EVALUATION OF THE CUSHIONS EFFECT ON PROCESS CONSISTENCY AND REPEATIBILITY

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Abstract

The importance of maintaining a consistent cushion in the injection molding process is universally agreed upon in the molding industry. However, the size at which the cushion should be set is not unanimously established. As such, several “rules of thumb” or “typical” cushion sizes are recommended and used by processors in the industry. These recommended cushion sizes have been deemed acceptable but without research being applied in order to determine their viability. This study will analyze and compare the variability and repeatability of the process and end product while applying various cushion sizes to a given process.

Introduction

The term “cushion” in the injection molding realm, refers to the plastic material that remains in front of the screw at either the end of the hold phase or the screw most forward position achieved during injection. There may be some confusion over which value received from the machine controller is to be regarded as the cushion, however there is not confusion as to the importance of consistency to the cushion in injection molding. The purpose of the cushion is to provide a pathway for the pressure applied during the holding phase of the molding cycle to reach the cavity of the mold. It is critical for this holding pressure to reach the cavity in order to complete the filling of the molded cavity and to compensate for the shrinkage of the polymer. If at any time during the holding phase of the molding cycle the screw reaches the zero position the risk of making an unacceptable product is increased. The resulting product will most likely be under packed and may result in a visual short shot.

In order to minimize this risk companies will often establish procedures within their facility that will require a certain amount of cushion to be maintained during processing. The amount of this cushion is often defined or determined by requiring a certain linear value, volumetric value, or a required percentage of the shot size. One theory is that a cushion is best stated as a distance because picking a particular volume as a rule of thumb would be a very small distance on larger screw diameters [1]. All, some or possibly even none of these current practices may be acceptable.

The goal of this research is to obtain and analyze real world data in order to determine whether cushion size has an effect on the variability and repeatability of the product that is being generated. Thus providing a scientific foundation for the basis of decision making in regards to cushion size.

Background & Theory

The injection molding industry typically recommends that the cushion be a minimal value, normally in the range of 3.2mm up to 6.5mm. The reasons stated for this minimal range is that this will allow for adequate compensation of shot-to-shot variation. In addition, a minimal amount of cushion will also provide better pressure transfer on the melt, minimize the risk of over packing a cavity, and help prevent excessive shrinks and voids [2].

It needs to be understood that the cushion, once determined, should not vary by the suggested range. Rather a range is provided to give a processor an idea of an acceptable cushion value for a given material. If the cushion for a given process is within the suggested range, the process is considered acceptable by those standards. Once the cushion is determined, it may vary slightly but should not vary over a wide range during the production run. Industry recommendations state that cushion size may be controlled to within 0.1mm – 1.0mm provided a molding machine is functioning properly [1] [3]. If the cushion does vary greatly, this is an indication that different volumes of material and different packing pressures may result in the mold cavities, thus creating variation in the part quality.
Using the Hagen–Poiseuille equation for pressure drop shown below, it is seen that the length \( l \) of the flow path is a contributing factor to pressure drop. To support the theory of the minimal cushion, the further the screw is from the mold cavity (increasing \( l \)), the higher the pressure drop will be and therefore less pressure would reach the cavity.

\[
\Delta P = \frac{8Ql\eta}{\pi r^4}
\]

\( \Delta P \) = pressure drop  
\( Q \) = flow rate  
\( l \) = flow length  
\( \eta \) = viscosity  
\( r \) = radius of the flow channel

Another factor in consideration for this research is the material compressibility, which may influence how much pressure and how consistent the pressure gets transferred to the cavity. The theory is that the more compressible the material, the more variation may exist in the measured cushion and cavity pressure which may then be amplified due to a larger cushion [4]. To compare material compressibility in the molten state, Pressure-Specific Volume-Temperature (PVT) plots were utilized (Figure 2). At the recommended melt temperature, the percent change in specific volume at 0 MPa versus 200 MPa was compared between materials. The data indicates that the Polycarbonate material is compressible by 14.4% while the Polypropylene is slightly less compressible at 13.2%. Thus more variation would be expected with the Polycarbonate material under these conditions.

Finally, it is well known that a material’s viscosity may change during a production run for a variety of reasons, such as moisture content or molecular weight distribution. As such, this study will also introduce a material viscosity shift with each cushion size. Again, the theory is that the smaller cushion will provide more control and a more consistent process overall.

This study will contrast the effect that cushion size has on consistency and recorded values of cushion, cavity pressure maximum, and cavity pressure integral.

### Materials & Equipment

Two thermoplastic material families were utilized for the experimental work in this paper. The two families were polypropylene (PP) and polycarbonate (PC). Within each material family that was studied two specific materials were evaluated in order to evaluate the effect of a viscosity shift. The baseline material for the PP was an impact copolymer manufactured by ExxonMobil™ and had a melt flow rate (MFR) of 8.0 g/10 min (230°C/2.16 kg). The PP material that was applied to simulate a viscosity shift was also an impact copolymer that was manufactured by ExxonMobil™. This material had an MFR of 35 g/10 min (230°C/2.16 kg). The baseline material for the PC portion of the study was manufactured by Covestro and had a MFR of 13.0 g/10 min (300°C/1.20 kg). The material applied in order to evaluate the effect of a viscosity shift was manufactured by SABIC Innovative Plastics and had a MFR of 8.0 g/10 min (300°C/1.20 kg).
The materials listed above were molded in a Krauss Maffei 40-125C injection molding machine. The machine utilized a 25 millimeter (mm) diameter screw. A SISE Expert PSP data acquisition system was used to analyze and interpret the machine and cavity pressure outputs that were critical in this research.

