# PIPE EXTRUSION PROCESS

## Principle

1. Extruder pumps the molten polymer through an annular die.
2. The tube of the molten material is then pulled into a calibration unit where the extrudate dimensions are finalized and the melt is cooled.
3. Finally the puller draws the cooled product into the wind-up or stacking unit.

## Components of a pipe extrusion line

1. Extruder
2. Annular die
    1. Inline
    2. Cross head die
3. Calibration system
4. Cooling system
5. Puller
6. Wind-up or stacking unit

## Pipe extrusion line

1. Extruder L/D ratio – 24:1 or greater
2. The screw design depends on the material
3. Conical twin screw extruder is used for PVC
4. Diameter of annular die is 25 to 100% of extruder diameter
5. O/P of the extruder depends ability of the downstream equipment to cool the product and hold tolerance
6. Since PVC is the predominant material used in pipe manufacturing, spider-arm die are the predominant design

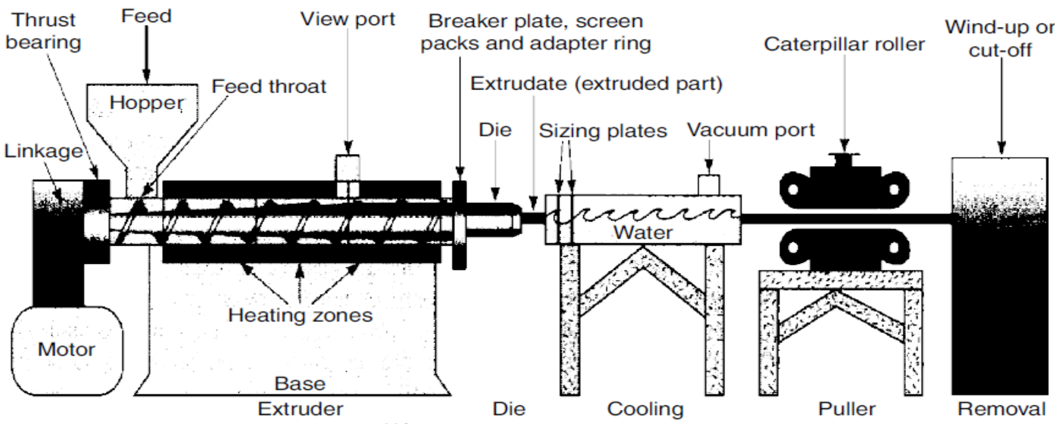



**Figure 5.48** Pipe extrusion line.[110]

**Pipe extrusion dies**

1. Dies for polyolefins have a longer distance between spider and land section to permit compression and decompression of the melt before it reached the land.
2. Other dies are
    1. Axial dies
        1. spider arm – PVC pipes
        2. screen pack – large diameter polyolefins pipe
        3. spiral flow – choice for all pipes, except PVC
        4. helicoids designs - tubing
    2. Side-fed or cross – head designs – catheters and tubing (they can coat over other materials)

**Final dimension control – Calibrators**

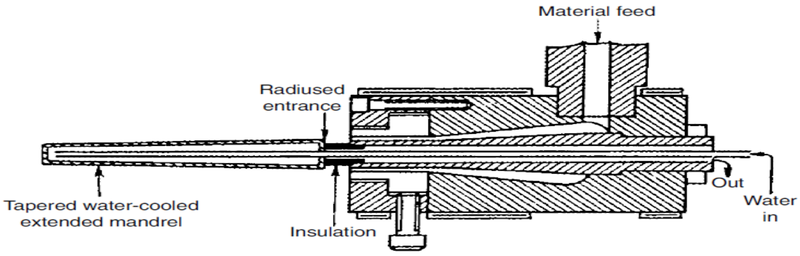
1. The extrusion die is often followed by a sizing die, where the actual dimensions of the pipe are primarily determined.
2. Such a device is generally referred to as a calibrator.
3. Calibrators are required if the extrudate emerging from the die has insufficient melt strength to maintain the required shape.
4. The calibrator is in close contact with the polymer melt and cools the extrudate.
5. When the extrudate leaves the calibrator, it has sufficient strength to be pulled through a haul-off device such as a catapuller without significant deformation of the extruded product.

**4 calibration systems**

1. Free forming
2. Extended water cooled mandrels
3. Vacuum calibration
4. Pressure calibration

1. Free formed
    a. Final dimensions are determined by pull-off rate
    b. Suitable only for high viscosity, high melt-strength materials (plasticized PVC garden hose and laboratory tubings)
2. Extended water cooled mandrel
    a. The diameter of the mandrel fixes the internal diameter of the pipe or tubing.
    b. Mandrel tapered to compensate for shrinkage of the plastic

c. Pope thickness is controlled by the die gap and pull-off rate
d. This system is difficult to control, it is used in the products where ID is critical.




3. Vacuum calibration system
    1. Vacuum is applied to ensure good contact between the calibrator and the extrudate and to prevent collapse of the extrudate.
    2. The use of a vacuum calibrator is generally easier than the use of positive air pressure within the extrudate because a vacuum is easier to maintain at a constant level.
    3. Positive internal air pressure tends to vary with the length of the extrudate and it is difficult to maintain when the extrudate has to be cut into discrete lengths.
    4. Calibration rings in the water bath establish the outside diameter of the pipe, while puller speed and die gap determine the wall thickness

Calibrators are useful when good, accurate shape control is important. When the requirements for shape control are less stringent, the extrudate shape is often maintained by support brackets placed downstream of the extrusion die. In fact, the extrudate shape can be modified substantially by the support brackets. This can be useful because it allows modification of the shape of the extrudate without changing the die, but only by changing the shape of the support brackets.

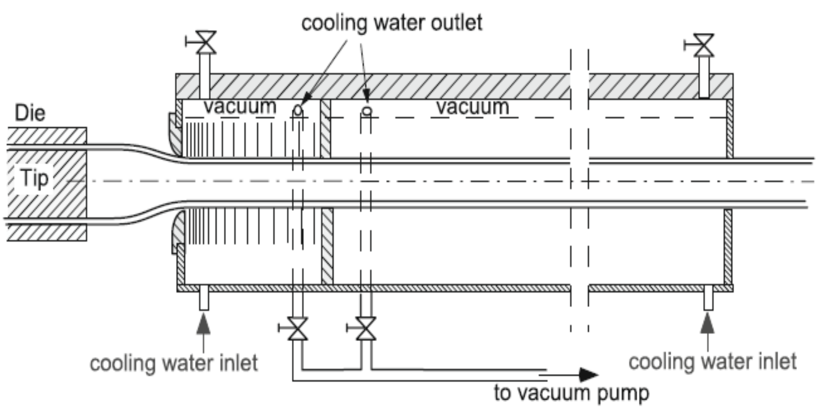



**Figure 9.47** Calibrator with external vacuum

4. Pressure calibration system
    - Air inside the pipe is pressurized while the air outside the pipe is at atmospheric pressure
    - The change in t pressure still forces the exterior of the pipe against the calibration rings, but the plug at the end of the pipe prevents the air from escaping.
    - Puller speed and die gap determine the wall thickness

