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Processing Thermoplastics Urethanes via Twin Screw Extrusion

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29.1 Introduction

Twin screw extruders (TSEs) are used to process virtually every type of plastic that is used today. The goal of this chapter is to define how twin screw extrusion (TSEs) can be used to process thermoplastic polyurethane (TPU) formulations that contain additive and fillers into pellets and shapes. Some simple formulas are interspersed with the text to provide insight into how TSEs are designed and the advantages of using TSEs for the synthesis, processing, and compounding of thermoplastic urethanes.

High-speed, energy-input (HSEI) corotating and counterrotating twin screw extruders are mass transfer devices that are the industry’s preferred manufacturing methodology for compounding, devolatilization, reactive extrusion, and blending. Materials that are typically compounded include fillers, colors, fibers, nanoparticles, lubricants, and stabilizers, as well as an infinite number of process aids and specialty additives. TPUs are also alloyed with other polymers, including with polypropylene as a PVC replacement.

Reactive extrusion is also possible. Each formulation requires its own system configuration and processing conditions. However, some generalities can be stated, for instance, TPUs can be easily overworked and degraded, which necessitates gentler TSE configurations and processing conditions as compared to most other polymers (Figure 29.1).

TSEs perform dispersive and distributive mixing. In dispersive mixing, solid agglomerates or liquid droplets held together by interfacial tension are subjected to mechanical stress for size reduction. The most important flow characteristics for dispersive mixing efficiency are the shear stresses associated with the extensional and planar flow fields as generated by TSE screw mixing elements. In distributive mixing, repeated rearrangement of the minor components without destructuring size enhances product homogeneity (Figure 29.2).
The modular nature of TSEs offers process flexibility with regard to screw design, barrel configuration, and shear intensity. The corotating intermeshing mode dominates the market, having captured ~90% of current installations. Counterrotating intermeshing and nonintermeshing TSEs are primarily used for specialty applications, including some specialty alloying and reactive processes (Figure 29.3).

In the plastics industry, TSE screw diameters range from 12 to 400+ mm with outputs from 1/4 to 50,000+ kg/h. Segmented screws convey and shear the materials being processed in channels bounded by screw flights and barrel walls, with short mass transfer distances. This is why TSEs are designated as “small mass” continuous mixers, as compared to “large mass” batch mixers. Solids conveying and melting occurs in the early stages of the process section followed by mixing and devolatilization. Discharge elements then build and stabilize pressure prior to discharge. The controlled pumping and wiping characteristics of the TSE screws in combination with a segmented design allows specific screw element geometries to be matched to the unit operations being performed in the TSE process section3 (Figure 29.4).

Process control parameters for a TSE include screw speed (rpm), feed rate, process temperatures, and vacuum level (to assist devolatilization). Melt pressure, melt temperature, motor amperage, and various in-line sensors also monitor the process to ensure a consistent/
quality product. State-of-the-art TSEs utilize programmable logic controllers (PLCs) for control, monitor, and logic functionality that integrate graphical touch screens, data acquisition, trending, and recipe management as standard features. For complex installations, “Flex I/O” is now common, where signal wires are wired to a machine-mounted junction box that combines terminal strip I/O with Ethernet communication to the PLC to simplify installation and troubleshooting. It is also now routine to integrate subsystem PLCs with a supervisory PLC, referred to as distributed processing, for systems integration of complex equipment from multiple suppliers (Figure 29.5).

Starve feeding refers to when the extruder is fed at a rate less than the forwarding efficiency of the screws. TSEs are almost always starve fed with the output rate determined by the feeder(s). The TSE screw rpm is independent and used in concert with the feed rate to optimize compounding efficiencies. Feed rate versus screw rpm, and screw design, also dictate the residence time (RT) and residence time distribution (RTD) for the materials being processed. Depending upon these factors, the RT can be less than 10 s or as long as

![Figure 29.3](image1)

Modular TSE process section.

![Figure 29.4](image2)

TSE segment screw set with unit operations denoted.
10 min. Typical RTs are between 15 s and 2 min for compounding and 1 s and 10 min for reactive extrusion applications.

