plate to monitor pressure for safety and to indicate when filter screens are plugged, and ideally one in the head for process monitoring. Transducers along the barrel are vital in test labs for acquiring screw design data, and can be used in production for feed loss and vent port flooding alarms. The industry has standardized on a 0.312-inch-diameter hole in the barrel with a 45° seat and $\frac{1}{2}$–20 threads for gauge interchangability and easy replacement.

Drive Power Measurement. Drive power consumption, an important process indication, is readily available in DC or AC drives in the form of a motor ammeter showing either percent load or actual amps. The correlating parameter in hydraulic drives is pump pressure.

Screw Speed Sensors. Extruders, although not positive displacement pumps, normally exhibit a fairly linear relationship between screw speed and output; so screw speed indication is a critical control parameter. On approach is to mount rpm counters on the screw drive shaft or any of the other shafts on the gear case, but the simplest method is to utilize the output of the drive motor's tachometer scaled to screw speed.

Temperature Control

Barrel temperature control is one of the most important and difficult requirements of the extrusion process. Barrel temperature setpoints affect the final output rate, quality, temperature, and stability. The barrel heating and cooling system not only must maintain a set inner-surface temperature, but must do so while providing varying amounts of heating to compensate for the melting requirements or cooling because of excessive internal heat generation. The control problem is complicated by the physical arrangement of the barrel. Of necessity, the barrel has a substantial wall thickness; so the source of heating or cooling is at a significant thermal distance from the desired control surface, causing a sort of "thermal inertia." A simple on–off controller cycles wildly about the setpoint because by the time the sensor "sees" the required temperature, the heater/cooler is already much too hot or cold. The ideal extrusion temperature controller not only must compensate for this thermal inertia, but should anticipate the required heating or cooling during a process change or upset.

PID Controllers. Most commercial temperature controllers incorporate a PID control scheme with proportional, integral, and derivative functions that can be adjusted to provide a relatively stable temperature. The proportional band adjustment on heating and cooling is the most important feature. It simply reduces the amount of heating or cooling as the indicated temperature approaches the setpoint. For instance, the controller might call for 100% heating at a 50° error, 50% at 25°, and 10% at 5°. Other features help to reduce over- and undershoot, and "offset" allows the controller to stabilize at a fictitious setpoint that results in the desired setting. Modern controllers usually are offered with some type of auto-tuning, thus eliminating the extremely difficult chore of correctly adjusting a PID controller. Barrel controllers are typically heat/cool models, whereas die, head, and adaptor zones are normally heat only.

Dual Sensor Controllers. Even the most sophisticated PID controllers rely on schemes and "fixes" to compensate for the inertia caused by the thermal distance between the sensor and the heat or cooling source. A unique solution to the problem is a patented, two-thermocouple control system that incorporates a second sensor mounted directly in the heater/cooler and, through the use of a special computer algorithm, eliminates the problem of thermal inertia and temperature cycling. These controllers are microprocessor-based and often are incorporated into complete line computer control or supervisory systems.

Controller Output. The output of any temperature controller, even with a proportional heating band, is usually on–off. The required heating or cooling ratio is achieved by time-proportioning the output during a set duty cycle. The heat output is energized for 5 out of every 20 seconds, for example, for 25% output. With the stabilizing effect of aluminum heaters and the large thermal mass of the barrel, this approach is entirely satisfactory. Low voltage heat outputs in turn activate line voltage contactors, preferably mercury relays, in a heat control cabinet. Cooling solenoids are connected directly, and electric blower motors can be either direct-wired for small single-phase types or connected to three-phase motor starter relays for larger designs. Temperature controllers often are available with proportional control output connected to an SCR or other type of variable power supply for the barrel heaters. Although this is theoretically a superior system, it is of little value in extrusion barrel control.

Pressure Control

Ideally behaved fluid processes normally control pressure directly because the output flow rate is a direct function of pressure. In plastics extrusion, however, this direct relationship does not exist. Variations in melt temperature, shear rate, material deviation, and other uncontrollable parameters all can independently affect pressure and output. In extreme circumstances, an increase in screw speed, which increases shear rate and melt temperature, not only increases the output rate; because of the lower viscosity that results from the higher melt temperature, the head pressure actually can decrease! Controlling the extruder speed directly with a head pressure controller is rarely done because of these problems. Pressure indicators often are used for alarmingly high or low conditions. Full control is applied to extrusion melt pump systems, where the pump establishes the output rate, and the extruder is controlled to maintain a constant pump inlet pressure. The other common use of pressure control is in the operation of automatic screen changers, where quite often two pressure transducers, one before and one after the filter, are used to control a constant pressure differential.

Melt Temperature Control

Extrudate melt temperature control has long been a desirable goal in extrusion, but in practice it is extremely difficult to achieve. Practical approaches change the setpoint temperature of the last one or two barrel zones, but their use must be limited because the barrel temperature also can affect the output rate and upset the process; hence they are rarely used.

Size Controls

At the output of most extrusion heads or dies, whether the product is sheet, wire, film, tubing, or any of the wide variety of shapes encountered in industry, it is always desirable to make some sort of measurement of the extrudate. This is the first opportunity to "see" directly into the process and effect some sort of change. Extrusion, being a continuous process, is a difficult one for on-line inspection, as the product cannot be held and measured or inspected in traditional ways until the end of the line. Often, the line involves a large inventory of product, which all can be off-spec if adjustments are not made until the end. Size monitoring and control devices on-line allow immediate feedback and reduction of scrap. Whatever the method of measurement or gauging, corrective action usually is taken on the most easily controlled parameter. Single extruder lines with simple downstream equipment configurations should change line speed in response to size variations. More complex lines and tandem extrusion systems need to change extruder speed, but must do so gradually and with an awareness of possible related effects, such as melt temperature and pressure changes. Large-step extruder speed changes often have a two-stage response—initially an immediate reaction, followed by a gradual change due to temperature, viscosity, and pressure changes, barrel control setting, and screw inventory renewal. Coextrusion lines must discriminate measurement as well as control responses among the machines.

Diameter and Profile Gauges. Among the first and presently among the most successful on-line gauges are laser gauges, which project a beam across a critical dimension of the part causing a "shadow" on the receiver on the other side. Optical gauges differ only in their light source. These gauges have evolved into highly reliable units, with compensation for environment and product movement, and with sophisticated controls. They usually represent very good value and can be justified easily in most round-section, continuous extrusion lines such as wire coating, tubing, hose, and pipe. They also can be applied to profile extrusions that have a critical prominent dimension. Compound gauge heads can provide *X–Y* data, and rotary heads can give ovality information.

Thickness Gauges. Sheet and film thickness gauging usually is accomplished by a scanning head that either transmits to a receiver on the other side of the web or reflects back through it, utilizing radiation to measure density. The important aspect of web thickness gauging is that transverse as well as in-line profiles are detected. The transverse profile data can be used to automatically control adjustable die gap devices. Wall thickness gauging for pipe is available utilizing ultrasonic sensors and for wire using capacitance devices; both types can be combined with diameter gauging.

