

# PERFORMANCE OF A DISTRIBUTIVE MELT-MIXING SCREW WITH AN ADVANCED MIXING TIP

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## Abstract

The DM2 high-performance screw combined with an Eagle mixer on the tip can be used in injection molding processes to decrease cycle times, reduce scrap rates, and provide high levels of mixing for coloring natural resins using color concentrates. The screw combination works by increasing the melting capacity and eliminating solid polymer particles from the discharge. The performance of this screw combination is presented along with the performance of a conventional screw.

## Introduction

Minimizing the cost to injection mold parts depends on many things including resin selection, cycle time, and scrap rate to name only a few. Resin selection is based predominantly on the end-use requirements and cost, but the resin must also provide adequate processability. In general and for a specific resin, the lowest cost to manufacture will occur at the highest production rate; i.e., the maximum parts molded per hour or the lowest cycle time per part. To minimize cycle time, the cooling step must be minimal and the rate-limiting step for the molding process. Thus, the plasticated (molten) resin for the next shot must be waiting and ready to inject the moment the tool is ready. That is, the plastication step should not be the rate limiting step of the process.

For processes that are rate limited by the plastication step, operation of the screw at higher speeds or with screws with deeper metering channels is highly desirable to decrease the cycle time. Increasing screw speeds and channel depths, however, can result in poor mixing and solid resin particles in the discharge for most screws due to melting limitations of the plastication process (1,2). In all cases, the discharge from the plasticator is expected to be homogenous in composition, color, and temperature. If the discharge is not homogenous, then defects can occur in the part and the cost to manufacture will increase.

High plastication rates require a combination of higher screw speeds and screws with deeper metering channels. Operation of a conventional, single-flighted

screw at relatively high speeds can cause some solid particles to discharge with the extrudate and thus create a poorly mixed extrudate. Increasing the depth of the metering section will increase the specific rate (rate divided by screw speed) of the process, but the melting capacity for the screw is unchanged. Again solid resin particles are highly likely to be discharged with the shot. 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 several high-performance screws currently on the market (3-7). The high-performance screw studied here is a distributive melt-mixing type developed by GLYCON and is called the DM2 screw. This screw will be referred to as the mixing screw in the remainder of the paper.

Combining a high-performance screw with a well designed mixing tip can improve the discharge quality, especially at high screw speeds and for coloring natural resins at the press using a color concentrate. The mixing tip studied here was developed by Westland and is called the Eagle (Trademark of Westland Corporation, 8) mixer. This device will be referred to as the mixing tip in the remainder of the paper.

The goal of this work is to describe the performance advantages of the mixing screw with and without the mixing tip as a function of screw speed. The melting and mixing abilities of the screw and tip will be compared to the performance of a conventional, single-flighted screw.

## Materials

The resin used was an acrylonitrile butadiene styrene (ABS) resin manufactured by The Dow Chemical Company, and it was designed for injection molding applications. The melt flow rate (MFR) of the resin was 10 dg/min. (220°C, 10 kg). Some of the resin was compounded with 2% TiO<sub>2</sub> and some with 30% carbon black pigment and then repelletized. The black pellets were designed for a letdown ratio of 35:1. The TiO<sub>2</sub> pigment was used here to accentuate the regions that were highly mixed from those that were poorly mixed. All resins were dried at 60°C for 12 h prior to use.

## Equipment

The injection molding screw performances were simulated using a continuously operating single-screw extruder. The extruder used had a 21 length-to-diameter (L/D) ratio, a 63.5 mm diameter barrel with three temperature control zones, and eleven pressure transducers distributed along its axial length (9). The extrudate flowed from the extruder through a restrictor valve that was either fully open or partially closed. A hand-held thermocouple was used to measure the discharge (extrudate) temperature.

Two screws were used for this evaluation: a conventional single-flighted screw and a mixing screw with a removable tip. The conventional screw was square-pitched with flight clearances of 0.07 mm. It had a 6-diameter long feed section that was 8.89 mm deep, an 8-diameter transition section, and a 7-diameter long constant-depth metering section that was 3.18 mm deep. The specific drag rate, the rate due just to rotation with no imposed pressure gradient, was calculated at 0.88 kg/(h rpm).

The mixing screw was fabricated with an 18.5-diameter long main section and a 2.5-diameter long removable tip. The main section of the screw had a lead length of 70 mm and a primary flight clearance of 0.07 mm. It had a 5-diameter long feed section that was 10.9 mm deep, a 5-diameter transition section, and an 8.5-diameter long mixing section. The feed and transition sections were single-flighted, and the mixing section, shown in Figure 1, was designed with two channels. Both channel depths were 3.0 mm at the entrance and 3.3 mm at the exit of the mixing section, and within the mixing section they oscillated between 1.27 mm and 6.86 mm. The period of these oscillations was out of phase for the two channels. The flights between the channels were undercut to 1.27 mm at strategic locations so that flow

could occur between the channels. The specific drag flow rate was calculated at 1.0 kg/(h rpm).

