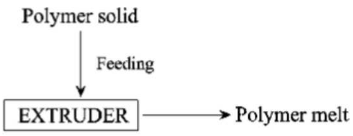
2 Physical Description of Single-Screw Extrusion

2.1 Overall Functions of a Single-Screw Extruder

This chapter is intended to provide an overall physical understanding of the single-screw extrusion operation, including the relevant polymer properties and operating conditions. Although this chapter is quite lengthy, the reader will immediately become familiar with single-screw extrusion and develop further interests to study more details presented in the following chapters. Comprehension of the physical descriptions presented in this chapter alone may prove to be sufficiently beneficial for many readers, and help them to improve their processes and products.

Referring to Chapter 1; Fig. 1.2, an extruder is used to melt a solid polymer and deliver the molten polymer for various forming or shaping processes. The screw is the only working component of the extruder. All other components (motor, gearbox, hopper, barrel and die, etc.) merely provide the necessary support for the screw to function properly. The overall functions of an extruder are depicted below.



Basic functions :
- Solid conveying
- Melting
- Metering

Secondary functions :
- Mixing
- Shear refining

The feeding function of transferring the feed polymer from the hopper into the screw channel occurs outside of the screw, and it essentially does not depend on the screw design.

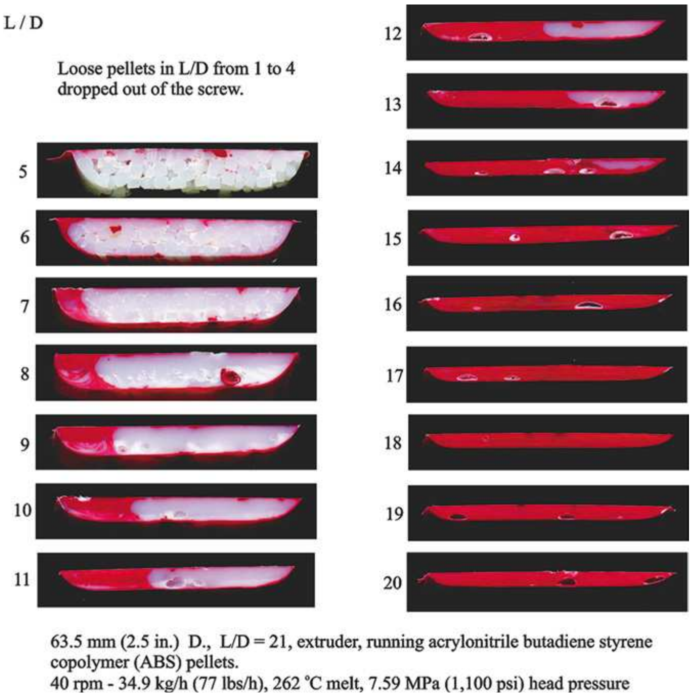
The screw performs three basic functions: (1) solid conveying function, (2) melting function, and (3) metering function or pumping function. The three screw functions occur simultaneously over most of the screw length and they are strongly interdependent. The geometric name of a screw section such as feeding section, shown in Chapter 1; Fig. 1.3, does not necessarily indicate the only function of the screw section. For example, the feeding section not only performs solid conveying function, but also melting and metering functions.

The screw also performs other secondary functions such as distributive mixing, dispersive mixing, and shear refining or homogenization. Distributive mixing refers to spacial rearrangement of different components, and dispersive mixing refers to reduction of component sizes as described in Chapter 2; Section 2.6.4. Shear refining refers to homogenization of polymer molecules by shearing.

A single-screw extruder is a continuous volumetric pump without back-mixing capability and without positive conveying capability. What goes into a screw first, comes out of the screw first. A polymer, as solid or melt, moves down the screw channel by the forces exerted on the polymer by the rotating screw and the stationary barrel. There is no mechanism to positively convey the polymer along the screw channel toward the die. The rotating screw grabs the polymer and tries to rotate the polymer with it. Suppose the barrel is removed from the extruder, or perfectly lubricated, such that it gives no resistance to the polymer movement. Then the polymer simply rotates with the screw at the same speed and nothing comes out of the screw. The stationary barrel gives a breaking force to the rotating polymer and makes the polymer slip slightly on the screw surface. The polymer still rotates with the screw rubbing on the barrel surface, but at a slightly lower speed than the screw, because of the slippage. The slippage of the polymer on the screw surface along the screw channel results in an output rate. A lubricated screw surface increases the output rate, but a lubricated barrel surface detrimentally reduces the output rate. It is clearly understandable why commercial screws are highly polished, and why grooved barrels in the feeding section are preferred. Although many commercial practices were developed empirically rather than based on theoretical analyses, they certainly agree with the underlying theoretical concepts.

