 and 0.04 inch (0.762 to 1.016 mm) has proved successful even at output rates up to 20 lb./hour/inch (3.6 kg/hour/cm) of circumference. The length of the land is usually 10 to 15 times its gap width. With this design, the draw down in the machine direction is about 12 for a 100 gauge (40 micron) film at a blow up ratio of 2.

LLDPE Land Design

The melt rheology of LLDPE leads to a different blown film die land design. Because LLDPE is more Newtonian than LDPE the shear stresses found in the die at high shear rates are higher than those seen for LDPE. It has been found that above a critical land shear stress of 15 psi. (1 bar), melt fracture will occur and give rise to a rough appearance in the film. The source of this melt fracture is thought to originate from slip at the walls of the land. There are at least three ways of reducing the melt fracture tendency and hence increasing possible output rates for LLDPE films. The die gap is increased to reduce the shear stress. The minimum gap required for a range of melt temperatures and outputs is shown in the following table:

Output Rate	**200˚C/392˚F**		**220˚C/428˚F**		**250˚C/482˚F**	
	(in.)	**(mm)**	**(in.)**	**(mm)**	**(in.)**	**(mm)**
5.6 lb/hr/in.	0.104	2.64	0.086	2.18	0.089	2.26
11.2 lb/hr/in.	0.152	3.86	0.122	3.10	0.099	2.51
22.4 lb/hr/in.	0.213	5.14	0.170	4.32	0.134	3.40

If the die design is such that high pressure drops over the land are needed to ensure the correct functioning of the distribution section, then the land is restricted in width upstream of the exit and opened out to the above figures immediately before the exit. The material of the walls of the die land is chosen to minimize the slip that produces melt fracture. It has been found that alphabrass once ‘run in’ allows higher output without melt fracture. The running in period is to allow wear to modify the surface of the land. Additives, such as fluor-elatomers, can be incorporated into the polymer. These ‘anti-melt fracture’ materials are deposited on the die surface and reduce melt fracture. Unless they are replenished their effectiveness diminishes. Grades of LLDPE are available with these types of additive included. Alternatively, master-batches with a high concentration of the additives may be blended with the virgin resin in the extruder hopper or used from time to time, in concentrated form, to replenish any coating that has worn away.

PIPE DIES

Standard pipe dies are made for pipes with diameters from 0.5 to 30 in. (12.7 to 762 mm). Most of these dies feed the melt to the base of a mandrel from which it spreads out, around the mandrel (Figure 30.). The mandrel is supported in position by up to 24 spider arms. These supports are streamlined to give the least disturbance to flow. Nevertheless, the melt must rejoin after the spiders. To assist fusion and prevent weld lines in the pipe, the channel cross section is reduced in the next section. There is a reduction in both diameter and channel width. In the final land section of the die (in all except the largest dies) there is an outer ring, which is adjustable relative to the mandrel, to correct for variations in pipe wall thickness. The length of the land varies from 10 to 30 times the pipe wall thickness. Dies for polyolefins tend to be longer between the spider section and the land. They are often designed with zones to compress and decompress the melt before it enters the land.

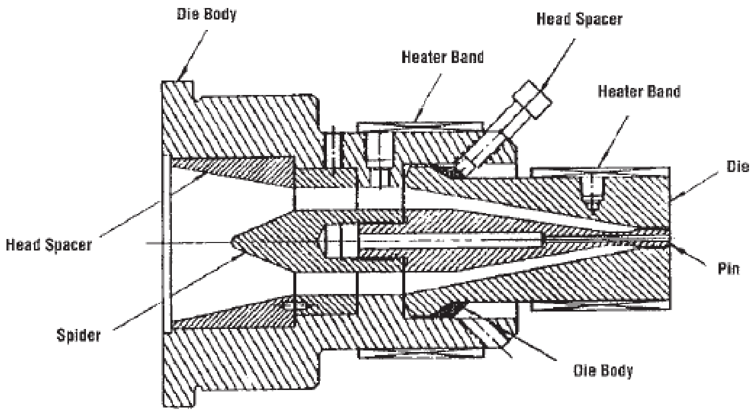


Figure 30. Pipe Die

Sizing of Spider Arms

The spider arms must be strong enough to withstand the shearing forces exerted by the high pressures upstream of the mandrel. For example, if the die mandrel has a diameter of 12 inches (304.8 mm) at the die exit and the pressure at the entrance to the die is 4000 psi (276 bar): The total load on the mandrel = 4000 x π x 62 in. = 452,448 Lbs. (276 x π x 15.242 = 201,412 kg). If there are eight spider arms, the shear force experienced by each arm is 56,500 lbs. (25,496 kg). Assuming that the maximum shear stress that should be applied to the steel spiders is 60,000 psi (4,138 bar), then the cross section of each spider must be about 1 in2 (6.45 cm2). Increasing the number of spider arms obviously allows for the reduction of the size of each individual arm.