Two different removable tips were built for the mixing screw for this study. The first tip studied was a single-flighted section that had the same lead length as the main mixing section and a depth of 3.3 mm. The other tip was the mixing tip (8), as shown by Figure 2. This mixing tip was constructed with two spiral in-flow channels and two spiral out-flow channels. Some material flows from the in-flow channel across a mixing flight and then into the out-flow channel. The lead length and the undercut clearance for the mixing flights were 170 mm and 1.27 mm, respectively. These mixing flights provided a level of dispersive mixing. Several bypass channels were designed into the mixing flight to allow some material to pass directly from the in-flow flute to the out flow-flute, as shown by Figure 2. These channels were 11 mm wide in the helical direction, and they provided a level of distributive mixing.

The barrel zone temperatures for all experiments were set at 200, 230, and 250°C for zones 1 (feed), 2, and 3, respectively. The valve and transition pieces downstream from the screw were set at 250°C. Screw speeds ranged from 30 to 180 rpm.

## Results

In order to understand the mixing and melting performance of the mixing screw and tip, it is first necessary to understand the performance of the conventional screw. The conventional screw was operated at a 100 to 1 letdown ratio of the white pigmented ABS to the black color ABS concentrate. Although not shown here, the axial pressure profiles for the screw were normal and indicated that the screw was functioning properly. The extruder was operated at screw speeds ranging from 30 to 150 rpm and extrudate samples were collected and then visually examined for mixing. The location for these visual cross-sections is shown by Figure 3. A perfectly mixed system would have a cross-sectional view that is a uniform dark gray color, while a poorly mixed system will have cross-sectional views with dark gray regions and white regions. As shown by Figure 4, the extrudate at screw speeds of 30 and 60 rpm contained essentially no solid particles (white round regions) and had only relatively small amounts of poorly mixed material. As the screw speed was increased further, however, some solid particles or pellet fragments were obvious. 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 the machine at speeds higher than the operational limits of the screw can cause solids to appear in the discharge. Since there are considerably more white pellets than black pellets in the feedstock, the solid particles will most likely cause a white streak to appear in the molded part. Although not popular with a molding plant, the best option for improving the mixing for this case is to reduce the screw speed and possibly increase the cycle time of the process.

Next, the mixing screw with the metering tip and with the mixing tip was studied as a function of screw speed. For these tests, the valve was in the partially closed position to simulate a pressure at the tip that is typical for a molding process. The axial pressure profiles for the metering tip and the mixing tip are shown by Figures 5 and 6, respectively. As indicated by these figures, all sections of the screw were full and under pressure. That is, the screw was functioning properly and without void regions (zero pressure regions) where polymer degradation could occur (10). If degradation were to occur, some of the degradation products would eventually exit the screw channels with the discharge, causing defects in the molded parts. As expected, the pressures in the channels and at the discharge increased with increasing screw speed.

The rates for the mixing screw with the metering tip and with the mixing tip were nearly identical to those of the conventional screw, as shown by Figure 7. At screw speeds less than 90 rpm, the rates for the mixing screw with the metering tip and with the mixing tip were identical. But at higher screw speeds, the rates for the mixing screw with the mixing tip were slightly higher than those for the metering tip. These higher rates for the mixing tip were caused by the higher pressure generation ability of the mixing tip as compared to the metering tip; i.e., the larger lead length and channel depths of the mixing tip.

The discharge temperatures were measured at all screw speeds and are shown by Figure 8. For all screw combinations and as expected, the discharge temperature increased with increasing screw speed. The temperatures for the mixing screw combinations were higher than those for the conventional screw. This result, however, is a consequence of the identical rate design criteria for the mixing screw. Lower or even higher discharge temperatures could be obtained by altering the geometry of the mixing section on the mixing screw while maintaining a uniform discharge.

Extrudate samples were collected for the mixing screw with either the metering tip or the mixing tip, and the cross-sectional views are shown by Figure 9. As

shown by this figure, the views for the mixing screw with the metering tip indicated that the extrudates were fairly well mixed at screw speeds up to about 120 rpm. At 150 rpm, all resin was molten but small and possibly some unacceptable white unmixed swirl regions existed. At a screw speed of 180 rpm, a small and unacceptable level of solid polymer particles was discharged, as indicated by the round white colored material. A comparison of these cross-sectional views with those for the conventional screw (Figure 4) show the enhanced mixing and melting abilities of the mixing screw with the metering tip.