The mechanisms inside a single-screw extruder are studied by examining the polymer cross-sections along the screw channel taken from “screw-freezing experiments”. In a screw-freezing experiment pioneered by Maddock [1], the screw is run to achieve a steady-state operation. Then, the screw is stopped and water cooling is applied on the barrel (and also on the screw if possible) to freeze the polymer inside the screw channel. The barrel is heated again to melt the polymer, and the screw is pushed out of the barrel as the polymer starts to melt on the barrel surface. Then, the solidified polymer strip is removed from the screw channel and cut at many locations to examine the cross-sections along the screw channel. Some colored pellets are mixed in the feed to visualize the melting mechanism and the flow pattern. The colored pellets retain their shapes if they remained as solid inside the solid bed before the screw stopped, but they are sheared and become streaks inside the melt pool if they were molten before the screw stopped.

Figure 2.1 shows the cross-sections of acrylonitrile-butadiene-styrene copolymer (ABS) strip obtained from a screw-freezing experiment conducted at the Polymer Processing Technology Laboratory of The Dow Chemical Company USA. ABS pellets were extruded using a 63.5 mm (2.5 in) D, L/D = 21 conventional screw at 40 rpm. The three barrel zones from the hopper were set at 200, 230, and 250 °C, respectively. The output rate was 34.9 kg/h (77 lbs/h) at 262 °C melt temperature against 7.59 MPa (1,100 psi) head pressure.

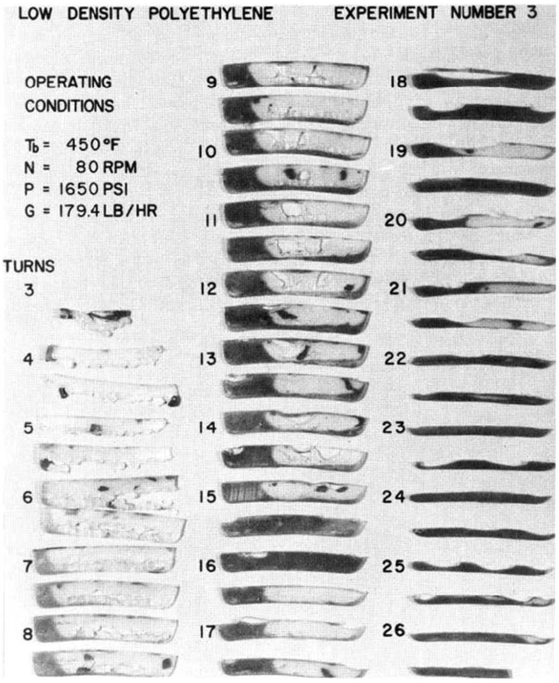


Loose pellets in L/D from 1 to 4 dropped out of the screw.

63.5 mm (2.5 in.) D., L/D = 21, extruder, running acrylonitrile butadiene styrene copolymer (ABS) pellets.
40 rpm - 34.9 kg/h (77 lbs/h), 262 °C melt, 7.59 MPa (1,100 psi) head pressure

Figure 2.1 Cross-sections of ABS strip along screw channel from screw-freezing experiment (courtesy of Mark Spalding, Kun S. Hyun, and Kevin Hughes, The Dow Chemical Co. USA)

Tadmor and Klein [2], in their book, presented many examples of screw-freezing experiments. Their Fig. 5.2 for branched low density polyethylene (BLDPE) is reproduced in this book as Fig. 2.2. BLDPE pellets were extruded using a 63.5 mm (2.5 in) D, L/D = 26 conventional screw at 80 rpm. All barrel zones were set at 232 °C. The output rate was 81.5 kg/h (179.4 lbs/h) against 11.385 MPa (1,650 psi) head pressure.



63.5 mm (2.5 in.) D., L/D = 26, extruder, running branched low density polyethylene (BLDPE) pellets.

