4
Extrusion Processes

The earliest extruders were used predominantly in rubber processing. The machines were short extruders because that process does not require melting per se as with plastics but merely softening and pumping through a shaping die. The traditional feed form of rubber is strips, which must be pulled into the screw by the screw's feeding flights and the feed section design features.

As plastics were developed, the extruder's design started to change in order to meet the new melting requirements. Barrel lengths increased, and heating of the barrel was more critical as the extruder needed to be heated in the 300–500°F range as opposed to the 100–200°F range for most rubber processing. The screw design for conveying rubber had to be noticeably altered to process the new polymers. Plasticating extruders as they are known today were first developed in the 1930s and 1940s as altered rubber extruders. Since that time understanding of the melting process has grown, as has processing experience with the various materials, leading to much more efficient designs of the extruders and the accompanying equipment.

Extrusion Concepts

Extrusion of thermoplastic materials can be accomplished through various means, depending upon the product being manufactured. Typically, extrusion with polymeric materials (plastics) involves a continuous operation as opposed to making a product with an intermittent process as done in injection molding. The various products made by extrusion include pipe, tubing, coating of wire, plastic bottles (blow molding), plastic films and sheets, various plastic bags (blown film), coatings for paper and foil, fibers, filaments, yarns, tapes, plastic plates and cups (thermoformed sheet), and a wide array of profiles.

Extrusion is accomplished by melting the material and forcing the melt through a forming die. The polymer material is fed to the extruder through a feed opening and can be introduced to the extruder in pellet (or cube) form or alternately as a powder, a granulate, or, in some processes, a melt. Extruders used in rubber extrusion and with some adhesives must accept a strip as the feed form. The extruders that are fed a melt are used for pumping to pressurize and to force the material through the die system or to aid in such parameters as cooling the melt from a melting extruder. The typical extruder is required to take a solid feed material and to melt, homogenize and pump the melt through the die system with acceptable output uniformity. The output consistency is measured by the uniformity of the dimensions of the finished product.

The extruded melt is continuously shaped and cooled by downstream equipment placed after the extruder. This sizing/cooling equipment can be comprised of cooling rolls, water tanks, vacuum sizing fixtures, air cooling tables, pulling devices, cutting equipment, coiling or winding equipment, and so on.

The extruders used to produce these products are overwhelmingly of the single screw vari-

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ety, with several other types of machines used in some situations. These single screw extruders are simply comprised of a flighted screw that rotates within a heated cylinder (barrel). The screw is rotated by a drive motor through a gear reducer. Alternate extruders to the single screw include multiscrew machines (usually twin screw), rotary extruders (screwless), and ram extruders. The twin screw and also the less popular quad-screw extruders are comprised of multiple screws within a heated barrel and are most popular for making rigid PVC (polyvinyl chloride) powders into pipe and various profiles (window profiles, house siding profiles, etc.). The melting performance of this material lends itself to the low shear pumping seen with these types of extruders. Most polymers require more energy to thoroughly melt and homogenize them than a typical twin screw extruder can efficiently produce. When a twin screw extruder is designed to develop shear levels comparable to those of single screw extruders, the performance is not improved over the single screw machines, and the economics and operational advantages favor the single screw extruder. That is why twin screw extruders have not widely penetrated the single screw marketplace, except for the PVC powder extrusion applications. Another use of twin screw extruders is in compounding where additives must be dispersed into a polymer. Here special mixing twin screw machines have been developed, which do a good job and are very expensive. These compounding twin screw extruders typically can deliver high output levels (2000–10,000 pounds/hour and greater) and are not economically practical for the extrusion of everyday products as described above.

Rotary extruders have been in use for the last ten to fifteen years but have seen limited use due to their sealing problems against melt leakages and their low pressure-generating capabilities. These machines are made up of heated discs that rotate with polymer between the plates where shear is developed and melting takes place. Some pressure can be developed, but nowhere near the typical 2000 to 10,000 psi levels of single screw or twin screw extruders. The possibility of melt leakage leads to concern for contamination due to degrading polymer because the system is not totally self-cleaning. Some large rotary units are being used for pelletizing or compounding applications, and a few smaller units are being used for products such as polypropylene sheet; but the single screw extruder still is and will remain the workhorse in polymer extrusion for the foreseeable future.

