# MELTING PERFORMANCE ANALYSIS OF A SINGLE-SCREW EXTRUDER WITH A NSB SCREW


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## Abstract

A recent design of a new screw referred to as the No Solid Bed (NSB) screw was introduced and the initial operation was presented [1]. This new screw has channels in the transition section that do not allow a compacted solid bed to form. The data presented here compliments the data that was previously published.


## Introduction

Increasing the rate of an extrusion line typically creates a lot of value to the converter [2] by decreasing the cost to manufacture and it delays the need for new lines as a market increases. For extrusion processes such as blown film, blow molding, and pipe extrusion, the converter will increase the screw speed until the discharge temperature increases to a level where the product is not properly formed or the process is unstable. The processer will then operate at a screw speed slightly lower than this point, maximizing the production capacity of the line. For most well-tuned processes, the discharge temperature will increase as the screw speed is increased [3]. Screws designs that discharge at a lower temperature can create opportunities for higher rates, especially for these applications.

The melting process was first described by Maddock [4] using solidification experiments. The experiment will be described later in this paper. Maddock used cross-sectional solidified slabs from the screw to view the melting process, as shown by Figure 1. The white regions of the cross section are the compacted solid bed while the black portion was molten at the moment of solidification. The largest amount of melting occurs at the interface between the melt film and the top side of the solid bed [5]. Material that is melted flows to the melt pool via the motion of the screw and is tinted black for this experiment. The material is black because of the mixing action of the melting process and the addition of a small amount of black masterbatch.

High pressures and high temperatures are required to achieve high melting rates [5,6] and compaction [7] of the pellets into a solid bed. The design of the NSB melting section is such that the solid bed is broken into smaller fragments due to the oscillating cross-channel depths [8], as shown in Figure 2. The goal of the design is to prevent the solid bed in Figure 1 from forming and use heat conduction to melt a portion of the solids. That is, use the solid fragments as a heat sink to decrease the discharge temperature. If the discharge temperature can be decreased, then higher rates may be obtained in a commercial process.

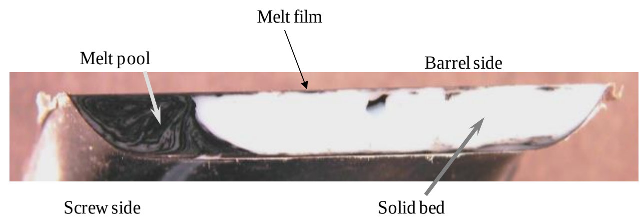


Figure 1. Photograph of resin solidified in the transition section after a Maddock solidification experiment for an acrylonitrile-butadiene-styrene terpolymer (ABS) resin [5]. The white material was solid when the screw was stopped, and the black material was molten.

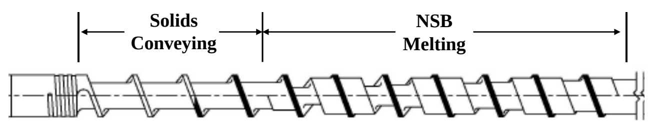


Figure 2. Schematic of the NSB section of the lab screw.

The original research [1] verified that the solid bed was broken up based on a Maddock solidification experiment. The experiment, however, was not available at the time the research was published. Pressure and discharge temperatures were acceptable for this screw trial, but the power train limitations on the extruder did not allow the screw speed to be increased higher than 45 rpm.

The goal of this paper is to expand the fundamental knowledge for the NSB screw by providing additional performance data and verify the condition of the solids in the melting section.

## Resin

The feedstock used for the experiments was a low density polyethylene (LDPE) resin with a melt index (MI) of 8.0 dg/min (190ºC, 2.16 kg) and a solid density of 0.918 g/cm$^3$. The resin is commercially available.

## Extrusion Equipment and Procedures

Extrusion trials were performed using a highly instrumented 63.5 mm diameter single-screw extruder with a 21 length-to-diameter ratio (L/D). The extruder had pressure transducers along the axis of the barrel. It was also equipped with three barrel temperature control zones. The extrudate flowed through a short transfer line, to a pressure control valve, and then a single hole die that was used to produce logs. The NSB screw built for this study [8] was designed with three sections: 1) a feed section that was 6 diameters in length with a constant depth of 10.9 mm, 2) an oscillating cross-channel depth NSB melting section that was 7 diameters long, and 3) a metering channel that was 8 diameters long with a depth of 3.18 mm. The compression ratio was 3.4 since the NSB section became shallower in the downstream direction. The lead length was 76.2 mm for the entire length of the screw. The specific rate due just to the rotation of the screw without an imposed pressure gradient was calculated at 0.8 kg/(h rpm) for the LDPE resin [9]. A photograph of the screw is shown in Figure 8. The cross-channel oscillations in depth are clearly visible in the Maddock experiment in Figure 8.

