Design for In-Flow to Strengthen Weld Lines in Injection Molded Polypropylene Parts

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Abstract

Weld lines in multi-gated and windowed products can act as flaws to weaken the mechanical strength of the part. A design of experiments with neat and 40% talc-filled polypropylene indicated that asymmetric melt in-flows during molding could be used to significantly strengthen weld lines in injection molded parts. Product design recommendations are provided.

Introduction

Weld or knit lines occur whenever the flow of the polymer melt splits and rejoins. In injection molded parts, weld lines occur when the part is either injected through multiple gates or the melt flows around an obstacle within the mold cavity such as a core or a pin. These weld lines act as flaws and weaken the overall mechanical properties in the region where they occur [1]. Wu et. al. attribute the weaknesses caused by these lines to a handful of factors, a) poor/incomplete entanglement of the polymer chains, b) formation of v-notch flaws at the surface of the weld line, c) presence of microvoids or contamination at the interface of the weld line, and d) unfavorable molecular or fiber orientation at the weld line [2]. In addition, Mielewski et. al. have observed that lower molecular weight chains and additives such as antioxidants can agglomerate at the weld line interface, further reducing the overall strength of the weld line [3].

Hagerman [4] defined the weld lines that occur when two melt fronts impinge on each other as a Class 1 weld line while two melt fronts that immediately rejoin after being split by an obstacle as a Class 2 weld line. The two classes of weld lines tend to exhibit different mechanical properties. Class 2 weld line strength is determined by the injection velocity, melt viscosity, and the filling time of the injection process and its effect on the interface of the two conjoining melt fronts.

Kazmer and Roe [5, 6] presented a method for increasing the weld line strength to or beyond the nominal strength of the material without requiring additional investment in tooling or processing. The technique relied on transient flow redirection during the packing stage to significantly increase the weld line interfacial area and filler orientation to locally improve part properties. This paper explores the role of in-flow and processing conditions on the strength of weld lines at various locations in a molded product. Here, in-flow is defined as the flow within the mold cavity, below the solidified layer, that continues after the local region of the mold cavity is filled. Since the direction and duration of the in-flow may differ from the original melt flow pattern that resulted in the formation of the weld line, the hypothesis is that the in-flow may be used to improve weld line properties such as strength and aesthetics.

Experiments

Experiments were conducted using a twin-gated ASTM tensile bar mold (not shown) and a numbered lattice mold (Figure 1). The numbered lattice mold provides an 11x11 array of holes on a 2.54 mm spacing for use as a pin grid array zero insertion force socket. As shown in Figure 1, the part is molded with two tab gates located on opposite ends of one side wall. Numerous Class 2 weld lines are formed by the mold cores for the 121 holes as well as other windows used for locating and mounting the part.

Figure 1: Molded lattice part (CPU cover)

Resins investigated in this experiment were an unfilled polypropylene (ECM Plastics) and a 40% talc-filled polypropylene (SABIC PP 19T1040). The overall weld line behavior of each material was characterized by first molding a set twin-gated tensile bar specimens at reference processing conditions shown in Table 1 using a 60 kN press (Arburg). These samples generated a Class 1 weld line in a
fixed position on the part to provide reference results for the parts produced by the lattice mold.

Table 1: Reference processing conditions

<table>
<thead>
<tr>
<th>Processing Condition</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed Throat (°C)</td>
<td>40</td>
</tr>
<tr>
<td>Nozzle (°C)</td>
<td>230</td>
</tr>
<tr>
<td>Zone 1 (°C)</td>
<td>225</td>
</tr>
<tr>
<td>Zone 2 (°C)</td>
<td>210</td>
</tr>
<tr>
<td>Zone 3 (°C)</td>
<td>205</td>
</tr>
<tr>
<td>Zone 4 (°C)</td>
<td>200</td>
</tr>
<tr>
<td>Zone 5 (°C)</td>
<td>190</td>
</tr>
<tr>
<td>Mold (°C)</td>
<td>40</td>
</tr>
<tr>
<td>Injection Velocity (mm/s)</td>
<td>20</td>
</tr>
<tr>
<td>Pack Pressure (MPa)</td>
<td>20</td>
</tr>
</tbody>
</table>

A set of thirty twin-gated tensile bar specimens were produced for both materials at the nominal processing conditions outlined in Table 1 to characterize the weld line behavior of the filled and unfilled polypropylene materials. After molding the samples were de-gated and placed in an environment at 21°C and 40% relative humidity. Tensile testing was then performed using the procedure outlined in ASTM D638 using an Instron 6063 testing machine.

Following the characterization of the tensile strength, a design of experiment (DOE) described in Table 2 was implemented for the molding of the numbered lattice parts using a 20 kN molding machine (Sumitomo). The four DOE runs testing the effects of high and low temperature, injection velocity, and packing pressure were centered around the reference process described in Table 1 with the injection velocity scaled for the smaller molding machine. The barrel and coolant temperatures are blocked to minimize the number of runs and so the main effects for temperature will confound these two factors. In implementing the DOE, the multiple zone temperatures were profiled relative to the reference profile of Table 1.

