3 The Plasticating System for Injection Molding Machines

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3.1 Introduction

The injection molding process is extremely complex with numerous unsteady-state events, a melting process, and a solidification process. In order to produce parts at an economically acceptable rate and with satisfactory quality, all processes must operate properly. The plasticator, or the screw and barrel combination, must provide a high-quality discharge, at high rates, and at the proper discharge temperature. Quality here refers to a homogenous discharge that does not contain solid pellet fragments (unmelts), free of degraded material, and without thermal gradients. For most processes, the plastication rate should be high enough, so that it is not the rate-limiting step, i.e., the cooling of the part in the tool should be the rate-limiting step. If the quality of the discharge or its rate is less than optimal, then the cost to manufacture the parts will be considerably higher. Production costs will increase due to higher scrap and recycle rates, higher labor charges, lost production time, and higher costs for quality control.

Considerable time and effort have been expended on the mold filling process and on the complicated controls for the injection molding machine. For most applications, the design of the plasticating screw receives less attention. A large amount of time is given to the design of the tool and the molding machine, while the plasticating screw is expected to deliver a high-quality discharge at all conditions and for all resins. A good example of this situation occurred during the start-up of the Saturn Corporation molding facility in 1992 [1]. Here, Saturn personnel were attempting to mold body panels from a polycarbonate (PC)/acrylonitrile-butadiene-styrene (ABS) resin blend, and they were producing parts with a very high scrap rate, due to a surface defect known as splay. The problem could not be eliminated via processing or mold tooling changes and resulted with a scrap rate of more than 25%. The problem, however, was resolved with the installation of a screw that was designed specifically for the PC/ABS resin, virtually eliminating the defect.

The style and channel depths of the plasticating screw play a key role in the operation and economics of the molding process. For an ideal and optimized system, the screw must deliver a high-quality discharge at a rate that is high enough so that part cooling is the rate-limiting step of the operation. A properly designed screw will operate full and under pressure during operation, will have a streamlined design to eliminate regions where material can have long residence times and degrade, will produce a discharge at an optimal temperature for molding, and will trap and melt solid polymer fragments before they discharge. The design of a screw to meet these requirements can often be a challenge, especially since the desire to have low
discharge temperatures often competes with the elimination of solid polymer fragments in the discharge.

Mixing in the plasticator is also highly important to a well tuned injection molding process [2]. The most common mixing operation is the addition of a pigment to a natural resin [3], producing a part with the correct color. For this process, the pigments are almost always pre-compounded into a base resin, using a twin-screw extruder to form a color concentrate pellet. The molder generally purchases the concentrate from a color-compounding vendor. The color concentrate is then added to the natural resin by the processor, at a ratio of between 25 and 75 parts natural resin to one part color concentrate; i.e., a 25 : 1 to 75 : 1 letdown ratio. In all cases, the final part must be uniform in color, requiring that adequate mixing take place in the plasticating machine. It allows the processor to dedicate a large silo to the natural resin and maintain only small quantities of the color concentrate. The system is considerably less expensive than maintaining an inventory of each resin in a factory color, and eliminates the possibility of having a large quantity of a factory resin in an obsolete color. If a machine is operating improperly and with a color concentrate and a natural resin, some of the natural resin may migrate to the discharge end of the screw as solids. These natural colored solids will cause a “color streak” in the final article. Thus, it is extremely important to verify that the plasticator is operating properly. Eliminating temperature gradients in the discharge is also extremely important in the injection molding processes. If the discharge from the plasticator is not uniform, then cosmetic surface defects are likely to occur [4].

The focus of the chapter is on the design and operation of single-screw plasticating screws that are commonly used for injection molding. The chapter will discuss those functions related to screw geometry, process operations, and mixing processes. The reader is directed to other sources for detailed mechanisms for single-screw plastration [5, 6] and troubleshooting methods [7].

### 3.2 The Plasticating System

The main sections of the plasticating system include the barrel, a screw that fits inside the barrel, a motor drive system for rotating the screw, a system on the shank of the screw to apply force resulting in the “back pressure” for the screw, and a non-return valve located at the tip of the screw. Many innovations on the construction of these components have been developed by many machine suppliers over the years. Only innovations related to the screw design will be discussed here.

The plasticating process starts with the mixing of the feedstock materials. Typically, several different feedstocks are added to the hopper, such as fresh resin pellets, recycle material, additives, and a color concentrate. The recycle material typically comes from the grinding of off-specification parts. Additives and color concentrates may be added as needed, to adjust the physical properties and appearance of the part. Often, these components need to be dried and blended prior to adding them to the hopper. Next, the pellets flow via gravity from the
hopper through the feed throat of the feed casing and into the solids conveying section of the screw. Typically, this feed casing is cooled, using water. The feed section of the screw is typically designed with a constant depth and is about one third of the overall length of the screw. Directly after the solids conveying section is a section where the channel depth tapers to a shallow depth metering section. The tapered depth section is commonly referred to as the melting section. In general, the metering section is also of constant depth, but many variations exist where the channels oscillate in depth. The metering section pumps the material through a non-return valve and is collected in the front of the screw for the next injection cycle. As the material is collected, the screw must retract to provide additional volume. A properly operating process will have a constant screw retraction speed for a fixed screw speed.

The pressure at the discharge of the screw will cause the screw to retract, resulting in the accumulation of molten resin between the tip of the non-return valve and the end of the barrel. The pressure on this material is maintained by a constant force applied to the shank of the screw via the drive system. This force is typically measured as a pressure applied to the shank and is referred to as the “back pressure’. The pressure, however, that occurs at the tip of the non-return valve is higher and directly proportional to the back pressure as follows:

\[ P_{\text{dis}} = k P_b \]  

(3.1)

where \( P_b \) is the back pressure reported by the molding machine controls, \( P_{\text{dis}} \) is the pressure at the tip of the non-return valve (discharge pressure), and \( k \) is a proportionality constant. Typically, \( k \) varies between 8 and approx. 14. Changing the back pressure on a machine can have a large affect on the performance of the machine and the appearance of the molded parts. For example, if the back pressure is increased, the specific rate of the screw will decrease and the discharge temperature will increase.

It is important to understand the factors influencing the plasticating rate for screw design and to make sure that the injection molding process is not rate limited by it. The plasticating rate is the mass rate that is conveyed, melted, and pressurized while the screw is rotating. It can be calculated as follows:

\[ Q = \frac{M}{t_p} \]  

(3.2)

where \( M \) is the mass of the parts and any runner systems that were produced during a single molding cycle and \( t_p \) is the plasticating time or the time required to produce the molten polymer during screw rotation. It is assumed here that the rotation speed of the screw is constant, and that screw start up and shut off time during the cycle are minimal. The specific rate of the screw is defined as the plasticating rate divided by the screw speed; i.e., kg/(h rpm).
3.3 Operation of Plasticating Screw Machines

The plasticating and mixing performance of the screw is highly dependent on whether it is operating properly. An improperly operating machine will show higher discharge temperatures, inconsistent plasticating times, lower specific rates, material degradation, and lower levels of mixing performance. The goal of this section is to describe the operation of a flood-fed, single-screw plasticator for injection molding machines.

The feed delivery system to the plasticator must provide an acceptable level of solids with uniform composition to the feed hopper. If the mixing in the feed delivery section is not adequate or the feed composition varies with time, then the quality of the discharged material can show signs of a poorly mixed system. For example, if a processor desires to use a 35:1 letdown ratio of a color concentrate, but instead, the feed delivery system provides momentary color letdown ratios varying from 20 to 100:1, color gradients are likely to appear across the part and also variations between parts.

Plasticators must perform multiple functions. These functions include the conveying of the solid feedstock resins from the hopper into the first section of the barrel, melting, pressurization in the metering section, and mixing operations, as shown in Fig. 3.1. In order to understand the performance in the device, it is first important to understand the operation of the sections. For single-stage processes, the metering section of the screw must control the specific rate of the process. If the metering section does not control the specific rate, then an operation upstream of the metering section is controlling, and sections of the screw channel:

Figure 3.1: Schematic of the melting and mixing process that occurs during the plastication of natural ABS (white) resin with a red color concentrate resin using a conventional, single-flighted screw
downstream of the rate controlling section will be operating partially filled. Partially filled channels can lead to inconsistent plasticating times, high cycle times (low production rates), high discharge temperatures, high scrap rates, material degradation, poor mixing, and high labor costs per part [8, 9]. It is imperative that the machine is operating properly before other performance criteria are assessed. Two-stage vented plasticators are rare, but they can be used effectively to vent gases, eliminating or minimizing the need for dryers. For two-stage plasticators, the first-stage metering section must control the rate. Otherwise flow of material out through the vent will occur.