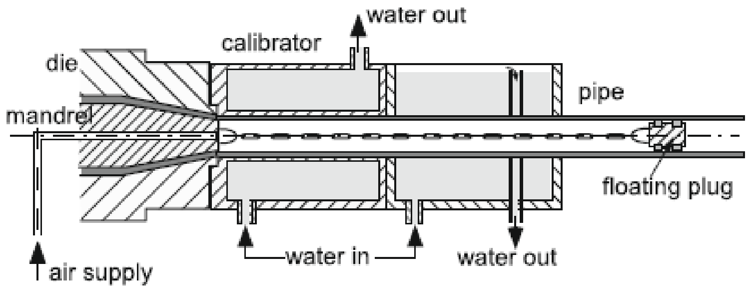


**Figure 9.46** External calibrator with internal air pressure

The air pressure is maintained by a sealing mandrel located inside the extrudate downstream of the calibrator. The mandrel is attached to the tip by a cable to fix its position. This type of calibration is used in larger diameter pipe for PVC (D > 350 mm) and PE (D > 100 mm).

**Cooling and haul-off unit**

1. Usually cooled in water bath (part of calibration unit)
2. Many lines required depends upon throughput
3. Large diameter pipes, the dimension are controlled by pressure or vacuum calibration and a water spray system
4. Caterpillar haul-off is used when pipe or tubing is rigid
5. Servo drive puller systems are employed with catheters and medical tubing

**PROFILE EXTRUSION**

Apart from rectangular and annular extrudates, there is a tremendous variety of extruded profiles with other shapes. Profile dies usually describe dies used to produce shapes other than rectangular or annular. Profile extrusions are the most difficult to make because changes in take-up speed or screw rotational speed alone are not enough to compensate for deficient product dimensions and also it is very difficult to accurately predict the required geometry of the flow channel that will yield an extruded product of proper shape and dimensions. In the case of sheet and film, if the edges of the sheet are not at the target thickness, they can be trimmed off and sent back to the extruder to be reprocessed. Profile extrudates are significantly affected by nonuniform die swell unlike sheet and tube products. In the case of profiles with corners and other irregularities, like a square profile, the die exit needed to achieve a square profile is not square owing to the influence of die swell. Fig. 5 illustrates a die exit required to achieve a square extrudate.

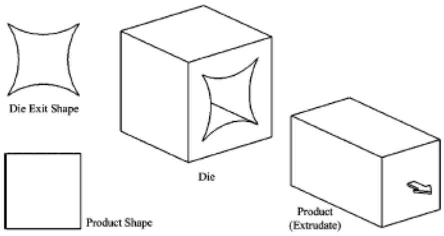



Fig. 5 Irregular die shapes required for regular extrudates.

Note that the corners have an acute cusp shape and the side walls are not flat. A melt exiting this required but nonorthogonal shape will swell into a desired, orthogonal square shape. Open profile dies are typically shapes, such as ‘‘Ushaped’’ or ‘‘L-shaped’’ channels, that are not axisymmetric, unlike tube shapes. Consequently, open profiles are more prone to cooling unevenly and thus may generate residual stresses in the solidified (frozen) extrudate that cause the product to bow. A critical design rule for open profiles is to maintain a uniform wall thickness throughout the product cross section. Examples of poor and better profile designs are shown in Fig. 6 with the poorly designed sections shown on the left-hand side and the improved designs on the right-hand side.

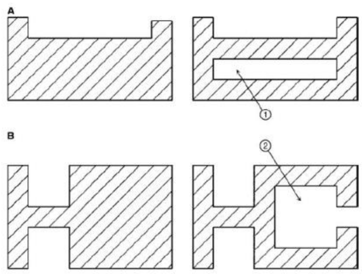



Fig. 6 Examples of poor (on left) and improved extrusion product designs (on right) to achieve uniform product thickness: (1) profile (A) made into a hollow profile and (2) profile (B) made into an open profile.

The difficulty with the original designs of both profiles A and B is the nonuniform wall thickness. The thinner sections will solidify first with the thicker sections still remaining molten in some core area. The result will be additional thermal shrinkage in the thicker regions and thus warpage of the final product. Product A will warp downward and product B will warp toward the right. These warping problems can be alleviated by making the entire cross section with more uniform thickness. Then, the entire cross section will solidify more uniformly and a little residual stress will be trapped in the solid extrudate. Design A illustrates a case where a hollow profile is used to solve the warpage problem whereas design B illustrates the use of an open profile to replace the thick region. The revised product designs of A and B will require more expense to fabricate the dies for these products as a set of mandrels must be made to form the hollow chambers. However, there are key benefits derived by making these changes:

- Better-quality products due to more uniform cooling and shrinkage: straighter products.
- Less material use by removing thick, unnecessary regions: savings of material costs.
- Faster cooling rates due to less hot plastic to cool: higher production rates.

Profile dies are commonly made with a series of plates that are stacked together to form a complex passage from the circular exit of the extruder to the required profile die exit. A stacked plate design makes for easier manufacture and permits adjustments to parts of the die assembly as needed during extrusion trials to fine-tune the die flow. An example of a stack plate die that makes a U-shaped profile is shown in Fig. 7. This figure illustrates an exploded view of a stack plate die, a cross-sectional view of the assembled die, and a detail of the die exit compared to the target profile. Stacked plate profile dies typically have these elements:

- Adapter plate: forms transition from circular extruder exit to approximate profile shape.
- Transition plate: forms streamlined transition from adapter plate exit to preland plate inlet.
- Preland plate: imparts significant flow adjustment by reducing thickness in high-flow areas and increasing thickness in low-flow areas anticipated downstreamin the die land to make flow more uniform.
- Die land plate: provides a uniform cross-section passage that is typically 10 times longer than the thickness of the extrudate to relax the viscoelastic stresses in the melt before leaving the die (reduces die swell) and forms the shape of the extrudate leaving the die. The die land profile has the required shape to compensate for extrudate deformation after the die (die swell and drawdown) and yield the desired shape downstream.

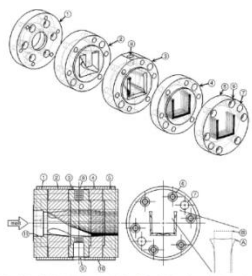


Fig. 7 U-Profile stack die: exploded view (top); section view (lower left); and end view (lower right): (1) extruder mounting plate; (2) die adapter plate; (3) transition plate; (4) preland plate; (5) die land plate; (6) die bolt hole; (7) alignment dowel pin hole; (8) thermocouple well; (9) pressure transducer port; (10) heater band; (11) breaker plate recess. Detail (lower right): (A) die exit profile and (B) product profile.