In addition to its role in regulating the mass transfer properties of the process, feeders also maintain formulation consistency and are situated to introduce ingredients in the proper order. Various delivery mechanisms are used, including vibratory trays and bulk solid pumps (for pellets), single screw (for pellets and some powders), and twin screw (for powders and granules). Liquid feed streams use piston, diaphragm, or gear pumps depending upon the viscosity of the liquid, and can be ambient or heated.

Volumetric feeders can be acceptable for premixes that do not segregate. When multiple feed streams are metered into the TSE process section, loss-in-weight (LIW) feeders on load cells are generally used that modulate the feed delivery mechanism to maintain a consistent mass flow to the extruder³ (Figure 29.6).

For quality compounding applications, i.e., for a medical device, the TPU pellet is dried in a desiccant dryer prior to metering into the TSE, and a nitrogen purge is integrated into the feeder hopper design. TPU compounding systems can use a combination of solid/liquid feeders. Reactive extrusion systems sometimes utilize only liquid feed systems. Whether for solids or liquids, premixing of some materials may be preferred, depending upon the number and characteristics of the ingredients.

The pressure gradient in the twin screw extruder is determined by the selection of screws. Flighted elements are strategically placed so that the screw channels are not entirely filled which results in a zero pressure underneath downstream vent/feed sections, which facilitates downstream feeding of fillers and fibers, and also prevents vent flooding (Figure 29.7).

A “side stuffer” is a device that is commonly integrated with a TSE to introduce fillers, fibers, and other materials into the process melt stream after plastication. Like a TSE, a side stuffer utilizes corotating, intermeshing, self-wiping screws to “push” materials into an
FIGURE 29.6
Loss-in-weight feeders at TSE feed throat.

FIGURE 29.7
Pressure profile in starve-fed TSE.
unfilled section of the TSE screws. Screws and barrel components are manufactured of abrasion-resistant metallurgies, and the barrel is jacketed for liquid cooling/heating. Side stuffers are also starve fed and require a metering feeder upstream to set the rate.

Side stuffing is desirable for processing filled compounds to facilitate more efficient melting/mixing with significantly less wear in the melting region of the process section. Side stuffing is preferred to minimize fiber attrition, and to process shear-sensitive fillers, such as a flame retardant. For instance, this is the ideal configuration to process a TPU/glass fiber compound to minimize both fiber attrition and wear (Figure 29.8).

The gearbox of a twin screw extruder transmits energy from the motor to the screws, and reduces the motor speed to the desired screw rpm while multiplying torque. To avoid gearbox damage, most twin screw extruders have a mechanical overtorque coupling that connects the motor shaft to the gearbox input shaft, and automatically disengages the motor in an overtorque situation.

The TSE motor inputs energy into the process via rotating screws that impart shear and energy into the materials being processed. Alternating current (AC) motors/drives are the industry standard (up to 1000 kW) that utilize digital communication, and can upload/download drive settings. The percentage motor torque is a particularly critical parameter to be monitored, and is measured as follows:

% Torque: This formula indicates % of available rotational force being used in a process, and is a typical readout in the control panel as a %. This is calculated as follows:

\[
\text{% Torque} = \frac{\text{applied motor power (kW)}}{\text{maximum available motor power (kW)}}
\]

where AMP is the electrical current or load from the main motor.

For example, if a TSE has a maximum rating of 500 kW and a process draw 400 kW, then the torque is 80% (400 kW/500 kW).

\[
\text{% Torque} = \frac{400}{500} = 80\%
\]
For quality control and process troubleshooting, specific energy (SE) is a critical parameter to be monitored, which can be determined as follows:

**Specific energy**: Specific energy is the amount of power that is being input by the motor into each kilogram of material being processed. This is calculated in two steps:

Applied power:

\[
\text{kW}\text{(applied)} = \text{kW}\text{(motor rating)} \times \% \text{torque} \times \text{rpm running/maximum rpm} \times 0.97
\]

Now the SE can be calculated:

\[
\text{SE} = \frac{\text{kW}\text{(applied)}}{\text{kg/h}}
\]

where

- SE is denoted in kW per kg/h
- kW = kilowatts (the motor rating, kW = HP × 0.746)
- % Torque = % used of the maximum allowable torque
- rpm = screw rotations per minute

For example:

A 40-mm twin screw extruder is processing a TPU/PP alloy at 100 kg/h, running at 200 rpm with 68% torque. The machine has a 56-kW (~75 HP) motor and a maximum screw rpm of 600.

\[
\text{kW}\text{(applied)} = 56 \times 0.68 \times 200/600 \times 0.97 = 0.154 \text{ kW per kg/h}
\]

A lower SE indicates that less mechanical energy is being used, and a larger SE indicates more energy. It is important that SE records be maintained, particularly for troubleshooting. For instance, if a product always runs with an SE of around 0.15 and suddenly changes to 0.26, and the process conditions are the same; this implies that the material or hardware has changed. SE can also be used as a benchmark for scale-up and/or comparing different manufacturing operations (Figure 29.9).

