PERFORMANCE OF A STRATABLEND MIXING SCREW FOR SINGLE-SCREW EXTRUSION

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Abstract

Experiments were performed on a mixing screw to assess its melting, pumping, and mixing characteristics. This was done by extrusion trials, extrudate sampling, extrusion solidification experiments, and comparison to results for a screw without a mixing section. Comparisons were made as a function of screw speed and color concentrate letdown ratio.

Introduction

This work was motivated by the need to understand single-screw mixing performance as driven by the transition to in-house mixing of natural resin with color concentrates. Not only are resins being mixed in-house, but there is also a growing demand to implement higher letdown ratios of natural resin to color concentrate (i.e., to use lower proportions of more highly pigmented color concentrate pellets). This is a push to lower costs by reducing the quantity of color concentrate that is pre-compounded.

The majority of the previous studies in this area focused on the color concentrate formulation or assessed single-screw mixing by analyzing injection molded samples (1-3). Few studies have focused on understanding how flow patterns in the screw channel affect the mixing quality of the extrudate (4). None that we are aware of have tried to understand how the enhanced melting and mixing mechanisms available in a mixing screw section combine to improve the level of colorant mixing.

This work shows the interrelation of flow, melting, and extrudate quality as it applies to in-house coloration. This was done by comparing experimental results for two screws of similar pumping capability. One screw had a mixing section on its downstream end; the other screw had a more conventional design and was without a mixing section. The mixing screw contained a Stratablend (trademark of NewCastle Industries) mixing section (5); that screw will hereafter be referred to as the mixing screw. Results are shown for axial pressure, rate, extrudate temperature, colorant mixing, and extrusion solidification experiments.

Experimental Equipment and Material

Experiments were performed using a highly-instrumented 63.5 mm diameter extruder having a 21 length-to-diameter (L/D) ratio. The extruder (6) was equipped with three barrel temperature control zones and eleven pressure transducers. These transducers were strategically distributed along the axis of the barrel. The extrudate flowed from the extruder through a restrictor valve that was either fully open or partially restricted. A hand-held thermocouple was used to measure the extrudate temperature as it exited the die.

Experiments were performed on a mixing screw and on a conventional screw. The mixing screw was designed for the same specific rate as the conventional screw. Both screws were square-pitched, single-flighted, and had flight clearances of 0.07 mm.

The mixing screw had 4 constant-depth feed flights at 8.89 mm deep, 5.5 flights of transition, 4.5 flights of a constant-depth metering section at a depth of 3.18 mm, and 7 flights of the mixing section. A schematic of the mixing section is shown by Figure 1. In the mixing section, the channel base depth was 1.27 mm. Three rows of 4.04 mm deep grooves were then cut into the base. Within each row, the grooves were parallel to the helical axis of the channel, were almost half a screw turn long, and were separated from each other by 3.18 mm long lands at the channel base depth. The conventional screw (6) had a 6 turn feed section that was 8.89 mm deep, an 8 turn transition section, and a 7 turn constant-depth metering section with a depth of 3.18 mm.

Two resins were used in this study: low density polyethylene (LDPE) and acrylonitrile-butadiene-styrene (ABS). The physical properties for the LDPE resin were presented previously (7). For the experiments using LDPE, the barrel zone temperatures were set at 150, 177, and 205°C for zones 1 (feed), 2, and 3, respectively. For the experiments using ABS, the barrel zone temperatures were set to 200, 230, and 250°C. Screw speeds ranged from 20 to 80 rpm.

Results and Discussion

Pumping and melting (or devitrification) in the mixing screw were assessed for both LDPE and ABS resins by measuring the steady-state axial pressures, extrudate temperatures, and rates as a function of screw speed. In these studies the valve at the discharge was in the partially restricted position.