Rate Controls

Hopper Weight-Loss Feeders Extruder throughput is not directly measurable until the end of the process line, but output rate can be derived and controlled in several ways. The simplest method is to accurately measure the amount of material flowing through the feed hopper. This can be accomplished by timing and weighing small batches in an intermediate hopper and calculating the rate or by doing weight-loss calculations on a continuously monitored feed hopper. Both systems require accurate load cell sensing, isolation of outside effects, and a means of ensuring a constant-flood feed supply to the extruder. They work well with pellet or granule feedstocks and not as well with powders. Feed hopper rate determination has a few drawbacks, as it is blind to changes within the inventory time of the screw; however, it provides a very accurate long-term average rate and can be used to control extruder speed in a slow response manner.

Gravimetric and Volumetric Feeders. Gravimetric and volumetric feeders require starve feeding; and although long-term average rates can be accurate, starve-fed single screw extruders are notorious for surging and short-term instability.

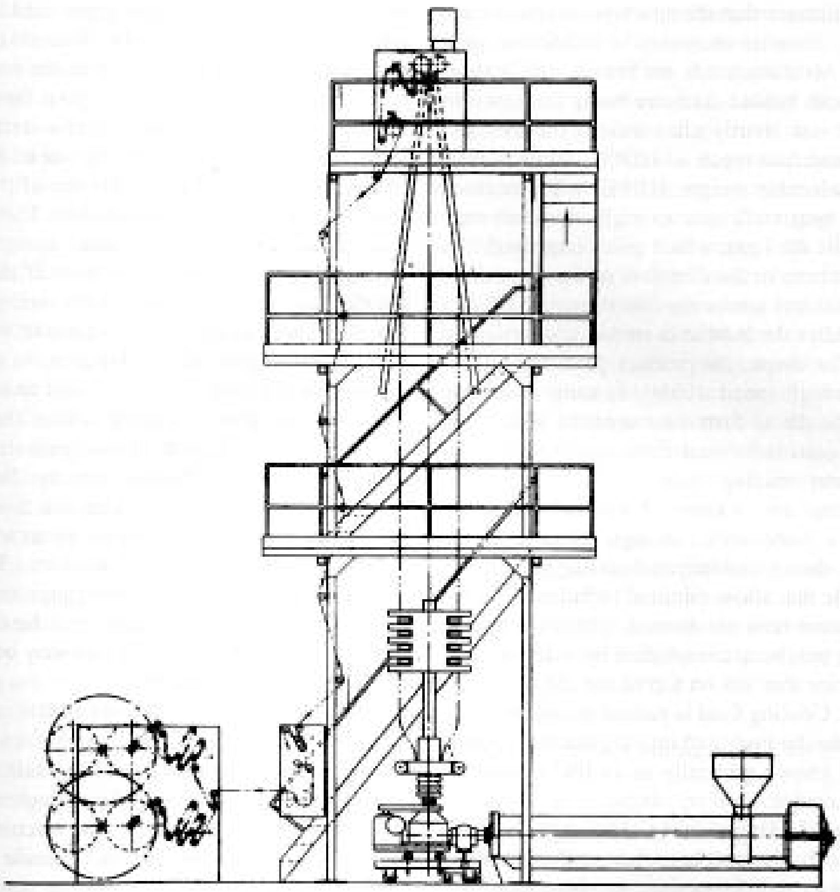
Calibration Curves. The extrusion output rate can be calibrated and calculated quite accurately in a three-dimensional grid of screw speed, pressure, and output. Test data must be collected at several speed and pressure levels and input into a simple curve fit program to find the proper function and constants; once this is done, the output rate is quickly calculated from speed and pressure. The technique can be incorporated into a computerized control scheme and used to adjust the extruder to compensate for the slow plugging of filters or other gradual changes.

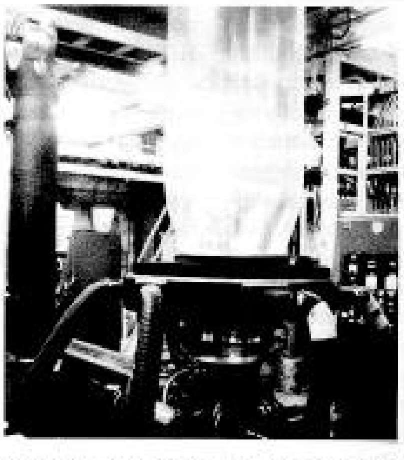
EXTRUSION PROCESSES

The extruder's function is complete when a good melt is pumped through the die system at an acceptable output rate, but success is not at hand until a usable product is formed in the downstream sizing and cooling equipment. Various products of countless shapes can be formed in a continuous manner with extrusion, making this process quite versatile. A brief description of some of the most popular products made with the extrusion process follows. The reader also is referred to Chapters 12 and 22, on blow molding and compounding.

Blown Film

In the blown film process, plastic melt passes through a die that forms it into an annular shape, usually directed upward. (See Figs. 4-11 and 4-12.) Air is introduced into the tube to inflate it and around the outside of the "bubble" to cool and solidify the melt. The cooled bubble is closed in a set of rolls (nip rolls) placed at some distance above the die. The amount that the bubble diameter is expanded is called the blow-up ratio (BUR), and is normally in the range of 2 : 1 to 4 : 1. Both stretching the bubble radially and pulling it away from the die axially impart orientation to the plastic, improving its strength and other properties.





Figs. 4-11 and 4-12. Blown film process. *(Courtesy Davis-Standard)*

The distance that the tube travels upward before its diameter increases is called the *stalk height*. Most materials are blown with a short stalk, with bubble diameter being increased to its final size shortly after leaving the die lips. Some materials (such as HDPE and especially high molecular weight HDPE) are processed with a long stalk (six to eight die diameters above the die lips), which gives improved film strength both in the direction of flow (machine direction) and across the film (transverse direction). After the bubble is cooled and collapsed into a flat shape, the product (layflat) is rolled up on a high-speed winder. In some cases, the layflat is slit to form two separate sheets and wound onto individual rolls, requiring two independent winding shafts.

Cooling air is directed upward along the bubble's outer surface at high speed, using an air ring. Some sophisticated air ring designs are available that allow minimal turbulence. When high output rates are desired, additional bubble cooling can be accomplished by using a cooling device that sits on top of the die inside the bubble. Cooling fluid is passed through orifices inside the die body and into the internal cooling device, known generally as an IBC or internal bubble cooler.

After traveling a fairly short distance from the die exit, the melt becomes solid in a usually noticeable area known as the frost line. Because the solidified material is more opaque than the melt, the frost line is easily visible. If the extruder is pumping melt consistently with uniform temperature, the die is doing an efficient flow distribution job, and the cooling air is being uniformly applied, then the frost line will appear quite well defined and in a horizontal plane. If there is instability in the extruder/die/cooling system, there usually is a ragged frost line and poor film thickness (gauge) uniformity, due to uneven melt pumping and solidification.