There are some materials in the fluoropolymer area and some materials such as ultra-high molecular weight polyethylene that will not process acceptably on the screw extruders mentioned above. For these materials, a ram extruder is employed. This device is a non-steady-state machine that discharges its volume by using a ram or a plunger to extrude the melted material. The polymer is melted by conducted heat through the barrel in which the ram travels. This extruder is not a substantial influence on today's extrusion markets.

SINGLE SCREW FUNCTIONAL DESCRIPTION

Because the single screw extruder is by far the predominant machine used in polymer extrusion, its operation is mainly described, with comments regarding alternative extrusion means added as appropriate. The basic function of this type of extruder is to accept material in the feed section of the screw and convey this material along a flighted screw enclosed in a barrel. (See Fig. 4-1.) The conveying is forced by the rotation of the screw via a drive motor and gear reducer. The material usually must be melted (plasticated) along the path through the extruder screw although some processes introduce the feed material already in melt form so the extruder need only convey it. The melting of the polymer is aided by heaters that tightly encapsulate the barrel's outside diameter and are separated on the barrel into zones. These zones can be set at different temperatures as appropriate for the particular process involved. The screw must develop enough pumping efficiency to force the material through the die system. The pressure developed can be substantial for highly restrictive die systems and can reach 8000 to 12,000 psi. Typically the die pressure levels encountered are in the 1000 to 5000 psi range.

The design of the screw greatly impacts the

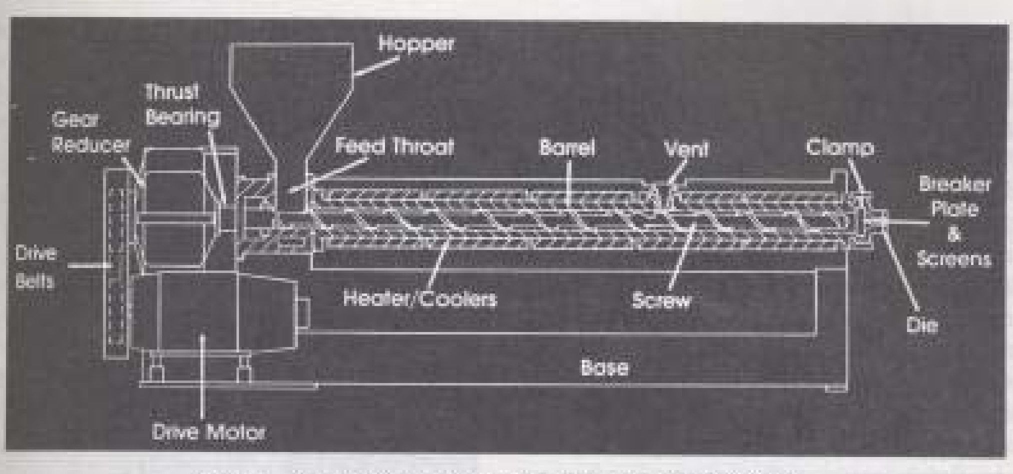


Fig. 4-1. Schematic figure of extruder. (*Courtesy Davis-Standard*)

extruder's performance and will be discussed in more detail in a later section. Much of the performance gains made by extruder manufacturers over the past 35 years have been due to improved screw designs. Numerous types of screws have been introduced over the years, some of them of great advantage while others are good for marketing but do little to improve the extruder's performance. Processors must recognize the benefits or shortcomings of particular screw design offerings to protect their interests and avoid the purchase of an ineffective design.

The extruder must produce its output (extrudate) within certain stipulations, as defined by the material, the end-product, and the process being accomplished. The extrusion goals and problem areas for various processes will be considered in a later section.

This section will cover the extruder's various functions and some ideas about how these functions can most effectively be accomplished. The basic function discussions will include feeding, melting, melt pumping, mixing, devolatilizing (venting) and the effects of some extruder add-on devices such as melt pumps, melt filters, and material preheaters.