Alternatives to Spider Arms

A number of alternatives to spider arms have been tried and used successfully in dies for polyolefins. They include a screen pack die in which the mandrel is supported by a metal screen containing many small holes through which the polymer melt passes. The holes are about 0.02 to 0.04 inches (0.5 to 1.0 mm) in diameter and spaced 0.05 to 0.07 inches (1.25 to 1.78 mm) apart. The screen is cylindrical in shape and fits onto the back of the mandrel. The dies are more compact than spider arm designs as there is no need for a large compression after the spider section. They have been used mainly for large diameter polyolefin pipes. Spiral mandrels, similar to those used in blown film dies, have also been successful.

Die Size Range

By using adapters and replaceable components, the rear section of a die, which includes the spider support, can be used to produce a range of pipes of differing diameter and wall thickness. This approach is obviously cheaper than buying a complete new die for each size. In the case of polyolefin production, the following table shows how four basic dies can cover a range of pipes of 0.4 in. to 28 in. (10 to 700 mm) in outside diameter.

Die	**Pipe Diameter**		**Wall Thickness**		**Max. Output**	
	(in.)	**(mm)**	**(in.)**	**(mm)**	**(lb/hr)**	**(kg/hr)**
1	0.4-2.5	10-63.5	0.08-0.15	2-3.8	450	203
2	0.8-6.3	20-160	0.08-0.25	2-6.4	1,000	451
3	3.5-16	89-406	0.10-1.1	2.5-27.9	1,300	587
4	9.0-28	229-711	0.35-1.4	8.9-35.6	2,000	903

Multiple Outlets

Dies can be purchased with more than one exit, so two or more pipes can be manufactured simultaneously. For PVC dies with two outlets are used, while for polyolefins triple heads are available. These dies make more use of the capacity of an extruder in situations where small diameter pipe has to be produced on an extrusion line generally used for large diameters.

Automatic Centering

To control the pipe dimensions automatically, the pipe wall thickness must be continuously monitored. This is usually done by means of an ultrasonic measurement in, or just after, the cooling bath. A water layer between the pipe and the ultrasound probe is required for accurate measurements. Changing the haul-off speed can reduce departures from the targeted average pipe wall thickness. Departures from wall thickness uniformity, around the circumference of the pipe, require adjustments to the die. Two methods that have been used are a thermal method and one based on motorized rings. In the thermal design, the heating of the land section of the die is split into 8 to 12 zones around its periphery. These zones are thermally separated by air gaps. The temperature of each zone is separately controlled in the range from 355˚F to 390˚F (180˚C to 199˚C) to adjust the pipe thickness distribution. In the alternative method, the pipe ring is positioned relative to the mandrel by means of slightly eccentric rings. Rotation of these rings shifts and alters the die gap distribution. By driving the rings through a gearing system, any departures from wall thickness uniformity can be reduced by automatic adjustment of the die gap.

WIRE AND CABLE COVERING DIES

Wire and cable covering dies are crosshead type coating dies, in which the melt enters from the side. The melt is then wrapped around a mandrel through the center of which the conductor is fed (Figure 31.).