Table 2: Design of Experiments

<table>
<thead>
<tr>
<th>Processing Condition</th>
<th>Design of Experiments Run</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Zone 1 Temperature (°C)</td>
<td>260</td>
</tr>
<tr>
<td>Coolant Temperature (°C)</td>
<td>21</td>
</tr>
<tr>
<td>Injection Velocity (mm/s)</td>
<td>20</td>
</tr>
<tr>
<td>Pack Pressure (MPa)</td>
<td>15</td>
</tr>
</tbody>
</table>

Testing of the numbered lattice samples was conducted by machining three sections out of a sample population of ten parts produced during each DOE run. The three sections (shown in Figure 1) evaluated different weld lines produced during the molding of the part. Section 1 evaluates the Class 2 weld line formed when the two melt fronts meet at the center of the part. Section 2 evaluates the Class 2 weld line formed by the converging of the melt fronts at the very end of flow. Finally, Section 3 evaluates a series of Class 1 weld lines formed during the formation of the lattice structure, allowing testing of the hypothesis that subsequent in-flow during filling improves the weld line performance.

The four run DOE of Table 2 was repeated for the neat and 40% talc-filled (TF) polypropylene (PP). In total, 240 tensile specimens were produced (4 DOE runs · 10 samples per run · 3 specimens per sample). Once all the test specimens were machined, they were conditioned in an environment at 21°C and 40% relative humidity. Tensile testing was then performed using the procedure outlined in ASTM D638 using the same Instron 6063 testing machine as for the tensile bar specimens.

Results

The two sets of thirty twin-gated tensile bar specimens (produced for the neat and 40% TF PP) having the Class 1 weld line were tested at an extension rate of 50 mm/min, corresponding to a strain rate of approximately 0.01 s⁻¹. The results are shown in Figure 2. It is observed that the neat PP has a modulus of 273 MPa (standard deviation of 70 MPa) and a weld line strength of 25.4 MPa (standard deviation of 2.1 MPa). By comparison, the 40% TF PP has a higher modulus of 492 MPa (standard deviation of 41 MPa) but a lower weld line strength of 9.9 MPa (standard deviation of 0.5 MPa).

Figure 2: Stress-strain behavior of twin-gated tensile bars molded of neat and 40% talc-filled PP
Figure 3 plots the stress-strain behavior of the specimens at three different locations for the neat PP resin molded at DOE run 1 conditions corresponding to high temperature, low injection velocity, and low pack pressure. It is observed that the Class 2 weld line at location 1 between the gates has an ultimate strength of 18.2 MPa, somewhat less than the behavior observed in Figure 2 for the twin-gated tensile bars molded of the neat PP resin.

The Class 2 weld line at location 2 at the end of flow has a much lower ultimate strength of 14.3 MPa. This lower strength at the end of flow would be expected by the underlying physics [7] that suggest the lower pressure and faster cooling at the end of flow reduces interfacial healing. By comparison, the weld line strength at location 3 is significantly stronger with an ultimate strength of 32.3 MPa. This result suggests that the in-flow caused by the melt flow within the part during subsequent mold cavity filling allows the weld to heal.

It is observed in Figure 4 that the weld line strength at location 3 is significantly stronger than at either location 1 or 2, with an ultimate strength of 19.1 MPa. This result again suggests that the in-flow caused by the melt flow within the part during subsequent mold cavity filling allows the weld to heal. This strength of 19.1 MPa is 93% greater than the 9.9 MPa strength observed in the tensile bar behavior plotted in Figure 2 and 80% of the tensile strength at break of the SABIC PP 19T1040 tested by the material supplier without a weld line.

Figure 4 plots the stress-strain behavior of the specimens at three different locations for the 40% talc-filled PP resin molded at DOE run 1 conditions again corresponding to high temperature, low injection velocity, and low pack pressure. It is observed that the Class 2 weld line at location 1 between the gates has an ultimate strength of 10.9 MPa, very close to that of the twin-gated tensile specimens molded of the same material plotted in Figure 2. The Class 2 weld line at location 2 at the end of flow has a much lower ultimate strength of 7.2 MPa due to poor interfacial healing. Examination of the fracture surface showed an agglomeration of talc filler at the interface of the weld line. This suggests that when undergoing tensile strain, the force is being transferred to the filler that’s bridged the gap between the two flow fronts instead of transferring into the resin and the mineral particles suspended within it.

Examination of the fracture surface showed an agglomeration of talc filler at the interface of the weld line. This suggests that when undergoing tensile strain, the force is being transferred to the filler that’s bridged the gap between the two flow fronts instead of transferring into the resin and the mineral particles suspended within it.

