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**Introduction**

Although Teflon™ PTFE fluoropolymer resins are thermoplastic materials, they do not flow readily when melted. Instead, when Teflon™ PTFE melts, it changes from a white solid to a transparent rubbery gel. Because of the extremely high viscosity of melted Teflon™ PTFE, special techniques have been developed for converting granular Teflon™ PTFE resins to finished products. The basic steps common to these techniques are:

- Compaction of the granular resin at a relatively low temperature
- Heating the compacted resin above its melting temperature (commonly called sintering)
- Cooling the sintered product to room temperature

Ram extrusion is a continuous process in which these steps are carried out in a single piece of equipment. Teflon™ PTFE granular resin is fed to one end of a ram extruder, and a continuous length of sintered rod, tube, or other extrudable shape emerges from the other end.

There are important differences among granular PTFE resins regarding their behavior during ram extrusion. For example, a free-flow resin—as opposed to a fine-cut resin used in molding—is a specialty product designed to provide excellent powder flow, high resistance to poker chipping (charge interface fracture), and excellent physical properties in products made over a wide range of extrusion conditions. Therefore, a free-flow resin is particularly suited for the ram extrusion of small diameter rod, thin-walled tube, or other shapes.

**Ram Extrusion Process Technology**

The ram extrusion of Teflon™ PTFE fluoropolymer resin, with either a horizontal or vertical extruder, consists of these steps:

1. Feeding a metered charge of granular resin to the cold end of an extruder die that is heated over most of its length.
2. Compacting the cold resin and forcing it a short distance into the die with a reciprocating ram, which then withdraws preparatory to repeating the cycle.\(^*\)

Succeeding ram cycles cause the compacted resin charges to advance, step-by-step, through the heated extruder die where sintering takes place. Individual resin charges are also welded together during the sintering phase of the ram extrusion process.

There are at least four essential ram extrusion processing steps warranting further discussion:

- Resin feed
- Resin compaction (or preforming)
- Sintering
- Cooling

Each of these steps is discussed in detail in the following sections of this guide.

**Resin Feed**

The objective during the resin feed portion of the ram extrusion process is to deliver resin to the ram extruder in individual charges of uniform weight evenly distributed throughout the feed section of the extruder.

The powder flow of any given Teflon™ PTFE resin is affected by resin temperature and the treatment to which the resin is subjected in the extruder feed system. Even free-flowing resins will tend to lose some of their free-flowing capability when they are heated. Therefore, it is suggested that, in the interest of preserving the best possible flow characteristics of the resin being extruded, the feed resin be maintained at a temperature of about 21 °C (70 °F). This can be achieved by water cooling the feed section of the section of the ram extruder (including that portion of the extruder die penetrated by the ram) and preventing heat up of the feed hopper and its contents. In no case should the feed resin temperature fall below the dew point temperature of the air, however, as moisture can then condense on the resin.

\(^*\)The reciprocating ram may be pneumatically, hydraulically, or mechanically operated. A screw could also be used.
Excessive working of the feed resin through severe agitation, aeration, vibration, shearing action, compaction, tumbling, and so forth can also have a deleterious effect upon powder flow—especially if the resin is not kept cool. The powder flow characteristics and uniformity of feed of the resin are best preserved in the long run by avoidance of heating and excessive working of the resin.

Uniform distribution of resin throughout the feed section of the ram extruder is sometimes more important than uniform charge weight. One example to illustrate the importance of uniform resin distribution is the ram extrusion of large-diameter, thin-walled tubing (such as 50 mm [2 in] OD x 1.3 mm [0.05 in] wall). Resin mobility within the feed section of the extruder and the portion of the extruder die penetrated by the ram is low in such cases because of the presence of a mandrel, which restricts the powder flow. Therefore, to obtain evenly compacted resin charges, the resin must be distributed uniformly around the mandrel during feeding. As resin mobility within the die entry of the extruder increases, somewhat more nonuniformity of resin distribution can be tolerated. However, because Teflon® PTFE fluoropolymer resins do not generally flow well under pressure, distribution of feed resin should be as uniform as possible in any event to ensure uniform compaction. Because uniformity of extrusion rate is directly related to uniformity of charge weight, variations in the latter will produce variations in rate. This, in turn, can cause nonuniform properties. Also, if resin is not fed uniformly over the product cross-section, the product may be curved and have nonuniform properties.

**Resin Compaction**

A charge of resin fed into the extruder is compacted during the advance stroke of the ram. The ram compacts the loose resin to a dense preform between the face of the ram tip and the rear face of the previous charge of compacted resin already in the extruder die. The actual pressure exerted on the resin charge by the ram depends mainly upon conditions downstream from the feed end of the extruder. The effects of these conditions are generally called “back pressure.” Once the back pressure (caused by frictional resistance to extrusion) is overcome by the ram, no further compaction of the resin charge occurs. Instead, the ram continues to move to the end of its stroke, advancing the contents of the extruder die a distance of one charge length.

The pressure applied to the charge of resin as it is initially compacted by the ram must fall between two limits, neither of which is sharply defined. On one hand, the pressure exerted by the ram must not be too high. When this happens, the result is that adjacent charges do not weld properly to each other during sintering, and the defect known as poker chipping will occur. At the other extreme, the pressure must be high enough to compact the loose powder to a preform of relatively low void content; otherwise, the extruded product will be chalky or grainy. These symptoms are very nearly like those seen in PTFE that has not been completely sintered because of a lack of sufficient heating time. It is, therefore, suggested that the possibility of insufficient pressure be considered as well as the possibility of insufficient heat should ram extruded PTFE have a grainy appearance or voids.

Teflon® PTFE fluoropolymer resins for ram extrusion have been processed under conditions for which the compaction pressure applied by the ram ranged from less than 5 MPa (725 psi) to more than 100 MPa (14,500 psi), without seeing evidence of under-pressuring (graininess) or over-pressuring (poker chipping). As an additional aid to promoting strong charge-to-charge bonds, it is suggested that the entry section of the extruder die ordinarily be water cooled over a length slightly greater than that penetrated by the ram. This will ensure that each charge of resin will be compacted against a previous charge whose rear face is still relatively cold. This has also been found to be an effective means of reducing some types of skin formation during extrusion and is effective in virtually eliminating “spring back” of resin in the die as the ram is retracted.

Spring back is the axial expansion and recovery of compacted resin that occurs in a direction opposite to the extrusion direction upon withdrawal of the ram. It has the greatest tendency to occur in the extrusion of sections having low ratios of perimeter to cross-sectional area (large diameter rod, for example). Therefore, water cooling of the die entry will have the most noticeable effect in the extrusion of sections, such as large diameter rod. Use of a water-cooled die entry in any given setup will increase the pressure required for extrusion over that needed for the same setup without cooling, as will be discussed in greater detail in the next section of this report.

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*Compaction pressure is computed by dividing the ram force needed to effect extrusion by the face area of the ram tip.*
Sintering

Once the Teflon™ PTFE has been compacted by the action of the ram, it is pushed into the heated part of the extruder die where sintering takes place. Two things are needed for proper sintering to occur:

- Adequate heat must be supplied during the passage of the resin through the extruder die to bring the entire cross-section of the compacted resin to a temperature above the melting point of the resin for a time that is sufficient for sintering to take place.
- Sufficient pressure must be exerted upon the resin, while at a temperature above its melting point, to cause elimination of particle boundaries and voids within charges and welding of adjacent charges.

In considering each of these requirements in more detail, the heat requirements will be treated first.