The performance of the NSB screw was compared to a single-flighted conventional screw. This conventional screw was designed with three sections: 1) a feed section that was 6 diameters in length with a constant depth of 10.2 mm, 2) a traditional melting section that was 8 diameters long, and 3) a metering channel that was 7 diameters long with a depth of 3.18 mm. The lead length was 63.5 mm for the entire length of the screw. The specific rate due just to the rotation of the screw was calculated at 0.7 kg/(h rpm) for the LDPE resin [9].

Barrel temperature for Zones 1 (feed), 2, and 3 (meter) was maintained at 160, 200, and 210ºC, respectively. All downstream sections were maintained at 210ºC. Axial barrel pressures and discharge temperatures were measured as a function of screw speed ranging from 30 to 110 rpm at 20 rpm increments. The discharge temperature was measured using a hand-held thermocouple probe such that the measurement was not influenced by the temperature of the surrounding metal for a probe positioned in the transfer line [10].

## Process Results

Discharge temperature and pressure data at the die were collected during the extrusion experiment with the NSB screw as a function of screw speed ranging from 30 to 110 rpm. The data are summarized in Table 1. The specific rate was 0.87 kg/( h rpm) at 30 rpm and decreased slightly as the screw speed was increased. At all screw speeds, the specific rate was higher than the calculated specific rate due just to rotation, indicating that a negative axial pressure gradient occurs in the metering channel.

As shown in Table 1, the discharge pressure increased with increasing screw speed and rate, which is expected for a single-screw extrusion process. The discharge temperature, however, decreased with increasing screw speed and rate. For most single-screw processes the discharge temperature increases with increasing screw speed. This can be explained by a higher amount of solid polymer fragments flowing into the downstream sections of the screw at higher screw speeds. These solid fragments act as heat sinks, and effectively absorb heat from the melt, and reduces the discharge temperature as screw speed increases. This is exactly the design concept for the NSB screw, and this set of results further confirmed the validity of this concept.

Table 1. Melt discharge temperature and pressure as a function of the screw speed for the NSB screw.

| Screw Speed, rpm | Rate, kg/h | Specific Rate, kg/(h rpm) | Discharge Temperature, ºC | Discharge Pressure, MPa |
|---|---|---|---|---|
| 30 | 26.2 | 0.87 | 208 | 2.8 |
| 50 | 42.8 | 0.86 | 204 | 3.5 |
| 70 | 58.0 | 0.83 | 202 | 4.2 |
| 90 | 74.3 | 0.83 | 201 | 4.8 |
| 110 | 90.6 | 0.82 | 194 | 5.5 |

The rate for the conventional screw was about 8% less than the rate for the NSB screw, as shown by Tables 1 and 2. This lower rate was expected due to the lower specific rotational rate of the conventional screw. The lower rate and lower specific rate for the conventional screw were due mostly to the decreased lead length. The specific rate was higher than the calculated rotational rate, indicating that a negative axial pressure gradient exists in the metering channel. The discharge temperature was slightly higher for the conventional screw, as shown by comparing the data in Table 1 and Table 2. Moreover, the discharge temperature decreased with increasing screw speed.

Table 2. Melt discharge temperature and pressure as a function of the screw speed for the conventional screw.

| Screw Speed, rpm | Rate, kg/h | Specific Rate, kg/(h rpm) | Discharge Temperature, ºC | Discharge Pressure, MPa |
|---|---|---|---|---|
| 30 | 24.5 | 0.82 | 207 | 2.5 |
| 50 | 39.1 | 0.78 | 207 | 3.2 |
| 70 | 53.9 | 0.77 | 205 | 3.8 |
| 90 | 69.2 | 0.77 | 203 | 4.2 |
| 110 | 83.5 | 0.76 | 195 | 5.2 |

To evaluate the melting capability of the NSB screw, extruded log samples from the single-hole die were collected at screw speeds ranging from 30 to 110 rpm. A small amount of black colored masterbatch resin was added to the natural resin at a letdown ratio of about 200 parts natural resin to 1 part masterbatch. The extrudate logs were cooled and a 1mm thick cross section was cut off the ends.