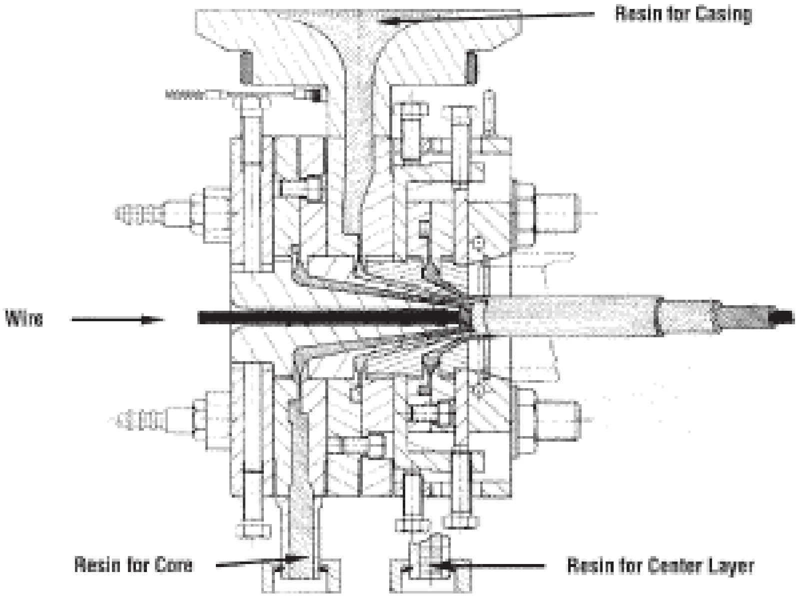


Figure 31. Multi-Layer Wire and Cable Die

Pressure and Tubing Dies

In a pressure coating die the melt and conductor are brought together inside the die. The conductor travels through the die land with the melt surrounding it. To prevent back leakage, the gap between conductor and mandrel is no greater than 0.002 inch. (0.05 mm). With line speeds up to 4,000 ft/min (1,219 m/min), wear of the mandrel is likely and special hardened inserts are used where the mandrel contacts the conductor. For larger conductors and cable coating, it is not possible to prevent back leakage of melt if it joins the conductor under pressure. Therefore, these act as tubing type dies in which the melt emerges from the die as a concentric tube around the conductor, as it emerges from the center of the mandrel. Vacuum is applied to the rear of the die and as the extrudate is pulled away from the die, the coating is drawn onto the conductor. Land lengths in coating dies are usually 0.2 to 2 coating diameters in the case of plasticized PVC and 2 to 5 diameters in the case of polyethylene (PE).

Distribution System in Coating Dies

These side-fed dies usually have a heart-shaped compensating plate in the side of the die where the melt enters that prevents the melt from going straight towards the die exit. The melt has to flow around the plate which converts a single feed into twin feeds from opposite sides of the die. The design of these plates has been largely by trial and error. Computer modeling of the flow passages around the mandrel is now common practice. The depth of the flow channel, throughput of material and the resultant shear rate and shear stress values are readily determined for a particular polymer and coating thickness. Such computer aided engineering (CAE) software packages have now replaced experience and intuition in the design of coating dies. In small dies, the melt can be split into two flow channels. The melt then flows around the die (through 90˚) to converge from opposite sides; each stream onto its own heart shaped compensating plate. Another system uses a manifold similar to that found in flat sheet dies. In the wire coating case the manifold is wrapped round the mandrel.

Pipe and Hose Coating

Circular cross-section substrates, such as steel piping or fabric fire hoses, can be coated with plastic melt using dies whose design principles are similar to those discussed above. The distributor can be a side-fed, heart-shaped compensator. Spiral mandrel designs have also been used for larger diameters.

PROFILE DIES

This is the name given to the dies used for the production of extrudates with complex and often non-symmetrical crosssections. Because of the lack of symmetry, obtaining the correct crosssection can be difficult.

Differential Flow Resistance

Variations in flow resistance in a die cross-section can result in different flow velocities in different parts of the extrudate. This will cause the extrudate to bend as it leaves the die. The flow velocity can be equalized over the profile by the use of a variable land length over the profile or by the use of restricting plates in the flow channel, where there is a tendency for too rapid a flow. Differential die swell can also distort the extrudate. Die swell is directly related to the shear stress in the land. As the shear stress increases, so does the die swell. These complicating factors have made the design of profile dies a skill based on experience and trial and error, rather than on an exact engineering methodology. The use of CAE, however, has enabled the processor to design complex profile dies with consistent accuracy.

Sectioned Dies

Many profile dies are split into sections. The die is sliced in a direction perpendicular to its major axis. It is then possible to change sections to produce slightly different profiles or to alter sections in the process of die development. In designing a sectioned profile die, it should be remembered that the flow channel should change size gradually and that supporting struts (spider arms) should be streamlined.

