MITIGATING GELS IN POLYETHYLENE PRODUCTS PRODUCED USING GROOVED-BORE, SINGLE-SCREW EXTRUDERS

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Abstract

Grooved-bore, single-screw extruders are commonly used in Europe, and they are used to a lesser extent in North America. In North America, they are often used as the extruders for blown film, blow molding, and pipe processes where the discharge temperatures need to be relatively low and the rates high. Screw designers for grooved-bore machines are very good at providing screws that discharge at low temperatures and high rates, but they typically are not focused on providing a gel-free extrudate. This paper will discuss methods to mitigate gels for grooved-bore machines running polyethylene (PE) resins.

Introduction

The quality demands for pipe and film products continue to become more demanding, with products that have improved properties and fewer blemishes. Blemishes for pipe products are typical caused by resin degradation and solid polymer fragments that did not melt during the extrusion process. Typical solid polymer fragments appear as “windows” when the pipe wall is cross section cut into a thin “ribbon” for inspection of the unmelts. A photograph of these solid polymer fragments are shown in Figure 1. Here the thin wall pipe was produced from a high density polyethylene (HDPE) resin and a black tinted masterbatch using a grooved-bore extruder. The windows are due to solid polymer fragments of the HDPE resin. Since this natural pellet did not melt and disperse, it contained no black pigment from the masterbatch. The solid polymer fragments in this case caused small pin holes to occur in the wall of the pipe, causing a weak point in the pipe which caused the pipe to fail. Resin degradation was also know to occur for this case. Resin degradation, however, can be difficult to detect for a resin tinted black. Degradation defects can, however, be observed as surface defects.

Gels are a frequently occurring problem for most blown film lines. The term “gel” is commonly used to refer to any small defect that distorts a film product, reducing the quality of the film. There are many types of gels [1-3]. The gels that are important to this discussion are those that are generated in the channels of the extruder screw due to long residence times and typically oxygen exposure of the resin: 1) highly oxidized polymeric material that appears as brittle black specks, and 2) polymeric materials that are crosslinked via an oxidative process and appear as soft gels. Soft gels often have a brown color. Improperly designed extrusion equipment and processes are common and can lead to the oxidative degradation of PE resins and crosslinked gels [2].

Figure 1. Photographs of solid polymer fragments that occurred in thin wall HDPE pipe. The feedstock was a natural resin and a black colored masterbatch.

Screw channel sections that are stagnant are known to lead to gels in the discharge and final films for smooth-bore extruders [4]. Gels can occur in grooved-bore extruders via the same mechanism; degradation of the resin in a stagnant channel segment, and then separation of the gel from the screw, contaminating the extrudate. Photographs of gels from a grooved-bore blown film line are shown in Figure 2.

Figure 2. Photographs of gels in a LLDPE film produced using a grooved-bore extruder.

Mitigating gels for processing PE resins using smooth-bore, single-screw extruders was discussed previously [2-4]. Many of the design features are the same for a well-designed screw for a grooved-bore machine, but there are also several notable differences in operation and practice. These common features and notable differences will be presented such that gel generation can be mitigated for grooved-bore screw designs.

Grooved-Bore Extruder Operation

Grooved-bore extruders are sometimes referred to as grooved feed, grooved sleeved, or grooved bushing extruders. This type of single-screw extruder has multiple grooves placed into the feed casing of the machine that are 4 to 5 diameters in length. The grooves can be parallel with the axis of the screw or they can be cut in a spiral pattern in the reverse direction of the spiral on the screw [5]. The
grooves are typically rectangular and start at about 2 to 4 mm deep by 5 to 8 mm wide, and they taper in depth as the groove progresses towards the discharge end of the feed casing, becoming eventually smooth to the barrel surface. A schematic of a feed casing with axial grooves is shown in Figure 3. The specific rate of the extruder depends on the size and shape of the grooves, the geometry of the screw channels in the feed section, the physical properties of the resin, the shape of the resin pellets, and the casing temperature [6-8]. In general, the specific rate of a grooved-bore extruder is higher than that of a smooth-bore extruder of the same diameter, causing the discharge temperature to be lower, which is due to the reduced residence time and viscous dissipation. There are several other advantages of grooved-bore extruders including constant specific rate as a function of screw speed and discharge pressure [9,10]. Disadvantages include difficulties in melting at the high specific rates, machine wear due to high internal pressures, and the inability to process film recycle. Most grooved-bore screw designers place elaborate mixing systems near the discharge end of the screws to trap and melt solid polymer fragments. These mixers can be locations where resin degradation occurs.

Figure 3. Schematic of an axial grooved feed casing for a grooved-bore extruder [2].