## WIRE AND CABLE

In wire coating, metal wire is covered with plastic insulation. This process requires a pay-off (input) drum, input capstan, pre heater, extruder, crosshead or offset die, cooling trough, spark tester, diameter and eccentricity gauges, output capstan and wind-up drum. The pay-off drum and input capstan unwind wire at high speeds and provide constant speed and tension. In the preheating station, a gas burner or electrical resistance heater preheats the wire to improve adhesion, reduce plastic shrinkage and remove any moisture or wire drawing lubricant from the wire. As the wire passes through the die, it is coated with polymer melt. The coated wire is cooled in a series of water baths and then the coating is measured and tested prior to being wound up on the wind up drum.

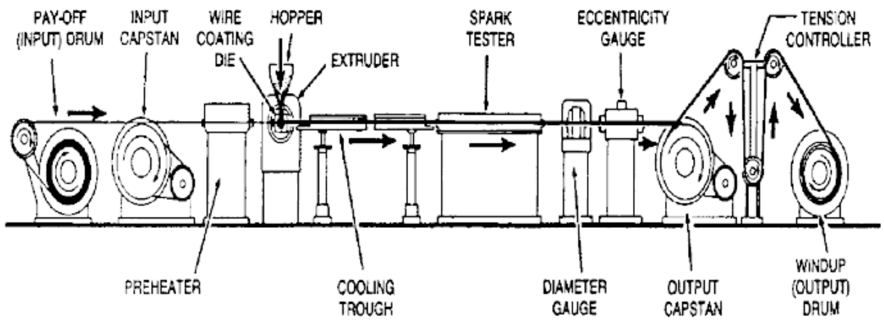


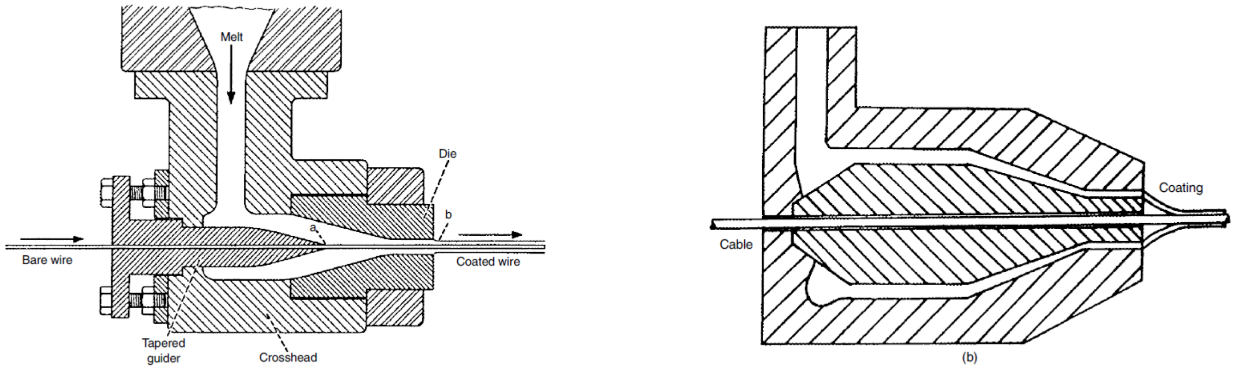

**Figure 5.51** Wire coating.[116]

Wire coating uses two die designs: (1) pressure-coating dies and (2) tubing dies.

With the more commonly used pressure-coating die, wire is fed into the die through a tapered guider. The space between the guider and the inside of the die is the “gum space”, and can be adjusted using bolts at the back of the die. Melt flows around and coats the wire before it exist the die and melt pressure forces the melt against the wire. The clearance between wire and mandrel is less than 0.05mm (0.002 in) to prevent back leakage of melt. In contrast, a tubing die coats the wire as it exists the die. A low level vacuum applied to rear of the die removes the air and pulls the melt toward the wire. Tubing tools are suited for larger wire and cable because excessive pressure produces back leakage of melt with larger wires.

As the wire passes through one or more cooling troughs, the wire speed and wall thickness determine the length of the cooling troughs. Gradual, controlled cooling is used for coatings thicker than 50 mm in order to avoid shrinkage in the resin wall next to the wire. Since quick cooling tends to harden the outer resin layers, this inner shrinkage produces voids along the wire, thereby reducing the integrity of the coatings. A retention time of more than 1 min is required for thick coatings. Coating thickness is typically 0.13 to 03 mm.

line speed is dictated by the speed of the wire and extruder output, with faster speeds requiring tighter control over the process. For fine wire {diameter <0.75 mm}, the line speed can be 2100 to 3000 m/min.




(a) (b)

**Figure 5.52** Wire-coating dies: (*a*) pressure-coating die[117] and (*b*) tubing tool.[118]

## COATING AND LAMINATION

Principle

1. In extrusion coating a layer of molten polymer is applied to a substrate such as paper, plastic or metal foil.
2. When the substrate is fed into the extrusion line, it is often preheated and may be pretreated to enhance adhesion.
3. Then an extruder pumps molten plastics onto the substrate.
4. The coated material is then cooled by chill rolls and collected on an wind-up roll.

2. Auxiliary equipment, such as slitters, corona discharge stations, and printing heads, may be placed between the chill and wind-up rolls.
3. Since extrusion coating offers high production rates and elimination of solvent-waste adhesives, it is frequently used for packaging.

Components of a Extrusion line

1. An Extruder
2. Substrate feed equipment,
3. A die,
4. A chill-roll assembly,
5. Slitters,
6. A wind-up system, and
7. Auxiliary equipment.

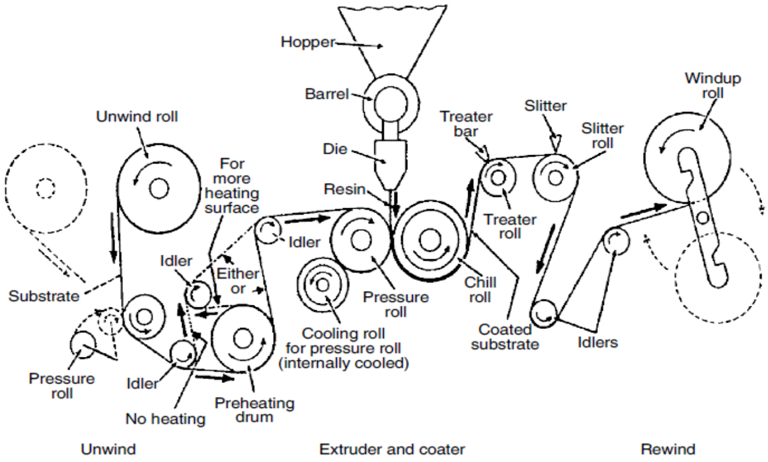



**Figure 5.53** Extrusion coating.[121]

Process control

1. In extrusion coating the primary controls are the
    1. barrel and die temperatures,
    2. substrate temperature,
    3. chill roll temperature,
    4. line speed and
    5. die gap
2. The barrel and die temperatures are very high, producing a melt temperature that is usually just below the degradation temperature of the polymer.

