EVALUATION OF VARIOUS WEIGHT REDUCTION STRATEGIES ON MECHANICAL PROPERTIES AND PART PERFORMANCE

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Abstract

Multiple options exist for decreasing the weight of injection molded automotive components. Each option offers unique advantages and limitations regarding weight reduction potential and mechanical performance of the final part. Advanced Composites has evaluated the effect of several strategies, including composite density reduction, wall thickness reduction, and foaming, on the performance of injection molded test specimens and parts made using a diagnostic tool. Densities and part weights were obtained as well as tensile, flexural, and impact properties. In the case of density reduction, the removal of mineral filler alone proved insufficient to maintain mechanical performance, indicating the need for optimization of the material formulation. The characteristics of foamed and thin-wall parts were also examined and demonstrate the need for careful consideration of part and material design.

Introduction

Automobile manufacturers are striving to meet the requirements set by the impending 2025 EPA and NHTSA fuel economy standards [1]. In addition to the multitude of engine and transmission improvements, hybrid, and fully electrical options for increased fuel efficiency, measures are being taken to reduce the weight of vehicles. While metal replacement is an effective technique that has experienced some success, pre-existing plastic parts are also being thoroughly investigated for weight reduction opportunities [2].

Thermoplastic olefins (TPO) are low-cost, recyclable, versatile compounds that are able to be modified to achieve specific balances of stiffness and impact strength. These features, in conjunction with their inherently low densities, make TPOs particularly suitable for demanding applications. Indeed, TPOs experience widespread utilization in an abundance of interior and exterior automotive components.

Although TPOs have inherently low densities, material and part manufacturers are being driven to identify and improve innovative techniques for further reducing the weight of plastic components. Of these innovations, three common methods include further material density reduction, wall thickness reduction, and foaming by introducing gas into the molding process using supercritical fluids or chemical foaming agents (CFA). Thin-wall and foaming techniques provide the added benefit of requiring less material, which has the potential to reduce costs as well as product weights [3].

Two current foaming techniques commonly employed are “short-shot” and “core-back” foaming. Short-shot foaming, which is less intensive in terms of equipment modification, involves introducing gas into the polymer melt, then injecting the melt to partially fill a mold cavity, resulting in an initially incomplete part. After the first fill stroke, the relief in pressure allows the dissolved gas to expand and the plastic foam to fill the remainder of the cavity.

Core-back foaming is accomplished by injecting molten plastic and dissolved gas to completely fill a thinner mold cavity than is ultimately desired. After the initial injection stroke, a sufficient pressure is applied to prevent material backflow but not force more plastic into the cavity. After a short delay to allow the skin-layer of the plastic to form, the moving-half of the mold is rapidly retracted to increase the cavity thickness. The ensuing depressurization allows the gas in the molten core layer to separate from the matrix, expand, and foam the part to the desired final thickness [4].

In prior work, Advanced Composites described some of the effects of wall thickness reduction and core-back foaming on injected molded test specimens [5]. Properties at varying thicknesses were of primary concern. Stiffness was calculated assuming a simple beam-in-bending model, shown in Figure 1. The relationship between stiffness (S, N/mm) and flexural modulus (E, MPa) for a beam-in-bending is described in equations 1 and 2:

\[ S = \frac{P}{\Delta} = \frac{48EI}{L^3} \]  \hspace{1cm} (1)

\[ I = \frac{Lh^3}{12} \]  \hspace{1cm} (2)

where \( P \) = applied load (N), \( \Delta \) = deflection (mm), \( I \) = moment of inertia (mm\(^4\)), \( L \) = span (mm), and \( h \) = beam thickness (mm) [6].
The goal was to determine whether an increase in thickness could offset the loss in flexural modulus upon introducing foam into the part and achieve comparable final part performance. It was shown for the foamed system in question, weight saving potential and stiffness improved as the part was expanded to greater final thicknesses. However, impact performance was diminished upon introducing voids into the TPO matrix [5].