The four materials involved in this study were processed in an eight cavity mold with a “geometrically balanced” runner system. The primary runner branch of the runner system was 3.23 mm diameter. The secondary runner branch measured 2.82 mm diameter and the tertiary runner branch had a 2.44 mm diameter. The mold required a shot volume of 11.83 cubic centimeters. The volume of the part took up 8.51 cubic centimeters with the remaining 3.32 cubic centimeters comprising the sprue, runner, and gates. The part geometry had a nominal wall thickness of 1.57 mm and a critical flow length in the cavity of 46.99 mm. The mold also had model 9211 force sensors made by Kistler Instrument Corporation that were located in the post gate (PG) and end of fill (EOF) locations of cavity 2B (See Figure 3).

![Figure 3: Illustration of the study mold showing the sensor locations](image)

In order to input the cavity pressure recordings into the SISE Expert PSP data acquisition system a Kistler Instrument Corporation charge amplifier was utilized. The model number for this charge amplifier was 5155.

**Procedure**

The PP and the PC materials were processed according to manufacturer recommended process settings for screw rpm, back pressure, mold and melt temperatures. Actual melt temperatures of the polymers were verified using a 0.5 mm thermocouple. The baseline process for the PP material was developed based on the material that had an MFR value of 8.0 g/10 min (230°C/2.16 kg). The baseline process for the PC material was developed around the material with a MFR of 13.0 g/10 min (300°C/1.2 kg). Both materials were processed in a manner that ensured that the fill phase of the molding process was not pressure limited. The fill time for each material was developed by using a fill time scan [5]. The packing pressure and time for each material was found by performing a pack pressure and pack time scan.

The initial phase of this research was to evaluate the process and product consistency over time when comparing a minimal cushion to a large cushion. The same procedure was followed for both the PP and the PC materials. The minimum cushion value was evaluated first for consistency. Both the PP and PC materials were processed while producing a cushion value of 1.27 mm. The data acquisition system was used to verify that at this minimal cushion the machine was not bottoming out. The process was allowed to stabilize for seventy-five cycles prior to any data being recorded for analysis. Once the process had stabilized the pertinent data for observation of process consistency were recorded with the data acquisition system for two hundred cycles. The cavity pressure values that were analyzed were peak pressure (PG and EOC) and cycle integral (PG and EOC). The outputs from the molding machine that were analyzed for this research were peak injection pressure, fill/pack integral of machine pressure, and cushion.

In order to adjust the process from the minimum cushion value to the large cushion value the shot size and transfer position were adjusted. To ensure that the processes could be compared equally the fill only part weight was matched from the minimum to large cushion values. The large cushion value for the PP and PC materials resulted in a value of 25.4 mm. The same pack and hold pressures were applied as the minimum cushion study and seventy-five cycles were ran in order to allow the process to stabilize. Once the process had stabilized two hundred cycles were recorded with the data acquisition system and the same cavity pressures and machine values were analyzed.

The second phase of this research was to evaluate the process and product repeatability of the minimal and large cushion processes when a viscosity shift is introduced. For the PP material the press was set up for the 8.0 g/10 min (230°C/2.16 kg) material at the large cushion process. Without changing any machine settings, the 35 g/10 min (230°C/2.16 kg) material was loaded into the molding machine. All of the previous cavity pressure and machine output readings were evaluated in order to determine how the process reacted to the viscosity shift. This scenario was repeated for the minimal cushion value.

For the PC the 13.0 g/10 min (300°C/1.2 kg) material was set at the minimal cushion process. The 8.0 g/10min (300°C/1.20 kg) material was then applied to the process and the data acquisition system was utilized in order to determine how the viscosity shift was received by the process. The same procedure was followed for the large cushion value.
Discussion of Results

The study compared the average and standard deviation of the measured Cushion, Peak Cavity Pressure and Cavity Pressure Cycle Integrals for processes run with a small and large cushion. The studies targeted Cushion sizes of 1.27mm (0.050in) and 25.4mm (1.000in) for the small and large cushion respectively. First, two Polycarbonates with different Melt Flow Rates were run with both a small and large cushion and then the study was repeated with two Polypropylenes with different Melt Flow Rates. By studying two different materials the hypothesis that a material with a higher compressibility (in this case Polycarbonate) would produce higher variation when run with a larger cushion could be studied as well.