The thin cross sections were then photographed using backlighting, as shown in Figure 3. The black regions indicate that the resin was fully molten and well mixed with the masterbatch. The white regions show unmixed natural resin that likely occurred due to solid polymer fragments exiting the screw. These fragments soften and appear as white swirls in the cross sections. Essentially no mixing occurs once the extrudate exits the screw channel; i.e., essentially no mixing occurs in the transfer line and die.

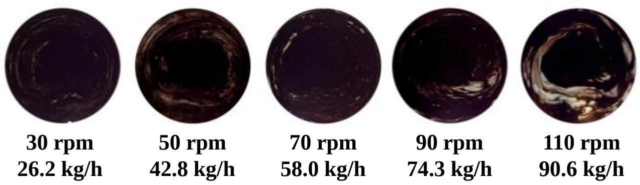


Figure 3. Cross-sectional views of the extruded log samples at screw speeds from 30 to 110 rpm.

As shown in Figure 3, from 30 to 70 rpm screw speed the cross sections are a very uniform black, indicating that very little solid polymer fragments discharged from the screw. As the screw speed was increased to 90 rpm, a substantial amount of unmixed natural resin emerges. At 110 rpm, a much higher portion of the cross section appears to be white from solid polymer fragments. During the experiment at 110 rpm, the extruded logs appear to have a lumpy and uneven surface appearance, implying large unmelt fragments in the discharge stream. While at a screw speed of 110 rpm, the black masterbatch was removed from the feedstock. The solid polymer fragments were clearly visible in the translucent extrudate, as shown in Figure 4. Clearly at 110 rpm, the rate of the process exceeded the melting capacity of the NSB section. The extrudate was discharged to the lab floor. Within a few seconds, the solid fragments were not visible since heat from the surrounding resin conducted into the fragment and the fragment melted.

## Pressure Response

The axial pressure profile as a function of screw speed was determined by averaging the high-speed pressure data measured from the transducers for the NSB screw, as shown in Figure 5. The pressure profile is very typical where the pressure increases in the melting section and then the metering channel controls the specific rate. For Figure 5, the pressure gradient is negative in the first portions of the metering channel, indicating that the process is running at a rate slightly higher than the rate due just to rotation. This is consistent with the specific rate as it is higher than the calculated rotational rate, as discussed previously. The maximum pressure at a screw speed of 110 rpm was relatively low at 7.4 MPa. This pressure is significantly lower than what would be expected from a conventional screw with a compression ratio of 3.4.

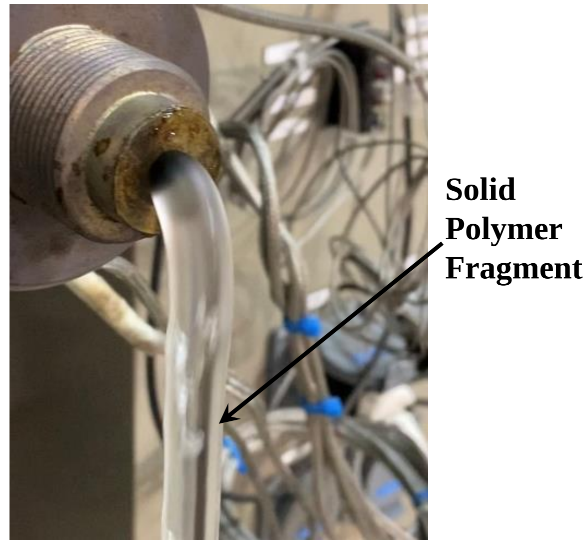


Figure 4. Discharge stream of LDPE at the die at 110 rpm screw speed for the NSB screw.

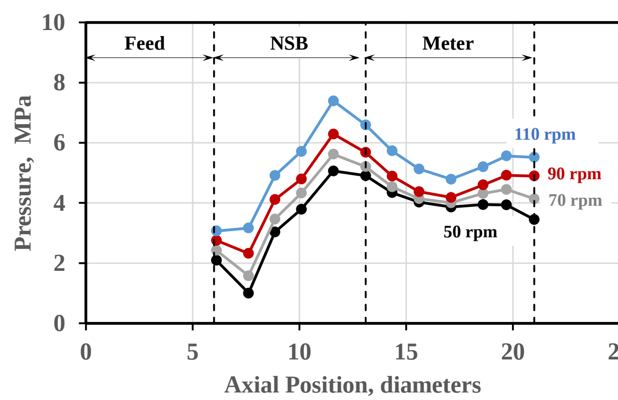


Figure 5. Axial pressure profile as a function of screw speed for the NSB screw.