This research complements previous efforts by exploring density reduction methods and material considerations. It then extends these applications to a part more representative of an actual automotive component and evaluates the effects.

Experimental

Materials

Two studies (1 & 2) comprise this research. For Study 1, three impact-modified TPO resins manufactured by Advanced Composites Inc. were used as candidates for density reduction. The base properties of interest are given in Table 1.

Table 1. TPO Mechanical Properties for Study 1

<table>
<thead>
<tr>
<th>Property</th>
<th>ISO Method</th>
<th>TPO 1</th>
<th>TPO 2</th>
<th>TPO 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt Index, 230°C, 2.16 kg (dg/min)</td>
<td>1133</td>
<td>32</td>
<td>28</td>
<td>17</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1183</td>
<td>1.06</td>
<td>1.04</td>
<td>1.02</td>
</tr>
<tr>
<td>Tensile Strength (MPa)</td>
<td>527</td>
<td>19</td>
<td>21</td>
<td>19</td>
</tr>
<tr>
<td>Flexural Modulus (MPa)</td>
<td>178</td>
<td>2150</td>
<td>2000</td>
<td>1950</td>
</tr>
<tr>
<td>23°C Notched Izod Impact (kJ/m²)</td>
<td>179</td>
<td>37</td>
<td>30</td>
<td>44</td>
</tr>
</tbody>
</table>

For Study 2, a material considered to have a good stiffness-impact balance for conventional automotive interior applications, TPO-4, was used as a control to compare to formulations optimized for reduced density and comparable mechanical performance, TPO-5 and TPO-6. Additionally, materials optimized for foaming and reduced wall thickness applications, TPO-7 and TPO-8 respectively, were evaluated. Properties of interest are listed in Table 2.

Table 2. TPO Mechanical Properties for Study 2

<table>
<thead>
<tr>
<th>Property</th>
<th>TPO 4</th>
<th>TPO 5</th>
<th>TPO 6</th>
<th>TPO 7</th>
<th>TPO 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt Index, 230°C, 2.16 kg (dg/min)</td>
<td>20</td>
<td>21</td>
<td>22</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.03</td>
<td>0.99</td>
<td>0.97</td>
<td>1.03</td>
<td>1.05</td>
</tr>
<tr>
<td>Tensile Strength (MPa)</td>
<td>19</td>
<td>21</td>
<td>21</td>
<td>18</td>
<td>22</td>
</tr>
<tr>
<td>Flexural Modulus (MPa)</td>
<td>1900</td>
<td>1800</td>
<td>1700</td>
<td>1750</td>
<td>2900</td>
</tr>
</tbody>
</table>

Preparation and Testing

Study 1 demonstrates the effect of density reduction accomplished by the removal of mineral filler in fixed increments from each TPO and subsequent normalization of the material formulation. In order to ensure that filler content remained the only independent variable, no additional adjustments were made to the formula. To obtain mechanical properties, solid ISO 527 Type 1A test pieces were prepared from the experimental materials using an 80 ton hydraulic injection molding machine. Mold shrinkage was determined using a measuring optical microscope on a 100 mm x 150 mm specimen prepared using the same injection molding machine.

Study 2 compares the effect of various weight reduction strategies on the performance of parts more representative of actual automotive components. A 500 ton electric injection machine was used to prepare samples from a diagnostic tool that simulates some of the features and geometries of a door panel. These parts are more complex than flat panels or standard molded test specimens and allow for observation in a more realistic application. A diagram is provided in Figure 2, and additional details are given in Figures 10 and 11.
and ISO 178 flexural specimens milled from the flat featureless region of the “mini-door panels” using a Mutronic Diadrive 2000 CNC router.

