Fundamental Approach to Screw Design

By Jeffrey A. Myers, President of Barr Inc.

Introduction
The single stage extruder screw remains as the most widely used piece of equipment in the processing industry today. Advancements in machine controls, drives, heating/cooling systems and screw design have increased the overall machine efficiency but the fundamental function of the single stage extruder screw remains the same. The main functions of an extruder are to:
1. Convey the solid polymer from the hopper.
2. Compact and melt the pellets.
3. Mix the resulting highly viscous polymer into a homogeneous melt.
4. Pressurize and pump the melt through a die.

The function of the extruder screw is the same regardless if it is a continuous Extrusion Blow Molding (EBM) process or an intermittent start/stop Injection Blow Molding (IBM) application. Figure 1 shows a typical EBM extruder.

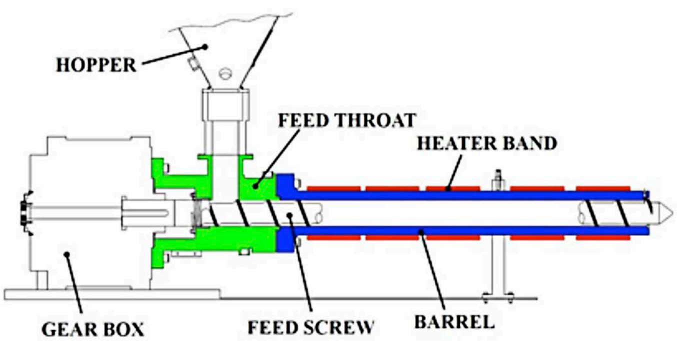

Figure 1: Typical extruder assembly.

Most extruders are defined by the screw diameter (D) and the L/D ratio (Length per Diameter). The length is typically defined as the effective flighted or working section of the screw.

Solid Conveying
Pellets entering the screw from the hopper must be forced down the screw. The feeding mechanism is largely influenced by the frictional forces between the solid pellet and the barrel wall. Because the coefficient of friction (COF) of the pellets acting on the screw surface is less than the COF on the barrel wall the rotation of the screw forces the material forward down the barrel.

Resins that have poor feeding characteristics may require internal screw cooling in the feed section to prevent the resin from sticking to the screw. High polish on the screw root surface also reduces the COF.

It is imperative to prevent early melting in the feed zone, therefore, a path must be maintained, letting the air contained between the pellets escape through the extruder feed throat.

'Grooved Feed Throat' (GFT) technology, which was developed in Europe over sixty years ago, has become more of a standard in providing answers for the most difficult feeding situations, i.e., extrusion of polyolefins. The principle behind a GFT is to create a high friction by mechanically wedging pellets in a series of axial grooves, hence preventing slippage on the barrel. Figure 2. This is a substantial improvement over a smooth bore feed throat (SBF).

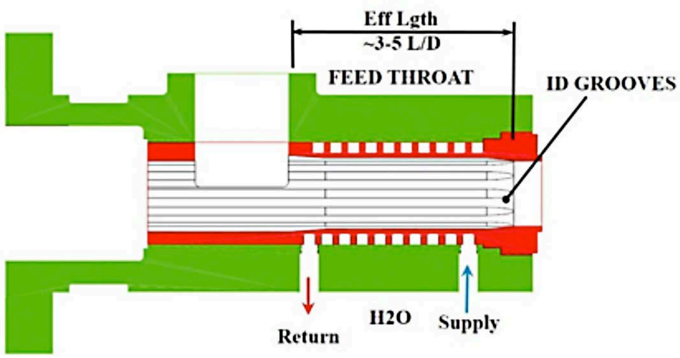

Figure 2: Typical GFT assembly.

The effective length of a typical GFT is between 3 to 5 diameters (pitches). The depth and width of the groove design in Figure 3 is material dependent and the number of grooves is mainly a function of the screw diameter.

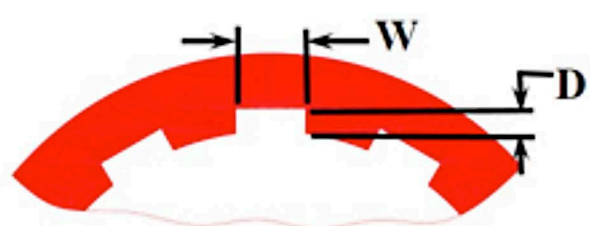

Figure 3: Groove width & Depth.

In order for a GFT to function properly and maximize the solids conveying, good cooling must be utilized. If the GFT is not adequately cooled, the mechanically generated heat will cause the resin to melt prematurely, filling the grooves with material and reducing solids conveying. A GFT tends to work well with materials that have a high shear modulus and melting point. A properly designed GFT system can improve the extruder output by 20 to 30% over a standard SBF but will require additional power to take advantage of the higher throughput rate.