The solids conveying section of the screw must be able to provide resin at a rate fast enough and under pressure to keep the melting and metering sections full of resin. If the solids conveying section is rate limiting, then downstream sections of the screw will be partially filled [8, 10]. Many design and operational factors can cause this defect, but, in general, it is related to a combination of the depth of the feed channel of the screw and the surface temperatures of both the screw and barrel in the solids conveying zone. The feed channel is generally 2 to 6 times deeper than the metering section of the screw, and generally has constant depth over its entire length. For a properly designed screw for the maximum use of recycle material, the best solids conveying will occur when the forwarding forces at the barrel wall and pushing flight of the screw are a maximum and the retarding forces at the screw root are a minimum [11]. These forces are directly proportional to the dynamic coefficients of friction for the pellets sliding on the metal surfaces of the screw and barrel wall. For a constant screw speed, changing the temperature of the feed zone of the barrel systematically to minimize the plasticating time is the best way to find the optimal temperature for solids conveying [7].

The melting processes that occur in a plasticator can be examined by performing a screw solidification experiment. The technique was pioneered by Maddock [12] in the late 1950s using an extruder. The technique consists of operating the extruder until a steady state is achieved, and then stopping screw rotation and simultaneously cooling the barrel, to solidify the molten polymer in the screw channels. Next, the screw with the solidified polymer is pushed out of the barrel and examined. Often, a small amount of pigmented polymer is added to the feedstock resin at a ratio of about 100 to 1 to demarcate regions that were solid or molten prior to stopping the rotation of the screw. The regions in the screw that were molten will be tinted with the pigment, while the solid regions will have the color of the main feedstock with small traces of pigmented particles. A cross-sectional view of the plastication process via a Maddock solidification experiment for an acrylonitrile-butadiene-styrene (ABS) resin is shown in Fig. 3.1. As shown, the natural (white) ABS pellet solids were compacted into a solid bed, and within the solid bed were smaller amounts of color concentrate solid pellets (red areas in the white bed). Plastication (or melting) occurs in a thin melt film between the solid bed and the barrel wall. The newly molten, highly viscous material is then conveyed by the motion of the rotating screw to the melt pool at the pushing side (left side) of the channel. Figure 3.1 shows that the melt pool is mostly red with some small streaks of molten natural resin, indicating the high efficiency of this primary mixing process during melting. The term primary mixing is used here to designate the first major mixing that occurs between the different solid particles that enter the machine. For single-flighted, conventional screws, Benkreira et al. [13] showed evidence that most of the mixing occurs during the melting...
process, with only small levels of additional mixing occurring in the downstream channel. As will be shown later, if melting does not occur inside the plasticator, significant defects will occur due to poor mixing. As melting progresses downstream, the width of the solid bed becomes smaller until all the resin is fully melted. For conventional single-flighted screws, the depth of the screw channel in the melting (or transition) section starts at the depth of the feed section and becomes shallower until it ends at the entry of the metering section. Recall that the metering channel depth is typically 1/2 to 1/6 the depth the feed channel. The melting process, however, is not limited to the transition section of the screw. In most cases, the melting process extends several diameters downstream of the transition section and into the metering section, especially at high screw speeds.

3.3.1 Proper Operation

As previously stated, the metering section of a plasticator has several functions and it must be the rate-limiting section of the extruder. The most important three functions of the metering section are the pumping capacity, the capacity to generate pressure, and secondary mixing. The flow in the metering section must also be equivalent to the flow in the other sections of the screw. Design flaws that result in drastically different theoretical flows for two different segments of a screw may result in vent flooding for a two-stage screw and void regions that can create cross linked or gelled material [14]. A simple and fast method of estimating the flow components (drag flow and pressure flow) in the metering section was developed by Rowell and Finlayson [15], and it was outlined by Tadmor and Klein [6]. Several other methods are available to estimate the flow components in the metering section of the screw, but they can be more complicated and time consuming [16]. An example of the calculation of the flow in a metering section was presented previously [17].

3.4 The Melting Process

The maximum plasticating rate for a screw is typically limited by its melting capacity. That is, if the plasticating machine has enough motor torque and has capabilities for high screw rotational speeds, the maximum rate of the screw will be limited by the ability of the screw to melt the resin. For example, at low screw speeds, most screws will provide a discharge that is free of solid polymer fragments. But as the screw speed is increased, a speed will be reached where solids are discharged. These discharged solids will cause a variety of defects in the molded parts. The goal of this section is to describe the melting process of the screw.

The melting process shown in Fig. 3.1 is depicted schematically in Fig. 3.2. The schematic is for a cross section perpendicular to the flight edge. The unwound channel is represented in Cartesian coordinates, instead of cylindrical coordinates. The reference frame for rotation is changed, such that the screw is stationary and the barrel is rotating. As the barrel moves (in both the cross channel and down channel directions) over the top of the thin melt film,
energy is dissipated and conducted into the solids bed. Some of this conducted energy will cause melting to occur at the solid bed-melt film interface. The newly molten resin is conveyed by the cross-channel motion of the barrel ($V_{bx}$) to the melt pool, causing the melt pool to increase in width. Some molten resin will flow over the flight clearance between the flight tip and barrel wall (leakage flow) and transfer to the flight in the upstream position.

For an idealized melting process, the width of the melt pool will increase and the width of the solids bed will decrease, as melting progresses in the downstream direction. Generally, the depth of the channel is also decreasing, as melting progresses. A convenient method of tracking the melting rate of the machine is to plot the ratio of the solid bed width, $X$, to the width of the channel perpendicular to the flight edge ($X/W$), as shown by Figs. 3.2 and 3.3. For the case shown in Fig. 3.3, the solids fill the entire width of the channel up to about 7 diameters from the start of the screw, i.e., the solids conveying section. At about 7 diameters, as indicated by curve “a” in Fig. 3.3, melting progresses at essentially a uniform rate, until melting is complete at about 16 diameters. If the process is altered, such as increasing the screw speed, so that melting is delayed and the axial length of the screw required for melting is longer, then the position where complete melting occurs will be pushed downstream, as shown by curve “b” in Fig. 3.3. Under extreme conditions, such as very high screw speeds, the solids bed can persist till very close to the tip of the screw. Moreover, any process upset can cause the solids bed to break apart and flow downstream. In both cases, transporting solids close to the tip of the screw or into the discharge will cause defects in the final parts. Increasing the back pressure on the screw can also have dramatic effects on the melting process, by changing the specific rate of the plasticating process. For example, increasing the back pressure will cause the melting process to be complete at a location further upstream in the screw. Thus, the discharge will be mixed better, but it will be at a higher temperature.

The melting profile shown in Fig. 3.3 is for an ideal system. Moreover, the model described above has several flaws and is under further development [18]. In general, the melting profile
The Plasticating System for Injection Molding Machines is considerably more complex, as shown in Fig. 3.4. These cross sections were obtained by performing a Maddock solidification experiment [19]. The solidification was performed at a screw speed of 74 rpm and a 220 : 1 letdown ratio of white colored (TiO₂) ABS resin to a black color ABS concentrate. As shown in Fig. 3.4, the solid bed spans the entire channel width at 6 diameters from the start of the screw. By 8.5 diameters, about 85% of the channel \(X/W = 0.85\) was occupied by the solids bed and about 15% by the melt pool. At 8.5 diameters, the depth of the channel has decreased and the pressure has increased, causing the solid pellets to compact into a bed. By 12 and 16 diameters, about 80% and 65% of the channel width is occupied by solids, respectively, and the channel depth has decreased further, as indicated by the thickness of the cross section. From these three cross sections, it is obvious that a considerable level of mixing has taken place via the melting process. At 17 diameters, the solid bed is not present in the view. Instead, the melt pool is occupying the entire width of the channel; i.e., \(X/W = 0\). However, at 18 diameters, there appears to be a relatively high level of white pigmented material in the center and right side of the channel. This high level of white resin was caused by a break up of the solid bed, and it represents solid material or material that is at a temperature near the \(T_g\) but not mixed with the black pigment from the color concentrate pellets. The cross section at diameter 19 shows even a higher level of solids or unmixed material. At diameter 20, a position 1 diameter from the discharge end of the screw, there are many striations between the white and dark areas, indicating that a significant level of mixing occurred during the melting process and the downstream sections of the screw. The cross sections shown in Fig. 3.4, however, are just a view of the operation at one moment in time. Unsteady-state processes can cause some solids or unmixed white material to flow very close to the tip and be discharged. Also, the letdown ratio of 220 : 1 that was used for this example is considerably higher than the typical 25 or 75 : 1 letdown ratios that are used commercially. Such a system presents difficult mixing requirements.