The dies used to form the thin annular melt can be fed from either the bottom or the side, with the bottom-fed die being prevalent today. The extruder usually has a low centerline height (15 to 20 inches, instead of the typical 42 inches for other processes) to reduce the distance from the top of the die to the floor. The material enters the die through an adaptor pipe and is split into a number of smaller flow channels (ports) that extend radially in the base of the die. The typical die is designed with a spiral flow path for each of the flow channels, with overlapping spirals to aid in flow uniformity out of the die lips. This design eliminates the use of "spider legs" of the type used in pipe dies. The material spreads radially and upward as it moves through the spiral channel section of the die; the die lips set the thickness of the melt exiting the die. There usually is an increased volume section just before the die lip area, to offer a chance for the melt to "relax" and to remove some of the flow "memory" from the path through the die system. Some materials develop visible flow problems from the die ports (port lines) or from uneven radial exit flow from the spirals. The die lips are set by experience for given polymers and product sizes. The lip gap is set larger than the final gauge to allow ample drawdown of the melt. The die lip gap for a 0.001 inch thick LDPE film may be set at about 0.020 to 0.040 inch.

If the lip gap is set too tight (0.010 inch or smaller) the die pressure at the end of the screw can reach undesirable levels (6000–10,000 psi), and some materials will exhibit a rough surface due to a phenomenon called melt fracture. Reducing this surface roughness (because of the poor slip properties of the melt on restrictive metal passages) is difficult except by opening the lip clearance to reduce the shear experienced by the melt. This phenomenon is quite prevalent with materials such as LLDPE and HDPE.

Die designs that must process high viscosity materials such as LLDPE and HDPE are given special consideration, in order to maximize the internal clearances and reduce pressure drops while still ensuring good flow uniformity as the melt exits the die lips. It is easier to achieve uniform die flow with tight die lips and restrictive internal passages, but the negative effect of the resulting pressure drop on output rate and melt temperature of the screw is seldom acceptable to the blown film producer. Bubble formation in this case is aided by having the lowest possible melt viscosity and, hence, the lowest practical melt temperature. The experience and the knowledge gained in today's die design decisions allow a much lower pressure drop through the die while preserving good flow uniformity.

Blown film is typically thin, with 0.0001 inch film possible with some materials. Film thicknesses of 0.125 inch and thicker are possible under some circumstances, but the typical range of film gauges encountered with this process is 0.0001–.050 inch. Other than the gauge dimension, a layflat width usually is given, which is simply the width of the bubble after collapsing into a flat film of double width. The layflat width dimension is the bubble circumference (3.14 × final bubble diameter) divided by 2.

A growing trend in this process is coextrusion, just as is seen in the flat die sheet process. The die is designed with multiple flow distribution channels so the layers come together after they have been evenly distributed in the annular configuration, prior to the die lips. Many layer configurations are used to achieve a variety of film properties. Barrier materials (for oxygen, moisture, odor barriers, etc.) usually require adhesive layers for adherence to the outer layers of the film structure. The barrier layer typically must be placed inside the film structure because environmental effects (moisture, etc.) can noticeably reduce the barrier material's effectiveness. The number of layers can be from the simple two materials up to eight to ten layers with very complex die systems. Typically, four to seven layers are found to cover most situations.

There is no trimming necessary in this process to make the film edges uniform in dimension, because of the cylindrical die opening. There is some amount of regrind material created with the blown film process, due to startup scrap while the lines are being tuned to the final gauge and scrap formed when the layflat is slit to form sheets. In coextruded film, regrind can be hidden in an inside layer. The regrind usually is added to the virgin feed material in the extruder hopper at 10 to 30% levels to avoid disruption of extruder processing efficiency due to the bulk density reduction seen with fluffy regrinds of these films. An alternative approach to reusing the regrind is to repelletize the fluff in a reclaim extruder and add the pellets to the virgin material on the production line, with little or no feeding efficiency loss.

Some extrusion lines have printing equipment on-line as well as bag-making machines, which form the sealed edges and the opening configurations. The folds, or gussets, typical on the sides of some bag constructions can be made in-line with this process by using a folding apparatus in the collapsing area. Simpler extrusion lines form the film or sheet and perform the printing and bag-making functions off-line. Depending upon the line speeds, there are arguments that support both methods of performing post-extrusion functions. Films made by the blown film process usually are of lower clarity than their cast film counterparts.

Some of the products formed by the blown film process are garbage bags, can liners, agricultural films, grocery bags (T-shirt bags, etc.), and thin films for paper and tissue products.

Common polymer materials used in this process include polyethylenes, polypropylenes, EVA, and flexible PVC.

Sheet, Extrusion Coating, and Cast Film

Sheet. The extrusion process used to form sheets continuously is illustrated in Fig. 4-13. The melt is formed through a die having a narrow slit aperture that forms the sheet and directs the melt to cooling and polishing rolls. The die takes the melt from the extruder, typically in a continuous rod shape, and uniformly spreads the melt into a wide sheet of uniform thickness. The die that spreads the melt into a uniform sheet is shown in Fig. 4-14.

The manifold of the typical sheet or film die resembles the shape of a coathanger and is designed, along with the remainder of the die clearances, to uniformly distribute the melt from the extruder into a wide, thin shape. Because many sheet and film extrusion lines must produce a range of products with different thicknesses over a range of output rates, melt temperatures, and sometimes different polymers, the die must perform its uniform distribution function under various conditions. The versatility of one die manifold configuration has limitations that are sometimes eliminated

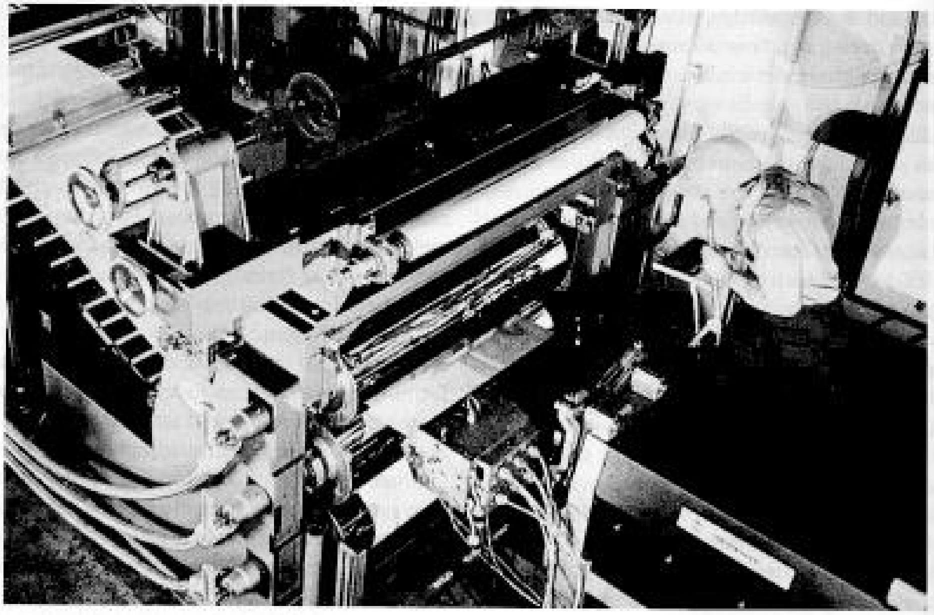


Fig. 4-13. Sheet extrusion line. *(Courtesy Davis-Standard)*

through the aid of a distributor or choker bar, especially with thicker sheet products. The die's uniformity can be roughly adjusted by lowering or raising the choker bar, and final gauge adjustments are made through the use of lip adjusting bolts. Some materials (such as vinyls) are more degradable than others and make the use of the choker bar impractical, because of the small potential hang-up areas on each side of the bar.