Extruder Screw Nomenclature
The most common type of single flighted extruder screw, also referred to as a Conventional or General-Purpose (GP) screw, is divided into three distinct geometric sections, as shown in Figure 4.

1. Feed Section (Lf): Constant depth.
2. Transition Section (Lt): Constant taper.
3. Metering Section (Lm): Constant depth.

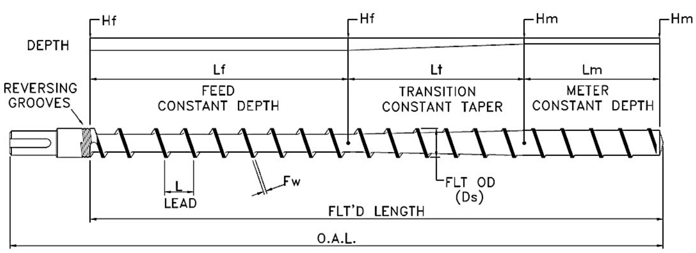

Figure 4: Standard Extruder Screw

The channel geometry for each section is shown in Figure 5.

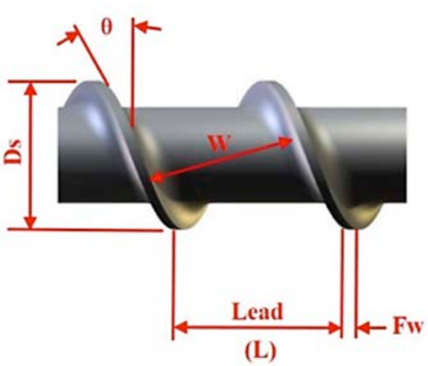

Figure 5: Channel Geometry

The description of each section is defined in the Table below:

Symbol	Description
Ds	Screw Diameter
L	Lead
Fw	Axial flight width
H	Channel depth
θ	Helix angle
W	Channel width

The Helix angle and channel width are calculated using the following expressions:

$$\tan\theta = \frac{L}{\pi * D} \quad \text{Eq. 1}$$

$$W = (L - F_w) * \cos\theta \quad \text{Eq. 2}$$

The compression ratio (Cr), is another characteristic typically used to classify GP type screws. The (Cr) is the ratio of the channel depth in the feed section to the depth in the metering section and is calculated using the following expression

$$Cr = H_f / H_m \quad \text{Eq. 3}$$

Cr indicates the reduction in channel volume between the two sections. Channel volume must be reduced as the density of the melt is much higher than the pellet bulk density, and for developing pressure. The same amount of material occupies much less volume once changed from pellets to melt. It is also used to classify GP type screws. The compression rate (R) indicates the channel volume reduction rate. This rate has a critical influence on melting performance, especially if it does not match the actual melting rate of the resin. The compression rate in the down channel direction is calculated using the following expression:

$$R = \frac{(H_f - H_m) * \sin\theta}{L_t} \quad \text{Eq. 4}$$

Where Hf is the channel depth in the feed section, H_m is the depth of the meter channel, L_t is the length of the transition and θ is the helix angle.

Melting
The resin starts to melt on the barrel surface within 3 to 5 L/D's from the feed pocket. The resin is packed into a solid bed at the trailing side of the channel in the downstream direction. The initial melting mechanism of a tightly compacted solid bed is mainly by friction against the hot barrel surface as it rotates with the screw. The function of barrel heating and cooling is to keep the barrel temperature constant, hence maintaining a uniform shear heating and constant melting rate, a critical requirement for establishing a steady state process. The solid bed

melts and forms a thin melt film on the barrel surface. High shear develops as a result of the friction between the solids bed as it rotates with the screw. The formed melt is then scraped off and collected into a melt pool by the advancing flight, as shown in Figure 6. In conventional screws, viscous shear heating is the principle source of energy to melt the polymer.

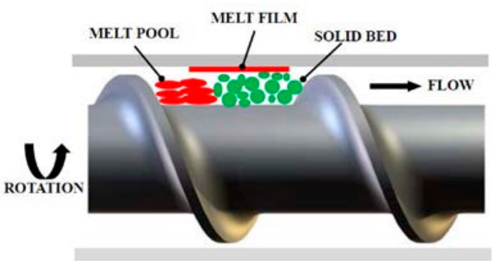

Figure 6: Solid bed formation

The forces pushing on the solid bed will gradually cause a reduction in solid bed width as the melt pool increases, with the progression down the length of the screw. The forces holding the solid bed intact will eventually diminish causing the solid bed to break up. The unmelted polymer fragments could be encapsulated by the surrounding melt, which must now melt by conduction of heat from the melt around it – a much slower melting mechanism. This situation could lead to poor melt quality of the extrudate.