TSEs are available with top screw rpms of 1200+. Due to the shear-sensitive nature of most TPU formulations, the motors and gearbox are generally specified for a top screw rpm of 500 or lower. The TSE should not be geared substantially higher than the required screw rpm. The following formula can be used as a guideline as to how to configure the motor/gearbox:

\[
\text{Shaft torque as it relates to screw rpm:}
\]

\[
\text{Torque} = 9550 \times \text{kW/top rpm}
\]
where

\[ 9550 = \text{constant} \]

Torque = total torque for both screw shafts, typically denoted in Nm (Newton meters)

\( kW = \) motor rating on the HSEI twin screw extruder

For example:

If an HSEI twin screw extruder with a 60-mm screw diameter has a torque rating of 3200 Nm and uses a 200-kW motor if geared for 600 rpm at full torque, then a 400-kW motor would be specified at 1200 rpm as indicated below:

\[
\frac{3200}{600} = \frac{9550 \times 200}{1200} = 9550 \times \frac{400}{1200}
\]

If a machine will never operate above 600 rpm, it should not be geared for 1200. Since the torque is a constant, a 60-mm twin screw extruder can be geared either at 600 rpm with a 200-kW motor or at 1200 rpm with a 400-kW motor (or with another motor/gearbox combination). At 600 rpm and below, the performance will be exactly the same, since the applied torque and free volume are unchanged. Accordingly, high rpms should not be specified for TPU processes unless it is planned to process other thermoplastics that benefit from higher screw speeds.

Sometimes the choice is between an HSEI twin screw extruder with a larger screw diameter operating at lower rpm or a smaller machine at higher rpm. The cost differential for both should be compared before a final selection is made, particularly for larger machines. For TPU, upsizing with a lower top screw rpm is probably preferred.\(^5\)

### 29.3 TSE Process Section: The “Key” to Success

The heart of the TSE is its screws and barrels, referred to as the process section. In a co-rotating, intermeshing twin screw extruder, the screws are termed “self-wiping.” The surface velocity of the screws in the intermesh region are in opposing directions, which results in
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The materials being forced to follow the figure 8 pattern down the length of the screws (Figure 29.10).

There are an infinite number of screw design variations, and the screw design can be made shear intensive or passive. There are, however, only three basic types of screw elements: flighted elements, mixing elements, and zoning elements. Flighted elements forward material past barrel ports, over mixers, and out of the extruder to the die. Zoning elements isolate two operations within the extruder, such as a melt seal prior to a vacuum vent. Through-hardened tool or stainless steels are generally specified for unfilled TPU products, while powdered metallurgies (PMs) are often specified when processing filled compounds.

Mixing elements may be dispersive or distributive. The most common mixing element is a kneader. The wider a kneading element the more dispersive it becomes as extensional and planar shear effects are forced to occur as materials are forced up and over the land. Narrower kneading elements are more distributive in nature by facilitating high melt division rate mixing with little extensional and planar shear. Distributive mixing elements allow heat- and shear-sensitive materials to be mixed, such as glass fibers or flame retardants, without degradation/attrition. Kneading elements can be arranged with a forward pitch (less aggressive), neutral, or reverse pitch (most aggressive). High liquid phase mixing generally benefit from specialty distributive elements that prevent “pooling” of the liquids in the TSE process section (Figure 29.11).

Modular TSE barrels typically use electric cartridge heaters and internal cooling bores for liquid cooling. State-of-the-art barrel designs utilize (1) inlet ports and (2) outlet ports for each barrel section to maximize coolant flow and cooling efficiencies. Increasing the coolant flow and heat transfer capabilities of the barrels is beneficial for heat-sensitive TPU formulations. Just like screws, through-hardened tool or stainless steels are adequate for most TPU processes, while PM liners are specified for highly filled formulations for increased wear resistance (Figures 29.12 and 29.13).