Heat Requirements

Heat is transferred to the compacted Teflon™ PTFE in a hot ram extruder die primarily by conduction. The minimum time required to heat up compacted Teflon™ PTFE to sintering temperature under given conditions of die temperature and product size and shape can be related to the thermal properties of the resin (thermal conductivity and heat capacity). Such relationships are very important, because they play a large part in determining the maximum production rates allowable for any given extruder setup. Maximum allowable extrusion rate equals heated die length divided by minimum allowable heating time required to achieve an adequate degree of sintering.

Minimum heating times required to achieve sintering temperature in solid round rod of various diameter, d, heated in an extruder die at 395 °C (743 °F) are given in Table 1. Increasing the die temperature above 395 °C (743 °F) will, of course, reduce somewhat the minimum heating time required below the value given in the table. It is suggested that extrusion temperatures not exceed about 425 °C (797 °F), however, and preferably they should be in the range of about 370-425 °C (698-797 °F), depending upon the size and shape of the stock being extruded. The temperature of 395 °C (743 °F) given as an example in Table 1 is used for all sizes of rod, so that they may be compared under a common heating condition. It does not constitute a recommendation that all ram extrusion be done at 395 °C (743 °F). Individual temperature requirements are determined by each processor for his/her own extruder setups and property requirements.

Note that the required minimum heating time is not a linear function of rod diameter. As a matter of fact, heating time varies with approximately the second power of rod diameter per the expression, time (minutes) = 3 d^2 (cm) or ~20 d^2 (in).

All the heating times given as guides in Table 1 are minimum times required to heat up the Teflon™ PTFE resin in the extruder die to the point where sintering can occur under the given die temperature conditions. Ordinarily, ram extrusion is carried out under conditions for which the residence time of the resin in the heated die far exceeds the minimum allowable values imposed by heating requirements. The excess residence time in these instances is usually beneficial, because the longer exposure of the melted Teflon™ PTFE fluoropolymer resin to the heat and pressure that exist in the hot extruder die contributes to the reduction of temperature gradients through the Teflon™ PTFE, the elimination of boundaries between particles and charges, and the reduction of voids. Over-sintering and degradation due to too long an exposure time at sintering temperature or too high a temperature must be avoided however.

Figure 1 shows how product quality, as determined by tensile strength, varies according to residence time for a 6.3-mm (0.25-in) rod extruded through a 635-mm (25-in) long die at 385 °C (725 °F). This is illustrative of one of the benefits to be derived from having residence time in excess of the allowable minimum heating time. Tensile strength is not the only possible criterion for quality, of course, but it is a meaningful measure.

The minimum heating times required for the ram extrusion of sections other than solid round rod depend upon the size and shape of the section being extruded, as well as the extrusion conditions. For example, the minimum heating time required for the ram extrusion of square rod 25 mm (1 in) on a side would be about 20% more than would be needed for solid round rod 25 mm (1 in) in diameter, if both sections were extruded under the same conditions of die temperature and pressure.
Pressure Requirements
Adequate heating of the compacted resin in the extruder die is only part of the sintering story. The simultaneous application of pressure is also necessary for proper sintering to occur. This is partly because the “preform” pressures used in ram extrusion to avoid poker chipping are considerably lower than the preform pressures ordinarily used in free sintered moldings. The sintering times are also considerably shorter in a ram extruder than they would be for a molded part.

Consider the ram extrusion of solid round rod. When compacted Teflon™ PTFE fluoropolymer resin is heated in the extruder die, it is prevented from undergoing its normal thermal expansion in the radial direction, because it is constrained by the die. What does happen is that, first the resin expands against the inner surface of the hot extruder die and into the voids within the compacted resin. Further heating results in the development of considerable pressure within the resin, because the resin can no longer expand radially. This pressure is the driving force that causes the final densification of the resin, the rapid coalescence of the individual melted particles to a homogeneous mass of void-free gel, and contributes to the welding together of individual charges. It is important that all parts of the cross-section be exposed to sufficient pressure while the material is in the gel; otherwise, improper sintering will result. The portion of a solid rod that will show first the results of too low a level of pressure is that part nearest the rod axis, with the effects (graininess or chalkiness of cooled rod or opacity in the gel—all symptoms of voids) diminishing with increasing distance from the rod axis.

Elimination of this type of defect is the primary purpose for taking care that adequate ram pressure is developed in the initial compaction of each charge of resin in the cold feed section of the extruder.

There is no point in attempting to properly sinter material that has not previously been compacted to a sufficiently low void content by the ram—it can’t be done.

The pressure of compaction exerted by the ram and the pressure developed within the resin due to restraint of radial expansion in the hot extruder die are related. The compacted Teflon™ PTFE fluoropolymer resin, when heated in the extruder die, presses against the die surface in its attempt to expand. There is associated with the pressure developed some frictional resistance to motion of the resin through the die under the action of the ram. This frictional resistance to motion is what determines the back pressure. Specifically, the total frictional resistance to motion, expressed as a force when divided by the cross-sectional area of the ram face, is back pressure.

It is equal to the compaction pressure that must be exerted by the ram to effect extrusion (or to avoid stall out). In the absence of a brake or other external influences, the back pressure developed with a given resin in the heated portion of a ram extruder die depends mainly upon these factors:

- The coefficient of friction between the melted resin and the die surfaces in the heated portion of the extruder die. This, in turn, depends upon such factors as die temperatures, die smoothness, and materials of die construction.
- The pressure within the hot resin, which depends in part upon such factors as temperature, uniformity of bore size, and void content of the resin, is compacted.
- The cross-sectional area of the hot die cavity.
- The surface area of the hot die cavity or, more generally, the area of sliding contact between stationary die surfaces and Teflon™ PTFE moving under the action of the ram.
- The rate at which the resin moves through the die.

In addition to those factors above that affect back pressure in the heated portion of the extruder die, there are analogous factors that affect back pressure buildup in the cold feed section of the die (if there is one). Normally, this part of the die extends from the die entry to a point slightly beyond that point reached by the ram at maximum penetration. However, when it is desired to create more back pressure with a given extruder setup, additional length of die beyond the point of maximum ram penetration may be kept at some appropriate temperature, usually below the melting point of PTFE. The further this cooled die entry length temperature is below the melting temperature of PTFE, the higher the back-pressure buildup per unit length of cooled die entry. A tenfold or greater increase in back pressure over that attainable with an identical die, without die entry cooling, can be realized by appropriate selection of die entry temperature and length.

*While gel opacity is generally symptomatic of voids, gel clarity does not necessarily guarantee freedom from voids.*
Table 1. Average Shrinkage, Required Heating Times, and Representative Die Lengths for Ram Extruders Used with Teflon™ PTFE Fluoropolymer Resins for Ram Extrusion

<table>
<thead>
<tr>
<th>Rod Diameter, d (mm (in))</th>
<th>Average Shrinkage, S (%/min)</th>
<th>Minimum Required Heating Time, min, 395 °C (743 °F)</th>
<th>Representative Die Length, mm (in)</th>
<th>For Representative Die Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Maximum Extrusion Rate, m/hr (ft/hr), 395 °C (743 °F)</td>
</tr>
<tr>
<td>3 (0.12)</td>
<td>6</td>
<td>1</td>
<td>250 (10)</td>
<td>15 (50)</td>
</tr>
<tr>
<td>6 (0.25)</td>
<td>8</td>
<td>1.25</td>
<td>500 (20)</td>
<td>24 (80)</td>
</tr>
<tr>
<td>13 (0.50)</td>
<td>11</td>
<td>5</td>
<td>1,000 (40)</td>
<td>12 (40)</td>
</tr>
<tr>
<td>19 (0.75)</td>
<td>12.5</td>
<td>11</td>
<td>1,500 (60)</td>
<td>8 (25)</td>
</tr>
<tr>
<td>25 (1.0)</td>
<td>13.5</td>
<td>20</td>
<td>2,000 (80)</td>
<td>6 (20)</td>
</tr>
</tbody>
</table>

*Die lengths considerably greater or smaller than the values given can be used with ram extrusion resins.