The melting and mixing performance of any screw is highly dependent upon the process conditions of the operation, especially the screw speed. For example, for the conventional,
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The extruder was operated at a 100:1 letdown ratio of white pigmented ABS to a black color concentrate. The extruder was operated at screw speeds ranging from 30 to 150 rpm, and extrudate sample cross sections were collected using an 11 mm diameter die. The locations of the cross sections are shown in Fig. 3.5. Figure 3.6 shows that the extrudate cross-sectional views at screw speeds of 30 and 60 rpm contained essentially no solid particles and had relatively small amounts of poorly mixed material. As the screw speed was increased further, however, some solid pellet fragments were obvious in the discharge. Solids were evident by the non-uniform diameter of the extrudate stream and by the cross-sectional views. Moreover, the solids level in the extrudate increased as the screw speed increased beyond 90 rpm. Some trace amounts of solids were first observed at about 80 rpm. Thus, operation of a plasticator at speeds higher than the operational limits of the screw will cause solids to appear in the discharge. As previously stated, these solids

**Figure 3.4:** Cross-sectional views for a conventional, single-flighted screw [19]. A black colored concentrate was added at a letdown ratio of 220:1 to a white tinted ABS resin. For each cross section, the barrel surface is along the top, the screw root is along the bottom, and the pushing and trailing flights are along the left and right edges, respectively. Labels indicate the axial distances in screw diameters from the start of the screw.

**Figure 3.5:** Extruder schematic showing location of the extrudate cross-sectional views.

single-flighted screw discussed previously, the extruder was operated at a 100:1 letdown ratio of white pigmented ABS to a black color concentrate. The extruder was operated at screw speeds ranging from 30 to 150 rpm, and extrudate sample cross sections were collected using an 11 mm diameter die. The locations of the cross sections are shown in Fig. 3.5. Figure 3.6 shows that the extrudate cross-sectional views at screw speeds of 30 and 60 rpm contained essentially no solid particles and had relatively small amounts of poorly mixed material. As the screw speed was increased further, however, some solid pellet fragments were obvious in the discharge. Solids were evident by the non-uniform diameter of the extrudate stream and by the cross-sectional views. Moreover, the solids level in the extrudate increased as the screw speed increased beyond 90 rpm. Some trace amounts of solids were first observed at about 80 rpm. Thus, operation of a plasticator at speeds higher than the operational limits of the screw will cause solids to appear in the discharge. As previously stated, these solids
will cause defects in the final molded parts. Although not popular with molding plants, the best option for improving the mixing for this case is to decrease the screw speed. If the machine is cooling-rate limited, the cycle time will not change. If the machine is limited by the plasticating rate, however, decreasing the screw speed will cause the cycle time to increase. For the process shown in Fig. 3.6, the highest possible rate that provides acceptable quality discharge for this screw will likely occur at about 75 rpm with a rate of about 70 kg/h. As will be discussed later, the addition of a secondary mixer or the use of a high-performance screw will mitigate this problem.

The extrudate samples and the solidification experiment clearly show the importance of the melting process for achieving the desirable mixing quality of the plasticator discharge. The cases shown here are for color masterbatches in natural or white resins, but the concept applies to any solid mixture or blend added to the hopper of a molding machine. Color masterbatches were used here because it is much easier to visualize, as compared to other compositional variations or thermal gradients.

Operation of the plasticator at high back pressures is a method of improving the mixing quality of the discharge. Increasing the discharge pressure will increase the pressure in the melting zone and improve the melting rate [20, 21], while reducing the tendency for solid bed breakup. Moreover, increasing the back pressure will improve mixing in the fully molten sections, but to a lesser extent. Increasing the back pressure will cause the specific rate of the screw to decrease and thus increase the plasticating time and also increase the discharge temperature.

The mechanism of mixing during the melting process was clearly demonstrated by Benkreira et al. [13] in 1992. For this mechanism, the solid particles move down the channel at the velocity of the solid bed. As melting occurs, the pellets exposed to the solid bed-melt film interface undergo a phase change (or devitrifies) and are transferred to the melt film, as shown in Fig. 3.7. This newly molten material is then accelerated and is forced to undergo elongation. The elongation occurs because the motion of the barrel relative to the screw is considerably higher than that for the solid bed and in a different direction. As the fluid element moves away from the bed, due to the introduction of newly molten material, the cross channel ($V_{bx}$) and the downstream ($V_{bz}$) components of the flow accelerate and stretch the element. The
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Elongation causes the material to form a thin striation of material, as shown in Figs. 3.1 and 3.4. Figure 3.7 shows that the thickness of the melt film increases in the cross-channel flow direction. This is due to the melting flux that occurs across the entire width of the bed.

Several features are illustrated in Fig. 3.7. Firstly, the melt film thickness increases in the cross-channel direction. This occurs due to the addition of newly molten material migrating from the solid bed-melt interface into the film. At the trailing flight side of the channel, the thickness of the melt film is the smallest and about the size of the flight clearance, and, as material is melted and accumulated in the film, its thickness increases. The thickest location occurs at the edge nearest the melt pool. The film thickness is enlarged in Fig. 3.7 to show the details of the melting and mixing mechanism. As the newly molten material is added to the film, it pushes the older material away from the interface and into a location where the velocity is higher, causing the fluid element to elongate. This elongation is shown in Fig. 3.7 by the reduction in width of the melting streak in the melt film. The material then flows to the melt pool, where the individual streaks create a pattern with many laminar striations. These streaks are shown here as a color mixing process, but they could be compositional or thermal differences.

The striations that occur in the melt pool are caused by streaks from many different pellets. Some of these streaks occur due to the pellets at the viewing cross section, but most are created by pellets that have melted upstream of the view. For color mixing processes, the best mixing that will occur during the melting process will be for very low color concentrate letdown ratios. With low color letdown ratios, such as 25 : 1 natural resin to a colored resin, the amount of colored pellets to natural pellets is extremely high. For this case, it is 4 colored pellets per 100 natural pellets. The larger number of colored pellets will create a larger number of color streaks during melting, and provide for a higher level of striations or interfacial area.

Figure 3.7: Schematic showing the mixing mechanism during the melting process. Several of the pellets were colored black to show the flow paths and the elongation of the fluid elements. The figure is for an unwound channel working in Cartesian coordinates, and the reference frame for rotation was changed such that the screw is stationary and the barrel is rotating. The melt film thickness is enlarged to show the elongation of the dark-colored pellets.
between the colored and natural materials. The cost, however, to use a 25:1 ratio will be higher than that for a 50:1 ratio.

The melting process described above provides the first and likely the best level of mixing. This mechanism, however, is sometimes difficult to maintain in a plasticator. The most common problem encountered is the break up of the solid bed. If the solid bed breaks up, then a solid bed fragment can flow with the molten material downstream and not be subjected to the high stresses that occur during melting. This solid bed breakup process is clearly evident in the cross-sectional views shown by Fig. 3.4. Solid bed breakup is a complicated process [22, 23] and it is poorly understood. In general, solid bed breakup is most likely to occur at high screw speeds. The solids in the discharge that are evident in Fig. 3.6 are likely caused by a combination of a melting rate limitation and solid bed breakup.

The melting-mixing mechanism described above is clearly illustrated with color masterbatch systems. Furthermore, the composition and melting characteristics of the masterbatch, relative to the natural resin, can affect the mixing that occurs during the melting process. Benkreira and Britton [24] have experimentally shown the effect of melt viscosity of the masterbatch on color mixing for these systems. In general, the masterbatch should be less viscous than the natural resin that will be colored. This viscosity difference will lead to higher stresses in the natural resin, such that the elongation of the colorant is effective during the melting process, as shown by Fig. 3.7. Their mixing experiments indicated that the viscosity ratio of the natural resin to that of the masterbatch resin, at the processing conditions, should be as high as possible. Masterbatches with very low viscosities, however, can be difficult to produce, since the stresses during the compounding operation may not be high enough to disperse the pigments. In general and as a compromise, the viscosity at processing conditions of the masterbatch should be about one half that of the natural resin. If the viscosity of the masterbatch is higher than that of the natural resin, then color streaking is very likely to occur. The best option for this kind of color streaking is to switch to a masterbatch with a lower viscosity; i.e., a viscosity less than that of the natural resin. In most cases, the same resin type as the natural resin is used for the masterbatch resin.

In many cases, the masterbatch melt flow rate (MFR) or melt index (MI) are compared to that of the natural resin. Since these indices are measured at shear rates considerably less than those occurring during processing, they are often not the best indicators for masterbatch selection. The viscosity at the temperature and shear rates for processing should be used and not the MFR or MI. For example, a PS resin with a MFR of 10 dg/min will have experienced a shear rate of 20 s⁻¹ during the flow rate measurement [25]. During the melting process in a plasticator, however, the shear rate is in the range of 1000 to 3000 s⁻¹.