Typical unit operations performed in the TSE process section include feeding, melting, conveyance, venting, and pumping. The length/diameter ratio (L/D) (the overall length of the process section divided by the screw diameter) of the TSE process section is matched to the number of unit operations that need to be performed. L/D ratios for TPU processes range from 28/1 for a premix feed to 60/1 L/D for some reactive processes.
The OD/ID ratio of a TSE is defined by dividing the outside diameter (OD) by the inside diameter (ID) of each screw. For instance, a TSE with an OD of 50 mm and an ID of 32 mm would have an OD/ID ratio of 1.56 (50/32). The torque-limiting factor for a TSE is the screw shaft diameter and design. Deeper screw flights result in more free volume, but with less torque, since a smaller diameter screw shaft is mandated. Based on the use of a symmetrical splined shaft, a 1.55 OD/ID ratio has been deemed to offer the best balance of torque and volume. The use of asymmetrical splined shafts improves the power transmission efficiency of the shaft so that a smaller-diameter shaft can transmit higher torque since the tangential force vector from the shaft tooth is isolated in transmitting power from the motor onto the shafts/screws/materials being processed and facilitates an increased OD/ID ratio of 1.66/1 (Figures 29.14 and 29.15).

**FIGURE 29.11**
Dispersive and distributive mixing elements.

**FIGURE 29.12**
End view barrel heating/cooling design.
A 1.66/1 OD/ID ratio, as compared to a 1.55/1 OD/ID ratio, results in a deeper channel and narrower kneader crest, with the materials passing over the kneader tip experiencing less residence time in planar shear. Both factors contribute to a lower average shear rate and are beneficial for processing many/most TPU formulations.

Whatever the OD/ID ratio, it is important to know the specific volume (SV) of the TSE:

Specific volume: SV represents the approximate volume for 1 L/D of the process section, which is useful in a number of other formulas:

Specific volume = \(0.94 \times (\text{OD}^2 - \text{ID}^2) \times \text{OD}/1000\)

where

SV is denoted in cc/diameter of length

OD = screw outside diameter (each)

ID = screw inside diameter (each)
For example:

For an HSEI twin screw extruder with a screw OD of 50 mm and an ID of 32.26 mm (a 1.55 OD/ID ratio), the approximate SV is as follows:

\[ SV = 0.94 \times (50^2 - 32.26^2) \times \frac{50}{1000} = 68.59 \text{ cc/diameter} \]

If the same screw centerline were used with a 1.66/OD/ID ratio, the OD would be 51.2 mm and the ID 30.84 mm, which would result in a 17.2% increase in SV, indicated as follows:

\[ SV = 0.94 \times (51.2^2 - 30.84^2) \times \frac{51.2}{1000} = 80.39 \text{ cc/diameter} \]

With the specific volume, the approximate RT in the TSE can be calculated.

*Residence time:* This formula provides the approximate RT in the process section. It is important to note that the RTD is dependent upon the degree of screw fill. The following formula can be used for RT:

\[
RT(s) = \frac{SV \times SG \times L/D \times \%fill}{Q \times 0.2777}
\]

where

- RT = residence time in seconds
- SV = specific volume in cc/diameter
- SG = specific gravity
- \(L/D\) = \(L/D\) ratio of extruder
- \% Fill = degree of fill, expressed as a decimal (i.e., 40\% = 0.4) (dependent on screw design)
- \(Q\) = kg/h being processed

For example, a 50-mm extruder with an SV of 70 cc/diameter and 36 \(L/D\) is running a TPU with a 1.0 SG at 270 kg/h with an assumed 50\% screw fill (0.5). The following applies:
In any starve-fed TSE, there are five shear regions inherent with the screws:

Channel is a low-shear region and is dependent on the degree of screw fill in a starve-fed machine: The mixing rate in the channel in a TSE is similar to that of a single screw extruder, and is significantly lower as compared to the other shear regions.

Overflight/tip mixing is a high-shear region and is independent of the degree of screw fill: Between the screw tip and the barrel wall, the material in this region undergoes significant planar shear effects.

Extension shear mixing is a high-shear region and is independent of the degree of screw fill: With the compression of the material entering the overflight region, a mixing-rate acceleration occurs from the channel, with a particularly effective extensional shear effect.