Figure 1. Tensile Strength vs. Extrusion Rates

- 6.3 mm (0.25 in) rod
- 635 mm (25 in) heated die length
- 385 °C (725 °F)
- Teflon™ PTFE fluoropolymer resins for ram extrusion
**Back Pressure Development in Rod Extrusion**

In a ram extruder designed for the manufacture of products such as solid rods or other extrudable shapes having cross-sections that contain no unfilled holes, there can be at least three distinct regions of back pressure development along the extruder die (in the absence of a brake): the water-cooled ram penetration zone (if used), the cooled die entry length beyond ram penetration (normally used only to augment back pressure in the extrusion of heavy sections from ram extrusion resins), and the heated die. In the extrusion of solid sections, no back pressure is generated in the die beyond the point at which the sintered product loses contact with the die surface as a result of shrinkage of the Teflon™ PTFE fluoropolymer resin. However, with a vertical extruder, the extrudate is often suspended from hot material, which is in contact with the die surface, and acts as an agent to reduce back pressure, becoming increasingly effective as extrusion proceeds and the extrudate lengths. Therefore, it is suggested that vertically extruded sections be cut into lightweight lengths or else supported by external means as they exit the extruder to avoid loss of back pressure and, ultimately, to avoid melt fracture or pulling the PTFE gel from the die. Some general observations concerning back pressure development in the extrusion of solid sections made based on an analysis of the effects of the factors discussed above are:

- The major geometric factors in back pressure development are the ratios of die surface area to die cross-sectional area in the water-cooled feed and ram penetration zone, the cooled die entry beyond ram penetration, and the heated die. In the extrusion of solid round rod through a die of diameter D, for example, back pressure depends upon the length to diameter ratios of the die in the three die regions just mentioned. An increase in any of these L/D ratios will affect the largest increase in back pressure per unit length of zone—greater by far (1.0 times or more) than the increase derived from lengthening the heated die by the same number of inches. There may be situations (for example, the extrusion of a very thin section) for which the water-cooled ram penetration zone should be kept very short (or perhaps not be used at all) to prevent excessive back pressure buildup. In such circumstances, careful consideration needs to be given to weighing the merits of water cooling and improvement of powder feed against the effects of the water-cooled feed zone upon back pressure.

The effects upon back pressure of changes in the L/D ratio in the cooled die entry beyond ram penetration (if used) are intermediate between the effects accompanying identical changes in either the heated die or the water-cooled feed zone, as the temperature in this region is intermediate between those extremes.

- Die temperatures can also affect back pressure development, as can the temperature profile of the die. For a given extruder setup operating at a uniform die temperature, there is some range of temperatures over which back pressure will increase with increasing temperature. There is also some range of temperatures over which back pressure will decrease with increasing temperature, as might be surmised from the discussion above concerning the relative back pressure generation characteristics in the cold ram penetration zone, the cooled die entry, and the heated die. The force required to extrude Teflon™ PTFE through a die at room temperature is generally very high (i.e., back pressure is very high). As die temperature is increased, back pressure is first reduced and then, as temperature continues to rise, back pressure begins to increase again. There is, then, at least one die temperature for which back pressure is at a relative minimum for a given extruder setup operating at uniform die temperature with a given resin. This temperature may be on the order of 40 °C (72 °F) above the melting point of the resin; however, because deviations can exist, no single value can be assigned for the temperature that will yield the minimum back pressure for every situation. Temperature profile can also have a strong influence upon back pressure, as indicated in the foregoing discussions concerning heated and cooled regions of the die. The use of a profile in which the temperature increases along the die in the direction of extrusion (as is the case where a cold ram penetration zone is followed by a cool die entry zone and then a heated die) generally leads to higher back pressures than would exist if the cooled die entry zone were not used. If the cold ram penetration zone is removed as well, back pressure is normally reduced still further, and establishment of a profile in which temperature decreases along the die may further reduce back pressure.
• Back pressure can also be affected by the rate at which the resin is advanced through the extruder die. The faster the resin moves through the die, during that portion of the ram cycle in which the resin is being moved by the ram, the higher the back pressure may be. Thus, back pressure can be affected by the way the ram is cycled as well as by the overall cycle time or extrusion rate. For a given extrusion rate with a machine having a ram operated on a timed cycle, the ram pressure required for extrusion can vary substantially according to what proportion of the total ram cycle time is allowed for ram advance and what proportion is allowed for ram withdrawal and powder feed. For a ram cycle properly proportioned with respect to powder feed, ram pressure, and dwell time at maximum ram penetration, back pressure can be expected to increase with increasing extrusion rate.

• Back pressure in ram extrusion generally increases with increasing charge length. This is particularly true if the portion of the die penetrated by the ram is water cooled.

**Back Pressure Development in Tubing Extrusion**

The ram extrusion of tubing requires the use of a mandrel that can be set up in a variety of ways. As is the case for rod extrusion, the ratio of area of sliding contact between resin and die to ram cross-sectional area has a major effect upon back pressure development in tubing extrusion. For the ram extrusion of tubing, a nonreciprocating mandrel of uniform diameter can generally be used.

With this type of tooling, the principal geometric factors contributing to back pressure development are die tube length, mandrel length, and the ratio of the length that the die tube and mandrel have in common to the ram wall thickness.

Most of the other general observations regarding back pressure development in the extrusion of rod apply to the extrusion of tubing as well throughout those portions of the die that contain a stationary non-tapered mandrel. However, because a mandrel need not necessarily have the same length as the die tube and often has a different temperature profile from that of the die tube, exceptions to the observations made with respect to rod extrusion can readily exist. For example, the use of a mandrel having greater length than the heated die can have the following effect upon back pressure: once the Teflon™ PTFE has been sintered and is being cooled in the extruder, shrinkage occurs that eventually causes the sintered resin to lose contact with the surface of the extruder die tube, as in rod extrusion. As the sintered tube shrinks away from the die tube, however, it also begins to shrink onto the mandrel. Continued cooling eventually results in an increase of back pressure, owing to the sliding friction built up between the cooling PTFE and mandrel. Back pressure from this source can, therefore, be controlled by altering the length of the mandrel, with a decrease in mandrel length being accompanied by a reduction of back pressure.

Back pressure in thin-walled tubing extrusion can also be controlled to some extent by adjustment of the temperature of the sintered tube of Teflon™ PTFE in the section of the die that follows the sintering zones of the extruder. By maintaining this temperature at the proper level (which may be between about 230–260 °C [446–500 °F] for thin-walled tube), back pressure in this area is near minimum, because the PTFE is cool enough to have shrunk away from the die tube and hot enough not to have shrunk very tightly onto the mandrel.

It is suggested that ram extrusion of thin-walled tubing generally be done using a nonreciprocating, non-tapered mandrel. Extension of the mandrel a few inches beyond the heated part of the die tube gives the sintered material a chance to shrink onto the mandrel without drastically increasing back pressure and results in improvement in appearance of the inside surface of the tube.

If the mandrel is shortened to the point where the PTFE tube passes over the end of the mandrel while still in the gel, the uniformity of the tube may be destroyed. That is, the tube may not be round and consist of alternating sections of large and small diameter (hour-glassing). This “hour glassing” can also happen to a greater or lesser degree if the tube exits the extruder die tube in the gel while still on the mandrel. This visual surface defect can be mistakenly interpreted as poker chipping, because its periodicity is equal to the charge length, whereas, it really is caused by inadequately supporting and confining the PTFE while it is in the gel. These effects become more pronounced as tube wall thickness decreases relative to tube diameter. They may be unobjectionable in heavy walled tube intended for some applications.
If poker chip sensitive resins are to be ram extruded to tubing, one of the following techniques can be tried. These procedures result in a reduction of back pressure, compared with the back pressure produced with a stationary mandrel of constant diameter, and will help to avoid poker chipping.

