



Teflon™ PTFE

Fluoropolymer Resins

Ram Extrusion Processing Guide



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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.

*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) $\sim 3 d^2$ (cm) or $\sim 20 d^2$ (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.

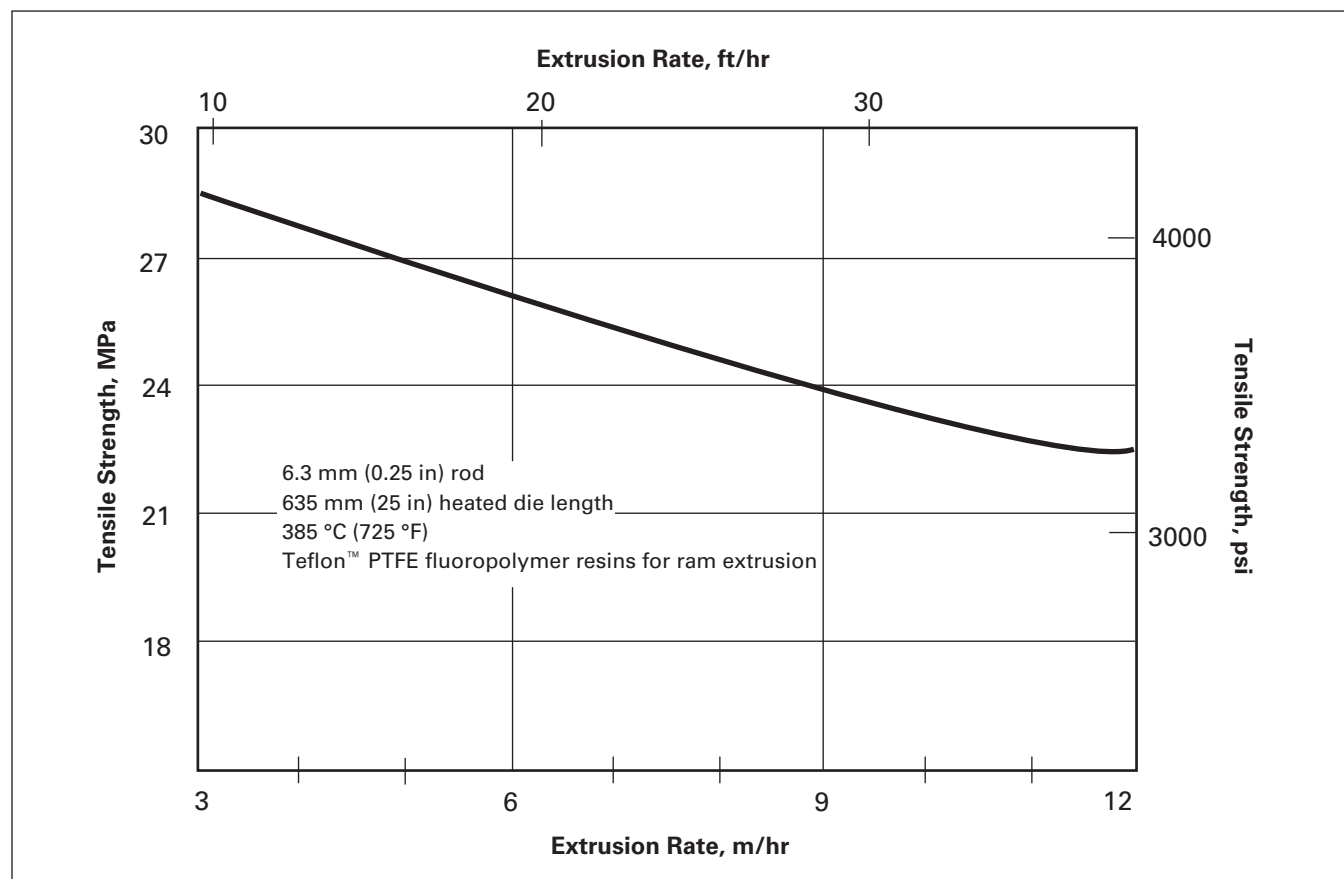
*While gel opacity is generally symptomatic of voids, gel clarity does not necessarily guarantee freedom from voids.

Table 1. Average Shrinkage, Required Heating Times, and Representative Die Lengths for Ram Extruders Used with Teflon™ PTFE Fluoropolymer Resins for Ram Extrusion

Rod Diameter, d Average Shrinkage, S mm (in) S/%	Minimum Required Heating Time, min, 395 °C (743 °F)	Representative Die Length, mm (in)*	For Representative Die Length	
			Maximum Extrusion Rate, m/hr (ft/hr), 395 °C (743 °F)	Typical Extrusion Rate, m/hr (ft/hr), 395 °C (743 °F)
3 (0.12) 6	1	250 (10)	15 (50)	10 (33)
6 (0.25) 8	1.25	500 (20)	24 (80)	12 (40)
13 (0.50) 11	5	1,000 (40)	12 (40)	8 (25)
19 (0.75) 12.5	11	1,500 (60)	8 (25)	4.5 (15)
25 (1.0) 13.5	20	2,000 (80)	6 (20)	3 (10)

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

Figure 1. Tensile Strength vs. Extrusion Rates



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 lengthens. 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 be accompanied by an increase in back pressure, if other factors remain unchanged. In general, increasing the length of the water-cooled ram penetration zone will affect the largest increase in back pressure per unit length of zone—greater by far (10 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 if 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.