Apex mixing is a high-shear region and is independent of the degree of screw fill: This is where the interaction from the second screw affects the material mixing rate as a result of the associated pressure fields, compression/expansion, and directional flow changes.

Intermesh mixing is a high-shear region and is independent of the degree of screw fill: This is the mixing region between the screws where the screws “wipe,” or nearly wipe (Figure 29.16).

It is worth noting that the four high mass transfer regions are basically independent of the degree of screw fill. This is why, in a starve-fed TSE, when rate is decreased at a constant screw rpm, more mixing occurs. The materials being processed will have a longer RT in the mixing regions. Conversely, as rate is increased, the low-shear channel region

\[
RT = \frac{70 \times 1.0 \times 36 \times 0.50}{270 \times 0.2777}
\]

\[
RT = 13.44 \text{ s}
\]
dominates more, and the materials being processed will spend less time in the mixing zones, and less mixing occurs.

In addition to mixing, TSEs are also efficient devolatilization devices. Factors that effect devolatilization efficiency include RT under the vent or vents (longer is better), surface area of the melt pool (higher is better), and surface renewal (higher is better), as well as the vacuum level being applied to venting zones. Increasing the screw rpm and/or decreasing the rate improves devolatilization efficiencies. Various types of vacuum pumps are used with a TSE, including water-ring, oil-ring, and rotary vane (dry) pumps. The type of pump and vacuum system design depends upon the level and type of volatiles being removed, and the environmental impact/requirements for the specific installation3 (Figures 29.17 and 29.18).

The following are some additional formulas that provide insight into any TPU TSE process:

*Peak shear and shear stress*: The peak shear is critical for dispersive mixing, and can also result in degradation. The following provides a benchmark for the peak shear in a TSE:
Peak shear rate = \((\pi D n) / (h \times 60)\)

where

\(D\) = screw diameter
\(n\) = screw rpm
\(h\) = overflight gap

So, for a TSE with a 27-mm OD screw and 0.1-mm overflight gap, the peak shear would be calculated as follows:

\[ ZSE - 27 = \left(\pi \times 27 \times 600\right) / \left(0.1 \times 60\right) = 8478 \text{ s}^{-1} \]

The formula can be used as a rough estimate to match rpms for TSEs with different diameters, or to estimate the shear at a particular rpm. Peak shear rate can be used to calculate shear stress, which is the critical factor to accomplish dispersive mixing:

\[ \text{Shear stress} = \text{peak shear rate} \times \text{viscosity} \]

In the early stages of the extruder, viscosities are higher and produce high stress rates that cause dispersive mixing, or can cause degradation of shear-sensitive materials. In the latter stages of the TSE process, the viscosities have fallen and decreased viscosities produce comparatively low stress rates. Increased cooling can increase the viscosity of the melt to achieve dispersive mixing. It must be noted that shear stress is not a measurement of extensional shear, which is much more complicated to calculate and requires modeling, but does provide a benchmark and insight into the dispersive mixing effect.\(^6\)

**Fill % approximation:** This formula provides the % of the available volume in the process section that is being utilized in the starve-fed twin screw extruder:

\[ \% \text{Fill} = \frac{Q 	imes 0.2777}{\text{SV} \times \text{rpm} / 60 \times \text{SG} \times \text{Ef}} \]

where

\(Q\) = flow rate in kg/h
\(\text{Ef}\) = average forwarding efficiency (~35% for a screw with 1/3 kneaders and 2/3 flighted elements, or 0.35)
\(\text{SV}\) = specific volume of extruder in cc/diameter
\(\text{rpm}\) = screw rpm
\(\text{SG}\) = specific gravity of the material being processed

For example, a 40-mm extruder with an SV of 34.8 cc/diameter is running 50 kg/h at 200 rpm:

\[ \% \text{Fill} = \frac{50 \times 0.2777}{34.8 \times (200/60) \times 1.0 \times 0.35} = 0.34, \text{ or 34\% filled} \]
This calculation might show that devolatilization-intensive processes run at 40% screw fill because a starved process section increases the surface area of the melt pools under the vent or vents. Another example might demonstrate that similar masterbatch formulations for film applications utilize a 40% fill volume, compared to 60% for injection molding applications, because of the comparative dispersive mixing requirements.