As a comparison, axial pressure data were collected using the conventional screw. The axial pressure profiles as a function of the screw speed are shown in Figure 6. In the melting section, the pressure increased with a considerably higher gradient as compared with the NSB screw, resulting in a maximum pressure that was more than twice as high as the maximum pressure for the NSB screw. For example, at a screw speed of 110 rpm, the maximum pressure for the NSB screw was 7.4 MPa and that for the conventional screw was 17.2 MPa. This difference in pressure profiles is likely due to the lack of a traditional solid bed in the melting section of the NSB screw. The melting behavior for the NSB screw will be shown in the next section using a Maddock solidification experiment. Previously, the melting profile for the conventional screw was very traditional for an ABS resin [5], and it is expected to be very traditional for this LDPE resin. Along the metering section of the conventional screw, the pressure profile showed a negative axial gradient, indicating that the process is running at a rate higher than the rotational rate of the screw. This is consistent with the specific rate as it is higher than the calculated rotational rate, as discussed previously.

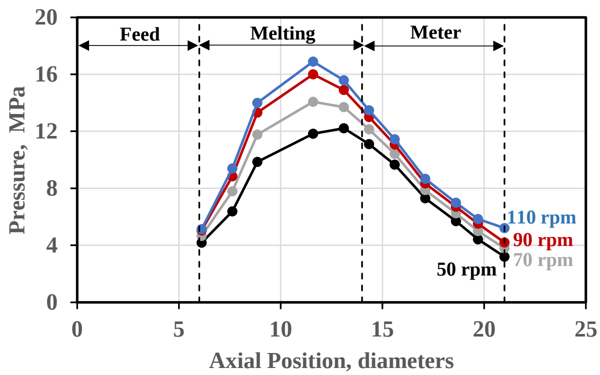


Figure 6. Axial pressure profile as a function of screw speed for the conventional screw.

The maximum pressures for the conventional screw indicate that a large amount of solids exist at the end of the melting section. If the pressure is high enough, the screw can be pushed up against the barrel wall, causing a high level of wear that can shorten the useful life of the screw. The maximum pressures for the NSB screw were considerably less and a lower wear rate on the screw flights would be expected.

Axial pressures were collected from the transducers at a rate of 30 Hz for the NSB screw. At this sampling rate the rotation of the screw and features of the channel can be observed. For example, the highest pressure of the oscillation occurs at the pushing side of the channel [5]. As the screw continues to rotate, the pressure decreases quickly as the flight passes underneath the transducer. The pressure is now the lowest at the trailing side of the channel. The pressure then increases as the rotation of the screw places the transducer in a path across the filled channel. This pattern is clearly observable for the transducers at 8.9 and 11.6 diameters of Figure 7. The high-speed data for Figure 7 were collected at a screw speed of 50 rpm. This is apparent in the figure since there are 12 pressure peaks (transducer at 11.6 diameters) in about 13.5 s or about 53 rpm.

The increasing pressure portion of the oscillation can also contain information about the level of solids and disturbances induced by geometry. For example, the transducer at 11.6 diameters is just downstream from the exit of the NSB section, and thus the channel is constant in depth at 3.18 mm. As shown by Figure 7, some of the pressure increases are not uniform. This is due to a high level of solids at this position. Other oscillations have the pressure increase across the channel that at are quite uniform. For this uniform pressure increase, the channel is filled with molten resin with no large solid fragments. The high-speed pressure data indicates that solid bed breakup is occurring at this location. The pressure oscillation for the transducer at 6.1 diameters is complicated due to the high level of solids and the start of the oscillating channel depth of the NSB section. The transducer at 7.6 diameters is also showing pressure variations due to both solids and channel depth.

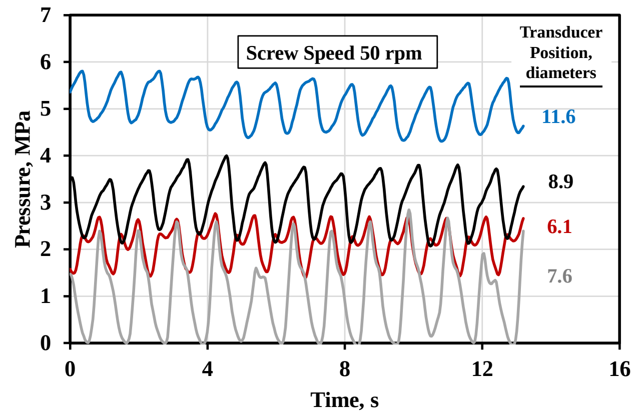


Figure 7. High-speed pressure data from transducers positioned over the NSB portion of the screw.