The axial pressure profiles for the mixing screw were similar to those for the conventional screw, as shown by Figures 2 and 3. This was expected, since the feed depths and metering sections were identical for both screws. The main difference for the LDPE resin was that the discharge pressure for the conventional screw was higher than that for the mixing screw due to a more highly restricting tape die that was used during the LDPE conventional screw experiments (6). As shown by Figure 2, the axial pressure gradients for the mixing section were negative, indicating that the screw was operating at a rate higher than that due just to rotation (i.e., drag flow). Although not attempted, higher discharge pressures would have reduced the rate to a level such that the gradient in the mixer would have been positive.

The specific rates for the mixing screw running ABS were 0.90, 0.88, 0.83, and 0.84 kg/(h rpm) at screw speeds of 20, 40, 60, and 80 rpm, respectively. This slight decrease in specific rate with screw speed is typical for flood-fed extruders. As a comparison, the specific rates for the conventional screw running ABS were 0.95, 0.95, 0.92, and 0.90 kg/(h rpm), rates that were 5 to 10% higher than those of the mixing screw. Similar results were observed for the LDPE experiments. For most applications, this rate difference could easily be corrected via processing conditions; i.e., barrel temperature profiles and screw speed. Slightly deeper channels in the mixing section, however, would have resulted in identical rates.

The discharge temperatures for the mixing screw were only slightly higher than those for the conventional screw. For ABS, the discharge temperatures for the conventional screw were 258 to 259°C at all screw speeds, while for the mixing screw the temperatures were 259, 263, 266, and 264°C for screw speeds of 20, 40, 60, and 80 rpm, respectively. The slightly higher temperatures for the mixing screw were attributed to the higher shear rates in the lands between the grooves. The rates, discharge temperatures, and pressure profiles indicate that these basic performance characteristics for the screws were similar.

A second set of experiments were performed to show the flow fields in the screw channels and to characterize the mixing performance of the mixing screw. The conventional screw was included in these experiments as a baseline for the mixing screw. The extruder was operated with a mix of pre-colored white ABS pellets (2 % TiO_2) and black ABS color concentrate pellets (30% pigment). For each screw, experiments were run using the following ratios of white to black resins: 35:1, 75:1, 100:1 and 220:1. The restrictor valve was fully opened; this reduced the discharge pressure to 7.8 MPa and minimized mixing brought on by high discharge pressures. In addition, the screws were run at the same rate of 70 kg/h, corresponding to 74 and 80 rpm in the conventional and mixing screw, respectively. Thus, the discharge pressure and rate were held constant, as they would be for a molder assessing a screw design.

Figure 4 shows cross-sectional slices of the extrudate strand samples for each screw and letdown ratio. In this figure, the white spiral patterns indicate regions where little to no mixing occurred between the white and black resins. These spiral patterns were caused by the flow of the resin over the tip of the screw. Depending on the process and application, these regions could cause streaking in sheet production for extrusion operations or poor part coloration for injection molding. The unmixed white regions were most evident in the samples produced using the conventional screw. The spiral patterns were also present in the mixing screw extrudate samples. These patterns for the mixing screw, however, were considerably finer and less pronounced, indicating that a much higher level of mixing occurred. Spiral patterns were observed at all letdown ratios. A similar set of experiments were performed using the color concentrate and natural ABS. For these experiments, spiral patterns could not be observed at any color concentrate level for the mixing screw.

Compression moldings of the extrudate samples confirmed improved mixing by the mixing screw. Compression molds at letdown ratios of 35:1 and 75:1 from the mixing screw were fairly homogeneous, with only a few fine streaks of white and black. The compression moldings from the conventional screw were heavily streaked at all letdown ratios.

The 220:1 letdown experiments were followed by solidification experiments, where screw rotation was stopped while the barrel and resin in the channels were simultaneously cooled. The combined effect caused the resin to solidify with its melting, mixing, and flow patterns frozen in place. After cooling, the screw was pulled from the barrel and the helical channel of resin was unwound from the screw. The helical channel was cut lengthwise along a plane running parallel to the screw axis, revealing cross-channel slices. Figure 5 shows these cross sections at 12, 16, and 19 diameters (or turns) from the feed throat. Like the extrudate samples, the white regions indicate where the white and black pellets did not mix because the resin had not melted yet or the melted material was not adequately mixed. Because the black color concentrate is such an effective colorant, dark grey areas indicate where the white and black pellets melted, came in contact, and were well mixed.