- The mandrel may be tapered and stationary. That is, the diameter of the mandrel in the feed and entry sections of the extruder is greater than at the exit end of the extruder. The mandrel may consist of two cylindrical portions of different diameter joined by a tapered transition zone. The location and extent of tapering are important from the standpoint of back pressure development (or back pressure relief). The taper is located so that the resin can expand radially inwardly while being melted.

- The mandrel may be made to reciprocate either with the ram or independently of the ram. If the mandrel reciprocates with the ram, the mandrel is usually tapered slightly so that the resin is not dragged back out of the extruder as the ram and mandrel are withdrawn. If the mandrel and ram reciprocate independently, the mandrel may be made of constant diameter. In operation, the mandrel is carried forward by the resin being extruded as the ram is advanced. Then, while the ram is kept in its position of maximum penetration, the mandrel is retracted a distance equal to its forward motion during ram advance. Then the ram is withdrawn, and the cycle is repeated.

The principle underlying these techniques is a reduction of back pressure by:

- Reduction of thermally induced pressure in the resin being extruded. This is reflected as reduced frictional drag, because friction is directly proportional to the pressure in the resin.

- Reduction of sliding contact area between stationary die surfaces and the resin being moved by the ram. This, too, reduces drag.

Because the ability of any resin to generate sufficient back pressure for extrusion falls off with a decrease in the ratio of die cavity surface area to ram cross-sectional area (die length to diameter ratio for rod extrusion), extrusion of a section such as large diameter rod through a short die may require some way of augmenting back pressure. This can be done by means of a brake that supplies a controlled amount of additional resistance to extrusion. This brake can consist of a collet/chuck or a gland that is made to grip the extrudate with a controlled amount of pressure. Back pressure can also be raised by using the cooled entry zone technique previously described or a tapered die (smaller at the exit than at entry).

**Cooling**

The final step of the ram extrusion process is that of cooling the sintered PTFE. The rate at which ram extruded PTFE is cooled determines the final crystallinity in the extruded product (crystallinity being generally about 55–60%) and, therefore, contributes toward final part dimensions and properties. Ram extruded shapes are often air quenched, leaving the extruder die at temperatures near or above the gel temperature; in which case, crystallinity and shrinkage are at a minimum.

The normal range over which the shrinkage of solid round rod ram extruded from Teflon® PTFE resins for ram extrusion can be controlled is about 10–14% of the die bore diameter—that is, the rod diameter can be made to be 86–90% of the bore diameter of the extruder die. Normally, however, the shrinkage will be 12–13% and is controlled by altering the temperature profile, changing extrusion pressure, or changing the cooling rate or the sintering time.

Shrinkage in tubing is also influenced by the above factors and the presence of the mandrel as well. In general, the cooler the PTFE is when it comes off the end of the mandrel, the lower the shrinkage (other factors being constant). Also, in general, shrinkage in ram extruded tubing is less than shrinkage in rod, being on the order of 4–6% of the die tube diameter for thin-walled tubing of Teflon® PTFE resins for ram extrusion.

Internal stress levels in ram extruded PTFE are affected by the cooling rate and other extrusion variables. Attainment of a sufficient degree of annealing or stress relaxation for dimensional stability during machining or certain end-use applications may require carefully controlled cooling or reannealing. It should be recognized that, while heat up and sintering of resin in a ram extruder are done under pressure, the cooling phase of the extrusion process is normally not done under pressure (except when a brake or a reverse tapered die is used; in which case, internal stresses in the extrudate may be high and dimensional stability may be poor). Once cooling (and the shrinkage that accompanies cooling) has proceeded to the point where the sintered material
loses contact with the die surfaces, further cooling takes place in the absence of pressure. Thus, the ram extrusion of large diameter rod (greater than about 50 mm diameter) can require controlled cooling (or at least slow cooling as opposed to air quenching for the gel) to avoid internal fractures in the rod. Slow cooling can often be accomplished by attaching an insulated cooling tube of appropriate length to the exit end of the extruder die. A practical limitation on minimum cooling rate attainable is the length of cooling tube that can be used, the relationship of the length to the temperature of the extrudate as it enters the tube, and the extrusion rate. Supplemental heating may be needed to establish the appropriate temperature gradient along the tube. Controlled cooling is usually of greatest importance in the extrusion of heavy sections where cooling must not be too rapid, in the extrusion of a section to a precise size, and in the extrusion to size of products, which, by virtue of their length or cross-sectional shape, cannot be centerless ground to size.

**Skins**

The formation of skins during the ram extrusion of Teflon™ PTFE is a classical problem of continuing concern. In the ram extrusion process, PTFE comes into sliding contact with the metallic die surfaces as it passes through the heated extruder while under considerable pressure. This being the case, there is sliding friction to be overcome to affect extrusion. This sliding friction is, of course, the source of back pressure. It is also the source of a shear stress at the resin/die interfaces. Because the shear strength of melted PTFE is low, and because neither the gel surface nor the die surfaces are perfectly smooth, the shear stress at the resin/die interfaces can locally exceed the shear strength of the PTFE. Thus, some material can shear away from the main body of the gel and remain attached to the die surfaces. The PTFE accumulates in the depressions in the die surfaces and fills them up, thus, tending to smooth the die and coat it with resin. Once this process has occurred, a PTFE/PTFE interface is created, and further shearing of Teflon™ PTFE is eliminated (except to replace areas of film depleted through degradation). This process is analogous to that which occurs when a block of soft wood is rubbed over sandpaper. The sandpaper soon “loads up” and no longer removes wood from the block.

This, then, is how one type of skin (which might be called a “normal” skin) is formed during the ram extrusion of Teflon™ PTFE. It coats all surfaces contacted by gel. This type of skin is innocuous so long as the extruder is running properly and the skin is pressed against the die or adheres to it. Because this skin remains in the die, it ultimately degrades and is renewed continuously. The products of degradation can attack the die walls, however, and give rise to die corrosion at varying rates, depending on die temperatures and materials of die construction. Even chrome plating is not complete proof against corrosion, because the metal behind the chromium can be attacked if there are any pinholes in the plating, and the substrate of the plating can erode and the plating can flake off.

When the extruder die is cooled down, the “normal” skin can pull away from the die locally, carrying with it the products of die corrosion and (possibly) poorly adhered chrome plate. When the machine is restarted, these portions of the “normal” skin can emerge as black patches on the surface of the extrudate. In this way, a second kind of skin, the black skin, is created. As soon as a coherent “normal” skin forms again in the die, the black skin goes away and should not return unless extrusion or extruder conditions are such that parts of the normal skin pull away from the die walls.

If ram clearances are too great, a quantity of resin can flash back past the ram as the ram enters the die. With repeated ram strokes, a skin of “smeared” particles can build up at the die entry. This skin tends to break up into flakes, which work their way into the resin and are extruded with it. Because the particles in these flakes are severely damaged by shearing action, they will not coalesce properly with the rest of the resin. Therefore, their presence results in product defects. Elimination of this type of skin is often accomplished by reducing ram clearances. Even with larger ram clearances, water cooling of the die entry will help to alleviate this problem. The magnitude of maximum tolerable ram clearance depends, among other things, upon the type of resin being extruded. Diametric clearances ought to be small enough with respect to resin particle size so that practically all particles of the resin are too large to fit between the ram and die.