High-speed pressure data were collected at higher screw speeds, and the data were very similar to that in Figure 7 except that the oscillations were at the higher frequency of the screw rotation speed. The data were omitted here for clarity.

## Solidification Experiment

Maddock solidification experiments are very useful for troubleshooting the flows in the channels. Maddock [4] developed the method to visualize the melting and mixing processes inside the extruder. For this experiment, the extruder was brought to a steady-state operation at 110 rpm. Next, a small amount of black colored masterbatch resin was added to the natural resin at a letdown ratio of about 200 parts natural resin to 1 part masterbatch, and then it was added to the hopper of the extruder. When the color appeared in the discharge, screw rotation was stopped and full cooling was applied to the barrel. The transfer line and die were immediately removed from the extruder, and the unextruded pellets were removed from the hopper using a vacuum cleaner. After the resin was solidified in the extruder, the screw was pushed out of the extruder using a hydraulic jack. The screw with the solidified LDPE resin is shown in Figure 8. Next, the solidified polymer was removed from the screw and was sectioned at about 1 diameter intervals.

Photographs of the cross sections as well as their corresponding locations along the screw length are shown in Figure 8. The black areas on the cross sections are where the resin had been melted and combined with low amounts of the black colorant. The white translucent areas were solids at the time that screw rotation was stopped. The bubbles or voids in section 7 and 10 occurred due to the cooling of the resin. When the resin was molten, the density was about 0.74 g/cm$^3$. When the resin cooled and crystallized, the density increased to 0.918 g/cm$^3$, causing the resin sections to shrink and thus creating the voids. Thus, the solidification of the resin caused the resin volume to shrink nearly 20%.

As shown in Figure 8, toward the end of the solids conveying section (section 5 in Figure 8), pellets are partially molten and loosely packed in the channel with visible boundaries. Along the NSB section of the screw (sections 6 to 10 in Figure 8), the pellets are being gradually melted, and the white translucent solid bed is gradually broken into multiple isolated domains. Thus, the melting mechanism is different from that shown in Figure 1. Along the metering section (section 11 to 18) after the NSB, these solid domains stay isolated from each other and do not recombine into large solid domains. This indicates that the oscillating channel depth design of the NSB screw is effectively breaking the solid bed into smaller segments, which meets the original intent of this screw design. As the polymer stream moves along the screw, the white domains gradually diminish, and the cross sections become mostly black, indicating the melting and mixing process is completed.

## Discussion

The cross-channel depth variation of the NSB melting section allowed the solid bed to compact but melting did not occur in the traditional fashion. Instead, the solid bed was elongated and then compressed as the channel depth in the cross-channel direction changed. A traditional melt pool did not occur either. Molten resin was also moved back and forth across the channel width. Solid bed breakup likely occurred in the downstream direction as indicated by the high-speed pressure data and the Maddock solidification experiment. Some molten resin accumulated between the bed breaks.

At screw speeds higher than about 70 rpm, the rate of the extruder exceeded the melting capacity of the NSB section. The solid polymer fragments that are discharging at 90 and 110 rpm would likely cause unacceptable defects in the product for most applications. The fragments, however, can be trapped, melted, and dispersed by using a dispersive mixer such a Maddock mixer [11,12] or the metering channel could be replaced by a variable barrier ENERGY TRANSFER (VBET) section [13,14]. In both methods, the flow is forced over restrictive barriers, trapping, melting, and dispersing the solid fragments. Including a dispersive mixer on the screw would likely allow even higher rates before discharging solids. At higher rates, the discharge temperature will decrease, providing a high-quality discharge at low temperature.

The rate and specific rate of the NSB screw was about 8% higher than that of the conventional screw. As previously discussed, the higher rate for the NSB screw was due to the longer lead length. The metering channel depths were equivalent. Thus, the NSB screw can provide an increase in rate, especially if a Maddock mixer is used downstream from the NSB section.

As previously discussed, the maximum pressure for the NSB screw was about half that of the conventional screw. This lower maximum pressure may reduce the wear rate on the flights at the end of the NSB section, extending the useful life of the screw.