**Properties of the resins**

1. Extrusion coating resins usually have lower molecular weight and so are more fluid than other extrusion grade materials.
2. Since the polymer melt has the lowest possible viscosity, the polymer melt flows onto and adheres to the substrate.
3. The high temperatures also promotes oxidation of the molten surface.
4. This oxidation occurs in the air gap, the space between the die lip and the nip of the chill and pressure rolls.
5. Larger air gap facilitates oxidation, but permit cooling of the polymer melt.

**The substrate**

1. The substrate can be preheated, and paper can be dried, before it reaches the pressure roll and the chill rolls.
2. The heated substrates and chill rolls allow the molten polymer to flow on the substrate and permit relaxation of the polymer chains.

3. This not only facilitates mechanical interlocking of the coating and the substrate, but also relieves stresses that would reduce adhesion of the coating to the substrate.
4. The chill roll temperature also affects the coating surface properties.
5. Since rapid cooling freezes in coating defects, the coated surfaces are not as glossy.

**Line speed and coating thickness**

1. Since higher screw speed increases extruder output, they produce thicker coatings with decreased neck-in.
2. In contrast, the chill rolls draw down the melt and thus reduce coating thickness and increase neck-in.
3. Typically high drawn is required for fast line speeds and thin coatings, whereas slower speeds are used for thicker coatings.
4. Increasing the chill roll speed also increases stress because melt drawing enhances uniaxial orientation, but the thinner coating freezes the polymer chains in their oriented states.
5. The result is reduced adhesion.
6. Thicker coatings also exhibit decreased adhesion due to the non-uniform stresses developed during the cooling of the coating.
7. Two other measures affected by the chill roll speed are coating weight per unit area and coating area output.
8. The former decreases as the coating thins while the late increases as more polymer is spread over a larger area of substrate.

**Die Gap**

1. Larger die gaps also increase coating thickness but reduce neck-in.
2. Larger air gap increase neck-in since the longer distance between the die and chill roll nip facilitates stretching of the molten polymer.

**Chill roll and its effect in surface finish**

1. The chill roll surface affects the coating surface.
2. Smooth rolls provide smooth, glossy coatings, whereas rough rolls are used for matte finishes.
3. Greater roll pressures force the polymer melt and substrate into closer contact, thereby improving adhesion.
4. Adhesion also increases with porous substrate, adhesion promoters, and priming of the substrate.

**Resins**

1. The resin most commonly used are
    1. polyolefins such as polyethylene, polypropylene
    2. Ethylene vinyl acetate copolymers, etc.

**Resin characteristics for extrusion coating**

1. Higher melt index required for better adhesion.
2. Additive free
3. Appropriate amount of antioxidants
4. Reduced neck-in properties
5. Good adhesion to substrate at higher line speeds

**Advantages of extrusion coating are**

**As a process:**

1. Double sided coating can be done to achieve desired properties.
2. Solvent/adhesive free
3. Thickness of the coating can be varied depending on the end use.
4. Higher line speeds.

**As an end product:**

1. Provides moisture barrier properties.
2. Avoid direct contact to the substrate.
3. Provide heat sealable characteristics.
4. Reduces loss of content.

Factors influencing coating performance

1. **Melt temperature:**
    1. Extrusion coating lines are normally operated at higher temperature.
    2. The resins for extrusion coatings contains lower level of antioxidants.
    3. Higher processing temperature oxidizes the polymer partially and promotes good bonding to the substrate.
    4. Further it lowers melt viscosity promoting uniform flow of melt through the die.
    5. Higher temperature (>300°C) is necessary to achieve acceptable level of adhesion to the substrate at high line speeds.

2. **Air gap:**
    1. The gap between the die exit and substrate on chill roll is called air gap which need to be optimized with respect to coating material.
    2. Some oxidation of the melt takes place after exit from the die, facilitating adhesion of polymer to the substrate.
    3. Higher gap leads to higher necking and cooling of the melt, leading to improper adhesion of polymer to the substrate.
    4. For LLDPE/LDPE blend, the air gap is normally maintained between 30-40mm.
3. **Die gap:**
    1. The die gap is the critical control point on any extrusion coating line.
    2. The slit die with die opening of 0.5mm to 0.8mm is commonly used.
    3. Higher die gaps give higher flow variation.
4. **Chilled roll temperature:**
    1. It has influence on coating adhesion and stiffness.
    2. Optimum chilled roll temperature for polyethylene is 30 °C

**BLOWN FILM EXTRUSION**

**Blown film dies**

Dies used to make film less than 0.01 in. thick include flat, slit-shaped dies called T-dies and annular dies for blown film. Blown film dies are the most common way of making commercial films. Because the blown film is so thin, weld lines are not tolerated,

**Crosshead Die**

A simpler die is the conventional crosshead die; see Fig. 9.24. This design is more susceptible to weld lines; however, with the correct design good blown film can be produced.

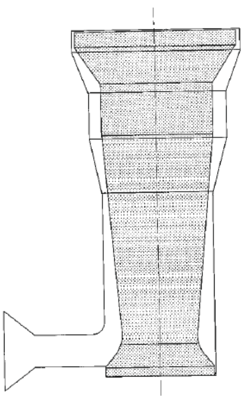


**Figure 9.24**
Example of simple crosshead die for blown film

The distribution characteristics of conventional crosshead dies may not be good enough for application in blown film extrusion, where wall thicknesses are generally quite small (the typical range is 0.005 mm to 0.25 mm). Spiral mandrel dies can achieve good flow distribution and largely eliminate weld lines. As a result, spiral mandrel dies are widely used in blown film extrusion. In this die, the polymer is divided into a number of spiraling channels with the depth of the channels reducing in the direction of flow. The popularity of the spiral mandrel die is due to its relatively low pressure requirement and its excellent melt distribution characteristics. Spiral mandrel dies can be used with a wide range of materials over a wide range of operating conditions.