Ram clearances of 0.1 to 0.2 mm (4 to 8 mil) on the diameter can usually be expected to yield satisfactory results, although smaller clearances may be dictated based on the resin properties discussed above or upon other factors such as product size and shape.
Another type of skin, the white skin, can be formed as patches usually loosely adhered to the surface of the extrudate or as bands or bracelets surrounding the extrudate, but not adhered to it. The formation of these bands is usually preceded by a reduction of extrudate diameter and then a roughening of the extrudate surface. These are the symptoms indicating that the skin is building up in the extruder. This buildup occurs at the end of the sintering zones of the extruder die. As the skin builds up in this area, the bore of the die becomes constricted and the PTFE is extruded through a smaller and smaller opening. This accounts for the reduction of size and roughening of the surface of the extrudate. Ultimately, the force required to dislodge the skin is exceeded by the force required to extrude the PTFE through the constriction made by the skin, and the skin emerges from the extruder on the extrudate. Alternatively, the skin may be so firmly adhered to the die that the extruder stalls or back extrusion around the ram occurs rather than forward extrusion. Formation of this type of skin is favored by a combination of events that lead to the production of PTFE having highly sheared particles loosely adhered to the surface of the extrudate. These particles can be torn free of the surface relatively easily as the PTFE is cooled in the extruder die after sintering and shrinks away from the die. Such particles accumulate on the die surface near the end of the sintering zones. Once the buildup has started, shearing of the surface of the PTFE is locally increased and more material is added to the skin in the die.

The most favorable circumstance leading to production of these white skins is a very rapid cooling of the Teflon™ PTFE in the die immediately after the last sintering zones of the extruder die. Rapid cooling results in fast shrinkage of the PTFE away from the die. Formation of the sheared surface particles is favored by large ram clearances, hot resin feed and compaction, fast extrusion, rough dies, and high temperatures. However, rapid cooling appears to be the major contributing factor in this type of skin buildup. Some materials of die construction ( unplated steels and some stainless steels) appear to favor the formation of skins. Extruding under conditions for which the PTFE emerges from the extruder in the gel is one means of virtually eliminating white skins, but this practice can lead to other difficulties (such as rougher surface, uncontrolled cooling rate, and lack of support and confinement of the gel).

Process and Equipment Design

Design Criteria

With general-purpose resins, the primary consideration (aside from powder feed) in the design of a workable ram extrusion process and apparatus has been the avoidance of high back pressure and consequent poker chipping. Ultimately, this has meant that in the past, relatively short extruder dies have had to be used, and that the low extrusion rates, dictated by the necessity for providing adequate heating time in a short die, had to be accepted. For example, if a 13 mm (0.5 in) diameter rod (requiring at least 5 min heating time) could be extruded through a heated die no longer than 500 mm (20 in) to avoid poker chipping, the maximum allowable rate based on required heating time would be about 6 m/hr (20 ft/hr), with the more usual rate being lower—again partly to avoid poker chipping and maintain adequate product quality. However, with Teflon™ PTFE resins for ram extrusion, one could extrude rod through a die, say, 1000 mm (40 in) long or longer, at rates of 1.2 m/hr (40 ft/hr) or more (5-min heat-up time is still needed), and make a non-poker chipped product of excellent quality. Thus, with ram extrusion grade resins, one need not use very short extruder dies and low extrusion rates to avoid excessive back pressure in the production of shapes such as small diameter rod or thin-walled tubing. These resins have been ram extruded at high rates with high back pressures (over 100 MPa [14,500 psi]) through extruder dies having ratios of die cavity surface area to cross-sectional area as high as 400 to 1.* The conditions used for generating the data for Figure 1 are one example: a 635 mm (25 in) long die having about a 6 mm (0.25 in) diameter bore.

Representative die lengths for various die diameters are given in Table 1 as a guide in the design of ram extruders for the fabrication of solid round rod. In each case, it will be noted that the ratio of die length to rod diameter is about 80 to 1. The die lengths given in Table 1 are for the extrusion of ram extrusion grade resins with high resistance to poker chipping at high pressures. General-purpose resins will normally require the use of shorter dies and lower extrusion rates to avoid poker chipping and maintain product quality.

*The ratio of die cavity surface area to cross-sectional area equals four times the ratio of die length to bore diameter for tubing extrusion setups having non-tapered, nonreciprocating mandrels of the same length as the heated die.
In many instances, PTFE can be extruded through shorter dies, provided only that back pressure is high enough. Variation of die length is possible for any given size of rod, and dies considerably longer or shorter than those given in Table 1 can be used at appropriate extrusion rates. We have, for example, made 25 mm (1 in) diameter rod by ram extruding through a die only 650 mm (25 in) long. Back pressure for the extrusion was increased by cooling the first 130 mm (5 in) of heated die to 300 °C (572 °F) (130 mm [5 in] of cooled die entry beyond ram penetration) and heating the remaining 500 mm (20 in) of die to 420 °C (788 °F) (as suggested by the discussion of back pressure developed earlier in this report). Product extruded at 1.7 m/hr (5.2 ft/hr) (20 min residence time in the heated die) has excellent properties.

The maximum extrusion rates given in Table 1 are found by dividing the die length given by the minimum heating time required for the given rod size at the temperature shown. Slower rates (if there is no degradation) will give higher tensile strengths, lower void content, and higher ultimate elongations. Thus, depending upon the individual requirements of the processor (or mechanical limitations of equipment), the rate may be adjusted downward from the maximum given in the table.

Extrusion Equipment

Ram extruders are built either to extrude vertically downward (Figure 2) or horizontally (Figure 3). There is no reason to suppose that a ram extruder could not be oriented in any direction one chooses (including inclined extruders or vertical upward extruders), granted workable solutions to feeding problems and sufficient justification for departure from classical practice. If there is a choice to be made between a horizontal and vertical extruder, it can often be made based on available space—a horizontal extruder generally requires more floor space and less head space than does a vertical extruder. Takeoff may be simpler from a horizontal extruder, and very long straight lengths of product (e.g., large rod, long lengths of tube) may be more easily made with a horizontal extruder, where available takeoff space or support of the extrudate might create problems with a vertical extruder. Certain types of tubing extrusion might better be done with a vertical extruder to simplify solutions to problems with mandrel centering or sag. In many instances, resin feed is simplified by using a vertical extruder (e.g., multicavity extrusion of rod, extrusion of very small rod). It is not universally true that feeding of a vertical extruder is simpler than it is for a horizontal extruder, particularly since the advent of high flow resins. All parts of a horizontal extruder probably are generally more readily accessible for maintenance than are all parts of vertical extruders, because they are all on one level. It may be easier to provide cooling of the extruder feed zone in a horizontal extruder than in a vertical extruder, because natural air convection over the heated die of a horizontal extruder is not directed toward the feed end of the die.

These observations lead to the conclusion that neither type of ram extruder can be said to be the best for every job.

A ram extruder has at least the following four basic component systems:

- Pneumatic system (or other drive system)
- Ram
- Die (with appropriate temperature control means)
- Feed system

Other optional components include a brake and cooling tube.

Extruder Drive System

The pneumatic system controls the action of the air cylinder used to drive the ram. A system with a line pressure of 0.7 MPa (100 psi) used with a 100 mm (4 in) cylinder provides enough force for the extrusion of a single end of any size of solid rod up to about 25 mm (1 in) diameter, from any granular Teflon® PTFE resin, and for many shapes and tubes having cross-sectional areas in this same size range. The control system for the air cylinder can consist of a pressure regulator and a solenoid valve (with appropriate timers and limit switches). One type of arrangement is shown in Figure 3. A pressure gauge mounted on the air cylinder can be used to good advantage in estimating back pressure.

