Direct flow visualization of hesitation during injection molding of thermoplastic polymers

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Direct flow visualization of hesitation during injection molding of thermoplastic polymers

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Abstract. A special mold provided with a glass window has been used in order to directly evaluate the flow progression during the filling phase of the injection molding process. The flow of the polymer was recorded at 500 frames per second using a high-speed camera. Two unfilled thermoplastic polymers, acrylonitrile butadiene styrene (ABS) and polypropylene (PP), were used to fill a 50 mm x 18 mm staircase geometry cavity, which was specifically designed to evaluate the hesitation effects. Complete and incomplete (short shot) filling of the cavity was performed with two different velocities and in the case of two geometry thicknesses of the same design. Two different methods for the reproduction of the short shots were used. In the first, the maximum applied pressure was limited and progressively raised (MP Method), in the second the desired positions were obtained with a consecutive increase of the stroke length (standard SS method). The analysis of the video recordings highlighted that flow progression and hesitation were mainly influenced not only by the geometry, but also by the velocity and the material.

Keywords: Glass Mold, High Speed Camera, Injection Molding, Afterflow, Hesitation, Thermoplastic.

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INTRODUCTION

In recent years, glass inserted molds have received great attention as a direct flow visualization methodology in injection molding and other related manufacturing processes. Although their use presents some limitations, several authors have chosen glass inserted mold coupled with various camera setups in order to analyze the flow behavior [1-9].

Murata et al. [1,2] have obtained simultaneous visualization from two directions thanks to a setup consisting of a camera on the glass side, projected light through the back side glass and mirrors. Yang et al. [3] have characterized a microinjection-molding tool and investigated the flow into micro parts with high injection speed. They used a quartz glass window in combination with a reflection mirror and captured videos at 1000 frames per second with high-speed camera.

Nian [4] has chosen the same setup but using different pigments in the polymer blend, he obtained further information about the flow. Han and Yokoi [5] used a higher speed camera capable of recording at 13,500 frames per second and a microscope in order to analyze the filling of micro grooves on a glass prism insert.

Layser and Coulter [6], investigated the hesitation of the melt flow in the mold cavity. Their results showed that the flow hesitation is primarily dependent on the material, but also on the melt temperature and packing pressure. Similarly, in the present paper, we observed a strong influence of the material, but also of the velocity and geometry used.

Spares et al. [7] have analyzed the thermal field generated during microinjection molding with a thermal imaging camera. Whiteside et al. [8] investigated micro molding with a high-speed camera and sapphire glass insert, which allowed them to study different effects in microinjection molding.

Recently, Sorgato et al. [9] have integrated a sapphire window and a mirror into a system originally designed for microinjection molding venting. Thanks to this new setup, they could evaluate the effect of vacuum venting on the replication and definition micro/nano features.

Flow visualization during injection molding has also been performed with mold designs different from the ones described. In other solutions, a transparent insert was directly applied to the mold cavity parallel to the injection direction, which allowed the direct filming of the flow from the side without the use of a reflective mirror.
Yanev et al. [10,11] added a sapphire insert to this mold design and performed a simulation comparison to verify the filling performance of the software. Similarly, Guerrier et al. [12] used a mold with a glass window and an integrated multi-turn induction heating to capture the effect of induction heating with a high-speed camera. Guerrier [13] used the same mold to directly compare simulation and experimental moldings from an injection molding machine.

The purpose of the present study was to characterize the hesitation effect in thin cavities using the experimental setup developed in [12],[13] where a turned insert parallel to the injection screw allows the direct visualization of the flow in the cavity.

**EXPERIMENTAL**

**Glass mold and Machine**

A special mold was used where the injection plane was approx. perpendicular to the opening and closing plane of the glass mold, not to hamper the opening/closing procedure. The glass was tilted of 8°, i.e. 82° with respect to the opening plane.

This angle was chosen in order to avoid a too tight fit and therefore a possible breakage of the glass when the holding force was applied. The glass window was made of a 55 mm thick Borosilicate glass (width 60 and height 140 mm), and it was capable of withstanding at least 130 MPa of machine pressure during injection, and 50 MPa during packing.

An AOS Technologies AG (Fislisbach, Switzerland) X-PRI high-speed camera able to record 1280 x 1024 pixels images at 500 frames per second was used. A spotlight and two light bulbs were installed to increase the brightness of the video. A signaling diode turned on when the filling phase began and turned off at the switch over point. In addition, the mold was provided by three pressure sensors, two thermocouples, two interchangeable inserts, a cooling system and an ejector system installed on an Engel e-motion 110 with a screw diameter of 25 mm.

**Test Part and Materials**

Two inserts with the same geometry were designed to match the constraints imposed by the glass mold geometry and the objectives of the study. The staircase geometry was chosen in order to evaluate the extent of the hesitation and the afterflow in steps of different thickness, particularly in very thin sections where those effects become preponderant. The geometry comprised of a later channel and several lateral steps. The only difference between the two inserts was the thickness of the lateral steps. The common dimensions of the inserts are presented in Figure 1a, while in Figure 1b the dimensions of the steps of the first (Cavity 1) and of the second (Cavity 2) insert are shown in black and blue, respectively. Cavity 1 had a thickness of 0.3 mm at the smallest step, it raised by 0.3 mm at each step to a final value of 1.5 mm; Cavity 2, had a thickness of 0.5 mm at the smallest step and it increased by 0.25 mm at each step to a final 1.5 mm.