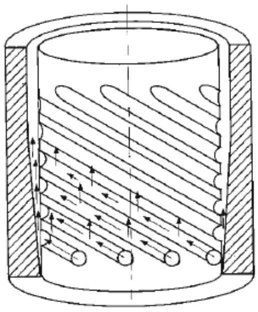


**Figure 9.25**
Example of a spiral mandrel die

The incoming polymer melt stream is divided into separate feed ports. Each feed port feeds the polymer into a spiral groove machined into the mandrel. The crosssectional area of the groove decreases with distance, while the gap between the mandrel and the die increases towards the die exit. This multiplicity of flow channels results in a smearing or layering of polymer melt from the various feed ports, yielding a good distribution of the polymer melt exiting from the die. It is obvious that local gap adjustment is not possible as it is with flat sheet dies. As a result, the wall thickness uniformity with spiral mandrel dies is generally not as good as with flat sheet dies. The latter can generally achieve a wall thickness uniformity of about} 5%, while the blown film die achieves a wall thickness uniformity of about} 10%. For this reason, the die is generally made to rotate to evenly distribute the wall thickness non-uniformities. If this were not done, the final roll of product would show very noticeable variations in diameter.

**Three design variables** have a strong effect on the flow distribution in spiral mandrel dies. These are the number of grooves, the initial clearance, and the groove helix angle. Increasing the number of grooves improves distribution and reduces pressure drop. Typical values of the number of grooves range from 1 to 2 per inch (25 mm) of die diameter. A small non-zero clearance improves the flow distribution and reduces pressure drop. There is an optimum initial clearance beyond which the flow distribution exhibits more variation. Small groove helix angles improve the flow distribution; however, this increases pressure drop. The optimum taper angle was found to be between 1° and 3°. The flow distribution uniformity improves with initial groove depth, while the pressure drop reduces at the same time. A gradually reducing groove width does not result in improved flow distribution. Obviously, the actual flow variation in spiral mandrel dies can be greater than the values predicted. Other variations in flow distribution can occur because of consistency variations in the polymer melt due to temperature non-uniformities and /or insufficient mixing. Flow variations can also occur due to mechanical variations in the dimensions of the die. Further, elastic effects can affect the flow distribution. As a result, good quality film requires not only a good die design but also an extruder with good melting and mixing capability, consistent resin properties, uniform film cooling, constant tension, etc.

**Blown Film Extrusion process**

**Principle**

1. Molten polymer from the extruder head enters the die, where it flows around a mandrel and emerges through a ring shaped opening in the form of a tube.
2. The tube is expanded into a bubble of the required diameter by the pressure of the internal air admitted through the centre of the mandrel.
3. Air contained in the bubble cannot escape because it is sealed by the die at one end and by the nip rolls at the other, so it act as a permanent shaping mandrel.
4. Even pressure of air pressure is maintained to ensure uniform wall thickness of the film bubble.
5. While nip roll colalpses the bubble they also stretch the film and serve as a take-off device for the line.
6. An air ring above the die cools the bubble so that the film is solid when it reaches the nip rolls.
7. After it passes thorough the rollers, the collapsed film is wound up on a roll.

**Components of a blown film extrusion line**

1. Extruder
2. Annular die
    1. Cross head die
    2. Spiral mandrel die
3. Cooling system
4. Take-off tower
5. Wind-up

**Extrusion line**

1. Single screw extruder
2. L/D ratio – 24:1 to 30:1
3. For polyolefin – screw often incorporates barrier flights in transition zone and dispersive mixing heads
4. Raw materials - Pellets, powder, flake, and fluff are all used, but pellets and fluff are the two most common forms for blown film.
5. For blown film, it is quite common to employ a grooved feed throat.
6. The purpose of the grooved feed throat is to increase throughput.
7. The grooves act to increase the friction between the pellets and the barrel, allowing the screw flight to force more pellets forward with each revolution of the screw.
8. This will lead to an increase in the rate of melt flow through the die (i.e., more product per hour).

**Raw materials**

1. Polyethylene (PE)
2. Low-Density Polyethylene (LDPE)
3. High-Density Polyethylene (HDPE)
4. Linear Low-Density Polyethylene (LLDPE)
5. Metallocene Polyethylene (mPE)
6. Polypropylene (PP)
7. Polystyrene (PS)
8. Ethylene Vinyl Acetate (EVA)
9. Ethylene Vinyl Alcohol (EVOH).
10. Polyvinyl Chloride (PVC)
11. Polyamide (PA)

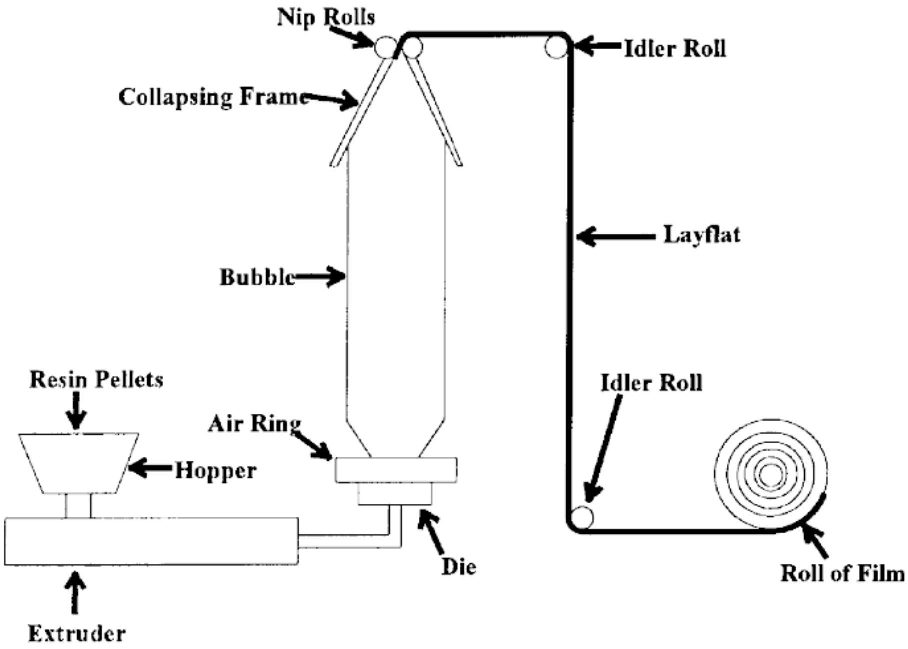


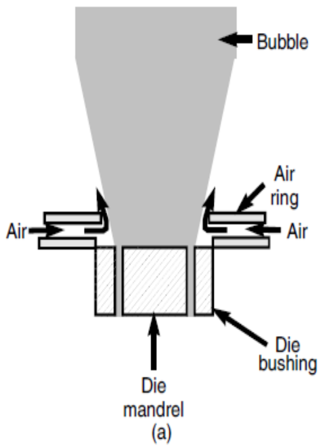

**Figure 5.38** Blown film line.

## Bubble Cooling

1. Accomplished by blowing a large volume of air on the film as it exits the die.
2. Takes place on only the outside of the bubble or on both the inside and the outside.
    1. Single lip air rings
    2. Dual lip air rings
    3. Internal bubble cooling (IBC)
3. Additionally, the bubble is kept inflated to remove more heat from the film as it travels up through ambient air in the cooling tower.