Cross-sectional views for the mixing screw with the mixing tip are shown by Figure 9. As shown by this figure, the discharges were all completely molten; i.e., no solid resin particles in the discharge. Moreover, the discharges are more uniform in color as compared to the mixing screw with the metering tip at all screw speeds. Thus, the melting and mixing performance of the mixing screw with the mixing tip exceeds that of the other two screws, allowing for the production of higher quality molded parts at higher rates.

## Discussion

From the cross-sectional views of Figures 4 and 9, the melting and mixing performance of the mixing screw and the added benefits of the mixing tip are obvious, especially at high screw speeds. Moreover, the mixing requirement presented here is extremely difficult and non-commercial. In practice, the letdown ratios are considerably lower and about 35 to 50:1 instead of the 100:1 ratio used, and the base resin that is colored is most often a translucent material without TiO<sub>2</sub> pigment. The TiO<sub>2</sub> pigment was used here to accentuate the regions that were highly mixed from those that were poorly mixed.

For processes that are rate limited by the plasticating step, replacing the screw with a mixing screw-mixing tip combination can reduce the cycle time of the process. For example if a molding operation required a 0.5 kg shot size to fill the tool and runner system, the plasticating times for the screw combinations studied here could be calculated using the highest screw speed and rate that will produce an acceptable quality discharge. For the screws combinations here, the highest screw speeds that deliver an acceptable discharge are 50 rpm for the conventional screw, 120 rpm for the mixing screw with the metering tip, and 180 rpm for the mixing screw with the mixing tip. At these maximum screw speeds, the instantaneous rates and the plasticating times for a 0.5 kg shot size are shown by Table 1. As shown by this table, the plasticating time required for the conventional screw is about 38 s. This time period would likely be longer than the cooling step of the process; i.e., this process is rate limited by the

plasticating step. For the mixing screw with the metering tip, the plasticating time decreases to 17 s, and for the mixing screw with the mixing tip the cycle time decreases to 11 s. For an 11 s plasticating time, the process may be rate limited by the cooling step using the mixing screw with the mixing tip, and thus operating at the maximum rate and at the lowest manufacturing cost.

The discharge temperatures for the mixing screw combinations were considerably higher than those for the conventional screw. The temperature, however, can be adjusted by changing the geometry of the mixing section. For example, if the desired discharge temperatures are less than those shown by Figure 8, the flight undercut clearances and the channel depths can be increased slightly with only a minor and likely insignificant reduction in mixing performance.

The mixing tip clearly provided an additional level of mixing as shown by Figure 9. This additional mixing is highly desirable at high screw speeds or color mixing operations for difficult-to-color concentrate mixing systems. The improved mixing is obtained without a reduction in rate or an increase in discharge temperature. Moreover, due to long lead length of the flights and the deep channels on the mixing tip an increase in rate is obtained.

## Conclusions

The enhanced melting and mixing ability of the mixing screw with the mixing tip has the ability to improve the appearance of molded parts, reduce cycle times, and reduce scrap rates by the elimination of solid polymer particles in the discharge. Moreover, the mixing screw and mixing tip combination can provide enhanced coloration of natural resins using color concentrates at high rates.

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**Key Words:** Mixing, Melting, DM2, Eagle Mixer, Screw Design, and Injection Molding.

Table 1. Maximum operating screw speeds and rates that provide an acceptable quality discharge.

Screw	Maximum Operating Screw Speed, rpm	Continuous Rate, kg/h	Time to Plasticate 0.5 kg, s
Conventional	50	47	38
Mixing Screw with Metering Tip	120	105	17
Mixing Screw with Mixing Tip	180	163	11

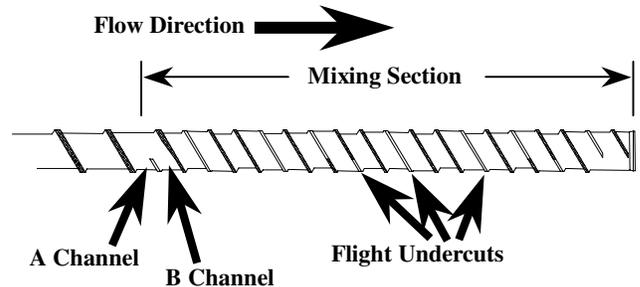


Figure 1. Schematic of the mixing section on the mixing screw. This mixing section replaces the metering section on a conventional screw.