The air cylinder, which drives the ram, is often operated on a timed cycle. There is a certain proportion of the cycle during which the piston rod of the cylinder is advanced or at rest in the position of maximum ram penetration, while the piston rod is retracted or rests in its withdrawn position during the remainder of the ram cycle. Use of a timed cycle, while not essential, is usually suggested as being preferable to alternative systems where the air cylinder is operated through limit switches activated whenever the piston rod (hence, the ram) reaches its maximum advanced or withdrawn position. One reason for this is that a timed total cycle length, including sufficient time delay for unhurried powder feed with the ram in its rear-most position, will often result in a more uniform extrusion rate.
Figure 2. Vertical Ram Extruder for Making Tubing of Teflon™ PTFE Fluoropolymer Resin
Figure 3. Horizontal Ram Extuder for Making Tubing of Teflon™ PTFE Fluoropolymer Resin
Some of the other things to consider in setting up a ram extruder to operate on a timed ram cycle are given in the following paragraphs.

The more time that is allotted for the ram to compact the resin and extrude, the lower the pressure required and more opportunity for air to be expelled from the resin being compacted.

Usually, only a few seconds are needed for automatic resin feed; thus, unless hand feeding is used, minimum time is needed for delaying the ram in its withdrawn position.

Some advantages to delaying the ram while in its withdrawn position are that more time is allowed for air that may have been compressed in the previous resin charge to diffuse out of the resin and the rear face of the last compacted charge in the die will have more time to recover or relax a little after being compressed by the face of the ram. This time delay is not ordinarily needed in the case of Teflon™ PTFE resins for ram extrusion, because whatever recovery occurs at this surface happens almost instantaneously upon withdrawal of the ram (the rear surface of the charge immediately takes on a pebbly texture).

One disadvantage in delaying the ram in its rearward position is that the likelihood of encountering excessive resin spring back is enhanced. Should back expansion or spring back happen to any great degree, the extrusion rate can be affected, because the length of subsequent charges can be decreased—especially if a volumetric feeder is used. Remembering the previous suggestion that the feed zone of the extruder die be water cooled and that frictional resistance between the cold resin and die wall is very high in this area, the likelihood of any major back expansion occurring is small—provided only that the length of the cold feed section of the die is sufficient. Back expansion can be practically eliminated by delaying the ram in its position of maximum penetration for part of the cycle.

The setup shown in Figure 3 is illustrative of the components of a ram drive control system. The limit switches and solenoid valves depicted could be connected with one or more timers of an appropriate type to incorporate features such as those listed below into the ram control sequence.

- Independently control the length of time during which the ram is being advanced or retracted.
- Control the dwell time with the ram at rest in the position of maximum penetration or withdrawal.
- Control the duration and intensity of air flow into the feeder (if this type of feeder is used).
- Provide stall out protection for the extruder.
- Control ram speed.

Rams

Rams are generally attached directly to the piston rod of the air cylinder, which requires that the axis of the cylinder be accurately aligned with the axis of the extruder. The usual practice is to make the ram in two parts—a shank of some standard stock size, smaller than the die bore, and a tip machined to proper size and attached to the shank by screw threads, press fit, or welding. Ram tips made of steel, hardened steel, brass, bronze, and other materials have proved to be satisfactory, depending, at least to some degree, upon the materials of die construction, ram clearances, and speed and temperature of operation.* The length of the ram tip need only be about the same as the tip diameter. With any given radial clearance between ram and die, lengthening the ram tip enhances the possibility of encountering difficulties associated with misalignment (rubbing, scoring, wear, excessive ram driving force, and marking of the extrudate). When the ram tip is kept short, however, radial clearance between the tip and extruder die can be on the order of 0.03 mm (1 mil), although greater radial clearance usually is satisfactory. The possibility of encountering some types of skin formation increases with increasing ram clearance, as discussed in the section of this report concerning skins.

It is suggested that, for tubing extrusion, the radial clearance between a hollow ram and nonreciprocating mandrel be about 0.05 mm (2 mil) or less to reduce the likelihood of skin formation. Concentricity of tubing is affected by ram clearances as well. The outer and inner diameters of the hollow ram need be machined to close tolerances only over a length about equal to the ram diameter.

*Because of the possibility that a ram tip may become detached from the ram and advanced through the hot extruder die, safety precautions would dictate that ram tips should be made only from materials that can withstand the temperatures involved in the ram extrusion of Teflon™ PTFE (possibly more than 425 °C [797 °F]).
For the extrusion of tubing and other hollow shapes from Teflon™ PTFE fluoropolymer resins, the use of nonreciprocating, non-tapered mandrel is suggested. As discussed previously, the mandrel can extend usually all the way through the extruder die and should be normally water-cooled at the feed end of the extruder, as should the extruder die tube. Mandrels can be solid or hollow and made of tool steel or stainless steel, ground smooth and plated. For extrusion of tubing of sufficient inside diameter, the mandrel can be fitted with internal heaters to affect a considerable decrease in required heating and residence time below that needed with the same geometry, but without a heated mandrel.

Dies

A ram extruder die normally has a bore or cavity of uniform cross-section over the length of the die. In the case of solid rod extrusion using Teflon™ PTFE resins, the die bore diameter should be about 1.14 times the diameter of the finished rod, keeping in mind that shrinkage in the rod can be controlled to some extent by adjustment of temperature profile, extrusion rate, back pressure and cooling rate. In the case of tubing extrusion, shrinkage is dependent upon mandrel length—or more specifically, the amount of cooling that takes place in the PTFE while it is still on the mandrel—as well as temperature profile, pressure, tube wall thickness, and extrusion rate. In general, shrinkage in tube is less than that for solid rod, and, accordingly, the die diameter for Teflon™ PTFE resins should be about 1.05 times the desired outside diameter of the finished tube for thin-walled tubes.

The choice of materials of construction for ram extruder dies depends upon the life, product surface finish, and surface cleanliness desired, as well as length of run between cleanouts. The die may be made of steel that has been chrome or nickel plated over its inside surface, or it may be made of corrosion-resistant materials such as some type of stainless steel, "Monel," "Hastelloy," etc. The use of some types of unplated stainless steels for ram extruder dies often contributes to excessive skin formation. The wall thickness of a die for extruding round rod need not ordinarily exceed one-half inch and, often, a thinner wall will suffice. The minimum required thickness of die wall increases with increasing bore diameter, just as does the wall thickness of pipe designed to operate with a given internal pressure. The use of thin-walled die tubes can sometimes lead to problems with skin formation.

The extruder die can be encased in split aluminum collars bored to fit the die snugly and having outside diameters of appropriate size to fit the heater bands normally used to heat the die. It is suggested that long dies be heated by several short, independently controlled heater bands rather than one long one. The length of the split collars should be the same as that of the individual heater bands, and it is suggested that these heater band/aluminum block combinations be placed on the die in such a way that adjacent heater blocks do not touch, but rather are spaced apart 0.5 mm (0.2 in) or so. In this way, separate non-communicating heat zones are created that can be set at widely different temperatures if desired. The spacing between zones ensures that no appreciable amount of heat will be conducted along the die from one zone to the next. This is particularly important at the feed end of the die where it is usually desirable to water cool the die entry section, yet have the adjacent part of the die at about 380 °C (716 °F) or so. Use of aluminum for the heater blocks will reduce any temperature nonuniformity around the die circumference to a minimum, because the thermal conductivity of aluminum is some 8–10 times that of the material from which the die may be made. A length of 125 mm (5 in) is appropriate for a heating zone, and 2,000 watts of heat per zone; 5 W/cm² (32 W/in²) is normally sufficient. The die can also be encased in an aluminum casting. In this case, it is suggested that, where it is desired to maintain temperature gradients along the die, the aluminum casting be grooved between heater zones.