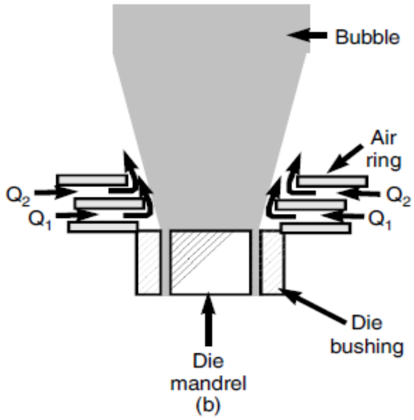
## Single lip air ring

1. Cools the exterior of the bubble using high velocity air
2. Increasing the air flow or refrigerated air can be used to improve the Cooling
3. Turbulent air flow provides better cooling, but destabilize the bubbles
4. Most common approach is dual lip air ring



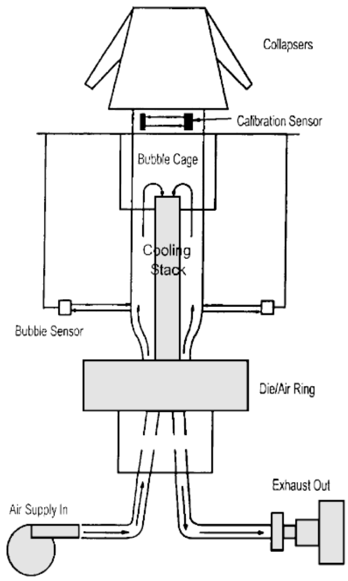
**Dual lip air ring**

1. Better cooling and improved bubble stability
2. Low velocity air floes from lower lip $Q_1$ stabilizes the bubble and acts as a lubricant
3. How velocity air flows from upper ring $Q_2$ cools the melt
4. Since $Q_2$ is much higher than $Q_1$ a dual lip ring provide high inlet velocity without turbulence



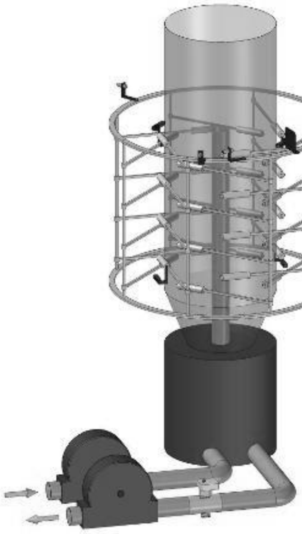

**Internal bubble cooling (IBC)**

1. IBC uses a dual lip air ring to cool the outside of the bubble while refrigerated air cools the inside of the bubble.
2. Internal cooling air is introduced through the mandrel
3. So IBC requires computerized monitoring of pressure with in he bubble in order to maintain the constant bubble pressure
4. Advantages
    1. Not only better cooling than air rings alone, permits increased output, faster startup and tighter lay flat control



**Bubble Stabilization**

1. A fifty-foot high, six-foot diameter bubble with a wall thickness of one thousandth of an inch is very susceptible to lateral movement from environmental effects such as drafts.
2. When movement of the bubble occurs, often called "dancing", the result is non-uniform wall thicknesses, originating at the die lips.
3. For this reason, bubbles are usually stabilized externally using devices such as cages and irises (Fig. 3.16).
4. In some cases, internal stabilization can be performed as well.



**Collapsing Frames**

1. As the bubble moves upward and approaches the nip rollers, it is "preflattened" by the collapsing frame.
2. This device provides a smooth transition from a round tube shape to a flattened tube shape.
3. Collapsing frames utilize wooden slats, metal rollers, Teflon-coated rollers, or an air cushion to perform the shape transition.
4. In addition to flattening the tube, the collapsing frame also helps eliminate wrinkles in the final product.
5. These devices are generally adjustable for both height and entry angle.
6. Proper positioning of these two adjustments is often used to correct wrinkling problems.

**Haul-off**

1. A pair of nip rollers (the haul-off device) is located at the top of the cooling tower.

2. Their purpose is to pull the film up from the die.
3. Also, the nip serves as an air seal for the top end of the bubble, so, at least one of the rolls is usually rubber covered.
4. While one of the rollers is located in a fixed position, the other uses pneumatics to be moved laterally into the closed or open position.
5. This allows for the line to be strung between the rollers for start-up.
6. The fixed-position roll is motor-driven to establish the line speed.
7. The size of the nip rolls and all downstream idle rollers, known as the roll face width, determines the maximum layflat width that the system is capable of producing.
8. The layflat width is related to the bubble diameter by the following equation: BD = 2 LF/π (where BD = bubble diameter and LF = layflat).

**Winders**

1. Winders are used to collect the wound roll packages.
2. They generally operate in a manner that produces rolls of constant web tension, as opposed to operating at a constant winding (rotational) speed.
3. There are two primary winder types:
    1. surface winders and
    2. axial winders

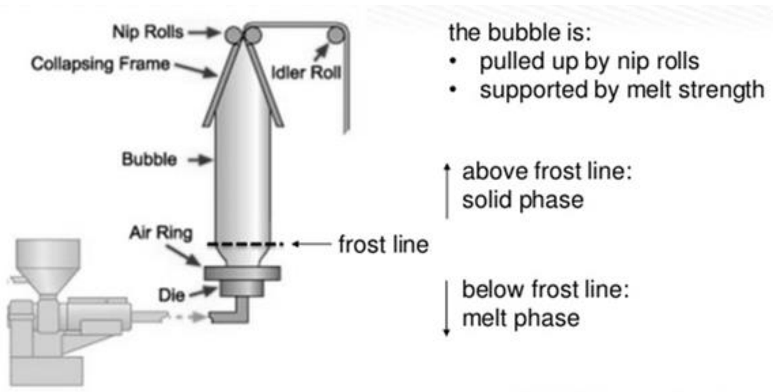
**Gauge Thickness**

1. Film thickness is usually monitored during the process.
2. A beta gauge detects the passage of beta rays through the film bubble, while capacitance gauges measure the increase in thickness as increased capacitance.
3. Blown film lines may also include corona or flame treatment to improve adhesion, sealing operations for bags, and slitters.

**Blown film process Control**

1. The principal controls for a blown film line are
    1. barrel and die temperatures,
    2. die gap,
    3. extrusion rate,
    4. internal air pressure,
    5. bubble diameter,
    6. cooling air flow or cooling rate, and line speed (take-off speed).