The cross-sectional slices at 12 diameters in Figure 5 correspond to the transition and meter sections of the conventional and mixing screw, respectively. Recall from Figures 2 and 3 that the pressure characteristics in these sections were similar; they increased in the downstream direction. As shown by Figure 5, a white compacted bed of unmelted and unmixed resin was near the trailing flight, and at the pushing flight a grey-colored melt pool with striated circular flow patterns of white material was evident. This circular flow pattern was expected and is consistent with how extruders are known to operate (8). At this axial position, melting had progressed slightly more in the mixing screw because of its shallower channel depth. Overall, however, the characteristics of both screws up to 12 diameters were very similar.

At 16 diameters, the conventional and mixing screws were two turns into their final metering and mixing sections, respectively. At this location, the pressure had reached a maximum and melting was near completion. For both screws, solid-bed breakup was observed in the solidified samples upstream of diameter 16. Some bed fragments flowed downstream and were evident at 16 diameters (Figure 5). For the conventional screw, the fragments occupied nearly 50% of the cross-sectional area; and a spiral pattern was evident in the melt pool. For the mixing section, the patterns were considerably different, as shown by Figure 5. Solids fragments were trapped in the deep grooves of the mixer and their spiral patterns followed the contour of the grooves. At this cross-sectional slice, only one of the three helical channel grooves was fully present (the middle groove). Of the two remaining grooves, the groove near the pushing flight was closing off and the groove near the trailing flight was opening up in the downstream direction. This periodic closing and opening of grooves caused the partially melted white fragments to divide and intertwine their flow with the mixed, grey melt. The resulting disruption to the predictable flow paths (so evident only a few turns upstream) was so dramatic that a segregated melt pool was no longer observed.

Furthermore, the fractional area of unmixed white resin in the cross section of the mixing screw at 16 diameters was smaller than that for the conventional screw at the same downstream distance. More mixing and melting had occurred in the mixing screw. This was because the resin in the mixing section flowed into the relatively deep mixing grooves and then was periodically forced out into the shallow lands interconnecting the grooves. Because the high shearing in the lands was brief and counter-balanced by low shearing in the grooves, high temperatures were avoided. This was demonstrated by the similar extrudate temperatures of the mixing and conventional screws; as previously stated, the extrudate temperatures were nearly the same at low screw speeds and about 7°C higher for the mixing screw at high screw speeds.

These trends continued at 19 diameters, as shown by Figure 5; some solid bed fragments had flowed into the discharge section of the screws. By the time the material exited the extruder, these fragments melted but it was too late for complete mixing. These unmixed regions were very evident for the conventional screw and they were nearly eliminated for the mixing screw, as shown by Figure 4.

The solidification experiments were performed at a screw speed of about 80 rpm in order to intentionally transport solids near the tip of the screws. In general, solids conveying rates increase directly with increasing screw speed, but melting rates increase to a lesser degree. For example, if the screw speed is increased by 50%, the conveying rate also increases by 50%. However, the melting rate per unit area (melting flux) may only increase by 20% (7,9), causing solids to be transported closer to the tip of the screw before melting. If the screw speed is increased further, a point is reached where the extruder discharges some unmelted or poorly mixed material, decreasing the quality of the extrudate. Although not evaluated here, the level of mixing of these screws or any other screw can be increased by decreasing the screw speed and rate of the extruder.

Conclusions

This report describes an experimental study of a mixing screw. Rates, axial pressures, and extrudate temperature measurements were used to assess the screw pumping and melting performance as compared to a conventional screw of similar design but without a mixing section. Mixing performance was assessed from extrudate samples at various letdown ratios of white to black pellets and from extrusion solidification experiments.

Axial pressures, rates, and discharge temperatures demonstrated that these basic characteristics for a conventional screw can be matched using the mixing screw design. The slight differences in these characteristics that were observed between the conventional screw and mixing screw were considered small and within typical design variations.