Acrylonitrile butadiene styrene (ABS), a thermoplastic amorphous plastic material with a melt flow index (MFI) of 34 cm³/10min and Polypropylene (PP), a thermoplastic semi-crystalline opaque polymer with a MFI of XX were used to characterize the influence of the material on the hesitation.
Experiments

For each material and each cavity the same setup of experiments was performed, for a total 20 runs. Table 1 summarizes the experimental combinations consisting of two complete fillings with a constant injection velocity of 40 mm/s (ComF) and 10 mm/s (ComM) and three short shots experiments. The short shots were obtained using two different methods.

In the maximum pressure (MP) method, the different filling percentages of the cavity were obtained limiting the maximum applied pressure and progressively raising the limit. MP short shots were produced with a very low injection speed.

In the second method, the desired positions were obtained with consecutive increments of the stroke length at a certain injection velocity. They were addressed as SS. Similarly to the complete experiments, SSF runs with an injection velocity of 40 mm/s, while SSM with 10 mm/s. Those velocities were chosen to allow a direct comparison between the complete and the short shots experiments.

The rest of the processing parameters were selected following the recommendations of the material suppliers and kept constant throughout the experiments.

To summarize:
- ComF refers to the complete filling experiments with an injection velocity of 40 mm/s;
- ComM refers to the complete filling experiments with an injection velocity of 10 mm/s;
- SSF refers to the short shots obtained varying the stroke length with injection velocity of 40 mm/s;
- SSM refers to the short shots obtained varying the stroke length with injection velocity of 10 mm/s;
- MP refers to the short shots achieved limiting the maximum applied pressure.

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Material</th>
<th>Velocity [mm/s]</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ABS</td>
<td>40</td>
<td>Complete Filling</td>
</tr>
<tr>
<td>2</td>
<td>PP</td>
<td>10</td>
<td>Short Shot (SS)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Short Shot (MP)</td>
</tr>
</tbody>
</table>

TABLE 1. Experimental Summary.
HIGH SPEED VIDEO ANALYSIS

Method

A reference system was set in order to accurately follow the video records of the cavity fillings. As presented in Figure 2, the zero point was at the intersection between the thin step’s external wall and the lateral channel internal wall. Y axis was parallel to the channel and the X axis was perpendicular along the step direction.

Measurements had been performed using “ImageJ” software [14]. The pixel distances were converted in millimeters with reference to the total length Y of the cavity.

The penetration degree X in the side steps was calculated as an average between the maximum penetration and the average penetration on each step. This value gives an estimation of the hesitation for a certain position Y in the lateral channel, which was then used as the reference for the evaluation. Therefore, the results are relative to a certain Y length traveled by the melt flow in the lateral channel. In the case of the short shots, this was the position where the melt stopped moving (before the retraction caused by the cooling), while in the case of the complete experiments, the same position was extracted by the video analysis. Although a total of three positions were chosen and the results were in agreement, for brevity only the results relative to Position 3 (Figure 2a and 2b) are shown in this paper.

The length of the cavity has been measured 12 times in order to evaluate the variability of the measurement method. The resulting standard deviation was 0.3 mm. The related uncertainty was calculated following the guidelines of GUM [15] and was equal to 0.098 mm.

Results

In all the experiments, the length of the melt flow in the lateral channel was chosen to match as accurately as possible the selected position. Therefore, the length Y was a measure of the accuracy of the position selection. Figure 3a shows the main effects plots for Y relatively to Material, Cavity and Type of experiment.

It can be noticed that the traveling distance in the lateral channel is lower in the case of Cavity 2 and PP experiments than in the case of Cavity 1 and ABS experiments. This suggests an overestimation of their relative hesitation. A notable difference of the length Y is also present between the short shots SS experiments and other experiments. Hence, on the opposite, the hesitation for the experiments SS will be underestimated.
Nevertheless, the main effect plots depicted in Figures 3b, 3c and 3d highlight that the hesitation is higher in the ABS experiments, and it is mostly affected by the thickness of the cavity, i.e. higher hesitation in thinner sections. In the case of the MP experiments, the flow was not able to penetrate in none of the steps due to the very low velocities applied; therefore, it will not be taken in consideration further in.

SS and Complete experiments were in close agreement, but a slight underestimation of the hesitation in short shots SS could be noticed. This needs certainly to be considered during the evaluation of filling in molds without glass windows.

It is also worth noticing how the effect of material and cavity diminishes for thicker steps, as expected by Equation 1. Similarly, the velocity (type of experiment) is more important than the material type for Step 1 (0.3 for cavity 1 and 0.5 mm for cavity 2) hesitation, while the opposite is true for thicker steps.

In conclusion, it was possible to draw a few summarizing observations:
- Thickness is the most important factor;
- The velocity of filling and the thickness are not linearly related;
- PP showed less hesitation effect than ABS;
- MP short shot method is not suitable for the characterization of the flow in the cavity;
- Short Shots underestimate the hesitation occurring during the filling phase.

CONCLUSION

The present study investigated the hesitation of unfilled thermoplastics through direct flow visualization. The setup included a transparent insert directly applied to the mold cavity. The mold cavity was parallel to the injection direction, so the flow was directly filmed from the side of the injection-molding machine with a high speed camera. The cavity, consisting of a staircase geometry specifically designed to investigate hesitation effects, has been filled with an amorphous (ABS) and a semi-crystalline (PP)
polymers. The cavity thickness had a strong influence on the hesitation of the plastic melt, whereas velocity and type of material affected it less. When the thicknesses decreases to 0.3-0.5 mm, the velocity becomes mainly dependent on the type of thermoplastic.

In addition, the short shots at very low injection velocity, varying the max pressure, namely MP, did not provide a suitable characterization of the filling of the cavity. On the other hand, the short shots at consecutive increments of the stroke length underestimated the hesitation of a complete filling but provided a more accurate representation.

REFERENCES