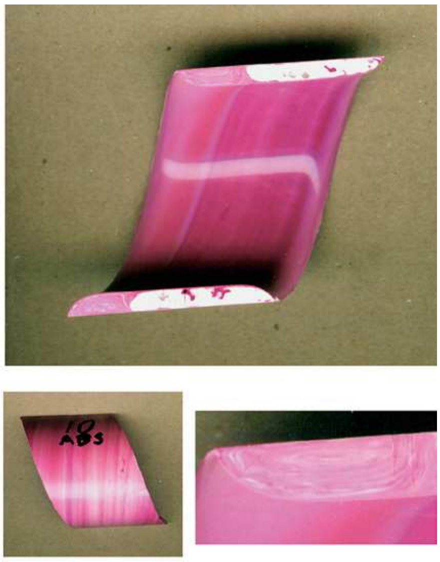
Figure 2.2 Cross-sections of BLDPE strip along screw channel from screw-freezing experiment (reproduced from Tadmor and Klein [2])

Referring to Figs. 2.1 and 2.2, polymer pellets fed into a screw stay loose over the first 2–4 L/D of the screw from the hopper until they are compacted. Loose pellets drop out of the screw when the screw is removed from the barrel. The pellets are quickly compacted over the next 2–3 L/D into a tightly packed “solid bed”. The solid bed moves down the screw channel as a rigid plug, and no mixing occurs inside the solid bed. The solid bed melts mainly by rubbing on the hot barrel surface as it rotates with the screw, and a thin melt film is formed on the barrel surface. The entire barrel immediately after the feed throat is set above the melting point of the polymer, unless an intensively water-cooled barrel section is used in the feeding section. The screw surface of the first several L/D is continuously cooled by cold polymer feed in a steady-state operation. The rest of the screw also becomes hot above the melting point of the polymer because of the heat conducted from hot melt. A melt film also is formed on hot screw surface, and the solid bed becomes surrounded by melt film. The thin melt film on the barrel surface is highly sheared by the rotating solid bed, and a large amount of heat is generated within the thin melt film. The thin melt film is scraped off the barrel surface and collected into a "melt pool" by the advancing flight. The melt pool is sheared and mixed as it is pumped or metered along the screw channel. The melt film on the screw surface is sheared only slightly by the slow movement of the solid bed relative to the screw, and it is not scraped off the screw surface.

The solid bed width gradually decreases and the melt pool width increases as the solid bed melts along the screw, as shown in Fig. 2.1. Melting of the solid bed is complete at about L/D = 15 in Fig. 2.1. The solid bed melts primarily by the heat conducted from the thin melt film on the barrel surface. The solid bed also melts on the hot screw surface and at the melt pool interface, but at a sufficiently lower rate to be ignored in comparison to the melting rate on the barrel surface. Melting occurs on the surface of the solid bed, and the interior of the solid bed remains virtually at the feed temperature along the screw. As the screw speed increases, the solid bed remains longer along the screw, as shown in Fig. 2.2, eventually reaching the end of the screw and causing poor melt quality. At high screw speeds, the solid bed and the melt pool coexist over most of the screw length. If the solid bed breaks up into small solid pieces before melting completely, the solid pieces become mixed with the melt pool and slowly melt by the heat conducted from the surrounding hot melt. Thus "solid bed breakup" leads to nonuniform melt temperature. Melting must be completed before the end of the screw and, preferably, the last several L/D of the screw should not contain any solid, in order to achieve uniform melt temperature.

The solid bed is strong under compression, but it can easily split under tension because the pellets in the solid bed are not fused together. The continuous solid bed strip along the screw channel will split if the front part accelerates or the rear part becomes wedged. The surrounding melt under pressure will flow into the broken area of the solid bed once the solid bed splits. Figure 2.2 clearly reveals such "solid bed splitting". The cross-sections at L/D = 16, 18.5, and also 19.5 contain only the melt without any visible solid, but the following cross-sections contain a large solid bed. Solid bed splitting causes pressure fluctuation or surging, resulting in output rate fluctuation.

Figure 2.3 is a typical segment of the solidified polymer strip in the melting section obtained from another screw-freezing experiment running ABS pellets. It shows the melt pool in front of the pushing flight and the solid bed in front of the trailing flight. The solid bed is completely surrounded by a thin melt film on both the barrel surface and the screw surface. The streaks in the melt pool show a circular flow path in the melt pool. Mixing occurs in the melt pool by the circular flow. The colored pellets in the solid bed retain their shapes, and they are not mixed at all with other pellets because the solid bed moves as a solid plug without internal deformation. The streaks on the bottom surface are the direction of the solid bed movement relative to the screw surface, and they have exactly the same helix angle as the flight because the solid bed can move down only along the screw channel. The streaks on the top surface indicate the direction of the solid bed movement relative to the barrel surface, and they have a slightly greater helix angle than the flight. The small difference, about 3° in this case, is the solid conveying angle, which is described further in Chapter 4; Section 4.2.2. The conveying rate of the solid bed, which is the same as the output rate of the extruder, depends on the solid conveying angle. A zero degree solid conveying angle corresponds to a zero output rate.