Extrudate samples at various colorant letdown ratios and extrusion solidification experiments, showed the screw with the mixing section improved mixing by disrupting flow and by causing additional solid melting in the shallow lands that interconnected its channel grooves. The combined effect of these mechanisms caused the resin to stretch, intertwine, periodically divide, melt, and to ultimately be better mixed.

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Key Words: Extrusion, Screw Design, Mixing, Stratablend, Letdown Ratio.

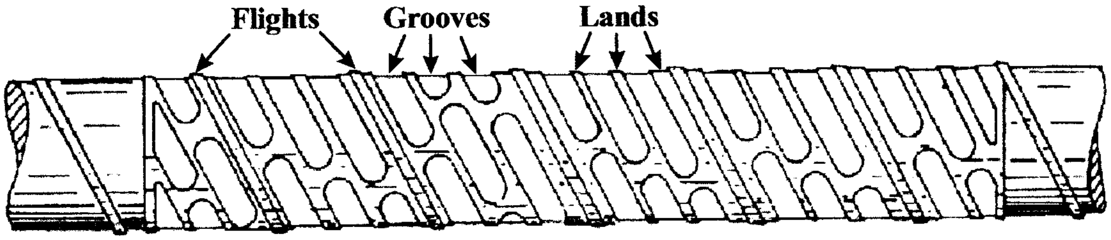


Figure 1. Schematic of the mixing section (5).

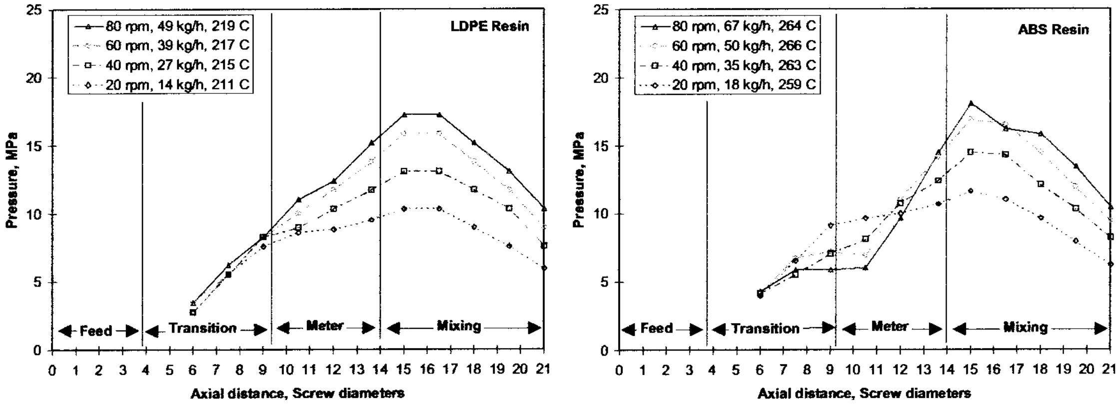


Figure 2. Pressure versus axial distance for LDPE and ABS for the mixing screw.

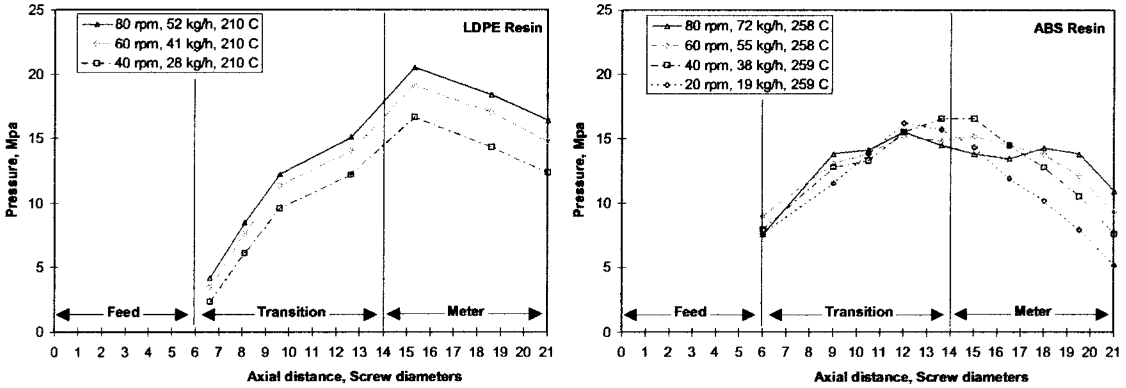


Figure 3. Pressure versus axial distance for LDPE and ABS for the conventional screw.