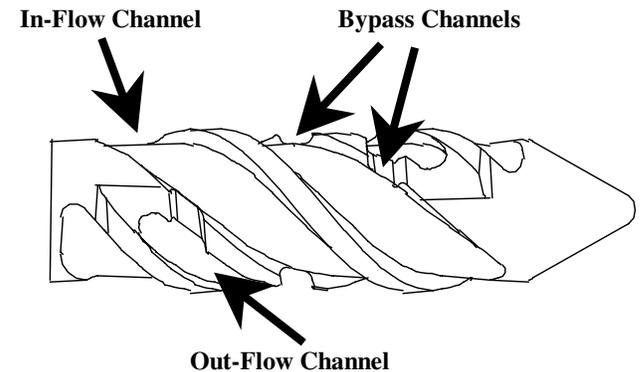


Figure 2. Schematic of the mixing tip (8).

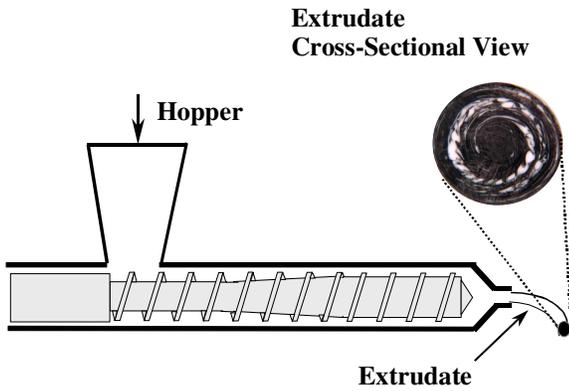


Figure 3. Extruder schematic showing location of the extrudate cross-sectional views.

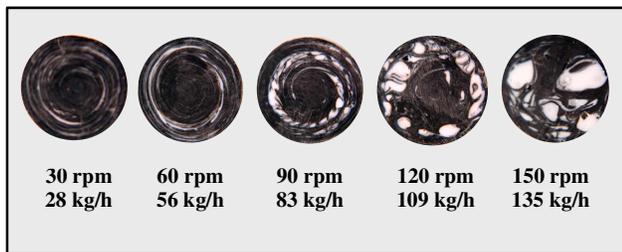


Figure 4. Cross-sectional views of extrudate samples for the conventional screw at screw speeds ranging from 30 to 150 rpm. The large round white regions for the cross sections at screw speeds of 90 rpm and higher are solid particles discharged with the extrudate.

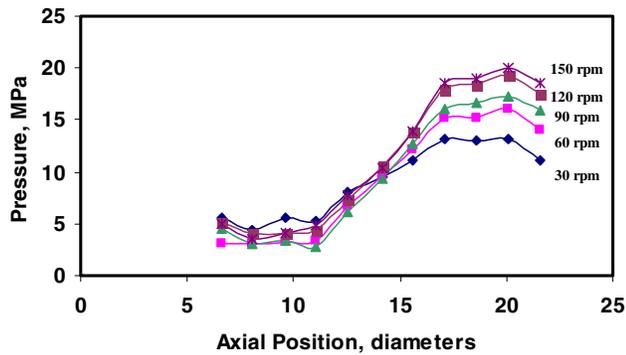


Figure 5. Axial pressure profiles for the mixing screw with the metering tip.

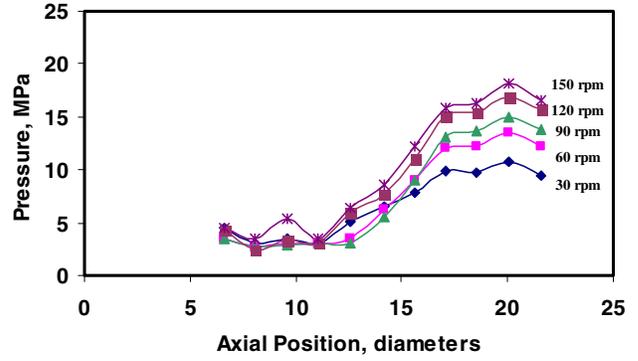


Figure 6. Axial pressure profiles for the mixing screw with the mixing tip.

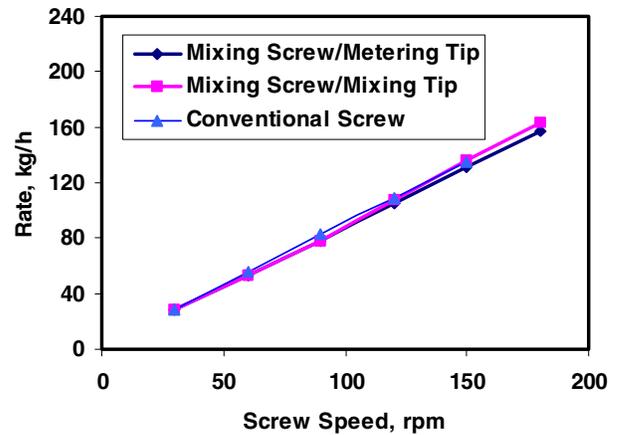


Figure 7. Rates for the conventional screw and the mixing screw with the metering tip and with the mixing tip.