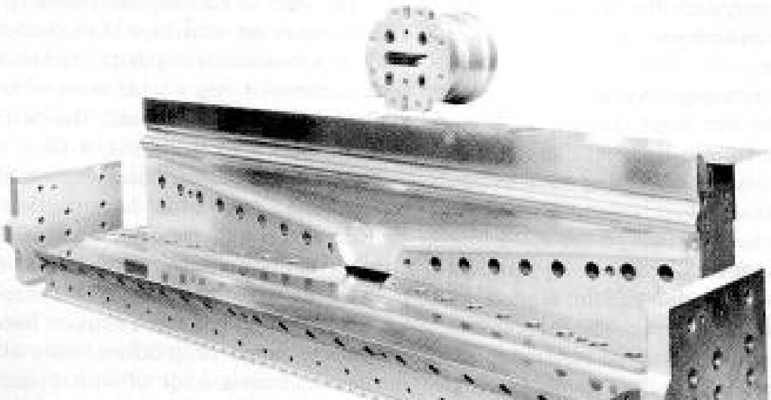


Fig. 4-14. Coathanger die. *(Courtesy Davis-Standard)*

The die lips are the final surfaces (lands) through which the material passes before exiting the die. The lengths of the lip lands are designed through experience and are usually 10 to 20 times the expected lip opening. The final lip opening usually is adjusted to approximately the thickness of the final sheet gauge. Based on experience, the amount of polymer swell or the desired drawdown of the material coming from the die lips will determine if the initial lip opening should be larger or smaller than the desired sheet gauge. Should a die be required to extrude products over a wide thickness range, the die must be designed so that the lower lip is removable for changing lip gaps over the broad range. The die's interior surfaces are highly polished and usually plated with a material such as chrome to ensure no flow interruption and to avoid any melt hang-up and resultant degradation or sheet uniformity problems.

The die has several heating sections (zones), which are controlled near the material's extrusion temperature. Adjusting these die heater zones independently of one another also will aid in altering material flow through the die and will give an additional parameter for rough sheet gauge adjustment, as the polymer flowing through the die is affected somewhat by the metal temperature of the die surfaces. Some sophisticated sheet extrusion systems incorporate an individual heater on each die lip adjusting bolt. Each of the lip bolt heaters is closely controlled to a temperature that will give a required expansion or contraction of the bolt and a resulting lip adjustment. These fine lip adjustments are determined by a microprocessor controller, which reads the sheet gauge from a scanning device placed after the cooling rolls, determines where the gauge needs correcting, and controls the proper die lip heaters to effect the change. The gauge must be set manually first, to a range close to the required uniform gauge, and final slight adjustments can be made by the lip bolt controller as the line is running.

The melted material flows out of the die lips and is wrapped around several cooling rolls, which impart the final gauge and surface finish characteristics. The most typical setup utilizes three rolls in a vertical arrangement with the melt entering between the top and middle rolls. The middle roll, which determines the surface finish, may be highly polished for a high-gloss sheet or embossed to produce a pattern on the molten material.

The rolls are driven either by a single DC drive connected to the rolls through a chain system, or by individual drives that all are closely coordinated for accurate speed control. The separate drive package usually is chosen for critical applications such as optical-quality sheet, where chain drives can impart "chatter marks" at a frequency related to the chain's pitch dimension.

The roll entry point (called the nip) is adjusted to a gap dimension 5 to 10% larger than the final sheet gauge to adjust for shrinkage of the material as it cools along the later roll surfaces. After passing through the nip, the material travels in an "S" wrap pattern, with one surface in contact with the center roll for 180°, and then does a reverse wrap, with the other surface contacting the lower roll for about 270°. The nip point between the middle and lower rolls usually is set close to the final sheet gauge because much of the shrinkage occurs as the material cools prior to entering the lower nip.

Sometimes the material is extruded "upstack," entering the rolls between the lower and middle rolls. Upstack extrusion allows the sheet to travel down the line with its embossed side up. An alternate arrangement is for the rolls to be set up on a horizontal plane with the material extruded downward. This allows very low viscosity materials to flow more uniformly to the rolls without drooping.

The cooling rolls are temperature-controlled by oil or water passing through their interior. Maintaining a minimal temperature differential across the roll surface is important, and the design of the cooling flow path must ensure high velocities and turbulent flow (a high Reynolds number) for the cooling fluid passing through the roll. The temperature of the cooling fluid for each roll is controlled by a separate system to allow different roll temperatures as required by the process. Usually the upper and middle rolls (downstack extrusion) are controlled at a higher temperature than the lower roll to temper the initial sheet cooling, control embossing, and control initial sheet surface cooling (hence surface appearance, etc.). The lower roll normally will be quite cool to maximize heat removal. Some atmospheric conditions may produce moisture condensation on cold roll surfaces, and increased roll temperatures may be required to avoid sheet surface marring by roll surface water droplets.

The size of the cooling rolls will depend upon the cooling time required, based on the extruder's output rate and melt temperature along with the sheet dimensions, which determine the line speeds and hence the time in contact with the rolls. The rolls are typically between 8 and 24 inches in diameter, with larger and smaller rolls possible under some conditions. The frame that holds the main rolls must be of sufficient mass and design to avoid vibrations and sheet quality problems (such as the chatter marks caused by the vibrations). The sheet line may require additional cooling after passing the three main rolls, which is accomplished through the use of auxiliary rolls placed downstream. The auxiliary rolls are often aluminum because of its good heat removal properties and the fact that the sheet's surface already is determined by the highly polished main steel rolls. The auxiliary rolls typically are controlled at as cool a temperature as is practical.

The die typically is a heavy block of steel with a wedged-shaped exit end. Because of the drawdown of the melted material after it exits the die and the trimming of the sheet's edges, the width of the die is greater than the finished sheet width by about 10 to 20%. When narrower sheet is required from a wide die, deckle bars may be used, which are restrictive bars that clamp onto and block off some distance from the die edges and across the lip surface. Instead of bars, rods may be used, which slide into grooves machined along or just prior to the die land. The pressures present in the die along with the sizable widths typically seen (up to 100 inches) require thick steel die body halves with many large connecting bolts, set on the extruder side of the flow manifold, to resist deflection and hence increased opening at the die lips, which would cause uncontrollable gauge. The die lips must extend between two of the main cooling rolls to a point fairly close to the nip to avoid excessive sagging of the melt. When very low viscosity materials are processed (such as polyesters), it becomes very critical to use sharp angles on the front of the die to allow close proximity of the lips to the nip point. Stiffer melts are not as great a concern in this respect because their melt strength will allow them to travel greater distances prior to the nip without drooping drastically and causing sheet forming problems, compared to the lower-viscosity materials.