Feeding and Solids Conveying

The extrusion process begins with the introduction of the material to the feed opening (feed throat) of the machine. The feed throat is located in a section of the extruder placed between the gear reducer and the barrel. This feed section typically is made from cast iron with cooling passages molded into the unit, and is designed to accept a material container (hopper) over the feed opening. This part of the extrusion process is of extreme importance because the failure of a consistent feed source will impact negatively on the stable performance of the extruder. Often in production situations, an unstable product gauge or dimension results from some poor feeding factor due to the material, screw design, or extruder feed area design. Most extrusion processes today are using polymers in solid form, either pellet, cube, powder, or granule. These require the full plasticating (melting) abilities of the extruder and will be the material forms of most importance to this discussion. Alternate forms of feed, including premelted material, rubber strips, reground material, and so on, will be touched upon as appropriate.

The conveying forward of the solid particles of material along the early portion of the screw is initiated by friction between the material and the feed section's bore. The conveying forces theoretically can become very high in a short distance and hence could lead to very high pressures. Actually, the pressures in the first portion of the barrel typically are 500 to 4000 psi. There are some materials that can exhibit very low pressures in the rear of the extruder due to poor solids-conveying efficiencies.

psi, as seen in added feed section and barrel wear as well as higher power usage from the drive motor. Most grooved feed sections thus are desirably produced from highly wear-resistant materials such as tungsten carbide lined cylinders.

Whether the feed section is smooth bore or grooved, the amount of wear definitely can affect feeding effectiveness and hence output rate and output stability. Worn smooth bore feed sections can be repaired with a sleeved section that will bring the bore back to original tolerances. Repair of grooved feed sections involves more effort because of the complexity of the machining.

Material Effects on Feed Section Design. The form of the material entering the feed hopper or feed section has an effect on the processing success of the extruder. Powders and fluffy regrinds, for instance, generally lead to more feed and processing difficulties than pellets, cubes, and heavier regrinds. The bulk density of the feed material determines how effectively the screw's feed flights are filled and how well the extrusion process can then commence. Most low-bulk-density regrinds and some powders (especially filled powders) will not readily flow down the hopper and through the feed throat to fill the feed flights adequately. When hopper flow problems are evident, special material forcing devices, such as compacting screws in the hopper/feed throat, sometimes are used to ensure a filled screw feed flight. Alternately, the materials that cause feeding difficulties can be pelletized or otherwise densified on other equipment to alleviate feed difficulties and hence processing inefficiencies on the production extruder.

Feeding melt to an extruder introduces the difficulty of obtaining a free-flowing situation through the feed throat area and may require a pressure-building source to push the material into the feed flights. Some processes drop a melted ribbon of material into the extruder's feed section, which makes a filled feed flight difficult to ensure. The screw feed flight design can help the feeding efficiency, but extrusion stability is not usually optimum.

Feed throat opening designs can vary, depending on the manufacturer and the process being performed. Today's typical, efficient throat design is a large rectangular opening directly above the screw. Through the years, feed openings have evolved from round shapes to oval to "obround" (lengthened oval-shaped) to rectangular. Today's rectangular throat design has an opening length of 1.5 to 2.5 times the barrel inner diameter dimension. The larger feed openings allow a free flow of material even with moderately high regrind percentages to ensure properly filled screw feed flights. The only uses of small feed openings in this era involve hoppers with force feeding screws (compactors) or force-fed melt conveying extruders.

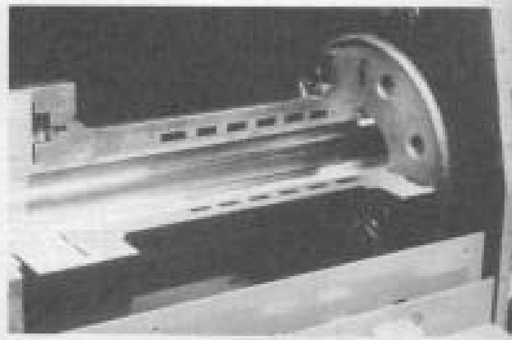
Tangential feed throats enter the screw area from one side and have added clearance around part of the screw's diameter. They are used for feeding rubber strips to allow partial wrapping around the screw.