The use of a barrier-flighted melting section is another method of obtaining a higher level of mixing through improved melting. The design of barrier melting sections is complex and many different types are available [5]. A simplistic schematic of a typical barrier melting section is shown in Fig. 3.8. As shown here, the solid pellets are compacted and melted in a separate channel. Like the conventional screw, melting occurs between the solid bed and the barrel wall via the relative motion between the barrel wall and the solids-melt interface. The newly melted material is then dragged over the barrel flight and is collected in the melt-conveying channel. The clearance between the barrier flight and the barrel wall is relatively
small, and it is typically about 0.8 to 1.1 mm for a 120 mm diameter screw. As previously indicated, there are many different types of barrier sections, such as varying the lead length of the barrier flight (decreasing the width of the solids channel and decreasing the width of the melt channel with the downstream position), and varying the depth of the channel. All barrier screws work by increasing the melting rate and thus the overall rate of the screw. Moreover, the barrier flight maintains the integrity of the solid bed and, thus, mitigates the breakup of the solid bed [23, 26]. In general, screws with barrier melting sections operate at higher rates, because they can melt material at a faster rate and, thus, maintain a highly mixed and homogenous discharge.

Barrier flighted sections are complicated and difficult to design. Both channels must be designed with the proper volume, such that the polymer maintains the channels full and under pressure. It is highly undesirable to have a secondary melt pool at the pushing side of the barrier flight and, thus, in the solids channel. If this melt pool develops in the solids channel, then the melting rate and, thus, the overall rate will be lower than expected. Moreover, the positioning and design of the entry region of this section is critical, due to the introduction of the barrier flight [14], i.e., a transition between a single flight in the solids conveying section to a dual-flighted region in the barrier section. If the entry region of the barrier flight is too restrictive, the specific rate for the screw will decrease, and melting and mixing can be poor. In some cases, the restriction causes the specific rate to decrease by up to 50%, causing downstream sections of the screw to operate partially filled and with zero pressure. As previously discussed, material degradation can occur in these void channels. This restriction can be easily removed for most applications [7, 14].

The clearance between the flight tip and the barrel wall is an extremely important parameter for both mixing and the performance of an extruder. For a typical machine, this clearance is about 0.1% of the diameter. This allows for enough mechanical clearance to permit rotation without seizing, yet provides a well-wiped barrel surface for maintaining acceptable heat transfer. The clearance will increase as the screw wears during service. Increased flight clearance in the melting section will cause the melt film between the solid bed and barrel wall to
increase (see Fig. 3.2). The increased melt film thickness will reduce the melting capacity of the screw, by reducing the level of viscous energy dissipation, requiring a longer distance in the barrel for melting [5, 6, 27]. If the melting capacity decreases too much, solids will discharge with the extrudate. Thus, an increased flight clearance in the melting section will reduce the mixing and melting performance of the screw. Increased clearance in the metering section with only molten polymer present, however, will cause the mixing performance to increase. Increased flight clearance will reduce the specific rate of the plasticator, causing the screw to rotate faster to produce at the same rate. The decreased specific rate will improve the mixing performance, but will cause the discharge to be at a higher temperature.

### 3.5 Basic Screw Design

Several general guidelines exist for the design of basic conventional screws. These guidelines are summarized in Table 3.1. For example, the lead length \((L)\) is typically constant along the length of the screw, and it is generally between 0.8 and 1.3 times the diameter of the barrel \((D_b)\). Many screws are square pitched where the lead length is equal to the barrel diameter. Due to the relatively small screw diameters for injection molding plasticators, the majority of the screws are single-flighted. The flight width perpendicular to the flight edge \((e)\) is often 10% of the barrel diameter, while the clearance between the flight tip and the barrel wall is about 0.1% of the diameter. Thus, a 140 mm diameter screw would have a flight width of 14 mm and an outside diameter of 139.72 mm, providing a flight clearance of 0.14 mm on each side of the screw.

The metering channel depth controls the specific rate, discharge temperature, and often the quality of the material discharged. It is also one of the most difficult parameters to specify. Typically, it has a value that is between 3 and 10% of the diameter of the barrel. The actual value is set by a combination of experience and numerical simulations, in order to meet the demands of the process. The feed channel depth and the length of the transition section are specified, using guideline ratios known as the compression ratio, \(C\), and the compression rate, \(R\). The definitions of these ratios for a screw with a constant lead length are as follows:

\[
C = \frac{H_f}{H} \quad (3.3)
\]

\[
R = \frac{(H_f - H) \sin \theta_b}{l_t} \quad (3.4)
\]

\[
\tan \theta_b = \frac{L}{\pi D_b} \quad (3.5)
\]

where \(H_f\) is the depth of the feed channel, \(H\) is the depth of the metering channel, \(l_t\) is the axial length of the transition section, and \(\theta_b\) is the helix angle at the barrel wall.
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For general-purpose polystyrene (GPPS) and high impact polystyrene (HIPS) resins in the pellet form, the compression ratio should be between 3 and 4, and the compression rate near 0.0035. Compression rates and ratios that are lower than these can cause air entrapment due to the poor compaction of the solids and can reduce the melting capacity. Compression rates and ratios that are greater than these can cause melting instabilities due to high channel pressures. If a low-density recycle stream is added to the feedstock, then the feed density to the screw will be reduced, and the volume change required to fully compact the resin would be higher. In these cases the, compression rate and ratio would need to be increased.

3.5.1 PS Injection Molding Case Study

An injection molding machine was producing a small part from a General purpose polystyrene (GPPS) resin. About 5% of the parts had unacceptable visual defects that reduced the yield for the process. Photographs for these defects are shown by Fig. 3.9. Analysis indicated that the defects were caused by two general sources:

- air entrapment in the solids, as they were forwarded on the screw, and
- unmelted resin disrupting the flow in the mold.

### Table 3.1: Typical Channel Dimensions for a Conventional, Single-Flighted Screw

<table>
<thead>
<tr>
<th>Geometric parameter</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead length, ( L )</td>
<td>0.8 ( D_b ) to 1.3 ( D_b )</td>
</tr>
<tr>
<td>Flight width perpendicular to the edge, ( e )</td>
<td>0.10 ( D_b )</td>
</tr>
<tr>
<td>Flight clearance</td>
<td>0.001 ( D_b )</td>
</tr>
<tr>
<td>Metering channel depth, ( H )</td>
<td>0.03 ( D_b ) to 0.10 ( D_b )</td>
</tr>
</tbody>
</table>

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- air entrapment in the solids, as they were forwarded on the screw, and
- unmelted resin disrupting the flow in the mold.

**Figure 3.9:** Visual defects for molded parts from GPPS resin using a screw that had a compression rate and compression ratio that were too low
The barrel diameter was 63.5 mm. The screw was single-flighted and conventional with a square pitched lead length. The feed channel and metering depths were 8.26 mm and 3.43 mm, respectively, and the transition length was 490 mm. Calculation of the drag and pressure flows for the screw indicated that the channels were full of resin and were pressurized. The compression ratio was calculated at 2.4, while the compression rate was 0.0030. Thus, both the compression ratio and rate were too low for this resin.

The screw was modified, such that the feed channel depth was increased to 10.3 mm and the transition section was lengthened to 600 mm. The additional length for the transition section was obtained by extending it into the metering section. The depth of the metering section was not changed. Both modifications were relatively simple since they required the removal of metal from the screw. The modified screw had a compression ratio of 3.0 and the compression rate was 0.0035. These modifications completely eliminated the defects from the parts.

### 3.6 High-Performance Screw Designs

The industry trend is to operate injection molding presses at increasingly higher rates. For high plastication rates, it requires a combination of higher screw speeds and screws with deeper metering channels. As previously discussed, operation of a conventional, single-flighted screw at relatively high speeds can cause some solids to discharge into the tooling, causing defects in the molded parts. Increasing the depth of the metering section will increase the specific rate of the process, but the melting capacity or the length of the transition zone for the screw is unchanged. Again, solid particles are highly likely to be discharged into the tooling. These limitations have been mitigated by the development of high-performance screws that have the ability to complete the melting process at high rates, discharge at a lower temperature, and provide a higher quality discharge. These devices all work by forcing the material to flow repetitively through regions with relatively small clearances. As the material passes through these clearances, large polymer solids will become trapped and forced to melt before passing through, and smaller polymer solids will be subjected to high elongational and shear stress fields that will aid in their melting. The lands for these clearances tend to be relatively short in the flow direction, while the rest of the channels are relatively deep. The deeper main channels allow the devices to maintain high specific rates and low discharge temperatures, while the regions with the small clearances provide a level of mixing by completing the melting process. There are numerous devices currently on the market, and several of these will be discussed here.