After passing through the roll stack and any auxiliary rolls, the sheet usually is trimmed on each edge (with slitter knives) to produce uniform sheet dimensions, and is passed through a two-roll nip with rubber rolls that are speed-controlled to create some tension in the sheet. The sheet line tension can be set by using a torque controller or just through the speed setting versus the main roll stack speed. The material trimmed off the sheet edges normally is ground into fairly small pieces and re-extruded as a blend with the virgin material. Typically, a 10 to 40% blend of regrind is utilized in this manner. Downstream from the rubber rolls there is a winder or shear, depending upon the sheet's thickness and pliability. Thin sheet (0.020–0.030 inch thickness and thinner) or very soft sheet (flexible vinyl) can be easily rolled up on a winder; thicker sheet (up to 1 inch thick) or stiff sheet is typically cut to specified lengths and stacked for subsequent operations. The very thin sheet (0.010 inch and thinner) usually is called film. When the film thicknesses become very small (0.005 inch or thinner), the nip point of a three-roll stack will start to present as problems. Maintaining a uniform contact across the nip surfaces becomes difficult because of the tiny nip dimensions required. Sometimes the top roll can be lifted away from the middle roll, and having no nip may produce an acceptable film. If the material is not contacting the roll uniformly, and perhaps is creating air entrapment between the material and the roll surface, an "air knife" sometimes may be used to force the material to the roll through a uniform jet of air blowing on the melt toward the roll surface. Sometimes the very thin films must be produced through a cast film method (see below).

Some of the uses for sheet and film made by the extrusion technique discussed here include thermoforming in molds, packaging, window glazing, and laminating.

One of the fastest-growing extrusion procedures is coextrusion, where several material layers are combined to create unique product properties compared to monolayer materials. Sheet and film production are enjoying much growth in the area of coextrusion in applications such as food packaging, where the moisture and oxygen barrier requirements are satisfied with different materials (EVOH, PVDC, etc.) and, hence, multilayered sheet structures. The combining of the various layers for a multilayered coextrusion sometimes is done in the die system and at other times is done after the melt exits the die, in a lamination process. The most efficient coextrusion is accomplished with the melt streams combined in the die or die adaptor system. The melt streams usually are combined in a coextrusion adaptor block positioned prior to the die, and the die flow channels form the final sheet dimensions of the combined layers of melt. The melt streams meet in a square, rectangular, or round adaptor geometry and then flow in a laminar fashion through the die system. As the coextrusion geometries become more complex with increasing layers because of the necessary product end properties, the various adhesive layers required, and the typical need for an adhesive layer in the structure, the number of extruders and the complexity of the die coextrusion adaptor system increase. A coextrusion sheet line can consist of a simple two-extruder setup or may contain five or seven extruders in a system, making seven to ten layers in the product.

Some materials exhibit noticeable property improvements, such as tensile strength and tear resistance, when the sheet is oriented both in the machine direction and across the sheet. This is a termed biaxial orientation. The natural pulling of the solidifying melt in the machine direction as the cooling and polishing is being performed will give some orientation, but cross-sheet orientation and high-machine-direction orientation are achieved by using tenter frames (see Fig. 4-15). These devices stretch the film's length and width by a desired amount up to 10:1), depending on the properties sought. The temperature of the film is controlled in ovens on the sheet line during orientation to yield the proper physical properties in the final sheet.

Some of the many polymers used in sheet production are polypropylenes, polyethylenes, PVC, polycarbonate, ABS, styrenes, and acrylics.

Extrusion Coating. The extrusion of a melt through a flat sheet die also can be used to produce a thin film for coating on a paper, foils, fabric, or some other substrate material, which is unwound off a feeder roll on an unwind station and passed through the first nip point of the roll stack. (See Fig. 4-16.) Sometimes the substrate is treated prior to the coating for enhanced adhesion. The coating typically is 0.0002 to 0.015 inch thick, and the substrate materials typically are 0.0005 to 0.024 inch thick. Common coating materials involved in this process include polyethylenes, polypropylenes, urethanes, ionomers, EVAs, nylons, polyesters, and PVCs. Extrusion coating often requires an elevated temperature (as high as 650°F) to produce a very low viscosity melt to enhance the flow properties and adhesion of the material. Parameters determining adhesion of the coating material to the substrate include the chemical structure of the resin, oxidation of the melted material between leaving the die lips and meeting the substrate, melt viscosity, line speed, coating thickness, pretreatment used on the substrate (corona, chemical, flame, etc.), and cooling rates of the coated structure.

To provide elevated melt temperatures, coating extruders typically are long (30:1 or 34:1 L/D) and employ a valve in the die adaptor to increase the resistance that the screw has to overcome.

The melt covers the surface of the moving substrate, which then travels through nip rolls where the surface finish is determined and cooling is performed. The rolls are cooled, as

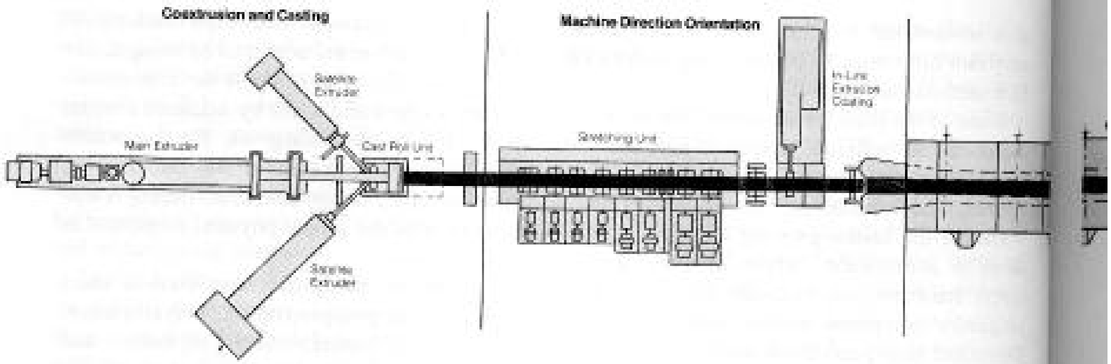


Fig. 4-15. Biaxially oriented film line using tenter frame stretcher. (*Courtesy Marshall & Williams Co. Providence, RI*)

with the sheet process, and the temperature of the cooling fluid usually is quite low to maximize heat removal. Some products are laminated with other layers, (e.g., scratch-resistant films), which are applied from rolls after the coating process.

In extrusion coating, the die normally is positioned so that the melt exits downward between a larger cooling roll and a smaller pressure roll. The material progresses around the large roll and exits to a secondary pressure roll about 270° from the initial contact. Sometimes, coating can be run with a vertical stack and a sharp die front angle to obtain close proximity of the lips and the nip point. Because of the low viscosity and weak melt strength of the thin extrudate, however, downward extrusion is most typical.

After cooling, the surface of the coated stock may be treated on-line for subsequent printing; untreated polyethylene, a common coating material, does not accept printing inks well. The coated material is trimmed to provide uniform edges and rolled up on a winder.