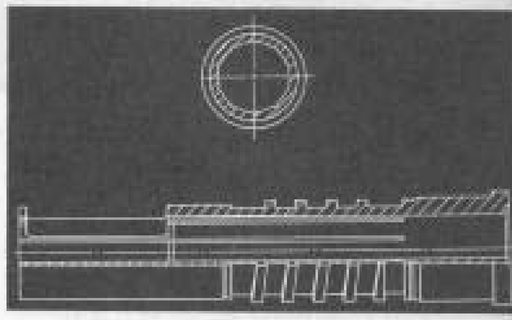
Most extrusion processes perform with best product uniformity when the screw is operated with full feed flights. Sometimes a metered feeder is used to run the process with starved feed flights for some processing reason; the extruder's stability must be acceptable or added processing devices must be used, such as melt pumps (see discussion of melt pumping later in this section). Twin screw extruders appear generally less sensitive than single screw machines to the starve feeding mode as far as output stability is concerned; but as the starving level is increased, even their output stability deteriorates.

Material Lubrication Effects. Some plastics formulations call for additives that create feeding and/or melting problems. The easiest place on the extruder to introduce additives is in the feed throat where the material is at atmospheric pressure. Should the material still feed and melt acceptably, the application of additives in the feed area is the most economical approach. When additives create feeding or melting difficulties, the possibility of injecting the additives somewhere along the barrel length is considered. Introducing liquid additives away from the feed area will help avoid solids conveying deterioration and, if far enough down the barrel, will avoid disrupting the melting perfor-

These materials include any highly lubricated formulations, members of the polypropylene family, and some of the high molecular weight high-density polyethylenes (HMW-HDPE). These low solids-conveying efficiencies usually lead to reduced output rates from the extruder, poor melting performance, and sometimes poor output consistency (output stability). The polypropylenes have enough conveying impetus to deliver moderate output levels and reasonable output stability as compared to easy-feeding materials such as most polyethylenes. When a material feeds very poorly, i.e., as screw speed is increased, the output increases very slightly or not at all, the extrusion process usually is unacceptable, and some feeding assistance is required.

Feed Section Design; Smooth Feed vs. Grooved. Typical commercially available polymers exhibit fair-to-excellent solids conveying; so the smooth bore of the feed section and barrel yield enough conveying force for stable extrusion at acceptable output rates. In these cases, melting and pumping performance can be maximized through screw design because no feeding inadequacies exist. When materials are encountered that do not have adequate solids conveying to allow the screw's melting or pumping functions to be reasonably maximized, feed assistance devices such as grooved feed sections are considered. (See Figs. 4-2 and 4-3.) These special feed sections contain grooves that start near the rear of the extruder's feed opening and continue past the feed opening area and usually beyond it by a distance of approximately three times the barrel inner diameter. The grooves usually are evenly spaced around the feed area's inner diameter and typically are deeper at their starting point at the rear of the feed section (gear case side). The grooves' depths then run out to the barrel inner diameter at their end. Typically, the grooves are cut axially along the feed section's bore; they also can be made in a helical configuration, which is believed to be more effective for the feeding of some materials but is more difficult to machine. Selection of the grooved feed section usually is justifiable only when there is a definite feeding problem. When the





Figs. 4-2 and 4-3. Grooved feed section. *(Courtesy Davis-Standard)*

material feeds moderately effectively, as most polypropylenes do, the use of a grooved feed section is debatable. When the use of a slightly larger extruder with a smooth bore feed section can match the performance of a grooved feed section extruder, the smooth bore usually is favored. Whenever additional extrusion features can be avoided in favor of operational simplicity with no sacrifice of performance, that is the favored choice.

The grooved feed section will increase output under most conditions with all materials, but if the screw is already pumping at or near the melting limits with a smooth bore feed section, any added output will not be useful. Grooved feed sections require intensive cooling to avoid melting in the grooved area, which defeats the conveying efficiency. Smooth bore feed sections are cooled typically, but only modest cooling levels are desired and required to avoid material softening and "bridging" in the feed area of the screw or in the feed throat.