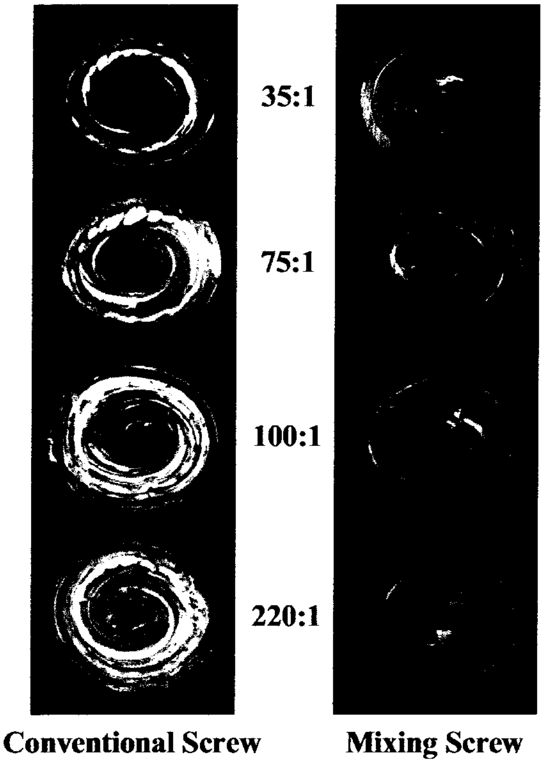
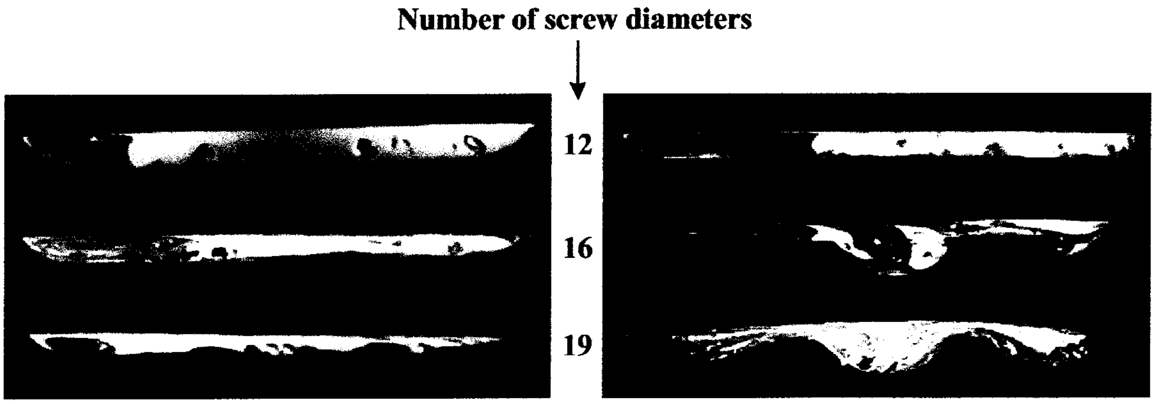


Figure 4. Cross-sectional slices of the extrudate samples at letdown ratios of 35:1, 75:1, 100:1, and 220:1.



Conventional Screw **Mixing Screw**

Figure 5. Cross-sectional slices at axial distances of 12, 16, and 19 screw diameters and a letdown ratio of 220:1. The barrel surface is perpendicular to the plane of the page and along the top of each slice. The screw root is along the bottom of each slice, and the pushing and trailing flights are along the left and right edges, respectively.