Cast Film. The cast film process is used to produce very thin films, down to gauges of 0.002 to 0.003 inch. The die, as with the extrusion coating process, is directed downward to lay a thin, low viscosity melt onto the primary cooling roll in a tangential orientation. The materials utilized for cast film are similarly low in viscosity, with melt temperatures of 350 to 550°F used to enhance thin film drawdown. Long extruders and die adaptor valves are used to elevate the melt temperature. The gap between the die lips is typically 0.010 to 0.020 inch, and the melt draws down from that dimension. (See Fig. 4-17.)

If the melt will not deposit uniformly on the

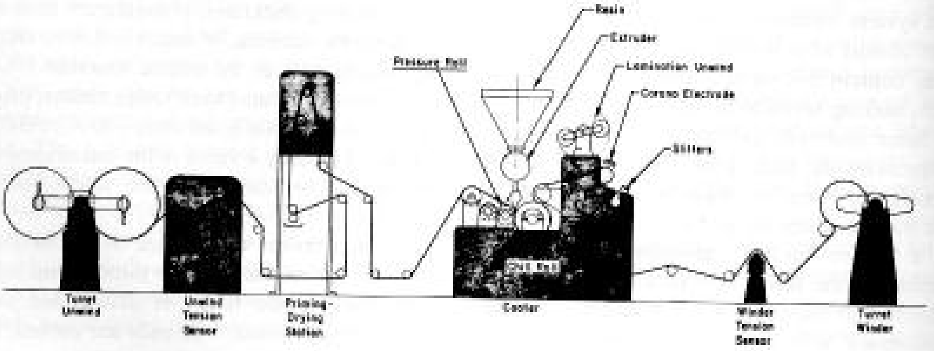


Fig. 4-16. Typical extrusion coating line. (*Courtesy E. I. du Pont de Nemours & Co., Inc.*)

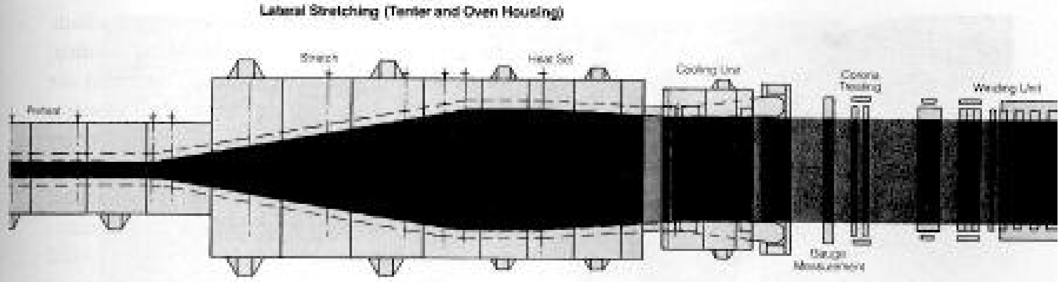


Fig. 4-15. *(Continued)*

cooling roll with no air entrapment, an air knife is required; it uses air jets to force the thin melt curtain onto the roll surface. The melt travels about 270° around the main roll, which is cooled with chilled water. The majority of the cooling and surface finish production occurs on the main roll, which usually is highly polished and chrome-plated to produce a smooth clear film.

The cooling process is completed as the film reverses its orientation and the opposite film surface contacts the secondary roll. The temperature of the cooling rolls is set on the basis of experience with the material being extruded and the degree of clarity required. Because the film is thin, it cools quickly, but line speeds are quite high and residence times thus are short. The rolls are driven at very precise speeds with DC drive systems to ensure consistent film dimensions. Gauge uniformity also depends on the extruder's pumping stability, die adjustment, cooling rate, alignment of die and cooling rolls (to avoid wrinkles), and melt uniformity from the screw.

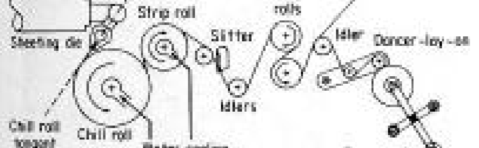


Fig. 4-17. Chill roll extrusion setup. *(Courtesy E. I. du Pont de Nemours & Co., Inc.)*

After cooling, the film is slit for edge trimming and perhaps for producing multiple film products at once. Edge trim is removed for regrinding and typically is re-extruded at low percentages (5–20%) with the virgin material. The low-bulk-density trim from these very thin products does not readily flow in a hopper and can cause feeding problems in the extruder at any high or even moderate percentage level. The possibility of introducing contamination in the regrind process, which would be very detrimental in thin film production, often precludes any reuse of trim or scrap.

The film winding tension is controlled by the speed of a set of rubber rolls and their relation to the cooling rolls' speed. The film is wound on a high-speed turret winder, which is capable of high-speed roll changes.

Profiles and Pipe

Profile Extrusion. Profile shapes can be produced by the extrusion process, from simple tubing or rods to complex custom shapes such as those used in window frame components (see Fig. 4-18). Methods of cooling and shaping the final products vary as widely as the number of shapes possible, from simple water trough cooling to complex vacuum sizing equipment that holds the outer surfaces fixed during solidification. The most common material formed by profile extrusion is rigid PVC, which has the needed processing and physical property balance. Other materials, such as polyolefins,

Fig. 4-18. Window profile. *(Courtesy Davis-Standard)*

styrenics, and various elastomers, also are utilized in profile applications.

Extruders utilized in profile extrusion typically have barrel lengths of 24 : 1 L/D, with 20 : 1 and 30 : 1 occasionally used. The output of a profile line is limited by the downstream cooling efficiency and the related ability to hold tolerances on the finished product; as a result, the extruder is not so fully utilized as in a process such as sheet extrusion. The allowable melt temperatures in most profile applications are lower than the temperatures for making film or sheet, where lower viscosities aid in forming the end product. The custom profile extruder may have to process multiple materials over wide processing ranges. Enhanced operational versatility may be achieved by using a modern barrier screw design.

Any shape with a large, solid cross section tends to present problems due to voids that develop in the center after the outer surfaces have cooled. The cooling rate at the center is much slower than at the outer surfaces because the material is insulated from the cooling medium. Because the polymer shrinks upon cooling, voids are formed in the center. This effect can be minimized by cooling the product in steps, starting with air or warm water before going into the cold water bath. Voids in rod extrusion also may be eliminated by cooling the die itself and using the puller to retard the exit of material. In this way, the shrinking center is filled under the pressure of incoming material.

Difficulties of predicting polymer flow in a three-dimensional die, coupled with drawdown unknowns, cooling rates, and so on, make the design of complex profile die systems very difficult. Dimensional corrections to the die are usually necessary after it is tried for the first time. Persons proficient in profile die work lean heavily on experience, sometimes combined with computerized die flow analysis, when building a new die. (See Figs. 4-19 and 4-20).

Very narrow die openings can produce a rough surface on the extrudate due to a phenomenon called melt fracture, which is related to the ability of the material to slide smoothly across the die's surface. The die opening may be increased to reduce shear, forcing higher drawdowns to achieve the final dimensions.