COOLING

Commercial plastics are poor conductors of heat. In addition, they have high specific heats and frequently have poor thermal stability. This means that they will resist absorbing thermal energy and once it is absorbed they will resist giving it up. And prolonged exposure to this absorbed heat may cause degradation. In addition, heat must be removed from a formed thermoplastic in order for the part to retain its shape. Because of the poor heat transfer properties of thermoplastics, the heat removal step may control the rate of production. In general, semi-crystalline polymers require more heat to raise them to their processing temperatures than amorphous resins. This extra heat, which is required to melt the polymer crystals, must also be removed when the part is cooled.

Extrudate Cooling

The heat contained in a molten extrudate is either lost to the surrounding air or to the cooling system/ haul-off. Polymer extrudates are most commonly cooled by air or water. It is best to cool all sides of the product, however, this may not always be feasible. It may be necessary, especially for thick extrudates, to cool different parts at different rates. This is especially true for semicrystalline or filled materials that may distort if cooled unevenly. The aim should be to cool the extrudate as quickly as possible while ensuring that defects such as poor surface appearance, changes in physical properties, etc., are avoided. For example, with thick walled products, hot water may be used initially to prevent the outside of the extrudate from cooling too quickly.

Heat Calculations

The amount of heat contained in a polymer melt can be calculated if the output rate, the specific heat of the polymer, and the melt temperature are known. From the output rate we can obtain the mass/ time and calculate the heat content or enthalpy from:

Heat Content = (Mass)Polymer X (Specific Heat)Polymer X [(Melt Temp)Polymer – (Final Temp)] (Eqn.18)

The heat contents calculated for several polymers, using a typical processing temperature for the melt and 20˚C (68˚F) as the final temperature, are shown in Table 15 (the differences between amorphous and semi-crys-talline should be noted). Since the specific heat changes with temperature the average value, over the temperature range, is used (specific heat has units of cal/g˚C, J/Kg˚K, or Btu/lb˚F). If the heat losses to the surrounding can be estimated, the heat content can then be used to calculate the amount of water required to cool the polymer extrudate.

TABLE 15.
Heat Contents of Some Thermoplastic Materials

Material Abbrev.	Temperature Melt/Mold		Difference	Specific Heat	Heat to be Removed
	(˚C)	(˚C)	(˚C)	(Jkg-1K-1)	(Jg-1)

TABLE 15.
Heat Contents of Some Thermoplastic Materials

Material Abbrev.	Temperature Melt/Mold (˚C)	(˚C)	Difference (˚C)	Specific Heat (Jkg-1K-1)	Heat to be Removed (Jg-1)
FEP	350	200	150	1600	240
PES	360	150	210	1150	242
CA	210	50	160	1700	272
CAB	210	50	160	1700	272
CP	210	50	160	1700	272
PEEK	370	165	205	1340	275
PET	240	60	180	1570	283
PETP(C)	275	135	140	2180	305
PEEL	220	50	170	1800	306
POM	205	90	115	3000	345
SAN	240	60	180	1968	354
BDS	220	35	185	1968	364
PC	300	90	210	1750	368
ABS	240	60	180	2050	369
PMMA	260	60	200	1900	380
PPS	320	135	185	2080	385
PS	220	20	200	1970	394
ASA/AAS	260	60	200	2010	402
HIPS	240	20	220	1970	433
PPO	280	80	200	2120	434
PSU	360	100	260	1675	436
PETP(A)	265	20	245	1970	483
PA 11/12	260	60	200	2440	488
PA 6	250	80	170	3060	520
LDPE	210	30	180	3180	572
PA 66	280	80	200	3075	615
PP	260	20	240	2790	670
HDPE	240	20	220	3640	801

(Where (A) is amorphous and (C) is crystalline)

EXTRUDATE TAKE UP

The extrudate must be pulled from the die and converted to a suitable form for removal from the extrusion line, packaging, and subsequent sale. If the extrudate is flexible, it is commonly collected on a reel or cut to length and stacked.

Nip Haul-Off

For film and sheet, haul off is provided by a pair of nip rolls which grip the extrudate across its width. For a constant rate of extrusion, the rate at which the extrudate is drawn through the haul off determines its average thickness. This means that the nip rolls must be driven at a controllable constant speed and with no slippage of the extrudate. It is common to have one polished steel roll and the other rubber coated. The hardness of the rubber roll should be checked periodically as it may degrade with exposure to the atmosphere. It is important that haul off rolls and other rolls in the take up system are all parallel to each other and parallel to the die face. It is easiest to make all rolls horizontal as this can be checked with a spirit level. In the case of blown film, the center of the nip rolls should be above the center of the die and should be checked with a plumb line. To assure that sets of rolls are parallel to each other, check that the distance between them is the same on both edges of the roll using measuring rods with a micrometer, or vernier adjustment.