Locating Stagnant Regions

The best method for locating regions in the screw that are stagnant and creating gels is to remove the screw hot from the extruder. For this procedure, pellet flow to the hopper is stopped while screw rotation is continued. The screw is rotated until resin flow out of the die stops. Next, screw rotation is stopped and the transfer line is removed from the discharge end of the extruder. The hot screw should be pushed out about three diameters and then photographed and studied for indications of resin degradation. The metal surfaces should appear clean with only mild discoloration. If a stagnant region exits, then dark colored, degraded material will occupy the space. Once the segment is studied, the hot resin should be removed from the screw using brass tools. Another three diameters are then pushed out and the process is repeated.

There are several locations on screws where stagnation and resin degradation are prone to occur. Common areas include at the entries and exits of poorly designed barrier sections, at the flight radii in channels where the resin is molten, and in poorly designed mixers or mixers that are not suitable for PE resins. Degradation is common for barrier section designs that use an advancing lead barrier flight. For this design, the barrier flight starts at the pushing side of the channel and ends downstream at the trailing side. This type of design is commonly referred to as a Maillefer design [11]. The original patent was issued in 1962 and since then many modifications have been made to mitigate this stagnation location. The design, however, is still used even though the defect is known to occur. A photograph of the entry region where stagnation can occur is shown in Figure 4a. As indicated by the photograph, the melt conveying zone at the entry is very deep and very narrow, causing flows to be very low and stagnant deep at the root. After the resin degrades, a small process upset can cause the degraded resin to separate from the screw, causing the material to discharge from the extruder and form a gel in a film product.

Another common design flaw for smooth-bore and grooved-bore extruders is making the radii at the flight too small. Small flight radii will cause recirculation flows at the flight called Moffat eddies [12]. The material in the eddies will be at the radii for long periods of time, eventually degrading the resin. The crosslinked resin will discharge from the extruder and create a gel in film products [2-4]. A common and improper practice is to design the flight radii at 0.5 times the local channel depth. Radii that are this size or smaller will create Moffat eddies and will cause resin degradation for most PE resins.

As previously stated, grooved-bore extruders typically operate at higher specific rates as compared to smooth-bore extruders. These high specific rates can exceed the melting capacity of the barrier melting section, allowing a large level of solid polymer fragments to flow downstream. If too many

Figure 4. Photographs of stagnant regions: a) the entry area of barrier melting section, and b) resin degradation at the flight radii due to Moffat eddies.
solid fragments occur, only a portion of them will be trapped and dispersed in the downstream section. Three common mixers designed into grooved-bore extruder screws are the cavity transfer mixer (CTM), the cross-flow plate mixer, and spiral dams. Photographs of a CTM and cross-flow plate mixers are provided in Figure 5. The CTM [13,14] is constructed by positioning concave cavities on the screw shaft and into the barrel wall. Different cavity shapes are practiced. Mixing occurs by forcing material into and out of the cavities. The cross-flow plate mixer is constructed by positioning circular plates on the shaft of the screw and cutting holes through the plates that flow resin from near the barrel wall to the root of the screw and also from the root to the barrel wall. The land of the plate is in close proximity to the barrel wall.

![Figure 5. Photographs of mixers commonly used with grooved-bore extruder screws, showing locations for resin degradation and stagnant regions: a) a CTM, b) cross-flow plate mixer with resin degradation, and c) side view of a cross-flow plate mixer.](image)

The CTM performs well to melt and disperse solid polymer fragments. This style of mixer, however, can increase the temperature of the extrudate to unacceptable levels and cause resin degradation deep in the cavities. Because of resin degradation, CTMs are not recommended for the extrusion of PE resins.

The cross-flow plate mixer has numerous sharp corners where the circular plates attach to the root of the screw. These corners create regions that are stagnant and allow resin to have extremely long residence times, causing the resin to degrade. Resin degradation is observable in Figure 5b. Small process upsets will cause the degraded resin to separate from the screw and contaminate the film product. Moreover, a large portion of the barrel wall in the section is not wiped by the screw, reducing the local heat transfer and allowing some material to have extended residence times. Cross-flow plate mixers are not recommended for the extrusion of PE resins.

Other mixer types are often used with grooved-bore extruder screws, including spiral dams. Spiral dams are created by positioning a spiral dam (or secondary flight) that starts at the pushing side of the channel and ends downstream at the trailing side, as shown in Figure 6. The small pockets at the entry and exit are typically stagnant and regions where resin can degrade. The design flaw here is essentially identical to that of a Maillote barrier section. Dispersive mixing occurs as the resin flows across the narrow dam clearance. Spiral dams are not recommended for PE extrusion.

![Figure 6. Schematic of a spiral dam.](image)

**Screw Design Process**

The screw design process with the focus of mitigating gels is complicated by the design of the grooves in the feed casing. Here a new screw must be designed and built such that rate targets are maintained and the gels are mitigated. In most cases, the exact design of the grooves are not known to the third party screw designer. Furthermore, measuring the grooves is very difficult without removing the hopper and the barrel from the casing. Most plant managers will not permit the machine downtime required to measure and count the grooves.