ABS segment at 10th L/D from 63.5 mm (2.5 in.) D., L/D =21, screw with a square-pitch flight (17.65° helix angle)

Figure 2.3 Segment of ABS strip during melting stage from screw-freezing experiment (courtesy of Kun S. Hyun and Mark Spalding, The Dow Chemical Co. USA) toring of the operating variables and the extruder performance helps to understand the screw functions and the problems correctly, leading to optimization of the screw design and the operating conditions.

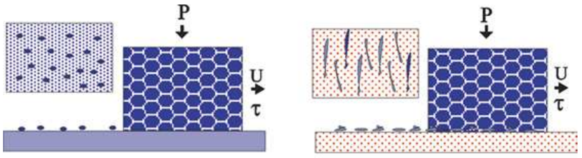
Two additional pressure measurements along the barrel, one called “P_1” at about one-third, and the other called “P_2” at about two-thirds of the barrel length from the hopper, are desired to understand what is happening inside the screw. The three pressure data, P_1, P_2, and P_h, provide diagnostic information. An unreasonably low or high value of P_1 indicates insufficient or excessive solid conveying rate, respectively. A low value of P_2 indicates insufficient supply of melt to the metering section in comparison to the pumping capability of the metering section. Severe fluctuations in P_1 or P_2 indicate inconsistent feeding, feed bridging, or wedging of the solid bed in the compression section. If the geometric compression or tapering of the screw channel in the compression section is more than the melting rate, the solid bed cannot go through the screw channel and becomes wedged temporarily until it melts enough to accommodate the geometric compression of the screw channel. If P_1 and P_2 are stable, the head pressure also should be stable.

The head pressure, measured at the end of the screw before the screen pack, slowly increases with time as the screen pack becomes clogged, slowly decreasing the output rate. The die pressure, measured at the adaptor after the screen pack, decreases as the output rate decreases. The die pressure should stay constant at a constant output rate and a constant melt temperature. A widely used feedback control slowly increases the screw rpm to maintain a constant die pressure, as the screen pack becomes clogged, assuring a constant output rate.

■ 2.12 Rubbing Mechanisms of Solid Polymer on Metal Surface

It is well known that feed pellets are compacted into a tightly packed solid bed inside a single-screw extruder. The solid bed rotates with the screw virtually at the same velocity as the screw, rubbing and melting on the barrel surface under high pressures. The solid bed slips slightly on the screw surface as it rotates with the screw, and the slippage of the solid bed on the screw results in the output rate. The extrusion behavior of a polymer depends on the rubbing mechanisms of the solid polymer on the metal surfaces of the barrel and the screw.

Figure 2.18 shows four possible rubbing mechanisms of a solid polymer on a metal surface. At low metal temperatures below the melting (or glass transition) range of the polymer, the rubbing mechanism is “friction”. Friction may occur with or without grinding the polymer. Grinding occurs if the polymer is brittle and the shear stress τ developed between the polymer and the metal surface is high, exceeding the shear strength of the polymer. Grinding produces fine polymer powders on the metal surface, and it corresponds to a high wear mechanism. τ in friction mainly depends on pressure P. τ is proportional to P in the ideal frictional mechanism, but τ increases less than proportional to P for polymers.

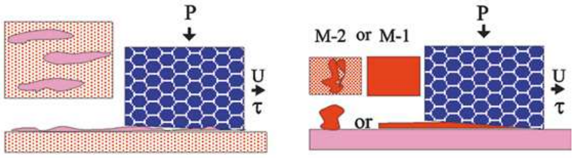


(a) Friction with or without grinding

$\tau = \Im(P) = \mu \cdot P$

$\tau \neq \Im(U)$

(b) Tearing with rubber-like abraded pieces



(c) Unstable melting with melt streaks

(d) Melting with melt film (M-1) or lump of melt (M-2)

$\tau \neq \Im(P)$

$\tau = \Im(U) = K \cdot U^{\alpha}$

Figure 2.18 Possible rubbing mechanisms of solid polymer on metal surface

At high metal temperatures well above the melting range of the polymer, the rubbing mechanism is “melting” and a thin melt film is formed between the polymer and the metal surface. The melting mechanism forming a smooth melt film on the metal surface is denoted by M-1 in Fig. 2.18d. The melting mechanism forming lumps of the melt on the metal surface is denoted by M-2 in Fig. 2.18d. The M-2 mechanism may result from poor adhesion of melt on metal surface, high melt elasticity, or melt instability at the high shear rates in the thin melt film. The shear stress τ in the melting mechanism mainly depends on rubbing velocity (U), increasing exponentially with increasing U, similar to the dependence of melt viscosity on shear rate. Rigid, highly crystalline polymers, such as polyesters, nylons, polypropylene, and high density polyethylene, and rigid amorphous polymers (glassy polymers), such as polystyrene and polycarbonate, make a distinct transition from the frictional mechanism to the melting mechanism with increasing metal temperature.