Temperature Control

Temperature control in a ram extrusion setup must be exerted over a wide range of temperatures up to about 425 °C (797 °F). Band type electrical heaters, mentioned in the preceding section, are comparatively easy to install and safe and economical to operate. Correct installation consists of staggering the flanges of the heater bands around the die to avoid concentration of cool spots in one area of the die and tightening in place, with final tightening being done at operating temperature.
It is suggested that each heat zone be provided with its own proportioning (preferably current proportioning rather than time proportioning) temperature controller and an additional indicating thermocouple to be used as a cross-check on the temperature indicated by the controller. Thermocouples should be placed in the center of the heat zone and extend through the aluminum blocks and contact the actual die surface with sufficient contact pressure to ensure vibration-proof operation. Some means of indicating or preventing overheating should also be provided as a precaution against damage due to controller or thermocouple failure.

The method suggested above is one way of ensuring that some representative extruder die temperatures can be accurately, reliably, and reproducibly controlled and measured. Because maintenance of the desired temperature profile is of great importance in the production of ram extruded PTFE that is uniformly high in quality, accurate control and measurement of representative die temperatures, by whatever means used, is of paramount importance.

**Powder Feed Equipment**

The method used to feed granular resin to a ram extruder is rarely the same for a horizontal extruder as it is for a vertical extruder, and several different techniques can be used for either. Powder can be fed on a weight or volume/demand basis. Demand feed consists simply of providing a feed cavity at the entry of the extruder die, which is filled by gravity flow of powder from a hopper each time the ram is withdrawn.

Feeding on a weight basis is well suited to vertical extrusion of rod and tube. With this system, powder flows from a hopper to a weighing device and is conveyed to the feed end of the extruder by means such as a vibrating tray. Volumetric feeding of resin to a vertical rod extruder might be done using a shuttle box.

Many variations of these two basic types of feed can be used where appropriate. These include the use of force feed systems, shuttle boxes, mechanical loaders, screw feeders, and so forth. The basic purpose of these arrangements is to provide powder charges of uniform weight to the extruder (with even distribution around the mandrel in the case of tubing extrusion), while avoiding contamination of the powder or damaging it such as by forming lumps in it or breaking up particles or classifying the particles (separating the large ones from the small ones, so that each charge does not contain the right amount of each).

**Accessory Equipment**

Suitable means for supporting ram extruded PTFE are often needed to ensure that the product will be straight and clean. Because ram extruded material is often subjected to machining operations in automatic equipment that cannot handle curved or crooked feed stock, curvature of the extrudate may be intolerable. This being so, care should be taken to avoid inducing even large radius curvature. Thus, the extrudate should not be bent or pulled when being cut off and cooled as uniformly as possible (not in a draft) and stored flat (not coiled) if straight pieces are needed. Uniform extrusion rate is of great importance in obtaining straight product—particularly for items such as small diameter rod.

**Typical Process and Property Data**

Data showing the typical response of Teflon® PTFE fluoropolymer resin to a variety of ram extrusion conditions are given in Figure 4. Figure 1 shows typical tensile strength of various sizes of rod and tube ram extruded from Teflon® PTFE.

**Special Extrusion Processes**

The discussion of the ram extrusion process up to this point has been centered around the extrusion of a single end of rod, tube, or other shape from an unfilled molding or extrusion resin. While this type of extrusion is widely done and serves to illustrate the principles of ram extrusion, multiple cavity extrusion and extrusion of filled compositions are two other important areas of ram extrusion that merit discussion.

**Multiple Cavity Extrusion**

Multiple cavity (or multiple end) extrusion is the simultaneous production of several, usually identical, ends of product (usually rod) from a single extruder having a plurality of identical dies. Ideally, each die in the multiple die extruder provides an extrusion environment (temperature, pressure, residence time, etc.) sufficiently close to that prevailing in all other dies in the same extruder, to ensure that product of uniform quality is produced by all dies of the extruder. Very slight differences between dies in temperatures, surface characteristics, and so forth, which lead to slightly differing degrees or rates of output, skin build-up, pressure changes, etc., can build up in time to yield large differences between properties of the several ends extruded from a given extruder. Because it is these cumulative effects of differences between dies (which may have been initially only slightly different) that can lead to a large majority of problems in multicavity...
Figure 4. Processing Data, Rod Extrusion

Typical processing data for Teflon™ PTFE ram extrusion resins

- DIAMETER SHRINKAGE
- LENGTH OF HEATING ZONE
- SINTERING TIME (CONSERVATIVE)
- LENGTH OF COLD ZONE (FOR BACK PRESSURE)
- DIAMETER SHRINKAGE
- EXTRUSION SPEED

Length, heating zone (mm)
Length, cold zone (mm)
Sintering time (min)
Shrinkage % ext. speed

NOTE: For control purposes, no brakes were used.
Ram Extrusion of Filled Compositions

Teflon™ PTFE can be combined with a variety of fillers to impart some specific set of properties to the final product. The primary differences between filled and unfilled compositions in ram extrusion processing are: back pressure development, back pressure requirements, sintering requirements, and extruder wear.

The ram extrusion of a given cross-section from a filled composition is often accompanied by somewhat higher back pressure than would exist in the extrusion of the same section from an unfilled resin under the same conditions of die temperature profile and extrusion rate. Because filled compositions generally require more pressure in processing than do unfilled resins, the higher back pressure generated in the ram extrusion of some filled compositions is of benefit in reducing the void content of the product. In some instances, however, back pressure may need to be further augmented in filled composition extrusion to bring product properties to an acceptable level. The combined poker chip sensitivity and high pressure requirements of filled compositions tend to make avoidance of poker chipping a difficult problem in the ram extrusion of these materials.

Parts molded from some types of filled compositions often need to be cooled under pressure after sintering to reduce the void content in the finished article. In a similar fashion, material ram extruded from some filled compositions should also be cooled under pressure, if the resultant product is to have a low void content. Because the cooling phase of the ram extrusion process does not normally take place with pressure applied to the resin (the extrudate is cooled exit the extruder die or it loses contact with the die as a result of shrinkage early in the cooling process), the void content of ram extrusion process can be achieved to some degree with the use of a brake.

The somewhat abrasive nature of many filled compositions results in an increase of the wear rate in some extruder parts (notably dies and ram tips). Thus, tool life in a ram extruder used with filled compositions can be improved somewhat with the use of chrome-plated, hardened steel dies.
Safe Handling Practices

When Teflon™ PTFE is heated above its melt point, it begins to decompose. Therefore, any process where PTFE exceeds its melt point of 342 °C (648 °F) should be properly vented. Although the rate of decomposition is small at temperatures below 425 °C (797 °F), adequate ventilation should be provided to prevent any unnecessary exposure to the fumes evolved. In ram extrusion, ventilation should be provided at the exit of the extruder barrel, because it is the most likely place where resin above its melt point, or decomposition products, would be exposed to the environment.

Smoking or the carrying of smoking materials should be prohibited when handling Teflon™ fluoropolymer resins to avoid possible contamination of the smoking materials.

Ram extrusion includes the use of high pressures to properly sinter the extrudate. Precautions should be taken to prevent exceeding the pressure limitations of the equipment.

High temperatures are also present during ram extrusion. Although most of the equipment might be insulated, the extrudate at the exit of the barrel is extremely hot. Burn protection should be provided in the extrusion area and especially at the barrel exit.

Because Teflon™ PTFE granular resins are in the form of small particles, safety glasses are recommended when handling the resin to prevent eye contamination.