Caterpillar Haul-Off

For pipes and some profiles, where the extrudate is rigid, a caterpillar haul-off is the most suitable. The simplest type consists of two rubber belts that rotate, one above the other, and grip the extrudate between a long parallel section of the two belts. Since the pulling forces can be quite high, the length of the caterpillar track should be sufficient to generate the pulling force without marking the extrudate. More than two tracks can be used in a single haul-off. Some manufacturers offer systems with up to 12 caterpillar tracks. The tracks are driven with a DC geared motor with a tachometer generator and thyristor control. The soft elements of the caterpillar are generally a shallow V-shaped in order to grip the extrudate. The following table shows typical properties for a range of caterpillar haul-offs.

Pipe Diameter (in.)	**Speed Range (mm)**	**(ft/min)**	**Max. Pulling Force (m/min)**	**(tons)**	**Gripping Length (in.)**	**(cm.)**
0.5-3.5	12.7-43.8	4-100	1.2-30.5	0.4	30	76
1.25-12	31.8-305	2.5-50	0.76-15.25	1.0	48	122
2.5-12	63.5-305	2-40	0.6-12.19	1.5	48	122
3.5-16	89-406	1.3-25	0.4-76.2	2.0	60	152
3.5-25	89-635	0.3-20	0.1-63.5	2.5	60	152

Other Haul-Off Systems

Belt drives can be used for small bore pipe and tubing above about 100 ft/min (30.48 m/min) where the caterpillar system becomes unsuitable. For wire and cable, the coated wire is looped round a capstan drum whose speed is maintained to provide the haul-off.

Reel Production

There are two basic types of reeling systems; center fed, in which the wind up is driven by its central shaft and surface winding, where the rotation is generated by friction at the surface of the reel being formed. A surface winder is generally cheaper than a center winding system.

Defects in Reel Production

Problems become apparent in the inner layers of a reel as it grows. The two most common problems are telescoping and buckling. Both are due to compression of the inner layers by the outside layers. Compression decreases the diameter of the inner layers and the tension in them. If the tension becomes negative, then buckling occurs producing a characteristic star shaped mark on the end of the reel. The loss of tension also reduces the friction between the layers and, if the reel is turned on its end, the layers will slip over each other to telescope the reel. Using larger cores reduces both of these problems as does reducing the tension in the extrudate as the reel diameter increases. Surface winding would be expected to give winding under constant tension. However, if there is slippage between the layer of film on the lay on roll and the top layer on the reel, the maximum tension will be set by friction and not by the line tension. As the reel grows and its weight increases, this maximum tension will increase, leading to a winding tension pattern which is the reverse of what is required. Mounting the growing reel on a curved support, so that the force between reel and lay on the roll remains constant, even as the reel grows, reduces this adverse effect. In center winding it is easy to wind under constant torque. Since the torque is the product of film tension and roll radius, as the radius increases the film tension decreases and so buckling and telescoping are less common. However, there is a tendency for outer layers to be loose. Various programmed winding systems are available to give a winding loading between constant tension and constant torque.

CUTTING AND STACKING

In sheet production the extrudate is cut across its width using circular saws or shears. For right-angled smooth cuts, it is essential to select the correct saw speed and blade for the polymer used and the thickness of the sheet. After cutting, the sheet is lifted by suction cups and stacked. In profile, cutting saws can be either under floor saws, where the cut goes underneath to the top, or immersion saws, that operate in the reverse direction. Small diameter pipes can be cut (up to a wall thickness of 0.75 in. (19 mm) for polyolefin pipes and 0.215 in. (5.5 mm) for UPVC pipes). Large diameter pipes are sawn with a planetary saw. Machinery is also available for chamfering the ends of pipes. Re-heating the ends of the pipe to soften them and then forming them over a correctly shaped mandrel, bells the pipe ends. The operation takes place on a moving system so that continuous line production is not interrupted. Usually the pipe is transferred from the cutting and heating station to an adjacent position for the forming and re-solidification of the belled end. Saws should be equipped with protective guards and extraction equipment to remove both dust and chips.