2. The final control variable is frost line height. The position of the frost line is very sensitive to any changes in the process.
3. The frost (freeze) line height, which is a ring-shaped zone where the bubble begins to appear "frosty" because the film temperature falls below the softening range of the resin and crystallization occurs, is an indicator for many of these variables.
4. These controls influence the film dimensions and properties.




5. Sufficient barrel temperature is required for good optical properties.
6. However, if the barrel temperature or melt temperature is too high, the viscosity becomes too low, and the bubble becomes unstable and may break.
7. Sufficient die temperatures also contribute to good optical properties.
8. Die temperatures usually match the extruder's metering zone temperatures.
9. Blown film extrusion offers excellent manufacturing flexibility such as film thickness and/or layflat width.
10. The most important processing characteristic is the ability to impart biaxial orientation into the film.

**Biaxial orientation**

1. Biaxial orientation means that polymer molecules are aligned in the plane of the film, i.e., in both the machine direction (MD, along the long axis of the bubble) and the transverse direction (TD, around the hoop direction of the bubble).
2. The result is a tough film that resists tearing in either direction.
3. This molecular structure is produced when melt exiting the die is stretched in both MD and TD at the same time.
4. Geometry of the bubble and the process conditions yielding the geometry are crucial to proper orientation.

## Characteristic of Bubble Ratios

Following are the conditions that influence bubble geometry.

1. Take-up ratio (TUR)
2. Blow-up ratio (BUR)
3. Forming ratio (FR)

**Take-up ratio (TUR)**

1. The TUR is the ratio of film velocity ($V_f$) to melt velocity ($V_m$), i.e., **TUR = $V_f$ / $V_m$**
2. This quantity provides an indication of the amount of stretching i.e. molecular orientation, in MD.
3. The **film velocity** is the upward speed of the film above the frost line (It is equivalent to the nip speed).
4. The **melt velocity** is the upward speed of the molten polymer as it exits from the die lips. (It is related to, but is not equal to, the screw speed).
5. The melt velocity can be determined experimentally by marking the film and tracking the mark, but an easier method is to employ the principle of conservation of mass.
6. The conservation of mass states that the mass flow rate (Kg/hour) is equal at all points along the bubble.

$$m_{\text{rate}} = \left(\rho\, A\, V\right)_{\text{nip rollers}} = \left(\rho\, A\, V\right)_{\text{die gap}}$$

where  = density, A = annular area, V = velocity.

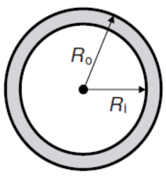
7. This equation can be rearranged to the form

$$\text{TUR} = V_{\text{f}} / V_{\text{m}} = \left(\rho\, A\right)_{\text{die gap}} / \left(\rho\, A\right)_{\text{nip rollers}}$$

8. The area of an annulus can be calculated from the following equation:

$$A_{\text{annulus}} = \pi\left(R_{\text{o}}^2 - R_{\text{i}}^2\right)$$

where Ro is the outside radius and Ri is the inside radius of the annulus.




Since the nip speed is always greater than the melt speed, the TUR is always greater than one.

**Blowup ratio (BUR)**

1. The BUR is the ratio of bubble diameter (Db) to die diameter (Dd), BUR = $D_b$ / $D_d$
2. This quantity provides an indication of the amount of stretching, hence orientation, in TD.
3. The bubble diameter is established by the control system and can be either measured directly or calculated by measuring the layflat (LF) width directly (Db = 2 LF / Π ).
4. The die diameter is fixed.

**Draw down ratio (DDR)**

1. TUR requires some calculating to obtain, so draw down ratio (DDR) was preferred to indicate the total degree of film stretching.
2. DDR is determined from three easily obtained measurements:
    1. the die gap,
    2. final film thickness, and
    3. BUR

$$\mathrm{DDR} = t_\mathrm{d} / (t_\mathrm{f} \cdot \mathrm{BUR})$$

where *td is the die gap and tf is the film thickness.*

3. However, even though DDR is easy to determine, it does not specifically indicate the degree of MD or TD stretching.
4. These are indicated by the TUR and BUR, respectively.

**Forming ratio (FR)**

1. Forming ratio is the ratio of the TUR to the BUR.
2. This quantity provides an indication of the balance of stretching, and so orientation, between MD and TD.
3. If a film has identical mechanical properties in MD and TD, it is said to have isotropic properties.
4. When a blown film is processed so that the FR approaches one, it is an indication that the properties of the film approach isotropy.
5. There is not an exact relationship between forming ratio, molecular orientation, and property balance
6. Employing TUR, BUR, and FR provides extrusion personnel with convenient measures of processing conditions.

**Summary of Blown film extrusion process**

1. Blown film extrusion is a scrapless operation with high outputs.
2. The films are versatile; they can be used as tubes or slit to become flat film.
3. Finally, the process inherently produces biaxial orientation.
4. However, blown film extrusion requires high melt-strength materials, and so is limited to polyethylene, polypropylene, poly(ethylene-co-vinyl acetate) (EVA), flexible poly(vinyl chloride), and some polyamide and polycarbonate grades.
5. The process provides slower cooling, and thus higher haze.
6. Moreover, gauge control is difficult.
7. Blown films are typically 0.0025 to 1.25 mm thick.

**COEXTRUSION**

**Introduction**

1. Coextrusion permits multiple-layer extrusion of film, sheet, pipes, tubing, profiles, wire coating, and extrusion coating.
2. It is used mostly in packaging applications to obtain desired barrier properties.
3. The process eliminates the need for a laminator for plastic-plastic surfaces, is less expensive, and provides property enhancement.

**Principle**

Coextrusion is the simultaneous extrusion of two or more polymers through a single die where the polymers are joined together such that they form distinct (not alike), well-bonded layers forming a single extruded product.

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**Advantages of coextrusion**

1. better bonds between layers,
2. reduced materials and processing costs,
3. improved properties,
4. reduced tendency for pinholes,
5. delamination, and
6. air entrapment between the layers.

7. Another advantage of coextrusion is that it is often possible to reuse scrap material and locate it in an inside layer of the extruded product so that it does not affect the appearance of the product.

**Disadvantage of coextrusion**

1. The tooling is more difficult to design and manufacture and, therefore, more expensive.
2. Further, it requires at least two extruders, and
3. it takes more operational skill to run a coextrusion line.

**Application**

Coextrusion is used in a variety of packaging applications to obtain the required combination of properties, for instance, good moisture resistance, gas barrier properties, reduced costs, tear strength, etc.