It is recommended that the “Guide to the Safe Handling of Fluoropolymer Resins” published by the Plastics Industry Association (www.plasticsindustry.org) or PlasticsEurope (www.plasticseurope.org) be studied prior to working with and fabricating Teflon™ PTFE granular resins in ram extrusion.
## Troubleshooting Guide

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<th>Problem</th>
<th>Possible Cause</th>
<th>Suggested Solution</th>
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| 1. Black (or other color) spots in product | a. Contamination in powder  
b. Contamination from extruder | a. Enclose feed portion of extruder (hopper, feeder). Filter air supply to air jet, more careful loading of hopper.  
b. Clean extruder die, reduce ram clearance, enclose feed area. |
| 2. Black lines at charge  
(See Figure 5) | Contamination from extruder due to mis-alignment (ram rubs on die and/or mandrel in tubing extrusion) | Align extruder—Guide ram tip prior to die entry. Open up ram clearance(s). Generally, eliminate rubbing of ram clearance(s). Generally, eliminate rubbing of ram clearance(s). |
| 3. Score lines or cracks running in extrusion direction | Buildup of dirt, etc., or burr in die | Clean die. |
| 4. Circumferential grooves or splits at charge interfaces. May not be visible all around product.  
(See also 8, 9, 12) | a. Too much back pressure (poker chipping)  
Back pressure can be estimated by dividing ram force (kg/lb) by ram face area (cm²/in²)  
b. Too little residence time in heated die  
c. Degradation (too much residence time in heated die at temperature being used)  
d. Too much ram clearance | a. Reduce back pressure (decrease rate, charge length, die length). Inspect die (and/or mandrel) for roughness. **Note:** Poker chipping can be revealed by placing extrudate in a circulating air oven (vented outdoors) at 380 °C (720 °F) for 2 hr (or until Teflon® PTFE fluoropolymer resin goes into gel), removing, air quenching. Poker chipped product will crack during this test, even if not apparent through visual examination of product before testing.  
b. Check residence time against values shown in Table 1. Reduce rate, raise temperature, lengthen die.  
c. Reduce temperature, increase rate, shorten die. Check thermocouples—readings of 50 °C (90 °F) low are not unknown.  
d. Reduce ram/die and ram/mandrel clearances. **Note:** This defect becomes more apparent with increasing length of operating time. Die (especially around the entry section) must be thoroughly cleaned as part of corrective action. |
| 5. Rough surface may be “waxy” or extrudate may even be full of voids, and surface may have blackened areas | a. Degradation  
b. Blackened areas may be caused by corrosion of extruder die | a. See 4-c above.  
b. Check area for pits, loss of chrome, nickel, or other plating if used. |

*continued*
## Troubleshooting Guide (continued)

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<tr>
<th>Problem</th>
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| 6. Graininess or chalkiness of cross-section, whole cross-section may be affected, or effects may only be visible at axis of section. View a thin slice of the cross-section (cut off with a wood plane, for example) by transmitted light, as this may reveal a slight haziness not otherwise detectable. If haziness is not observed or is very slight, tensile strength of product will not be noticeably affected. (See Figures 6a, 6b) | a. Insufficient heat  
b. Insufficient pressure | a. See 4-b.  
b. Increase back pressure (increase rate, charge length, die length, length of cold entry of die. Reduce temperature of first 130 mm [5 in] or so of heated die below about 370 °C [700 °F]. Continued reduction of temperature will produce increased back pressure). |
| 7. Nonuniform charge length or wavy charge marks | Nonuniform feed | Cool feed hopper, feed zone, die entry. Use an air jet in hopper to promote better feed. Promote more uniform distribution of resin in extruder feed cavity. |
| 8. Circumferential rings on product | Extruded in gel-marks caused by “frozen in” gross dimensional changes in product at die exit | Reduce temperature at die exit so product does not exit in gel or at least reduce this temperature so that the gel has been cooled below its maximum temperature before it exits the extruder. This defect is most pronounced in thin-walled tube extrusion where the tube exits the extruder in the gel on the mandrel. If the mandrel extends far enough beyond the die so that the tube shrinks firmly to it, the material exiting the barrel in the gel will buckle (or even split), resulting in an “hour glassed” section. Thin-walled tubing should not exit the extruder in the gel. |
| 9. “Hour glassing” in tube—especially thin-walled tube | a. Teflon™ PTFE fluoropolymer resin exits in gel on mandrel  
b. Lengthen mandrel in die or reduce temperature at free end of mandrel so tube is not in gel when it leaves the mandrel. |
| 10. Internal voids or cracks (See Figure 7) | a. Trapped air or other gas or vapor  
b. Too rapid cooling of thick sections | a. Increase ram clearances, reduce length of ram tip. This is not a common problem with Teflon™ PTFE.  
b. Reduce cooling rate by adding insulated tube to exit end of extruder, for example. Usually a problem only with larger 50 mm (2 in) rod. |

*continued*
## Troubleshooting Guide (continued)

<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible Cause</th>
<th>Suggested Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a. Circumferential temperature gradients in die</td>
<td>b. Reduce air currents.</td>
</tr>
<tr>
<td></td>
<td>b. Nonuniform cooling</td>
<td>c. See 7 above.</td>
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<tr>
<td></td>
<td>c. Nonuniform feeding</td>
<td>d. Center mandrel and provide uniform feed to keep mandrel centered.</td>
</tr>
<tr>
<td></td>
<td>d. Mandrel off-center in tube extrusion (tube is also non-concentric)</td>
<td></td>
</tr>
<tr>
<td>12. Circumferential grooves at charge interfaces. Grooves not necessarily visible all around product (See Figure 8)</td>
<td>a. Poker chipping</td>
<td>a. See 4-a.</td>
</tr>
<tr>
<td></td>
<td>b. Too much ram clearance, allowing ram to be non-concentric with die. In tubing, these grooves may be visible only over the part of the tube where wall thickness is greatest and may be seen inside and outside</td>
<td>b. Reduce clearances, align equipment, provide uniform feed distribution. Tubing extruders are not self-aligning. They must be aligned to start and kept in line by ensuring that feed resin is uniformly distributed over the feed cavity (or, at the very least, by randomizing nonuniformities of feed so that any nonuniformity of distribution does not exist in the same place in the feed cavity for every charge).</td>
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<tr>
<td>13. Resin springs back when ram is withdrawn</td>
<td>Some spring back is normal. If too much occurs:</td>
<td>a. Increase ram penetration.</td>
</tr>
<tr>
<td></td>
<td>a. Ram penetration may be too small</td>
<td>b. Increase dwell time with ram at full penetration. Try to keep ram forward until extrudate stops moving.</td>
</tr>
<tr>
<td></td>
<td>b. Dwell time with ram at full penetration may be too short</td>
<td>c. Increase ram penetration or water cool feed area.</td>
</tr>
<tr>
<td></td>
<td>c. Feed cavity too hot for given ram penetration</td>
<td></td>
</tr>
<tr>
<td>14. Skins</td>
<td>a. Black skins or patches on product (See Figure 9)</td>
<td>a. If the black skins have not disappeared after slightly more than one die length of product has been extruded, clean die, check temperatures, and check die plating and die surface for pits, etc.</td>
</tr>
<tr>
<td></td>
<td>b. White or gray patches in product</td>
<td>b. Reduce ram clearances, Sharpen edge on ram face and eliminate forward taper on ram, if any.</td>
</tr>
<tr>
<td></td>
<td>c. White skins or patches on product (See Figure 10)</td>
<td>c. Reduce cooling rate of product in die, reduce ram clearances, and provide a sharp edge on the ram face, water cool die entry.</td>
</tr>
</tbody>
</table>
Troubleshooting Guide (continued)

Figure 5. Black Lines at Charge

Figure 6a. Grainy Cross-Section   Figure 6b. Chalky Cross-Section
Troubleshooting Guide (continued)

Figure 7. Internal Voids or Cracks

Figure 8. Circumferential Grooves
Troubleshooting Guide (continued)

**Figure 9. Black Skins or Patches**

![Image of black skins or patches]

**Figure 10. White Skins or Patches**

![Image of white skins or patches]
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