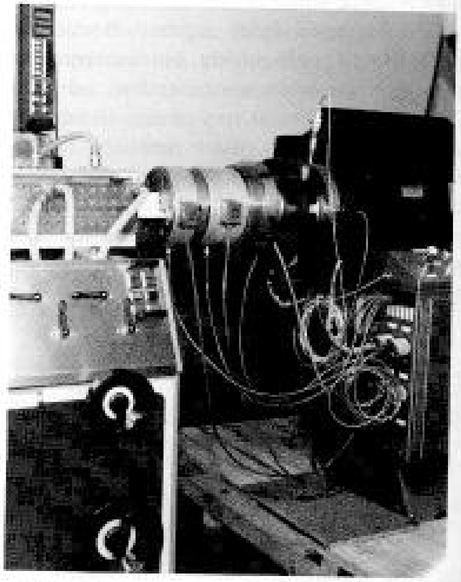


Fig. 4-19. Profile die. *(Courtesy Davis-Standard)*

Fig. 4-20. Profile extrusion line. (*Courtesy Davis-Standard*)

Alternatively, the die metal may be polished further and/or coated with a material to reduce friction. If mechanical adaptations are not successful, it may be necessary to substitute a less viscous polymer.

Downstream from the profile extrusion line die, the material is pulled through a cooling area to a cutoff or coiling station. Cooling methods are designed to produce an accurate shape for the profile, minimize cooling voids and other distortions, ensure a good surface finish, and maximize line speeds. Simple shapes made from high viscosity materials such as rigid PVC can be successfully sized and cooled by air blowers, using jigs that hold the part as it passes over a table. Thicker areas of the part will cool more slowly than thinner areas and must be favored with extra cooling medium if possible. When water cooling baths are used, straightness sometimes is maintained by using radiant heaters positioned to alter the cooling process.

When hollow shapes are made, vacuum usually is employed to hold the outer walls of the part in place during cooling. Vacuum cooling of intricate parts such as window profiles is done in one or more cooling stations built with the part's outer shape on their internal openings. Vacuum passages and cooling fluid passages are bored in these stations (vacuum calibrators) so that heat is transferred from the part as it is held in position. (See Fig. 4-21.) Allowances for part shrinkage are designed into the calibrator(s). As the output rate increases (along with the extruded part's linear speed), the cooling time in each calibrator decreases, requiring more units to ensure part tolerances. Some systems use water sprays between and directly on the calibrators' outer surfaces to add cooling capacity. These calibrators usually are made of aluminum with wear-resistant coatings applied to the inner contact surfaces. The calibrators are from about 6 inches to 36 inches long. As the number of calibrators increases, the additive drag over the units increases, requiring a fairly large-capacity puller.

Profile pullers have long contact lengths (up to about 40–80 inches) and high squeezing force capacity. There are some limitations to the amount of force that the puller can exert in the holding function, due to possible part deformation. These forces usually are quite high

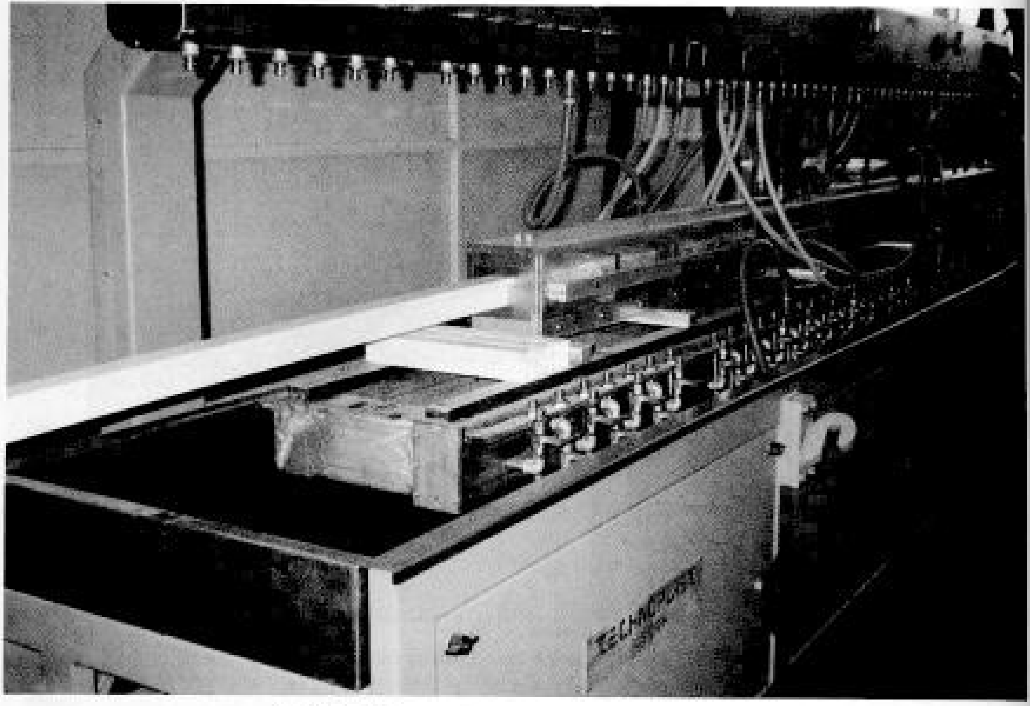


Fig. 4-21. Vacuum calibrator. *(Courtesy Davis-Standard)*

with rigid PVC window profiles, and an intricate part with small protrusions can be run on a puller with formed belts or cleats for the particular profile. This way, the part's main body will absorb the forces, and the protrusions are protected by reliefs cut into the belts or cleats. The part then is cut to length with a traveling saw and stacked on a collection table.

Less intricate parts are extruded and pulled through a water bath, and their shape can be held without external fixtures. Between the simple and complex shapes are a host of profiles that are cooled and sized with differing levels of shaping fixture complexity. The difficulty in cooling and sizing a particular part determines the output rate possible from an extruder. Melt temperature and corresponding viscosity also play a large part in determining attainable line speeds.

Coextrusion is seen in the profile processes with such products as window profiles, where there may be a rigid PVC profile with flexible PVC sealing ribs for the window panes, which are slid into some of the window frame profiles. Some pipe or tubing also is produced with coextruded wall geometries to achieve some unique properties, such as foam inner layers for weight and material cost reductions or coextruded weather-resistant material over a cheaper substrate for parts that must be used outside.

When a part is to be made of foam for weight reduction, sizing usually is initiated in a sizing block at the beginning of the cooling tank. Once the outside of the part is set, the sizing block is not needed and thus usually is quite short (2–12 inches long). Often, vacuum is applied to the sizing box through small orifices, forcing the material's outer surfaces to be in positive contact with the sizing block. There are natural forces from the foaming material that cause it to swell and contact the block's surfaces; nonetheless, some materials yield better part shape uniformity and surface finish when vacuum is used. Most profile foam shapes are produced by using chemical blowing agents (CBAs), which are added to the polymer prior to extrusion. This method allows density reductions of up to about 50%. If lower density is required, a physical blowing agent such as nitrogen, pentane, or a chlorofluorocarbon must be employed. Coextrusion may be selected to form a profile with low density and a smooth surface.

Pipe and Tubing Extrusion. Pipe and tubing are produced from similar die designs, except for very large pipe (10 to 60 inches in diameter), where the dies more closely resemble those used in making blown film. To form the rod-shaped extrudate into a hollow shape, pipe dies contain a spider, a contoured inner section held in position by several ribs. After the pipe exits the die, it is pulled through a cooling and sizing apparatus. (See Fig. 4-22.)