The strong positive conveying efficiency of the grooved feed sections, when efficiently designed, causes high pressure levels at the end of the groove section, up to 10,000 to 20,000 mance. The concern for injecting late along the barrel is for mixing efficiency. Sometimes a mixer after the screw is helpful in blending the additives. One of the difficulties encountered when the additive is injected along the barrel is the need for a pump system to overcome the pressure in the barrel at the injection port. This pressure can be substantial, up to 5000 psi, so the pump system must be specified to meet the injection rate goal and to perform against whatever pressure is present. An additional advantage to injecting the additive later along the barrel is that the injected material does not remain in the barrel as long as the main polymer and is affected less by heat and shear. This is important where heat-sensitive materials, such as some liquid colors, are injected.

Melting Considerations

As solid material is conveyed from the feed throat and travels through the feed section of the screw, some compaction takes place. When it reaches the heated barrel, a melt film immediately forms on the barrel I.D. The melt film grows in thickness as the material moves down the barrel until it is thicker than the screw flight clearance with the barrel. Then the melt begins to collect at the rear of the screw channel (the pushing side of the flight). As the melt film goes through this thickness growth, transporting forces are developed by the shearing of the melt film. This conveying mechanism is termed *viscous drag*. (The material in the channel during the early melting process is sketched in Fig. 4-4.) The shearing of the melt film creates most of the energy for melting of the material at moderate to high screw speeds. The higher the viscosity of the melted material, the more heat is generated via melt film shearing. Stiffer materials such as rigid polyvinyl chloride (PVC) or high-density polyethylene (HDPE) generate much heat in the melt film, and the melt temperature reflects that fact as screw speed is pushed to moderate to high levels. Low viscosity materials exhibit much lower melt temperature rises as the screw speed is increased.

The barrel heat contribution at high or moderate screw speeds is often minimal, with melt film shear producing enough energy for the entire melting process. In fact, many extrusion situations require some of the barrel zones (especially those farthest from the feed area) to be cooled to remove excess heat created by the melt film. Barrel cooling has only a modest effect on lowering melt temperature levels in high-speed extrusion of high viscosity materials because of the short residence time in the barrel and poor conductivity of most polymers.

The screw designer's typical goal is to design a screw geometry to maximize output and control the melt temperature level required for the particular process. The discussion of "Extruder Screws" later in the chapter will further expound on melt temperature controlling factors.

Melt Pool Development. As the solid bed moves along the screw, the energy from the barrel heaters and the shearing of the melt film contribute to further melting. The melt being scraped off the barrel wall as the flight passes is trapped on the pushing side of the channel (rear) and forms a melt pool. The idealized

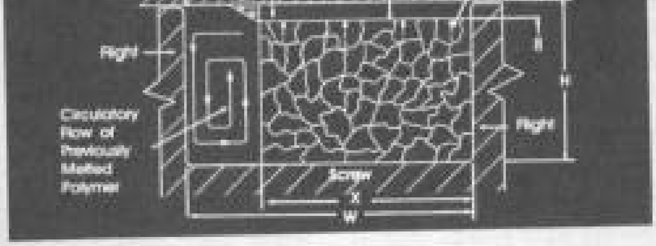


Fig. 4-4. Melting in channel. (*Courtesy Davis-Standard*)

melting process suggests that this melting continues in a well-defined pattern with the melt pool increasing in size as the solid bed declines in size until all is molten. This full melt condition optimally would occur before the material reached the die system to ensure a good end product. The screw channel does not normally maintain an organized melt and solid bed arrangement (as shown in Fig. 4-4) but instead exhibits a random breakup of the solid bed.

The breakdown of the melt/solids relationship in the screw channel leads to several potential extrusion problems. First, stability is adversely affected because of pressure surges created when the solids break up. This pressure variation typically is seen to start in the early (near feed section) to mid-barrel locations through the use of pressure recording devices. Should the pressure variations be large enough, the upsets can be seen all along the barrel and into the die system. Pressure variations in the die system relate to output variations and hence product irregularities. A second concern of the breakdown is that a less-than-efficient melting situation created by solids breakup can cause unmelted material to find its way farther down the screw and sometimes into the die system. Screw design can control the melting situation and/or damp out the negative performance aspects to some extent. (Screw features will be discussed in the screw design section.) The effects of solid bed breakup are magnified as screw speed is increased on conventional screw designs, a fact that has led screw design to today's specialized screw geometries.