This formula is a rough estimation and is meant primarily to provide some insight into the dynamics of a starve-fed TSE process section, as compared to an absolute value. More advanced/accurate calculations are available that take into account the specific screw geometries, the viscosity of the melt, and the degree of screw fill.

Higher fill levels result in a tighter RTD and less shear, and lower fill levels are associated with wider RTD and more shear. Fill level approximations help explain why processes benefit from different feed rates versus screw rpms (Figure 29.19).

Scale-up formula: Scale-up is useful for estimating rates for the production of twin screw extruders based on lab experiments. The geometries for the two extruders should be nearly identical for this equation to be valid. For processes that scale up volumetrically, the formula is as follows:

\[
\text{Scale up: } Q_{\text{target}} = Q_{\text{reference}} \times [(\text{OD}_{\text{target}} / \text{OD}_{\text{reference}})]^3
\]

where

\( Q \) = throughput rate (in any units)
\( \text{OD} \) = screw outside diameter (each)

For example:
A 27-mm twin screw extruder is producing 100 kg/h and the process is not limited by heat transfer or mass transfer boundary conditions. To estimate how much a 75-mm twin screw extruder will produce, the following calculations will apply:

\[
Q (75 \text{ mm}) = 100 \times (75/27)^3
\]
\[
Q (75 \text{ mm}) = 100 \times 2.78^3 = 2148 \text{ kg/h}
\]

FIGURE 29.19
Residence time distribution for various levels of screw fill.
The greater the difference in extruder sizes, the less reliable this calculation becomes. For a heat transfer-limited process, the exponent is closer to 2. For devolatilization and many TPU processes, the scale-up exponent is between 2.3 and 2.5. Advanced formulas and computer modeling approaches are also available for more intensive scale-up work.\(^5\)

How the TSE is configured and operated makes the difference between success and failure. In addition to the process section design (screws/barrels), feeds rate, screw rpm, temperatures, and sequence/location of feed streams all play a role in the shear intensity to which the materials are exposed. The following table provides a brief overview of how a TPU process can be managed:

<table>
<thead>
<tr>
<th>Conditions Regulating Process Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Processing</td>
</tr>
<tr>
<td>Screws’ speed</td>
</tr>
<tr>
<td>Mixing rate in each of the five mass transfer regions along the screws is proportional to screw rpm</td>
</tr>
<tr>
<td>Screws’ fill</td>
</tr>
<tr>
<td>Starving the feed increases remastication and time in mixers</td>
</tr>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>Lowering the temperature increases the controlling modulus in dispersive stress rate (= E_c \times \text{strain rate} )</td>
</tr>
<tr>
<td>Extensional/planar shear events</td>
</tr>
<tr>
<td>Increasing the number, intensity of mixing events increases process severity</td>
</tr>
<tr>
<td>Sequential feed</td>
</tr>
<tr>
<td>Sequential feed may be employed to either capture or avoid high stress rate exposure</td>
</tr>
</tbody>
</table>

The balance between the rate set by feeders and the screw rpm is critical, as well as the temperature and screw design.

### 29.4 Downstream Systems

Pelletization is a downstream operation that transforms the molten TPU into a pellet to facilitate consistent feeding into an injection molding machine or single screw extruder. Various types of pelletizing systems are available, with the type selected based upon the material characteristics, throughput rate, and lot size. Pellet size ranges from 1/2 to 4 mm.

Strand pelletizing systems cut strands into cylinders and are widely used to produce TPU pellets. The TSE pumps the melt through a “spaghetti” strand die and the strands are then pulled through a water bath by feedrolls and cut by a bed knife/rotor assembly. Water baths utilize guide rollers to facilitate strand management prior to the pelletizer, with TPUs often utilizing multipass stranding through the water bath for space conservation. Upon exit from the water bath, an air stripper removes surface moisture using either an air blower or vacuum. TPU strands are “drawn down” in diameter after
Exiting the die with the diameter controlled by the die hole size and the speed at which the feedrolls pull the strands. The feedroll speed is usually set in a fixed ratio to the cutting head based on the number of cutting edges and the desired pellet length. Independent drives can also be utilized for the feedroll and rotor to facilitate variable length pellets. Softer TPUs often do not cut cleanly in a strand pelletizer, and require an underwater pelletizer. A classifier, a vibratory conveyor device with screens, can also be used after the pelletizer to screen out undersized and oversized pellets (Figures 29.20 and 29.21).