For all experimental iterations in Study 2, a final wall thickness of 2.8 mm was targeted. To evaluate wall thickness reduction for TPO-8, a final wall thickness of 1.8 mm was used. A single mold cavity thickness setting was used for the solid and short-shot samples. TPOs 4-7 were used for the solid 2.8 mm samples. The short-shot specimen was achieved by mixing 1% CFA with TPO-7, injecting the material into the mold in a single fill stroke and then omitting the pack and hold phase of the injection cycle. After the initial stroke, relieving the melt pressure allowed the gas evolved from the CFA to expand and fill the remainder of the part. The core-back iteration was achieved by mixing TPO-7 with 2% CFA and then injecting at an initial thickness of 1.8 mm. Similar to the short-shot method, the pack phase of the injection cycle was omitted. The moving half of the mold was then retracted 1 mm, which allowed the gas evolved from the CFA to expand and foam the part to a final thickness of 2.8 mm.

Because Study 2 emphasizes part performance, property measurements were not normalized by test piece dimension as is typical with conventional mechanical property reporting. Rather, extrinsic properties, specifically maximum tensile load, flexural stiffness, and part mass were obtained. Additionally, multiaxial instrumented impact (MAII) was conducted to ASTM D3763 at 23°C for all samples and -30°C for the optimized reduced density formulations to evaluate energy absorption and failure behavior.

Results

Study 1

Study 1 examined the effect of reducing the amount of mineral filler in three TPO materials and normalizing the formulation with no attempt to compensate for the expected change in properties. As anticipated, the resulting samples exhibited a decrease in density. The relative performance as a function of density reduction for TPOs 1, 2, and 3 are provided in Figures 3, 4, and 5 respectively. There was a substantial reduction in flexural modulus in all three materials at a percent decrease of three to four times the percent reduction in density. A percent increase in the measured mold shrinkage, about three times the percent change in density, was also observed. TPO-1 and TPO-2 displayed moderate improvement in notched impact performance with a percent increase of approximately two times the percent decrease in density, but TPO-3 showed little variation. This is likely due to the fact that TPO-3 initially had a lower filler loading and higher impact resistance than TPO 1 and 2, and less opportunity for improvement. Given this, it is reasonable to suspect that the impact advantages provided by the decrease in density for TPO 1 and 2 would eventually diminish. There was minimal change in the tensile strength for all samples.
Study 2

Study 2 evaluated various weight reduction techniques using the diagnostic tool. Due to slight variation in processing behavior of the individual materials, small adjustments to shot size had to be made between each sample run in order to produce acceptable parts. Although the changes to overall part performance due to process changes are expected to be minimal, the process variations could potentially account for some variation in final results, namely part mass.

Relative density and part weight reduction are in good agreement for most of the 2.8 mm samples as expected for a constant volume part. However, one will notice a large discrepancy between the measured relative density and relative part mass for the core-back sample (Figure 6). This is owing to the complex geometry of the part. Maximum expansion is possible for regions of the part in planes perpendicular to the direction of retraction. Curved areas or features that are closer to parallel with the core-retraction direction, see little to no expansion. This also explains why the measured part mass for the thin wall specimen, which was achieved using unidirectional shims, is 16% higher than estimated based purely on the wall thickness ratios.

Similarly to Study 1, reducing the density had little negative impact on the tensile properties in the case of the optimized formulations, TPO-5 and TPO-6 (Figure 7). TPO-6 actually exhibits marked improvement. Conversely, the maximum tensile load was significantly reduced in both foamed samples. Relative to the solid TPO-7 sample, there was a maximum tensile load percent decrease of two and three times the percent reduction in part mass in the cases of short-shot and core-back foaming of TPO-7 respectively. The thin-wall TPO-8 sample exhibited the best trade-off, with a 24% reduction in part weight for only 11% reduction in maximum tensile load.