Some of the more widely used high-performance screws include the Energy Transfer (ET) screw [28], the Variable Barrier Energy Transfer (VBET) [29] screw, the Double Wave screw [30], the Stratablend [31] and Stratablend II [32] screws, and the Unimix screw [33]. Versions of these screws are commercially available for both injection molding and extrusion processes. However, other devices can act as a trap for solid materials from the melting section. These devices include Maddock-style mixers, spiral dams, and blisters, and they will be discussed in detail in the section on secondary mixing processes.
Higher rates and improved melting and, thus, mixing quality of the discharge can be obtained by using a screw with an ET section. In this screw design, the metering section of a conventional, single-flighted screw is replaced with an ET section. Unlike a conventional metering channel, the ET section [34] consists of two channels, as shown in Fig. 3.10. One channel is positioned one-half turn downstream from the other, and both channels are of equal width. In order to create cross-channel mixing, the depths of both channels are periodic and out of phase. An undercut in the flight to the rear of a channel starts when that channel decreases in depth, permitting flow from the channel to the channel behind it. The undercut ends when the depth of the channel in front of that flight starts to increase. Most ET screws are designed with three regions where the channels become shallow; i.e., peaks in the channel profile. The peak clearance and flight undercuts are the same for all three peaks. These peaks and flight undercuts create cross-channel mixing and disperse and melt the solid polymer fragments entering the section [19]. Some of the larger solids will remain as solids after passing through the first peak region, but will be reduced in size. The increased surface area of the smaller fragments will have a higher melting rate through heat conduction while being transported to the next peak region. Repetitive flow through the three peak regions produces discharges with improved temperature homogenization, lower temperatures, lower levels of temperature fluctuations, and at increased rates as compared to conventional screws.

A Maddock solidification experiment was performed, using a 21 L/D, 63.5 mm diameter extruder with an ET screw [19]. The details of the channel dimensions have been reported elsewhere [19], but changes in the channel geometries are obvious from the cross-sectional views shown by Fig. 3.11. As expected, the cross-sectional views for the ET screw were very similar to those for a single-flighted screw (see Fig. 3.4) at axial lengths less than about 14
diameters, i.e., the section upstream of the ET section, as shown in Fig. 3.11. At an axial
distances of 14.4 diameters and greater, the channels of the ET section are clearly visible; i.e.,
two channels connected by an undercut flight.

Extrudate samples using the extrusion method shown in Fig. 3.5 were also collected for the
ET screw, at screw speeds ranging from 30 to 150 rpm, using a white pigmented ABS resin
to black color concentrate letdown ratio of 100 : 1. The cross-sectional views of the extrudate
samples are shown in Fig. 3.12. At a screw speed of 30 rpm, a few white streaks were evident
in the extrudate samples, likely due to inadequate mixing at the lower screw speed. When
the screw speed was increased to 60 rpm, the extrudate was free of defects. The same result
was achieved when the screw speed was increased to 90 rpm. As the screw speed was further
increased to 120 rpm, subtle spiral patterns became obvious and solid resin fragments began
to appear in the extrudate samples. When the screw speed was increased to 150 rpm, the
amount and size of the solid resin fragments in the extrudate increased further, as shown in
Fig. 3.12. The highest possible rate, while providing an acceptable quality discharge for this

Figure 3.11: Cross-sectional views for the ET screw at a letdown ratio of 220 : 1 white pigmented ABS
resin to a black color concentrate [19]. The A and B mixing channels are labeled. The
views were for a screw speed of 66 rpm and a rate of 70 kg/h using a 63.5 mm diameter extruder

Figure 3.12: Cross-sectional views of extrudate samples at a letdown ratio of 100 : 1 of a white
pigmented ABS resin with a black color concentrate for an ET screw. The samples
were produced at screw speeds ranging from 30 to 150 rpm. The large round white
regions for the cross sections at screw speeds of 90 rpm and higher are solid particles
discharged with the extrudate
ET screw, will likely occur at about 90 rpm and a rate of about 85 kg/h. This rate is about 20% higher than the single-flighted conventional screw described previously, as shown by the extrudate samples in Fig. 3.6. Processes operating at high rates should always consider a high-performance design, in order to mitigate mixing problems due to poor melting. Additional performance data for ET screws can be obtained in references [19, 34–36].

The VBET screw is an enhanced design, based on the ET screw [37]. The original VBET design was a replacement design for blown film applications, where a barrier section was followed by an ET section. For this application, the VBET section replaces the barrier and ET sections. In general, there are more peaks and undercuts for a VBET screw, as compared to a standard ET screw. As previously discussed, ET screws have three peaks or channels with shallow regions, and all peak depths are identical. A VBET screw, however, will have five or more peaks, and the peaks become more restrictive as flow moves downstream.

A VBET screw was designed and built that was comparable to the ET screw presented previously [38]. Details of the screw geometry were presented earlier [38]. However, unlike the ET screw, the undercut clearance was gradually decreased from 2.3 mm at the entrance of the section to 1 mm at the discharge end of the screw for five peaks. In contrast, the ET screw had 3 peaks and the undercut clearance was a constant 1.40 mm. The specific drag flow rate for ABS resin was calculated at 1.0 kg/(h rpm) for the VBET screw, which was the same as the ET screw. Like the conventional and ET screws, the VBET screw was operated at a 100 : 1 letdown ratio of white pigmented ABS to a black color concentrate. The extruder was operated at screw speeds ranging from 30 to 150 rpm, and the extrudate samples were collected. Cross-sectional views of the extrudate samples for the VBET screw are shown in Fig. 3.13. As before, the white spiral patterns indicate regions, where little to no mixing occurred between the white and black resins, and, as previously discussed, these patterns would not be visible for a typical commercial application. At a screw speed of 30 rpm, very few white streaks were evident in the extrudate strand samples. When the screw speed was increased to 60 and 90 rpm, the extrudate changed little. As the screw speed was further increased to 120 rpm, the spiral patterns became more obvious; there were no solid resin fragments in the extrudate samples. Some solid fragments, however, were evident in the extrudate for the ET screw at this speed, as shown by Fig. 3.12. When the screw speed was increased to 150 rpm, a few solid resin fragments began to appear in the extrudate, as shown in Fig. 3.13. The measured extrusion rate for the VBET screw is also shown by Fig. 3.13. The specific rate was nearly constant at 1.0 kg/(h rpm) over the range of the screw speed. These results clearly

![Figure 3.13: Extrudate samples as a function of screw speed for a 100 : 1 letdown ratio of white ABS (TiO2) to black ABS resin using a VBET screw [38]](image)
indicate that the VBET screw has improved melting and mixing capacity, as there were fewer unmelted pellets in the extruder discharge at higher screw speeds and at higher specific rates than the ET screw.

The data presented here clearly show the advanced melting and mixing capability of the VBET screw section. As shown by the extrudate samples, the VBET mixing screw can be designed to allow higher screw speeds and rates before solids are discharged in the extrudate. For the cases presented here, the ET screw can be operated at a maximum rate of about 85 kg/h at a screw speed of 90 rpm, while the VBET screw can run at about 121 kg/h at 120 rpm. Thus, the maximum rate for the VBET screw was about 40% higher than that for the ET screw, while maintaining high melt quality. The additional two peaks and the strategic tightening of the undercut clearance with each successive peak created the additional mixing and performance of the screw. In comparison, the conventional screw was only able to run at a maximum rate with a quality discharge of 70 kg/h at 75 rpm. All screws, including high-performance designs, will discharge solid material, if the screw is rotated fast enough. Additional performance data for VBET screws may be found in references [37, 38].

The Stratablend and Stratablend II screws are also high-performance designs that are capable of high rates while discharging high-quality mixed extrudates. The Stratablend screw is designed by positioning a Stratablend mixing section [31] in the metering section of a conventional screw. The device is constructed by placing three smaller advancing channels (or grooves) in the root of the main flight and parallel to the main flight, as shown in Fig. 3.14. The base depth of the channel is generally very shallow relative to a standard metering section. The distance between the root of the small channels or grooves and the barrel wall is about the same depth of a standard metering channel for the same rate. The small channels are typi-
cally a half a screw turn in length. These series of small channels provide multiple regions, where solid fragments can be trapped, melted, and dispersed into the main flow of the resin. Experiments were performed on a 63.5 mm diameter extruder, using a Stratablend design, and the results were presented previously [39].