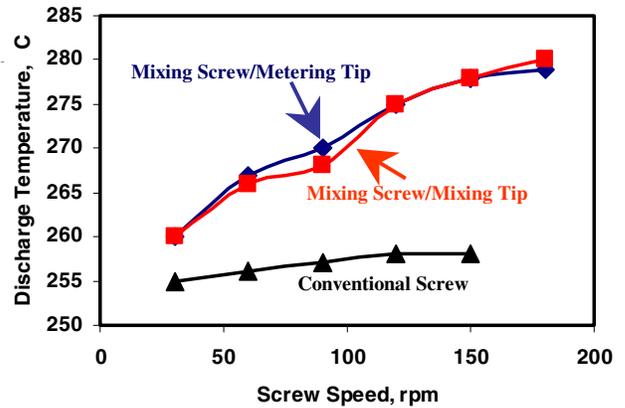


Figure 8. Discharge temperatures for the conventional screw, and the mixing screw with the metering tip and with the mixing tip.

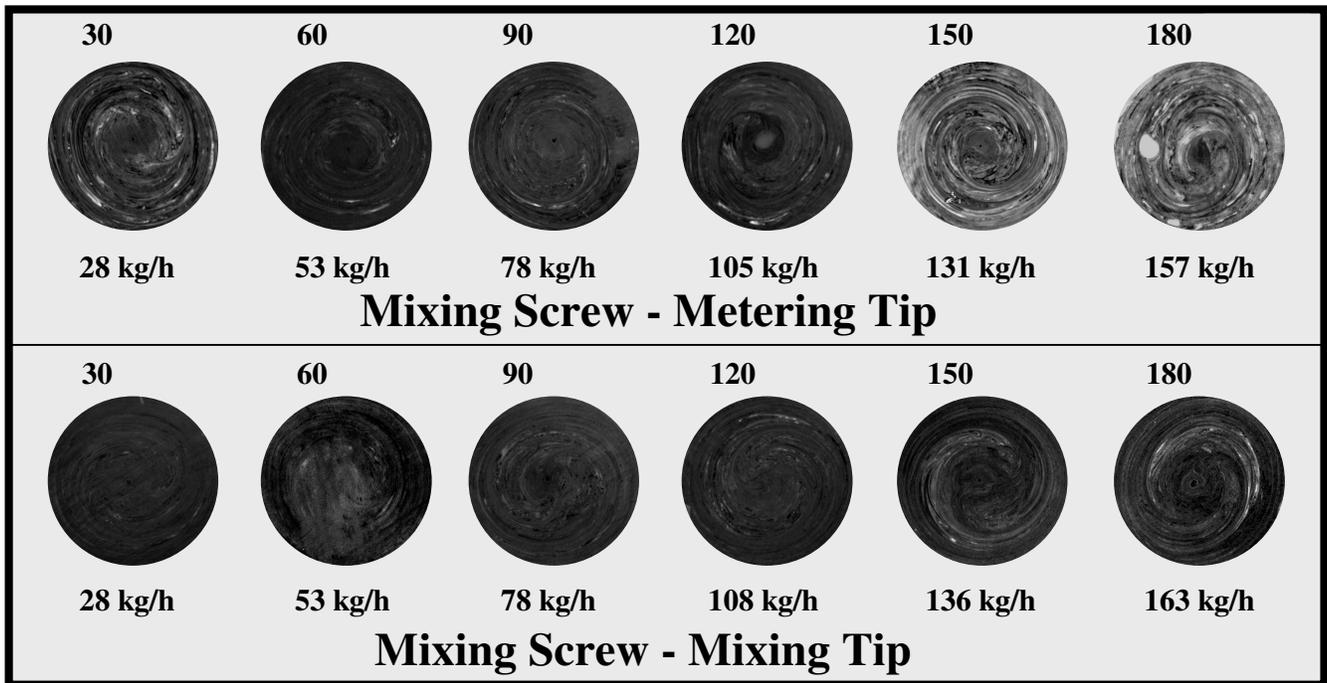


Figure 9. Cross-sectional views of the extrudate samples for the mixing screw with the metering tip and with the mixing tip at screw speeds ranging from 30 to 180 rpm.