As the pipe comes out of the die, the melt normally swells slightly; the extrudate first is drawn down into a slightly oversized (compared to the final pipe O.D.) sleeve at the end of a water-filled tank. Air is introduced inside the pipe through a hole in the die pin, helping to maintain the internal dimension. Most commonly used pipe materials (rigid PVC, ABS, HDPE) will easily slip through the sizing sleeve; for materials that tend to stick, a precooling stream of water, perhaps containing a lubricant, is dripped onto the melt as it exits the die. The cooling tank contains enough water to cover the pipe completely, and vacuum is drawn in the air space between the water and the tank cover.

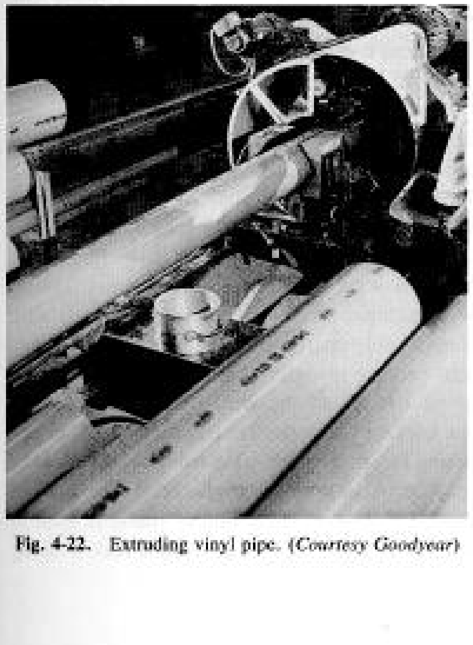


Fig. 4-22. Extruding vinyl pipe. *(Courtesy Goodyear)*

The length of the initial cooling tank may be as short as 6 feet, depending upon cooling requirements of the pipe and line speeds being run. Additional cooling is performed in secondary water tanks with no vacuum. After the final tank, the pipe passes through a belt puller and is sawn into lengths.

Some pipe processes do not use vacuum sizing but instead have a plug attached to the die pin. The plug is placed at a distance of 1 to 12 inches from the die and sets the I.D. rather than the O.D. of the product.

The extra buoyancy of large-diameter pipes in water baths makes it difficult to maintain straightness; so spray cooling often is chosen. High-velocity water sprays provide improved heat removal for thick-walled large pipes. The takeoff equipment for large pipe also is different; in place of belt pullers, special devices are used that have driven rubber tires located around the periphery. Cutting saws rotate around the pipe's circumference while moving along the line with the pipe.

Smaller-diameter pipe and tubing (under $\frac{1}{2}$ inch O.D.) usually can be sized without the use of vacuum. The dimensions of the product are determined by the tooling dimensions and by fine control of the air pressure inside the tube as it goes into the cooling tank. Some small tubing (e.g., with thin walls or made from soft melts) can benefit from vacuum sizing.

Pipe and tubing also can be produced by using a crosshead die, which directs the melt perpendicular to the extruder axis. This type of die, which is widely used in wire and cable coating, is described in the following paragraphs. Its advantages in making tubing are the ability to coat a core (another tube, a metal pipe, etc.) and to eliminate the die spider, which sometimes gives "knit" lines where the melt reconnects. The crosshead die has one knit line on the side away from the extruder, whose effect must be minimized by a well-streamlined flow path.

Coextrusion is used in the pipe and tubing industry to create products with improved properties over monolayer constructions. Foam inner layers, for example, are used to reduce weight and cost in ABS and PVC pipe. Coextruded tubing can be made in a tandem process where a finished tube is passed through a crosshead die that deposits the second layer on its outer surface. Today's die technology, however, allows the different layers of the tube to be produced in a single extrusion operation.

Wire and Cable

Wire coating is one of the oldest extrusion processes for thermoplastics. The die used on a wire coating extruder is unique, as a wire must pass through the die for coating. (See Fig. 4-23.) There were some early attempts at passing the wire along the screw's core, exiting out of a clearance hole in the screw tip and through a straight die. Sealing problems involved with this method led to the development of today's crosshead wire coating dies. A simplified sketch is shown in Fig. 4-24.

Two tooling designs are typical in wire coating with crossheads. One is pressure tooling (shown in Fig. 4-24), where the melt is applied to the wire inside the die under whatever pressure exists after the wire exits the guider tip. The space between the guider tip and the tapered shape of the inside of the die is termed the gum space; it can be adjusted by using bolts on the back of the crosshead (where the wire is entering). With the second design, called tubing tooling, the melt is applied as the wire exits the die. Here there is no pressure forcing the melt onto the wire; in some instances, a low level of vacuum is drawn in the die core to aid in pulling the melt onto the wire and avoiding trapped air. (See Fig. 4-25.)

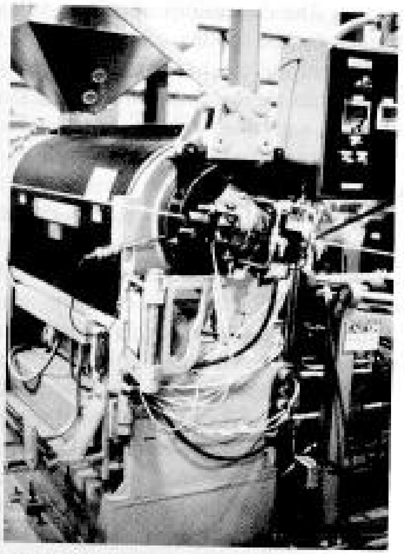


Fig. 4-23. Wire line and crosshead die. (*Courtesy Davis-Standard*)

In wire coating, the bare wire is unwound from a reel and fed through the extrusion die. Line speed is determined by a puller called a belt wrap capstan. (See Fig. 4-26.) The coated wire then runs through a cooling trough for solidification of the polymer. A winding device at the end of the line pulls the wire from the trough and produces reels of finished product. The trough lengths are determined by the size of the wire and the coating thickness. Some materials require cooling in stages, with warmer water used closer to the die.

Preheating the wire prior to coating enhances adhesion of the insulation being applied. Both flame and induction heating are commonly used. Wire straightening devices also are popular for ensuring uniform coating. Another optional auxiliary device is a spark tester, which is placed after the cooling trough to detect wire breaks or insulation defects. Printing equipment and footage counters are used on the majority of wire lines.

Because the melt is supported by the wire, high line speeds are possible, and melt temperatures can be relatively high compared with profile processing. Some small-diameter wire coating (e.g., under 0.030 inch O.D.) can be run at 7000 to 10,000 ft/min. Winding of the finished wire requires a sophisticated takeup with automatic reel changeovers. Small wire that is being coated at high line speeds may utilize cooling troughs with the ability to handle several loops of the wire (multi-pass) so that the cooling residence time is multiplied, as opposed to using single-pass troughs of very long lengths. Also with the high-speed wire lines, a series of sheaves on a sliding frame is used to accumulate the wire as a winder reel is being