Like the Stratablend screw, the Strataplend II mixing screw [32] is constructed by placing a Strataplend II mixing section in the metering section of the screw. The Strataplend II section is similar to the earlier design in that three advancing grooves are positioned between and parallel to the flight edges. The enhancement in mixing and melting performance is obtained by the addition of traversing grooves that allow flows in the cross-channel direction, as shown in Fig. 3.14.

Like the previously discussed high-performance screws, the Unimix [33] screw is designed by replacing all or part of the metering section with a Unimix mixing section. The Unimix section is designed with three channels positioned between the main flights, as shown in Fig. 3.15. All channels vary (oscillate) in depth with respect to the downstream direction. The center channel is the deepest for most sections of the mixer, and the depth can be as large as twice that of the metering section channel that it replaces. At strategic locations, the center channel depth decreases to a minimum depth for a very short axial length. At this location, all three channels have identical depths, providing a mechanism to trap and melt solid polymer fragments. The channels near the pushing and trailing flight edges typically vary to a lesser extent and these channels are shallower than the center channel. A typical Unimix screw is designed with at least three of these melting traps, where the channel depths are the same and at a minimum. For a 63.5 mm diameter screw, the minimum channel depth of the Unimix section is on the order of 1 mm.

![Figure 3.15: Schematic of an Unimix section](image)

- **a) Unimix Section**
- **b) Channel Cross Section**

Figure 3.15: Schematic of an Unimix section: (a) the section is used in place of a metering section, it has three channels with oscillating depths, and (b) cross-sectional view perpendicular to the flight tips showing channels at a local position (courtesy of Lee Prettyman of Glycon)
All the high-performance screws presented here and others have the objective of completing the melting process as early as possible in the device. As indicated earlier, complete melting is the first key to successful mixing in plasticators for injection molding machines. High-performance screw sections are typically designed with multiple regions, where the material must pass briefly through small channels, trapping and melting any solids present in the flow. Since the residence times in these small channels are very short, viscous dissipative heating of the resins is minimal, and thus temperature increases due to the devices are in general not significant. However, since the main channels of these devices are typically deeper than a conventional metering section, the specific rates are higher and the discharge temperatures are typically lower than those for conventional screw designs.

Many of the color mixing experiments presented here were designed under extremely difficult mixing conditions, using well designed screws. The extruder used was relatively short at an $L/D$ of only 21. Most commercial plasticators have an $L/D$ that is comparable to this machine or slightly longer. A longer barrel length would allow improved melting and mixing capabilities. Moreover, the masterbatch color mixing experiments were performed by coloring a white pigmented (TiO$_2$) ABS resin instead of the commercial practice of coloring a natural resin. In several of the experiments, where incomplete mixing was observed for the white pigmented resin, the same experiment was performed using the natural resin. In all cases, the color streaks were not visible in the natural resin. Poorly designed high-performance screws can provide lower levels of mixing and lower levels of performance.

### 3.7 Secondary Mixing Processes and Devices

Traditional mixing devices [40] are commonly designed into screws, downstream of the melting section. These mixers are effective in trapping and melting solid fragments, homogenizing molten streams, and mitigating thermal gradients. As previously discussed, the first main mixing operation occurs during the melting process upstream of these mixers. Since these mixers are developed and are implemented as a secondary process, they will be referred to here as secondary mixers. For liquid additive injection through the barrel wall and into the molten polymer stream, the correct combination of distributive and dispersive mixing is required to produce an optimal discharge. These mixers can be extremely important, especially for processes operating at very high rates or for processes that demand a very high-quality discharge.

Secondary mixers will mitigate the color streaks shown in the melt pool of Fig. 3.1 or the spiral patterns shown by Figs. 3.6, 3.12, and 3.13 and trap and melt any solid fragments entrained in the melt. There are many secondary mixer designs on the market, all having advantages and disadvantages with their use. Some of the more commonly used secondary mixers for dispersive mixing include Maddock-style mixers, blister rings, and spiral dams. These devices work well when it is highly desired to trap and melt solid polymer fragments, impart a high shear stress to the polymer, or create interfacial area between components. But, since these devices all work by flowing the molten stream through a narrow passage, energy dissipation can be...
3.7 Secondary Mixing Processes and Devices

high, causing the temperature of the material exiting the device to be higher than desired. If the passageway is too large (not restrictive enough), then the mixing effect will be reduced and thus may not be acceptable for the application. Moreover, if the entering stream has too high a level of polymer solids, blockage of the device is possible and the rate of the process will be reduced. Some of the common distributive mixers on the market include pin mixers, gear mixers, knob mixers, and pineapple mixers. These mixers all work by the multiple dividing, reorientation, and then re-combing the flow. This reorientation of the flows provides an excellent way to create interfacial mixing at an exponential rate. Since the channels on these devices are relatively large, there are typically only low levels of viscous dissipation and only minor increases in the temperature of the resin. However, since the channels are open (not restrictive) they cannot trap and melt polymer solids that may have come from the upstream sections of the screw. These solids have the potential to flow through a distributive mixer unaffected, causing a defect in the final part, especially at high rates. Although a mixer may be classified as either a dispersive or a distributive mixer, many mixing devices provide a combination of the two types of mixing.

Maddock-style mixers [41] are very commonly used due to their low cost to manufacture and their ability to disperse solid fragments, trap and melt polymer solids, and mitigate color and compositional gradients. Many styles are on the market under two basic types:

- flutes parallel to the screw axis, and
- flutes in a spiral pattern in the same direction as the flights.

Schematics for these devices are shown in Figs. 3.16 and 3.17. For small-diameter screws, the mixer is generally constructed with four in-flow flutes (or channels) and four out-flow flutes. Larger diameter screws will have more paired flutes, due to the larger available area at the screw circumference. For a Maddock mixer with the flutes parallel to the axis of the screw, molten polymer flows into the in-flow flutes via a pressure gradient, and then either continues to flow downstream in the flute or is passed through a small clearance between the mixing flight and the barrel wall. This small clearance is responsible for providing the dispersive mixing characteristics of the device. The clearance for a 63.5 mm diameter screw is typically about 0.5 to 1.2 mm, although for some applications and designs, the clearance can be smaller. The material that flows across the mixing flight is accumulated in the out-flow flute, and then flows via pressure to the discharge end of the mixer. For mixers with the flutes in a spiral pattern, some of the flow in the flutes is due to the drag flow associated with the movement of the flute relative to the barrel wall. Performance and simulation details can be found in the following references [42, 43].

The specification of the clearance on the mixing flight for Maddock-style mixers is critical to its performance. As previously stated, all material must flow through these clearances. If the clearance is too large, some medium and small size solid fragments will not be trapped and melted by the device. If the clearance is too small, then a high-pressure gradient can occur and there exists the possibility of increasing the temperature of the resin beyond its thermal capabilities, resulting in degradation. As a general rule, the clearance of the mixing flight of a Maddock mixer, with the flutes parallel to the screw axis, should be no smaller than the point where the pressure gradient across the flight is zero:
Figure 3.16: Schematic for Maddock-style mixers: (a) a mixer with the flutes aligned in the axial direction, and (b) a cross-sectional view perpendicular to the screw axis showing the clearance for the mixing flight (courtesy of Jeff A. Myers of Robert Barr, Inc.)

Figure 3.17: Schematic for Maddock-style mixers: (a) a mixer with the flutes aligned in the axial direction, (b) an axial mixer with a pressure relief zones at the entry and exits, and (c) a mixer with spiral flutes (courtesy of Jeff A. Myers of Robert Barr, Inc.)
where $h$ is the clearance of the mixing flight, $n_f$ is the number of in-flow flutes (or out-flow flutes), and $L_m$ is the axial length of the mixing flight. The geometric dimensions for the metering section of the screw are as follows: $p$ is the number of flight starts, $H$ is the channel depth, $W$ is the channel width, and $\theta_b$ is the helix angle. The helix angle is calculated using Eq. (3.5). This calculation sets the drag flow rate across the mixing flight to the drag flow rate in the metering channel. As an example, the minimum clearance that would be used for a 63.5 mm diameter ($D_b$) extruder with a single-flighted ($p = 1$), square-pitched ($L = 63.5$ mm) metering section would be about 0.39 mm ($h$). The metering section width ($W$) and depth ($H$) for this case are 54 and 3 mm, respectively. The Maddock mixer has four in-flow flutes and four out-flow flutes ($n_f = 4$), and it has an axial mixing length of 100 mm ($L_m$). Thus, if the extruder is discharging a low level of solids like that shown in Fig. 3.6 at 120 rpm, then the mixing flight can be decreased to no smaller than about 0.39 mm. For most applications, the clearance will likely be larger than this. The screw would be removed from service and a weld would be applied to the mixing flight, and then the flight would be ground down to a clearance of 0.39 mm. This type of procedure is designed for typical low to medium viscosity materials, with relatively low levels of solids in the stream. The actual application, however, may require a larger clearance; i.e., the clearance calculation is a guideline only.