The extrusions here were performed using an 8 dg/min MI LDPE resin. Many of the applications suited for low temperature extrudates including blown film, pipe, and blow molding use resins with a lower MI value. It is highly desirable to rerun these experiments with a 1.0 MI resin.

## Summary

This paper summarizes experimental studies conducted on a design of a new screw referred to as the No Solid Bed (NSB) screw. Maddock solidification experiments validated the solid bed breakup mechanism of the NSB design concept. Polyethylene extrusion experiments with the NSB screw and comparison with a conventional screw confirmed the effect of the NSB design on lowering the melt temperature and identified the melting capacity limit of the NSB screw, which can be potentially further improved by including a dispersive mixer such as Maddock mixer downstream of the NSB section. Rates, specific rates, screw wear rates were all favorable for the NSB design.

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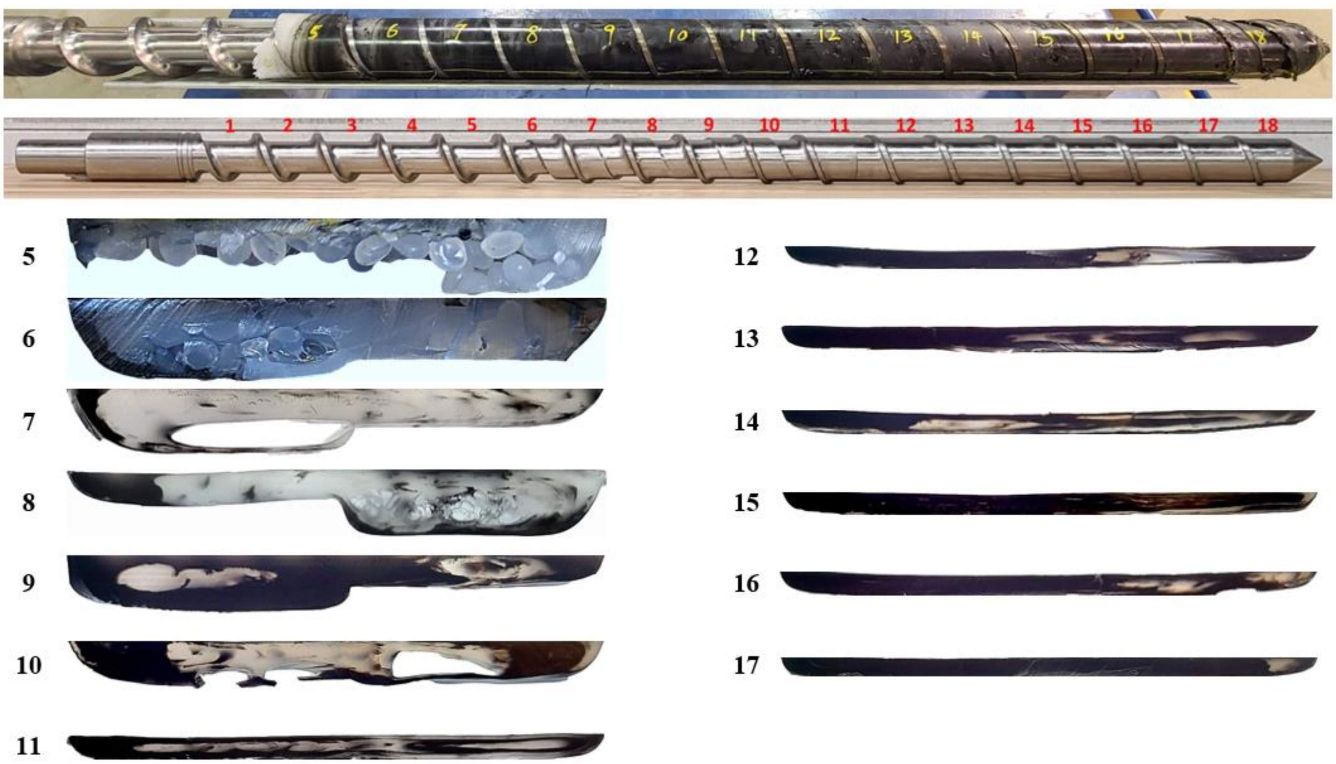


Figure 8. Photographs of the cross sections of the solidified polymer layers for a Maddock solidification experiment. The experiment was performed at a screw speed of 110 rpm. The cross sections are labeled by turns and not diameters.