Since the specific rate depends on the size and shape of the grooves, the geometry of the screw channels in the feed section, the physical properties of the resin, and the shape of the resin pellets, the specific rate can be maintained if the feed channel geometry on the existing screw is reverse engineered onto the new screw. Gels are not generated in the feed section and thus maintaining the existing feed channel design is acceptable. The feed channel includes all channels up to and including the decompression section downstream of the feed channel.

The current grooved feed technology has found that the optimal lead length in the grooved section of the screw is 0.8 times the barrel diameter, and after the groove bushing section the lead length is increased to a square pitch,
providing a decompression of 25%. This decompression helps to reduce the internal pressure and reduces the excessive screw and barrel wear that was experienced in the past.

Downstream of the decompression section should be a barrier melting section. Here, the best design will have the lead length increased to about 1.2 times the diameter, and the barrier flight positioned parallel to the main flight. The melt conveying channel is typically one third of the full channel width and the solids conveying channel the other two thirds. The undercut on the barrier flight should be relatively small at about 0.5% of the diameter. The exit of the solids conveying channel should be a depth of about 1.5 to 2.5% of the diameter.

The metering section should be nearly identical to that of the existing screw. That is, the lead lengths and channel depths should be identical.

In order to eliminate resin degradation created by Moffat eddies, the flight radii should be increased so that they are about 1.4 times larger than the local channel depth \([2-4]\), as shown in Figure 7b. The radii should be large for all sections of the screw that contain molten resin.

A dispersive mixer should be positioned in the metering channel about two diameters upstream of the screw tip. The preferred dispersive mixer is a spiral Maddock or an Egan-type mixer. Design of the mixer will be presented in the next section. The mixer will be used to trap, melt, and disperse solid polymer fragments discharged from the barrier melting section.

The second different feature of the Maddock mixer used is of a typical design except for two features [17]. These design features include setting the mixing flight undercut to about 0.5% of the diameter. Most designs set this undercut at 1 to 1.5% of the diameter. The small undercut specified here will trap and disperse all solid polymer fragments that happen to flow out of the barrier melting section. A larger undercut of 1 to 1.5% of the diameter can allow solid polymer fragments to discharge from the extruder. Moreover, a mixer with a small undercut will disperse highly entangled or unmixed gels [3]. Unmixed gels are typically high molecular weight polymer chains that are highly entangled and thus difficult to disperse during the extrusion process. When made into films, these unmixed gels solidify first and produce a gel that looks like a solid polymer fragment.

The second different feature of the Maddock mixer recommended here is that the depth of the in-flow and out-

![Figure 8. A schematic of a Maddock-style mixer.](image_url)
flow flutes should be half the width of the flute [17]. If the flutes are made deeper, resin degradation can occur, creating gels in the film product. A schematic of the recommended flute shape and a flute design that is too deep is provided in Figure 9. Maddock mixers with extremely deep flutes and large clearances on the mixing flights are common on smooth-bore extruder designs.

![Figure 9](image_url)

**Figure 9. Cross-sections of common flute designs for Maddock-style mixers: a) recommended design, and b) a deep flute that will cause resin degradation.**

**Discussion**

Degraded resin and solid polymer fragments are two defects that are common in PE articles produced using grooved-bore extruders. Processors, however, do not have a specific rate for the process. Since the resin will be visually detected as black, although they are likely present in the pipe. Since the fragments are black like the surrounding resin, they cannot be visually detected. When the natural resin and black masterbatch are extruded, natural solid polymer fragments are easily observed in a black tinted matrix. Solid fragments from the masterbatch would not be visually detected although they are likely present too.

On numerous occasions, a processor will switch from a pre-compounded black PE resin to a natural resin plus a black masterbatch. No other changes to the process are typically made. The processor typically does not complain about solid polymer fragments with the pre-compounded resin although they are likely present in the pipe. Since the fragments are black like the surrounding resin, they cannot be visually detected. When the natural resin and black masterbatch are extruded, natural solid polymer fragments are easily observed in a black tinted matrix. Solid fragments from the masterbatch would not be visually detected although they are likely present too.

**Summary**

Resin degradation and solid polymer fragments are common in extrudates discharged from grooved-bore extruders. The degradation and solid fragments cause defects in the articles produced. The methods needed to mitigate these defects are presented.

Like smooth-bore extruders, the screw channels of a grooved-bore extruder must be streamlined in order to eliminate stagnant regions. Regions of the screw that are stagnant will cause PE resin to degrade, and the degraded resin will eventually contaminate the final product.

**References**