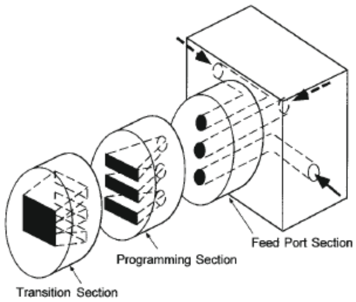
- A combination of polyethylene/nylon /polyethylene is popular in sterile-packaged disposables.
- A combination of LDPE / HDPE is used for shrink film and shopping bags to obtain a balance of rigidity and low cost.
- PS/foamed-PS coextrusion is used in production of egg cartons and meat trays.
- In sheet extrusion, the combination ABS/polystyrene is used for refrigerator door liners and margarine tubs. The ABS is applied for chemical resistance and the polystyrene for economy.

**Coextrusion techniques**

There are basically three different techniques for coextrusion.

**Feed block die**

1. In feed block die, various melt streams are combined in a relatively small cross-section before entering the die.
2. The advantage of this system is simplicity and low cost.
3. Disadvantages are that the flow properties of the different polymers have to be quite close to avoid interface distortion.
4. There is no individual thickness control of the various layers, only an overall thickness control.




**Multi-manifold internal combining dies**

1. The different melt streams enter the die separately and join just inside the final die orifice.
2. The advantage of this system is that polymers with large differences in flow properties can be combined with minimum interface distortion.
3. Individual thickness control of the different layers is possible; this enables a higher degree of layer uniformity.
4. Disadvantages are complex die design, higher cost, and limited number of layers that can be combined.

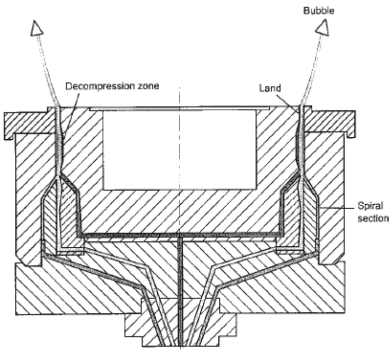
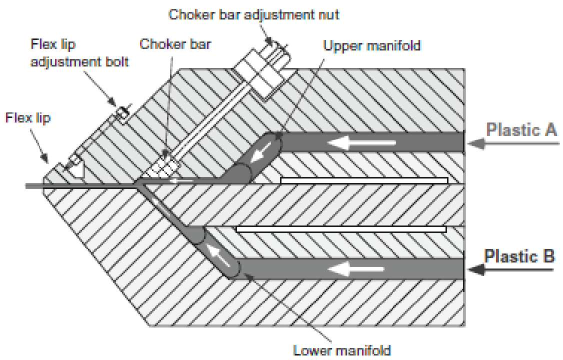



**Figure 9.38**
Multi-manifold blown film die, three layers

**Multi-manifold sheet die for two-layer coextrusion**

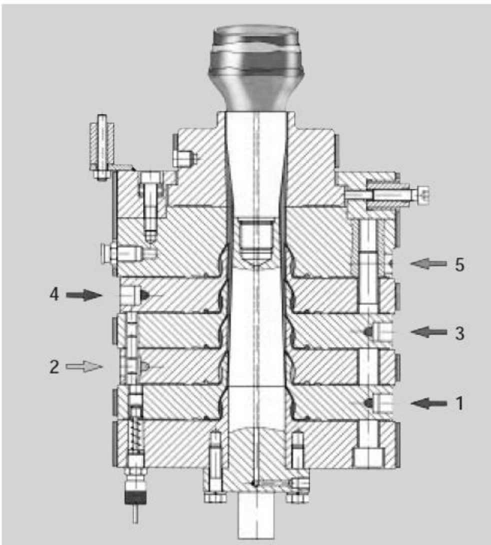
1. The upper layer can be adjusted with a choker bar, while the final combined layer thickness can be adjusted with the flex lip.
2. Coextrusion of more than three layers is difficult in a sheet die because the die geometry becomes quite complex.

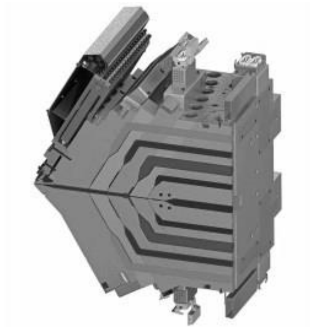


**Multi-manifold external-combining dies**

1. These dies have completely separate manifolds for the different melt streams as well as distinct orifices through which the streams leave the die separately, joining just beyond the die exit.
2. This technique is also referred to as multiple lip coextrusion.
3. The layers are combined after exiting while still molten and just downstream of the die.
4. For flat film dies, pressure rolls are used to force the layers together.
5. In blown film extrusion, air pressure inside the expanding bubble provides the necessary pressure for combining the layers.
6. This technique is more expensive than the feed block technique; however, gage control of individual layers is more accurate, pinholes are eliminated, and the system is easier to start up.

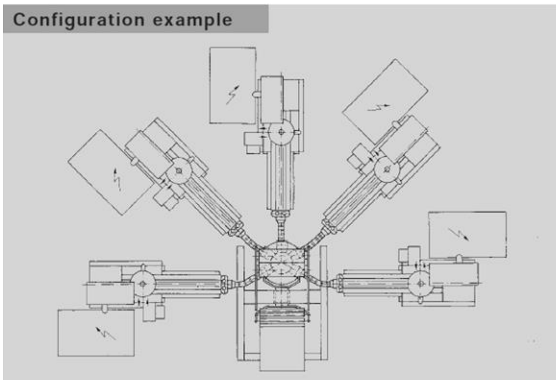
The patented 5-Layer Coextrusion Die Type RWT



**Co extrusion general**

1. In general, extruders are located as close to the feedblock or multimanifold die as possible to minimize the length of transfer lines (which connect the extruder to the feedblock or die) and so reduce the residence time of the melt.
2. Typically, the extruder located closest to the feedblock contains the heat-sensitive polymer.
3. Adhesive resins tend to cross-link if their residence time is too long.
4. The barrier resin, poly(vinylidene chloride), is also heat sensitive.




**Adhesive resins or tie layers**

1. Adhesive resins or tie layers often connect two incompatible polymers such as a polyolefin and a barrier resin.
2. These adhesive materials include ethylene-vinyl acetate copolymer (EVA), styrene-butadiene (SBS), and styrene isoprene (SIS) block copolymers, styrene-ethylenebutylene- styrene (SEBS), ionomers, and ethylene acrylic acid copolymer (EEA).
3. The principal barrier polymer is ethylene vinyl alcohol (EVOH), with poly(vinylidene chloride) used in some cases.
4. A typical coextruded structure is comprised of a barrier layer sandwiched between layers of the structural resin; two tie layers would facilitate adhesion of the barrier layer to the structural resins.

Coextrusion is practiced on a wide scale in blown film. There are many five-layer blown film coextrusion dies used in the industry; five-layer films are now considered a commodity. Even seven-layer dies are not unusual. Some coextrusion dies use as many as 8 to 10 layers. Most of these multi-layer dies are used in high barrier packaging for food.