Soft, semi-crystalline polymers with a broad melting range, such as low density polyethylenes, exhibit intermediate rubbing mechanisms between friction and melting. “Tearing” and “unstable melting” are two representative intermediate rubbing mechanisms. Tearing occurs when the polymer at the metal temperature behaves like an elastomer, and it produces rubber-like, abraded polymer pieces on the metal surface. Unstable melting combines the tearing and melting mechanisms, producing melt streaks on the metal surface. High shear stresses are developed in tearing and unstable melting.

The rubbing mechanism of a solid polymer on a metal surface depends on the thermodynamic, mechanical, and melt rheological properties of the polymer over the temperature range from the polymer temperature to the metal temperature. These properties, in turn, depend on the molecular and morphological characteristics of the polymer.

All barrel zones of an extruder, except the first zone next to the hopper, are set at temperatures far above the melting point of the polymer in most cases, and the rubbing mechanism on the extruder barrel will be melting. The first zone is set at a lower temperature, but still well above the melting point of the polymer, to avoid the sticking problem of the feed materials on the feed throat and the screw. A barrel temperature below the start of melting mechanism, where grinding, tearing, or unstable melting mechanism occurs, should be avoided because an unnecessary high torque would be required without effectively melting the polymer.

2.13 Relationships Between Screw Channel Geometries

Referring to Chapter 1; Fig. 1.3, the pitch *P* and the helix angle ϕ of a flight are related. Figure 2.19 shows one turn of the flight removed from the screw root and unwrapped on a flat surface. The following relationship is found:

$$\tan\phi = \frac{P}{\pi D}$$
$$\phi = \tan^{-1}\left(\frac{P}{\pi D}\right) \tag{2.13}$$

For the square-pitch with $P = D$, $\phi = 17.65°$ is found using Eq. 2.13.

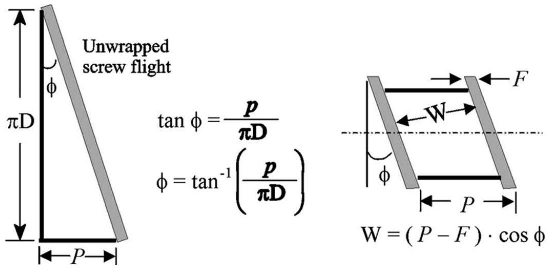


Figure 2.19 Relationships between screw channel geometries of a single-flighted screw

The cross-sectional area of the screw channel used for flow rate calculations is equal to (the channel depth H) × (the channel width W measured perpendicular to the flights). The relationship given below between the pitch *P* and the channel width W of a single-flighted screw is also shown in Fig. 2.19.

$$W = (P - F) \cdot \cos\phi \tag{2.14}$$

or

$$W = \pi D \cdot \sin\phi - F \cdot \cos\phi \tag{2.15}$$

where F = flight width measured along the screw axis.

2.14 Variables Controlling Polymer Extrusion

The performance of an extruder for a polymer depends on polymer properties, feed characteristics, screw design parameters, and operating conditions, as discussed previously. Also, feeding conditions assuring a consistent feeding rate are essential. Table 2.1 summarizes these variables. Descriptions of the polymer properties relevant to processing are presented in Chapter 3.

Table 2.1 Variables Controlling Polymer Extrusion

Polymer properties
Thermodynamic properties
Melting characteristics – melting range
Heat capacities and thermal conductivities of solid and melt, heat of fusion
Melt rheological properties
Viscosity; elasticity; shear sensitivity; temperature sensitivity

Table 2.1 Variables Controlling Polymer Extrusion *(continued)*

Mechanical properties
Modulus; yield strength
Solid density and melt density
External friction on metal surface
Thermomechanical stability
Additives
Feed characteristics
Size and shape of feed pellets, and their distribution
Bulk density of feed pellets
Internal friction of feed pellets
Feeding conditions
Feed temperature – preheating or drying of the feed
Gravity, forced or metered (starved) feeding
Constant feeding rate, in weight
Consistent composition if more than one component feed
Recycling
Screw design parameters
Pitch (or lead)
Number of parallel flights
Feeding section depth and length
Compression (or transition) section length
Taper or reduction rate of the channel area in compression section
Metering section depth and length
Compression ratio (CR)
Mixing section design
Special channel geometry
Single or multiple stages
Operating conditions
Screw rpm
Barrel temperature settings
Head pressure
Die design; screen pack; breaker plate; adaptor
Screw temperature control