![Figure 7. Maximum tensile load relative to TPO-4 for Study 2](image)

TPO-5 and TPO-6 exhibited losses of two and one percent stiffness per percent part mass reduction respectively, which shows improvement over the Study 1 results (Figure 8). Compared to the solid TPO-7 sample, the short-shot TPO-7 sample exhibited a 9% loss in stiffness for an 8% reduction in mass, which is a moderately better trade-off than the core-back sample’s loss of 34% stiffness to 24% reduction in part mass. In contrast to its relatively moderate loss in tensile properties, thin-wall TPO-8 had a significant loss of stiffness, approximately 54%.

![Figure 8. Stiffness relative to TPO-4 for Study 2](image)

MAII energies at both temperatures were comparable to the control for the optimized reduced density grades, and ductile behavior was maintained (Figure 9). Conversely, both foamed TPO-7 samples exhibited significant decreases in energy absorption with core-back being the most severe example. Failure behavior was more difficult to characterize. Both samples yielded, but in a manner atypical with conventional solid ductile materials. There was no loss of product or fragments detaching from the specimen nor was there the usual drawing phenomenon. Rather, the foam structure displayed a splitting or tearing that was much more apparent in the heavily foamed core-back sample. The loss in MAII peak energy for the thin-wall TPO-8 sample was proportional to the reduction in wall thickness.
Figure 9. Multiaxial instrumented impact peak energy relative to TPO-4 for Study 2

**Discussion**

Decreasing the amount of mineral filler not only lowered the composite density but also had deleterious effects on flexural properties and dimensional stability while either maintaining or bolstering both tensile and impact performance. These findings reaffirm that there are additional considerations needed to delivering an improved product beyond mere removal of mineral filler.

The optimized reduced density formulas performed well in the diagnostic tool compared to their injection molded test piece counterparts. The differences in flexural moduli of TPO-5 and TPO-6 relative to TPO-4 were reflected in their relative stiffness along with increases in tensile properties. Given that the MAII performance was likewise comparable to the control, it appears evident that material density reduction with careful material optimization is a viable option for reducing part weight for many automotive applications, including those components in which safety is an important consideration.

As evidenced by the TPO-7 trials, short-shot and core-back foaming provided marginal to substantial reductions in part weight at the expense of mechanical performance. Although core-back foaming provides the greatest opportunity for weight reduction, it also carries the greatest risk for property deterioration. Previous efforts by Advanced Composites suggest that this may be offset by starting with a greater initial fill thickness and then expanding to an even greater final thickness to improve stiffness while still maintaining a lower total part weight [5]. Given the nature of the foamed MAII behavior, short-shot and core-back foaming are not recommended for applications with stringent safety requirements.

As expected for TPO-8, wall thickness reduction caused a moderate reduction in maximum tensile load and a substantial decrease in both part weight and stiffness. Using the available 1.8 mm thickness drastically lowered the final part weight but resulted in unacceptable stiffness. Assuming the beam-in-bending model, a 52% increase in flexural modulus might only enable a 13% reduction in wall thickness. In a large part, this could offer tremendous weight savings with no penalty to stiffness. The thin wall sample exhibited ductile failures during MAII testing at 23°C, but its proportional loss in energy absorption to wall thickness reduction reiterates the necessity of careful consideration in part design and application end-use.

**Conclusions**

Several weight reduction strategies were evaluated in these studies. Of these three techniques, reduced density compounds provided the least benefit in terms of weight reduction potential but also caused fewer detrimental consequences to part attributes than either thin-walling or foaming. Wall thickness reduction shows promise but has practical limits set by the cubic dependence of stiffness on wall thickness. For significant weight savings, the increase in flexural modulus relative to the base material must be far greater than the relative decrease in wall thickness. Finally, foaming offers further weight savings potential, but the introduction of voids poses new difficulties in optimizing material formulation, processing, and part design. Future studies will more thoroughly investigate the relationship between starting thickness, final thickness, process parameters, and properties to find the ideal balance between weight reduction and performance.

**References**

Figure 10. 3D rendering of “Mini-Door Panel” tool

Figure 11. Rear view of “Mini-Door Panel” tool