Several other design factors are important for the correct operation of Maddock-style mixers. These include the positioning of the mixer downstream from the melting section, the distance between where the metering flight ends and the mixer starts, and the elimination of polymer stagnation regions. The mixer must be positioned on the screw downstream far enough such that only low levels of solid polymer fragments exist. If the level of solids is too high in the stream, then the fragments may be melted and dispersed at a rate lower than the rate of the entering solids, causing the mixer to become plugged with solids and reducing the rate of the machine. As shown in Fig. 3.17, the mixer should be positioned about 0.3 to 0.5 diameters away from the end of the upstream metering section flight. This creates an annular gap, where the material is allowed to flow evenly into all in-flow flutes of the mixer. The annular gap is often undercut as shown in Fig. 3.17(b). If the flights extend close to the mixer entry, then it is possible that the in-flow flute near the trailing side of the flight will not operate full of resin and may cause the resin to stagnate and degrade. Moreover, flute depths should be streamlined and shallower at the entry-end of the out-flow flute and the exit-end of the in-flow flute. A common design error is to make these regions too deep, creating stagnation regions and polymer degradation.

Thus, it is highly important that:
- the undercut on the mixing flight be set right, to create the level of mixing and stress required for the application;
- the device is positioned properly on the screw; and
- the device is streamlined, such that it does not cause material to have long residence times and thus cause resin degradation.
Blister rings are another common type of dispersive mixer used on plasticator screws. These devices are constructed by positioning the root of the screw near the barrel, creating an annular flow path between the screw and barrel, as shown in Fig. 3.18. For a 63.5 mm diameter screw, the clearance between the barrel wall and screw is typically 1 mm and the axial length is between 0.3 to 1 diameters. Like the Maddock-style mixers, blister ring mixers are positioned well downstream from the melting section where only low levels of solids are present. The relative motion between the screw and the barrel creates shear stress that can break some solid fragments into smaller particles, melt low levels of polymer solids, and mitigate thermal gradients.

Spiral dams are dispersive mixers that are easily designed and constructed and work well as a trap for solid polymer particles. The mixers are typically 2 to 5 diameters in length and are designed with a mixing flight starting at the pushing side of a flight channel and ending at the trailing side, as shown in Fig. 3.19. They are generally positioned at the end of metering (melting) sections. Material entering the section on the trailing side, is forced to flow through a small clearance between the mixing flight tip of the secondary flight and the barrel wall, and then flows out of the device at the pushing side of the channel. The mixing flight clearance for a 63.5 mm diameter screw is typically between 0.5 and 1 mm. A mixer designed with a smaller clearance may mix and trap solids better, disperse other fragments, but will also cause the temperature of the material to increase and may reduce the rate of the plasticator. Like the Maddock-style mixers, the mixer channels depths should be streamlined and shallower at the entry-end of the out-flow channel and the exit-end of the in-flow channel, minimizing stagnation regions and thus the likelihood of polymer degradation.

The shear rate and the stress that the polymer experiences over the mixing clearance for these dispersive mixers are approximated by Eqs. (3.7) and (3.8). For the shear rate calculation,
3.7 Secondary Mixing Processes and Devices

the contribution due to pressure flow is relatively small, compared to the component due to rotation, so it was neglected.

\[ \gamma_M = \frac{\pi D_b N}{h} \]  
\[ \tau_M = \eta \gamma_M \]  

where \( \gamma_M \) is the shear rate for flow across the mixing clearance, \( h \) is the mixing clearance, \( N \) is the rotation rate, \( \eta \) is the shear viscosity, and \( \tau_M \) is the shear stress.

Distributive mixers work by dividing, reorienting, and the re-combining the flow streams. For most devices, this process is performed multiple times. As previously stated, the flow channels on these devices are typically large, creating high mixing with very little pressure gradients and energy dissipation. These devices work well for streams that are completely molten, but they lack the ability to trap and melt solid polymer fragments. Pin mixers are commonly seen commercially due to their effectiveness at reorienting the flow, their low cost, and the ability to install them as a modification to an existing screw. Gear mixers have been used extensively to mix blowing agents into molten streams for foamed product applications. Other types of distributive mixers are commonly positioned near the tips of injection molding screws in order to eliminate fine color streaks and mitigate thermal gradients.

Pin-type mixers perform well for reorientation of the flow fields and improving the mixing for fully molten streams [44]. These devices are constructed by welding a series of strategically positioned small metal rods at the root of the screw, as shown by Fig. 3.20. The configuration shown in Fig. 3.20 is for a retrofit modification, where the pins were added after the screw was determined to have less than acceptable mixing performance. Another and likely preferred
design is to place the pins in a region with no flights. For this case, the axial distance between the pins should be large enough to allow the polymer to reestablish flow in the absence of the pins [44]. Positioning the pins too close together provides a lower level of mixing, since the flows tend to channel through a path of least resistance, i.e., the pin rows act as interrupted flights rather than as individual pins. Regions with very long residence times can occur at the downstream side of the pin, leading to polymer degradation. In an effort to minimize degradation, a pin mixer design with a hole bored from the barrel side of the pin on the upstream edge down to near the screw root on the downstream edge was developed [45, 46]. The hole diverts some of the resin from an area of high flow to the region where flow is very low and residence times are very high. The design has not had a strong commercial interest.

Gear-type mixers are distributive mixers that perform well for the addition of liquid additives to molten polymer streams. For this application, the liquid additives are injected through a hole in the barrel wall, typically up-stream of the mixer where the polymer is fully molten. Applications include foam production where a blowing agent is added. Many styles of gear mixers are available and they are typically designed using a multi-flighted channel design and then slitting the flights to allow material to flow into the adjacent channel, as shown in Fig. 3.21. In general, a well-designed gear mixer depends solely on a pressure gradient to flow material through the device.

Figure 3.20: Schematic for several common distributive mixers: (a) pin mixer with the pins positioned in the circumferential orientation; (b) a knob-type mixer; and (c) a pineapple mixer (courtesy of Jeff A. Myers of Robert Barr, Inc.)

Figure 3.21: Schematic of a gear-type distributive mixer (courtesy of Jeff A. Myers of Robert Barr, Inc.)
The open channels of distributive mixers do not have the ability to trap and melt small solid polymer fragments from incomplete melting in upstream processes. Moreover, combination mixers that perform both dispersive and distribute mixing often only force a fraction of the resin to flow across a restrictive flight, and, thus, some of the material can pass by without being subjected to a high shear stress. As previously indicated, devices that do not have the ability to trap and melt solid polymer particles can cause poorly mixed extrudates, especially at high screw speeds. Mixers that do not have the capacity to trap and melt solids should not be used, if solid fragments are likely to occur in the melt stream.

3.7.1 Dynamic Mixers

Dynamic mixers are a class of secondary mixers, where part of the mixing device is allowed to move relative to the barrel and screw surfaces, or to have an active channel positioned in the barrel wall. In general, these mixers provide improved mixing over traditional secondary mixers, but they are more complicated and costly to produce, require higher maintenance levels, and tend to have higher levels of wear. These devices are typically located at the tip of the screw and are often incorporated as part of a non-return valve. Like other secondary mixers, there are many of these mixers available on the market. The most common of these mixers include the Cavity Transfer Mixer (CTM), Twente Mixing Ring (TMR), and the Barr Fluxion ring mixer. The CTM mixer [47, 48] is a device that is attached to the end of an existing extruder. It has both a barrel section and a screw section. Both sections have concave pockets bored into them, allowing the flowing material to be transferred between the rotor cavities on the screw and the stationary cavities on the barrel wall. The device combines a unique blend of elongational flows and dispersive mixing, in the tight clearance regions, and flow reorientation in the cavities. The disadvantages of the device include cost and the need for a barrel extension. Additional mixing performance data for the device may be found in reference [48].

The Twente mixing ring [49, 50] and the Barr Fluxion ring mixer [3, 51, 52] are adaptations to the CTM design, allowing the addition of the mixer to the screw, without requiring a barrel extension with inset cavities. Schematics of the mixers are shown in Figs. 3.22 and 3.23. Both devices are designed with a floating sleeve ring that is allowed to rotate freely from both the screw and barrel. For example, at a screw speed of 80 rpm, the speed of the sleeve rings were measured using high-speed data acquisition from pressure transducers at about 10 to 13 rpm [52]. The ring of the TMR is perforated with cylindrical holes, as shown in Fig. 3.22. The material in the ring is temporarily suspended in the holes until it is allowed to transfer to the hemispherical cavities in the root of the screw. The floating mixing ring for the Fluxion mixer consists of a series of perpendicular holes that extend through the ring, as shown in Fig. 3.23. Each series of holes is divided by a dam that prevents material from flowing directly into the adjacent channel. Material is only allowed to transfer to the adjacent channel by entering the grooves in the root of the screw. As expected, the performance of these mixers exceeds that of the typical secondary mixer, but because of the floating sleeve, the potential for wear is high. Moreover, small amounts of foreign material that does not melt can get trapped in the holes of the sleeve, creating a restriction to flow and ultimately requiring a shutdown.
for cleaning. The sleeve can be designed to slide in the axial direction and thus perform as a non-return valve [3].