To further understand the role of in-flow on weld line strength, analysis of variance (ANOVA) was performed to verify the statistical significance of the investigated factors. To remove outliers, a multiple regression was first performed for the 240 tested specimens as a function of the factors in the design of experiments described in Table 2 as well as the material (coded as 0 for neat and 1 for talc-filled) and the in-flow (coded as 0 for abutting welds without in-flow and 1 for welds with in-flow). Outliers were identified by checking the residuals of the modeled strength and removing those observations with significant error; ten outliers were found. The remaining 230...
The results of the ANOVA (constrained, type III sum of squares) are provided in Table 3. The results indicate that the two most significant factors are the material being talc-filled (TF) followed by the presence of in-flow. The temperature, injection velocity, and pack pressure of themselves were not found to be statistically significant at the 95% confidence level while their interactions with the material and type of flow were found to be significant. These results imply that the effect of the processing parameters is dependent on the type of material and flow forming the weld line.

\[
S = c_0 + \sum_{i=1}^{n} c_i \cdot x_i \tag{1}
\]

where \(c_i\) are the model coefficients for the various factors \(x_i\). The factors are normalized where in 0 is the minimum setting of the DOE run conditions listed in Table 2 (or absence of talc-filler or in-flow) and 1 is the maximum setting of the DOE run conditions (or presence of the talc-filler or in-flow). The confidence intervals for the fit model coefficients \(c_i\) are provided in the right two columns of Table 4. A model coefficient, such as \(c_4\), is not statistically significant if the confidence interval includes 0.

Based on the ANOVA results, a multiple regression model was fit to the 230 strength observation as a function of several interactions and their significant two-way interactions. The model for the strength, \(S\), has the form:

The results suggest that the effect of in-flow is not only statistically significant but physically dominating, with the presence of in-flow increasing the weld line strength by 14.1 MPa. Adding the 40% talc-filler reduces the weld line strength by 7.0 MPa. By comparison, the process conditions have a relatively minor effect, with increases in temperature and pressure respectively increasing the weld strength by 3.1 and 1.4 MPa. The \(c_6\) and \(c_7\) interaction terms suggest that, when processing the talc-filled (TF) material, the weld line strength can be increased by using in-flow as well as increase the temperature. The \(c_8\) interaction term suggests that weld strength is increased with higher temperature and the presence of in-flow.

**Discussion**

The in-flow phenomenon is depicted in Figure 5. At left, when the flow is balanced about an obstruction in the mold, the joining melt fronts meet and the weld line strength is dependent on limited intermolecular diffusion across the rapidly cooling interface. As shown at right, in-flow associated with ongoing melt flow within the cavity causes the polymer melt to continue to stream across the initial weld interface. This in-flow not only causes a larger interfacial area but also conveys additional heat by melt convection that serves to delay cooling and foster greater intermolecular diffusion to increase the weld strength such as previously reported by Kazmer and Roe [5, 6].

![Figure 5: Weld line formation with no flow (left) and in-flow (right)](image-url)
The use of in-flow to strengthen weld lines suggests some simple guidelines for product and mold design, and indeed some counterintuitive rules that fly in the face of traditional injection molding best practices:

- Consider the centered edge gate place such as shown at left in Figure 6. While such designs are common to achieve balanced flow, it is suggested that slightly offsetting the location of the edge gate as shown at right in Figure 6 can improve the weld lines’ strength by inducing in-flow after each window. The effect of the lateral cavity pressure imbalance can be minimized by using a slightly lower velocity to pack (VP) setting to complete filling under a pressure condition followed by a profiled packing pressure.
- Figure 7 provides two alternative gating strategies with a pin-point gate at left and an edge gate at right. Again, the edge gate selection will provide improved weld-line performance due to the in-flow around each window associated with continued mold filling. Such a design was recently used in practice for a 0.6 mm thick polycarbonate part with no apparent weld line and excellent structural properties.
- Figure 8 depicts a center gated part that may cause knit-line issues. The use of an off-centered over-flow as shown at right will tend to improve the weld line performance due to post-filling in-flow such as for LCP [8]. The over-flow is designed to minimize melt pressure imbalances while also being designed with a gate to easily remove and recycle.

Conclusions

The results of Figure 2 should flag caution to designers of injection molded products with structural requirements. Glass, talc, and other fillers are often used to improve the stiffness and strength of molded products. However, the existence of weld lines resulting during the molding process can greatly undermine the performance of the composite materials and their intended use.

The foregoing results suggest that the weld line strength may be significantly increased by using strategically designed products, molds, and processes to generate in-flow. The in-flow not only causes a larger interfacial area at the weld line but also conveys additional heat by melt convection that serves to delay cooling and foster greater intermolecular diffusion to increase the weld strength. The amount of in-flow need not be excessive as even a small volume of in-flow relative to the weld line cross-section area can produce significant results. It is likely that physics-based modeling can and will be incorporated into numerical simulation to predict weld line strength to assist designers in improving injection molded part designs and end-use performance.

References