Polycarbonate Material

The Makrolon 6455 Polycarbonate (MFR 12.5g/10min @ 300°C, 1.2kg) was run first with a small cushion (average 1.57mm) and then with a large cushion (average 25.78mm). Only the Shot Size and Cutoff position were adjusted to run at the large cushion to produce the same 95% full Fill Only parts. The study was then repeated with they Lexan 2014R Polycarbonate (MFR 8g/10min @ 300°C, 1.2kg ) run at the Makrolon small and large cushion process settings yielding a small cushion (1.35mm) and a large cushion (25.58mm) respectively. No other process changes were made when the Lexan 2014R material was run in order to determine if a small or large cushion performed better when a viscosity shift occurred.

Figure 4 shows no change in the cushion Standard Deviation when changing from a small to large cushion with either Polycarbonate material. Furthermore, the data shows no change in cushion variation when a viscosity shift was introduced.

Figure 5 shows a slight reduction in the average cavity pressure values for the Makrolon PC when changing from small to large cushion. It should be noted that the reduced cavity pressure when running with a larger cushion aligns with the Hagen–Poiseuille equation discussed earlier. Figure 6 shows only minor differences in the standard deviation of the Makrolon PC cavity pressure values when changing the cushion size.

A viscosity shift was then introduced by repeating the experiment with a higher viscosity Lexan 2014R Polycarbonate material (MFR 8) to determine if either the small or large cushion performed better.

Once again the process with a higher cushion shows reduced cavity pressure values – see Figure 7. Figure 8 provides the Cavity Pressure standard deviation values for the higher viscosity Lexan material that shows little difference in the variation when running with either a small or large cushion.
Figure 7: Average Cavity Pressure values for the Lexan 2014R Polycarbonate (MFR 8) run with small and large cushion

Figure 8: Standard Deviation of Cavity Pressure values for the Lexan 2014R Polycarbonate (MFR 8) run with large and small cushion

Polypropylene Material

The testing was completed with a pair of Polypropylene materials to determine if a less compressible material exhibited a response to a small vs. large cushion. The PP7033E2 Polypropylene (8g/10min @ 230°C, 2.16Kg) was run first with a small cushion (average 1.24mm) and then with a large cushion (average 25.96mm). Only the Shot Size and Cutoff position were adjusted to run at the large cushion to produce the same 95% full Fill Only part. The study was then repeated with the AXO3BE3 Polypropylene (35g/10min @ 230°C, 2.16Kg) run at the PP7033E2 small are large cushion process settings yielding a a small cushion (1.12mm) and a large cushion (25.86mm) respectively. Once again no other process changes were made when the AXO3BE3 PP material was run in order to determine if a small or large cushion performed better when a viscosity shift occurred.

Figure 9 shows little change in the cushion Standard Deviation when changing from a small to large cushion with either Polypropylene material. The cushion variation increased by .025mm when the viscosity change was introduced to the small cushion process. This is only a minor shift in variation.

Figure 9: Standard Deviation of Cushion for both Polypropylene materials run with a small and large cushion

There was little change in the average cavity pressure when running the PP7033E2 Polypropylene with a small and large cushion – see Figure 10. Also note that Figure 10 once again shows that the average cavity pressure decreases slightly when changing from a small to large cushion. Figure 11 shows minor differences in the standard deviation of the cavity pressure values when changing the cushion size, the trend indicates lower variation at the higher cushion size.

Figure 10: Average Cavity Pressure of PP7033E2 run with a small and large cushion
A viscosity shift was then introduced by repeating the experiment with a lower viscosity AXO3BE3 Polypropylene material (MFR 35) to determine if either the small or large cushion performed better.

The average cavity pressure values for the AXO3BE3 Polypropylene were nearly identical when changing from a small to large cushion – see Figure 12. For this material the average cavity pressure did not decrease for the large cushion as was expected due to the longer flow length.

Overall, when one compares the standard deviation of the measured values the Polycarbonate materials had higher variation than the Polypropylene materials – see Figures 4, 5, 9, and 12. The Polycarbonate materials are more compressible but they also required significantly higher injection pressures and cavity pressures to fill and produce an acceptable part - the additional pressure further compresses the Polycarbonate material. The effects of material compressibility on measured cushion and cavity pressure values when run at different cushion sizes needs to be studied further before any conclusions can be made.
Conclusions

Overall the average cavity pressure data did not clearly indicate that a small or large cushion provides a more consistent measured cushion and/or cavity pressure values. The research showed that a larger cushion resulted in an increased pressure drop for three of the four materials run – this matches the calculations using the Hagen-Poiseuille equations as $l$ is increased. However, using a slightly higher Hold Pressure could compensate for this small additional pressure loss due to the larger cushion. The measured cushion standard deviation was within .025mm when changing from small to large cushion for all the materials run. However, the standard deviation of the measured cavity pressure was inconclusive because the data showed lower variation for the small cushion or for the large cushion depending on the run and measured cavity pressure variable. Overall, there was no clear data indicating that a small or large cushion size produces more repeatable measured cushion and cavity pressure values. The data indicates that whatever cushion size is selected that it should be maintained from run to run to avoid pressure loss differences resulting in cavity pressure variation caused by $l$ changing in the Hagen-Poiseuille equation. In addition, there is higher risk of damaging a mold if a process setting is entered incorrectly when running with a larger cushion.

References

3. The Dynisco Injection Molders Handbook, Page 36