The melting capacity of the extrusion screw must be satisfied by an ample amount of feeding capacity. This is handled through screw design.

Material Effects On Melting Performance. The materials being extruded have a great effect on melting performance, just as they can affect feeding efficiency. The amount of heat developed in the melt film is a function of the viscosity of the material and the effects of any additive. Just as lubricating additives can disrupt the solids friction that drives the feeding, they can have an effect on melting performance.

The melting rate of the material has a determining effect on extrusion melting performance. This melting rate is determined by such properties as thermal conductivity and specific heat. Any fillers in the material usually will alter the melting and conveying performance of the material to some extent. Polymer blends are quite popular today because of the properties available from each of the components. The makeup of the blend will affect the melting performance because of the varied melting characteristics of the blend's basic materials. These blends can create sizable screw design challenges in the efficient handling of the melting performance.

Inconsistencies in the material also pose a threat to extruder output consistency. The use of reground extruder scrap and off-spec product can lead to inconsistency due to varying feed particle sizes and differing percentages of the regrind as time passes. When regrind is used from thin gauge sheet or film extrusion, the bulk density of the feed material has an effect on the material's hopper flow and how the screw's feed flights are filled, which can lead to output reduction and at some point a starved screw. In processes that are controlled by feeding limitations, such as the starved screw case in low-bulk-density reground films, it is generally difficult to maintain good output consistency and high output rates as screw speeds are increased. Inconsistency of the base material due to its manufacturing accuracies can yield a feed material that will process with variations as the lot of material is used. The extruder's feeding and melting performance can be noticeably altered by these variations in the feed materials.

The form of the material being introduced to the extruder also has an effect on solids conveying and melting efficiency. The material forms available include pellets of various sizes, granulate (like sugar consistency), powders of various particle size, regrind of various sizes, and strips (as in rubber extrusion or some melt extrusion). The shape of the feed material usually is determined by either economics (cost/pound) of material manufacture or extrusion performance features. For example, the most economical form of rigid PVC is powder, and many of the processors using large volumes of this material produce some or all of their extruded product from powder. The negative aspects of powder include the requirement of a vented extruder (see below) and extra plant maintenance caused by fine powder that travels through the air and can corrode electrical components such as drive systems and temperature control circuitry. Producers of PVC profiles who can dedicate an extruder to a small number of items can use a vented extruder and powder feed material. When part versatility is required, a vented extruder has operational problems due to varying restrictions on the extruder; it is recommended that producers choose PVC in pellet or cube form. Producers of thin, clear PVC sheet typically use pellets on non-vented single screw extruders; the melting mechanics and shear input of the single screw extruder better fit the higher temperature processing. Also, the high die pressures (5000–8000 psi) would preclude effective venting on this type of extruder. Economics provides the strongest driving force in the selection of the material's feed form as long as the processing considerations are not highly negative for the lowest-priced material.

Melt Pumping

Pumping of the material against the die resistance can begin back near the screw's feed section, especially when the die pressure levels are high. Melting starts early on the screw in most cases, and pressurization of the melt can begin there. In actuality the three basic functions of the extruder—solids conveying, melting, pumping—cannot be separated into three discrete regions along the extruder. The functions intermesh so strongly that they all must be studied together. As the material advances down the screw toward the die, more melt is present, and the predictions of the pumping theory developed many years ago can be understood. This theory is well known,* and includes the prediction of the pumping capacity of a simple metering section against no die resistance (drag flow) and the output-reducing tendencies of the die resistance (pressure flow). These equations reduce to fairly simple terms and give a form of rough output calculation for conventional metering screws with materials that feed well. The conclusions of the melt pumping analysis are stated below:

$$OUTPUT = Q_{drag} - Q_{pressure}$$

$$Q_d = \frac{F_d \pi^2 D^2 N h \left(1 - \frac{ne}{t}\right) \sin \phi \cos \phi}{2}$$

$$Q_p = \frac{F_p \pi D h^3 \left(1 - \frac{ne}{t}\right) \sin^2 \phi}{12 \mu L} \Delta P$$

where:

- Q_d = Drag flow pumping term
- Q_p = Pressure flow resisting pumping
- F_d = $.140(h/w)^2 - .645(h/w) + 1$ (channel correction factor)
- F_p = $.162(h/w)^2 - .742(h/w) + 1$ (channel correction factor)
- D = screw diameter
- N = screw speed (rpm)
- h = screw's meter section channel depth
- w = screw channel width (normal direction, not along axis)
- n = number of flights on the screw
- e = thickness of flight
- t = flight lead (pitch)
- ϕ = flight helix angle
- μ = viscosity of melt (shear rate = $\pi ND/h$)
- L = length of the metering section being investigated

This estimation of the output pumping of a screw is applied to the shallowest section of the screw because that is the region that limits the screw's output. Several simplifying assumptions were used to derive this flow estimation, including (1) a Newtonian material, (2) a fully developed melt flow situation, (3) no screw flight-to-barrel clearances, and (4) some other factors that help make the equation work rea-

*See E. C. Bernhardt, *Processing of Thermoplastic Materials*, Van Nostrand Reinhold, New York, 1959.

sonably well when some experience factors are employed.

Some examples of these alterations to the drag flow estimation include a 0.85 multiplier when mixing sections are employed and a 0.5 multiplier when cold water is circulated through the screw's core. When a barrier screw is used, the metering section may not control the output, so this equation could give poor results.

Wear Effects on Pumping

As screw flights and barrel I.D.'s wear, the pumping ability of the screw is diminished. Some materials and some additives will cause higher wear than others; for example, linear low-density polyethylene (LLDPE) will cause more wear than conventional LDPE or polypropylene. Many fillers, such as titanium dioxide (used for white colors) and reinforcing fibers, also create high wear situations. Under some conditions, screw/barrel wear can lead to instability of the extruder's output, but typically the main effect is output reduction. At some point, extruder wear will create an unacceptable situation that necessitates rebuilding or replacement of machinery parts such as the screws, barrel, and feed sections. Changes in the ability to increase the screw speed and still produce an acceptable melt contribute to the decision about when wear has passed acceptable limits.

Variations involved in production operations, including the materials run, screw speeds used, die system pressures, barrel set temperatures, screw design, screw flight hardening material, and barrel lining material, make it impossible to predict wear life accurately. The suggested way to understand the wear in a process is to set base conditions when the equipment is new and unworn; that is, run a commonly used material, and record all performance parameters, including output rate, screw speed, drive amperage, barrel temperature profile, product quality, and dimensional consistency. Whenever the opportunity to perform scheduled maintenance occurs, measure equipment clearances and rerun the process at the base conditions to compare performances to determine the extent of deterioration. The wear pattern then can be plotted to show the screw and barrel life for the given production case.

Mixing

Many extrusion processes require better mixing than a single screw delivers. For example, good dispersion of color masterbatches and proper mixing of polymer blends need higher shear mixing devices. This is particularly true where the masterbatch is based on a dissimilar material to the one being colored, and where polymers being blended have different melting temperatures and flow properties.

Two types of mixing usually are discussed in polymer processing, distributive and dispersive. In distributive mixing the material(s) are uniformly blended on a scale where any small particles or agglomerates are not broken down. These particles can be "gels" from various sources or small clusters of a material such as carbon black, which is not physically broken down without very high shear levels. Dispersive mixing includes very high shear mixing from extremely tight clearances (about 0.001 to 0.005 inch) where small particles or agglomerates are physically broken down to smaller pieces and distributed into the main mass of material. Such high shear, dispersive mixing can be seen with some of the kneading block geometries on compounding twin screw extruders. Mixing in single screw extruders is generally not on the scale of the very high shear levels characteristic of dispersive mixing. Typical mixing elements can yield very good distribution of a material's mass and its additives, but any small particles (gels) or agglomerates will still be present, although well spread throughout the melt. Should the presence of these undispersed particles create a problem in the final product, the origin of the particles must be determined, and their cause must be avoided in polymer blending methods or base material particle size selection. Examples of common mixing devices can be seen later in the screw design discussion. These mixing devices can be placed on the screw proper, can be attached to the screw tip, or can be placed after the screw in the die adaptor pieces.

The need for specialized and highly effective