The mixing performance for a TMR and a Fluxion ring mixer was measured using a 63.5 mm diameter, 21 LD extruder and a conventional screw with a removable tip [52]. The tip was 2.4 diameters in length and could be exchanged between a conventional flighted section, a TMR mixer, or a Fluxion mixer. The conventional flight tip had a channel depth of 3.56 mm.

Figure 3.22: Schematic for a Twente mixing ring: (a) mixer with a cut away section of the ring exposing the surface of the rotor; (b) flow path for the mixer

Figure 3.23: Schematic for a Barr Fluxion mixing ring: (a) mixer with a cut away section of the ring exposing the surface of the rotor; (b) flow path for the mixer
The experiments were performed with the same ABS resin as those for the studies presented previously. For these runs, the extruder was operated at a screw speed of 80 rpm with a 220:1 ratio of white ABS to a black color concentrate ABS resin. The extrudate samples, as collected via the schematic shown in Fig. 3.5 are shown in Fig. 3.24. It shows that considerable levels of solid polymer and unmixed material were discharged, using the conventional flighted screw tip, i.e., no mixer present. Figure 3.24 shows that similar high quality mixing levels were obtained from the TMR and the Fluxion mixer. This level of mixing for the extrudate was extremely remarkable, considering that the materials entering the devices are essentially 60% unmixed (white pigmented ABS), and considering that the mixing criteria here exceed the current demands of the commercial community. Other performance characteristics were previously presented in the references [3, 49, 50, 52].

**3.8 Screw Design Issues Causing Resin Degradation**

Improperly designed screws or processes, which are operated incorrectly for a specific resin, can cause defects to appear in the discharge. Often, these defects are incorrectly diagnosed as having mixing deficiencies as the root cause. Several of the actual factors have been discussed previously. They include a metering channel that is not operating full and regions in a mixer design that have extremely long residence times, such as the entry and exit regions for Maddock-style mixers and spiral dams and regions at the downstream side of a pin at
the screw root. Under special conditions, these long residence time regions can cause the resin to degrade, additives to plate out and accumulate, or old material (different lot, type, or color) to linger. During a minor process upset, material from these stagnant regions will dislodge and discharge into the mold, creating a defect that may look like poor mixing, i.e., a non-uniform discharge.

The most common design error for screws is the use of very small flight radii in sections of the screw where the resin is molten. Small flight radii can cause regions that are either stagnant or have extremely long residence times, causing almost all resins to degrade [53]. The degraded resin will accumulate with time, as shown by Fig. 3.25. These degradation products will eventually migrate from the stagnant region to the main flow, contaminating the discharge. Depending on the color of the resin and degradation products, the contamination can be improperly diagnosed as poor mixing performance from the screw. Moreover, when changing resin color or type, the older resin can be very difficult to purge from screws with small flight radii. Sometimes, the older resin can reside at the flight radii for days, as shown in Fig. 3.26. Eventually, the older resin from the stagnant region will migrate to the main flow. If the older resin does not have sufficient time to disperse well in the main flow stream, color streaks will appear in the discharge, indicating “poor” mixing.

The specifications of the flight radii are commonly made using a combination of personal experience and guidelines from The Society of the Plastics Industry, Inc. (SPI) [54]. These guidelines state “unless otherwise specified the root radius will not be less than 1/2 of the flight depth up to 25 mm radius”. Often, during the fabrication process, however, manufacturing errors can result in flight radii that are less than that specified in the design. For metering and melting sections [53], the radii are selected in order to minimize polymer degradation at
3.9 Non-Return Valve

During the injection step, the screw is forced forward to move the material accumulated in the barrel downstream from the tip through the nozzle and into the mold. The pressure exerted on this material is extremely high, often up to 200 MPa. In order to make this process work, a non-return valve is positioned at the tip of the screw to prevent material from flowing back through the screw channels and out through the hopper. Many innovations have occurred during the last 20 years on the design of the valve, with many companies competing with different technologies [55]. In general, the valves have either a ring, poppet (torpedo), or ball that is moved out of the way during the plasticating process, allowing material to flow downstream of the screw tip. Then the valve slide moves back to block the plasticating flow path during the injection step, as shown by Fig. 3.27. The clearance between the main body of the valve and the barrel wall is relatively small, such that very little material bypasses the valve flow path. The valve is typically attached to the screw, using machine threads.

Figure 3.26: Photograph of a screw channel showing old black-colored resin at the flight edges. The screw was removed from the plasticator and examined while hot. The plasticator was running the gray-colored resin for several days after the black-colored resin. Some of the black colored resin was migrating from the stagnant region to the main flow region (gray-colored resin). The customer was complaining about poor part quality caused by poor mixing. The photograph, however, shows that the problem was caused by black-colored material in the stagnant area of the flight radii migrating to the main flow region.
A well designed valve must have a streamlined flow path such that material degradation does not occur. If degradation of the resin occurs in the device, splay due to resin degassing and black specks can contaminate the part. The valve must also be able to shut off quickly, when the screw is forced forward during injection. If the valve does not shut off quickly and consistently, then material flow back into the screw may reduce the volume of the resin for the shot to a level that is less than that needed, causing the mold to not fill completely. Since non-return valves have moving parts and have a tight clearance between the body and barrel wall, wear of these parts must be low enough, so that the valve has an acceptable lifespan. Often these parts are made from tool steels.

**Nomenclature**

- **C**: Compression ratio of the screw, dimensionless
- **D_b**: Inside diameter of the barrel [m]
- **e**: Flight width perpendicular to the flight edge [m]
- **h**: Clearance of the mixing flight (distance between the mixing flight and the barrel wall [m]
- **H**: Channel depth of the metering channel [m]
- **H_f**: Channel depth of the feed channel [m]
Nomenclature

$k$ Proportionality constant or pressure intensification factor between the hydraulic back pressure on the back of the screw and the pressure at the tip of the screw, dimensionless (typically varies between 8 and about 14)

$l_t$ Axial length of the transition section [m]

$L$ Lead length of a screw flight or axial distance traveled to make a complete rotation [m]

$L/D$ Barrel length divided by the barrel diameter, dimensionless

$L_m$ Axial length of the mixing flight for a Maddock mixer [m]

$M$ Mass of the parts and any runner systems that were produced during a single molding cycle [kg]

$n_t$ Number of in-flow flutes (or out-flow flutes) for a Maddock mixer, dimensionless.

$N$ Screw rotation rate [revolutions/s]

$p$ Number of flight starts on the screw, dimensionless.

$P_b$ Back pressure reported by the molding machine controls [Pa]

$P_{dis}$ Pressure at the tip of the non-return valve (discharge pressure) [Pa]

$Q$ Instantaneous plasticating rate [kg/s]

$R$ Compression rate, dimensionless

$t_p$ Plastinating time or the time required to produce the molten polymer during screw rotation [s]

$T_g$ Glass transition temperature of a resin [°C]

$V_{bx}$ Cross-channel motion of the barrel relative to the screw [m/s]

$V_{bz}$ Downstream motion of the barrel relative to the screw [m/s]

$W$ Width of the screw channel perpendicular to the flight edge [m]

$X$ Width of the solid bed in the melting section of the screw perpendicular to the flight [m]

$\theta_b$ Helix angle at the barrel wall [radians]

$\dot{\gamma}_M$ Shear rate for the flow across the mixing clearance of a Maddock mixer [1/s]

$\eta$ Shear viscosity [Pa-s]

$\tau_M$ Shear stress for flow over the mixing flight of a Maddock mixer [Pa]

Acronyms

ABS Acrylonitrile butadiene styrene resin

CTM Cavity transfer mixer

ET Energy transfer screw

GPPS General purpose polystyrene resin

HIPS High impact polystyrene resin
The Plasticating System for Injection Molding Machines

MFR  Melt flow rate for a resin [dg/min]
MI  Melt index for a resin [dg/min]
PS  Polystyrene resin
SPI  The Society of the Plastics Industry, Inc.
TMR  Twente mixing ring
VBET  Variable barrier energy transfer screw

References

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References