The underwater pelletizing method is exactly as the name implies; a TPU is pumped through a die and is cut and quenched by the rotating blades in water. This system produces a spherical pellet that results from being cut in a submerged environment. The water/pellet slurry is then pumped to a spin dryer for dewatering and surface drying. Underwater pelletizers are recommended for softer TPUs that do not cut in a strand pelletizer, and for longer run production applications. The direct contact of water with the die can cause die hole “freezing,” and therefore the start-up sequence of the extruder, cutter, and water flow is critical and benefits from the use of a PLC for consistent and repeatable start-up management. Micropellets (<1 mm) are also possible.
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with an underwater pelletizer with the use of a gear pump front-end attachment (Figure 29.22).

Combining TSE compounding/devolatilizing with direct extrusion (i.e., of a sheet or tube) presents challenges, in that the TSE system must combine high mass transfer processing with consistent pumping. To maintain dimensional tolerances, a gear pump (a positive displacement device) that builds pressure and dampens pressure fluctuations, is typically integrated into the TSE system. As an alternative to a gear pump, a single screw pump (10 to 15/1 L/D), essentially the metering section of a single screw extruder, may be specified, particularly if additional cooling of the melt is required (Figure 29.23).

A screen changer, a device that provides melt filtration, is also often specified. There are numerous types of screen changers that are designed for continuous or discontinuous filtration. If coarser filtration levels are opted and/or if there are high levels of contaminants in the melt stream then the screen changer should be situated before the gear pump. For fine-level filtration, the screen changer should be situated after the gear pump. Some processes require filtration both before and after the gear pump. Filtration can be challenging and needs to be thoroughly investigated.

The TSE system performing direct extrusion is more complex as compared to a single screw extrusion line. Typically, a PLC control system “manages” the system and an algorithm is utilized to analyze the inputs from key points in the system, make numerical calculations, and apply corrections to the screw rpm and feed rate to maintain the gear pump inlet pressure at its set point. If this is accomplished, the backpressure in the twin screw extruder is held constant, which provides for consistent melt temperature, shear, and mixing. With a stable melt delivery to the gear pump (or single screw pump), the discharge flow and pressure to the die will be uniform. When sequential feed streams are introduced at different positions in the process section, the closed loop control becomes more complicated, as various RTs must be managed (Figure 29.24).
Whether it is a pelletization or a direct extrusion system, the quality of the product is affected by the melt temperature, which is directly affected to the front-end pressure of the TSE.

*Temperature rise caused by pressure*: Pressure generation in the extruder front end caused results in a temperature rise. The more restrictive the front end the higher the pressure and melt temperature rise, which may adversely effect product quality. The temperature rise formula is as follows:

\[
\Delta T \text{ (°C)} = \Delta P \text{ (bar)}/2
\]

where
- \(\Delta T\) = change in temperature in °C
- \(\Delta P\) = change in pressure (1 bar = 14.503 psi)

For example:
If a TSE is processing 500 kg/h and the die pressure is 40 bar (580 psi), the associated melt temperature rise can be 20°C (\(\Delta T = 40/2\)).
This formula is meant to be insightful, if not necessarily accurate, as TSE rpm and the geometry of the discharge screw elements play significant roles in the actual melt temperature.9

29.5 Examples of TPU Processes Performed on Twin Screw Extrusion Systems

The following summarizes a few examples of related processes/applications:

TPU reactive extrusion system with underwater pelletization: Polyurethanes can range from being hard like a thermoplastic to being flexible like an elastomer, with the properties determined by the balance between the isocyanates, polyols, chain extenders, and catalysts in the formulation. These liquids are often premixed in a reaction vessel prior to the TSE to increase the RT for the reaction. Reaction cylinders and high-speed mixers for monomer mixtures and prepolymers are commonly integrated into the design.10

Liquid feed streams are metered into the TSE by precision injection pumps utilizing mass flow meters or loss-in-weight (LIW) monitoring/control to maintain the correct stoichiometry. The L/D of the TSE is typically between 32 and 52/1 to allow for a sufficient RT in the TSE process section, typically in the 1–6 min range. Longer RTs are also possible. Intimate mixing with a low peak shear is managed by the selection of distributive mixing elements, such as “combing elements,” as compared to dispersive mixing elements. Since polyols and isocyanates are immiscible before the reaction occurs, this issue must be addressed in the TSE screw design (Figure 29.25).