Improved Screw Designs

The General Purpose (GP) screw design will process most resins but frequently not at the melt quality or efficiency required to compete in today's blow molding industry. More modern screw designs utilize a barrier flight as shown in Figure 7.

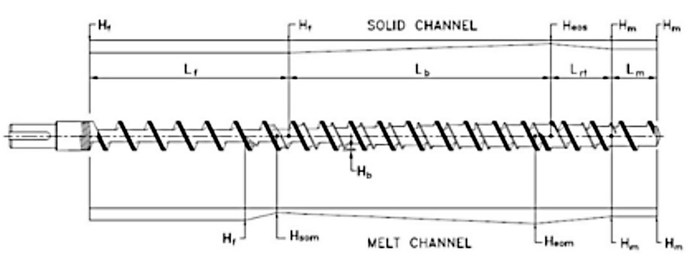

Figure 7: Barrier screw

As the melt film is wiped off the barrel surface by the main flight, the melt is deposited into a separate melt channel. The clearance over the barrier flight separating the solid and melt channels allows only melt to pass, as shown in Figure 8. Removing the melt from the solid bed keeps it from becoming unstable and breaking up prematurely.

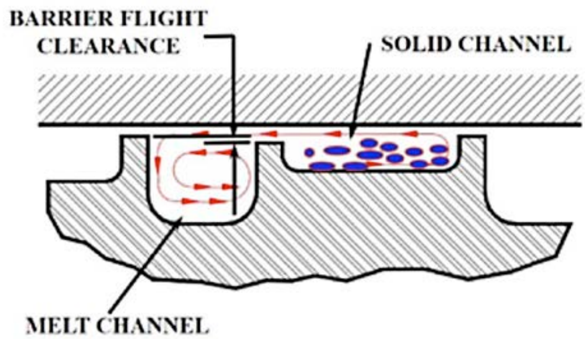

Figure 8: Barrier screw channel

It also allows for a greater solid bed surface area on the barrel wall where shear heating takes place, hence, maximizing the melting rate. Since the melt film thickness is limited, the shear energy generation is increased. However, the corresponding melt temperature is higher, which is undesirable in most applications. Approximately 90% of the polymer is melted by the high shear in the barrier section. A barrier screw is susceptible to solid pellet wedging if the start of the barrier section is not properly positioned to match the melting characteristics of the resin, i.e., if the reduction in channel volume does not match the melting rate of the resin. This could lead to process instabilities, such as, flow surging.

Recognizing the inherent problems and limitations of barrier type screws, the solid/melt dispersion type screws were developed [2]. The original "Wave" screw was patented in 1975 by George Kruder at HPM. The Energy Transfer- ET® [2,3] was developed and patented by BARR and Chung [4] in 1983, as shown in Figure 9.

Figure 9: Energy Transfer- ET®

The principle of these types of screws differs from the barrier designs in that the metering section is divided into two equal sub channels by a secondary flight. The solid bed is intentionally broken up at the end of the melting section to allow some solids to enter the mixing section. The clearance of the secondary flight is much greater than the clearance of the barrier flight on a barrier screw, allowing unmelted pellets to pass through Figure 10.

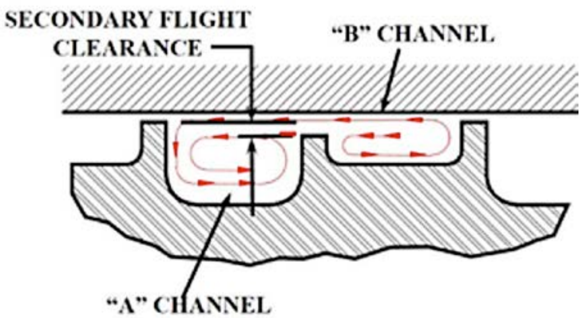

Figure 10: ET® screw channel

The depth of the solid subchannel "A" decreases while the depth of subchannel "B" increases, forcing the melt to flow over the secondary flight at relatively low shear rates. Solid bed fragments are further broken down to yet smaller fragments by passing over the secondary flight. The secondary flight undercut also provides for dispersive mixing. The polymer fragments are continually mixed with the melt promoting conduction of heat from the melt to the pellets for melting. Consuming heat from the melt for final melting of the solid fragments, results in lowering the melt temperature. Additionally, mixing and melt uniformity is improved as well, allowing for an increase in throughput rates at a lower melt temperature. The "Wave" screw and the "E.T." screw were the first designs to utilize this technology. Several commercially available screws utilize this technology.

While the "Wave" and "ET" screws may look similar, the material flow path is very different [4]. In the "Wave" screw, the main flight and the secondary flight are two distinct and continuous flights. The material is transferred from the discharge side of one sub channel to the adjacent channel upstream channel by the drag flow resulting from screw rotation. The next melt transfer is in the opposite direction of the drag flow, as illustrated in Figure 11.

This requires a high pressure buildup in the adjacent channel to overcome the pressure flow. The results could cause the polymer to stay in the same sub channel instead of flowing over the secondary flight.

In the "E.T ®" screw, the main flight and the secondary flight are interchanged so the melt is always transferred in the drag flow direction. The main flight becomes the secondary flight and the secondary flight becomes the main flight. The secondary flight is not continuous as with the "Wave" screw and allows material to easily transfer from one sub channel to the other in the drag flow direction promoting improved pressure stability and heat transfer.

The Variable Barrier Energy Transfer V.B.E.T. ®[2,5] is the latest generation of the Solid/Melt designs which has proven to yield increased mixing and higher melting capacity compared to the ET® design. The Solid/Melt section depth profile comparison between the ET® and the VBET® section is illustrated in Figure 12.

The VBET® design utilizes a decreasing undercut clearance over the secondary flight and an increasing distance between each series of sub channels. Experiential

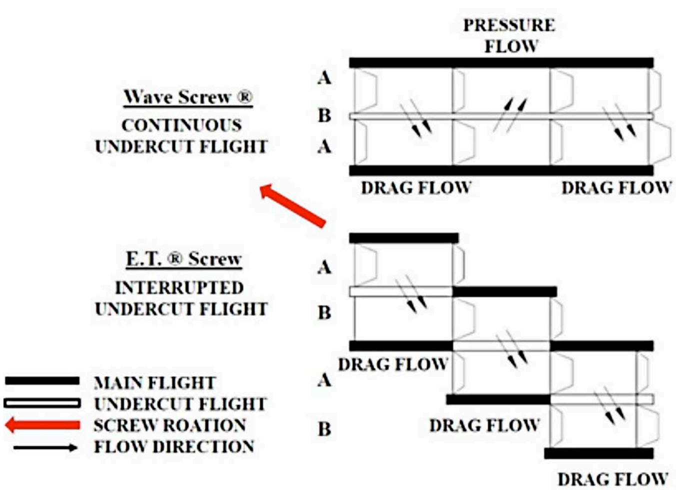

Figure 11: Schematic of the Flow path for the "Wave" and "E.T.®" screws.

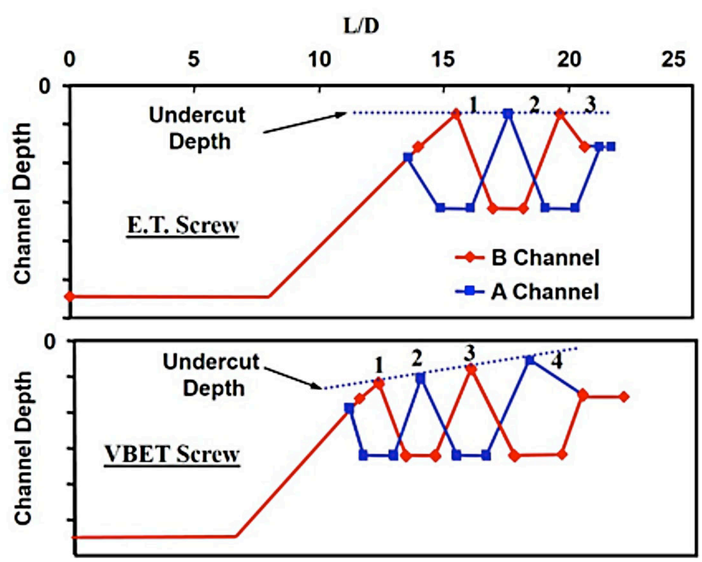

Figure 12: Channel depth for "E.T.®" and VBET® screws

studies [6] have shown that an increase in the conductive melting and heat transfer of the melt to the colder pellets was achieved by varying the length and clearance over the secondary flights.

Conclusion

The goal of this paper was to explain some basic fundamentals in screw design and the different types of feed screws available. It does not encompass all screw designs or the advancements in dispersive and distributive mixing devices. Having a better understanding of the four main functions of the extruder and how each one interacts is the key to a successful process.

References

1. G.A. Campbell and M.A. Spalding, "Analyzing and Troubleshooting Single-Screw Extruders." Hanser, (2013)

2. "ET" & "VBET" are Registered Trademark of Robert BARR Inc.

3. C.I. Chung and R.A. Barr, U.S. Patent 4,405,239.

4. C.I Chung, Extrusion of Polymer, Hanser, (2000).

5. R.A. Barr, U.S. Patent 6,599,004 (2003).

6. J.A. Myers, R.A.Barr, SPE-ANTEC Tech. Papers, 48,154 (2002)