The TSE screw design, process section temperatures, and operating conditions all play a role in the final molecular weight and molecular weight distribution. The feed rate versus TSE screw rpm manages the required RT and RTD to facilitate the reaction. The stress rates and temperatures also play roles in controlling the reaction and urethane formation. Volatiles, which must be handled in an environmentally friendly way, are removed by vacuum venting, which can be staged.

A TSE is then mated to an underwater pelletizer. A melt flow diverter may be utilized, and the start-up sequence of the extruder, cutter, and water flow is managed by a PLC for consistent and repeatable process management. Gear pumps can also be integrated into the system if elevated pressures are a requirement, as would be the case for micropellets (<1 mm) production or ultrafine filtration (i.e., in the 40–50 micron range) (Figure 29.26).

FIGURE 29.25
Close-up “combing” mixing elements.
Radiopaque TPU direct sheet extrusion: Dried TPU pellets are metered into the main feed throat by a LIW feeder with a nitrogen-purged hopper. Additives are also metered into feed throat by an LIW feeder. Solids conveyance and melting (and mixing) is typically completed in the first 12 L/D of the process section. Barium or bismuth is then introduced into the melt stream by a side stuffer that “pushes” the filler into the melt stream. The radiopaque filler is metered to the side stuffer by an LIW feeder that is synchronized with the other LIW feeders. For high-level filler levels (i.e., 80%), multiple side stuffers and an extended L/D may be required. A relief vent is typically integrated into the process to allow entrapped air and residual moisture associated with the fillers to be evacuated. The materials are then mixed with kneaders, vacuum vented, and discharged from the TSE.

A gear pump is integrated between the TSE and die. The die and downstream system are identical as if a single screw extruder was the melt delivery mechanism. A wide variety of products can be extruded, including embossed patterns and laminates. The same process sequence applies to other extruded parts, such as a film, tube, filament, fiber, or profile. The TSE can also be integrated as part of a coextrusion system, integrating single and twin screw extruders (Figure 29.27).

Extrusion of TPU/supercritical CO₂ foamed profile: The TPU and additives are metered into a TSE by LIW feeders and melted/mixed in the early stages of the process section. Dynamic seals are integrated into the screw design to accommodate the high-pressure injection pressures inherent with supercritical CO₂. Oftentimes, one-piece barrel sections (20 to 1 L/D) are specified to eliminate the possibility of leakage at the barrel junction flanges. The supercritical CO₂ injection system is equipped with a precision pump with chilled/temperature-controlled plumbing connections.

Once the supercritical fluid is injected, it is intimately mixed with the molten TPU via high division distributive mixers that minimize viscous heating. The latter part of the TSE process screw design then utilizes low energy input pumping elements to allow the
TSE barrels to serve as a heat exchange device to cool the process melt. At lower throughputs, it may be feasible to cool the extrudate and pressurize the die directly from the TSE. In this instance, a longer $L/D$ (i.e., 52/1 $L/D$) is required and the latter stages of the TSE functions as both a pump and a heat exchange device. At higher rates, for improved cooling, a single screw pump is specified, which is essentially an oversized, slow turning single screw extruder that provides process length to cool the melt and then pressurize the die\textsuperscript{31} (Figure 29.28).

![Figure 29.27](image1)

**FIGURE 29.27**
Line drawing of a TSE direct extrusion sheet system.

![Figure 29.28](image2)

**FIGURE 29.28**
Schematic TSE supercritical injection system.
29.6 Summary

Twin screw extruders are widely used in all facets of the plastics industry, including for a variety of TPU processes. The TSE is a proven continuous mixer that produces consistent and repeatable products. Each TPU application requires an understanding of the process dynamics, capabilities, and limitations of the TSE for optimum system design. It is important to also recognize that the twin screw extruder is just another tool, albeit a powerful and versatile one, in the process. The engineer needs to assess the required process requirements, and integrate the TSE with upstream and downstream systems utilizing the technologies that are available. Fortunately, there are many design options from which to choose.

References