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<td><strong>Authors(s)</strong></td>
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Miniaturization/process dependent mechanical properties of microinjection moldings

Nan Zhang and Michael Gilchrist

*Product miniaturization and high shear/cooling rates in microinjection molding increase the volume of highly oriented skin layer, which modifies a product’s mechanical properties and needs careful consideration for product design.*

Microinjection molding (μIM) has been successfully developed as a mass production technology for small, high precision, high value-added plastic parts. It typically involves micro components weighing a few milligrams or large parts having micro/nano scale surface features. Such products characteristically have a high surface to volume ratio, up to $10^3$–$10^6$ m$^{-1}$, and a correspondingly faster cooling rate than larger components. Because of the intrinsic low thermal conductivity of polymer materials, a large thermal gradient exists across the part thickness. In order to fill such small features, high temperatures and high injection speeds are applied to reduce melt viscosity by shear thinning; these materials experience correspondingly high stresses and shear rates. Such a variable thermomechanical environment influences the nucleation and growth rate of crystalline entities and thus a micropart’s mechanical properties.

Recent efforts to understand the morphology of microparts has focused on comparing millimeter and micrometer sized parts. Although such comparisons identified significant differences$^{2,3}$, they did not reveal systematic or intrinsic microstructural changes and the consequences for final product mechanical properties. Thus, such comparisons cannot direct inform micro product design. Additionally, previous research ignored the consequences of extreme processing (high shear rate and high cooling rate) and underestimated the variation of process induced properties. Our work has focused on both size- and process-induced crystallization and their effect on mechanical properties.

We designed a series of dumbbell shaped mold inserts to form miniature tensile specimens of part thickness 100, 200, 300, 400 and 500µm (Figure 1), which were used to characterize miniaturization induced crystallization and the consequences for mechanical properties. We also varied injection velocity and mold temperature to relate process induced crystallization to mechanical properties.

![Figure 1. Miniaturized tensile specimen having volume about 3 standard polymer pellets made by Poly(ether block amide) Pebax 7233 SA01.](image)

Experimental results indicate that when part thickness decreases from 500µm to 100µm, the volume ratio of oriented skin layer increases from ~10% to ~67%, while the molecular orientation factor increases from ~0.37 to ~0.6 (see Figure 2 & 3), which means more polymer chains are oriented along the flow direction. The lamella orientation is characterized by Herman’s orientation factor $f$, which indicates the orientation of crystalline lamellae relative to the reference direction (melt flow direction...
in this work). The increased oriented structure enhances the Young’s modulus and yield stress (Figure 3), both of which increase after aging, while the elongation decreases (Figure 3).

![Figure 2. Morphology comparison of parts with thickness from 100µm to 500µm of 22 days after molding (before ageing) and 401 days after molding (after ageing).](image)

![Figure 3. Effect of cavity thickness on mechanical properties before and after natural aging: (a) Young’s modulus and strain at break, (b) Yield stress.](image)

Regarding process induced crystallization for a fixed 400µm thick part, the oriented skin layer decreases with increasing injection velocity and it reduces from when mold temperature increases. Higher temperatures suppress the cooling rate and results in a thinner orientated skin layer, while higher injection velocities both increase the density of nucleation and suppress fast cooling, which have a complicated effect on crystallization. Cooling rate was found to be more significant than velocity in forming highly oriented skin structures. The overall molecular orientation follows the variation of skin thickness. Young’s modulus, elongation and yield stress generally increase with an increase of skin ratio.

However, compared to standard tensile specimens (4mm thick), miniaturization results in decreased Young’s modulus and elongation, while yield stress increases. The effect of process on mechanical properties for a 400µm miniature tensile specimen indicated that the Young’s modulus is approximately half that of a standard tensile specimen; strain at break is 30% less than expected from material supplier data sheets, and yield stress is almost double than standard samples. Such comparisons suggest miniaturization and process-induced crystallization have a similar influence on product mechanical properties for microinjection moldings. For the fixed cavities thinner that 200µm, the process window becomes narrower because of fast cooling.

The quality of part design depends on the availability and accuracy of material characteristics. For microinjection moldings, measurement of mechanical properties at the micro scale is necessary for a successful micro product design, although the effect of thickness is similar for microinjection molding and conventional injection molding. Our recent work has indicated that shear stress is a good
candidate to characterize the onset of oriented structures under real molding conditions. This means that using shear stress as an in-line feedback signal during processing could enable in-line control of product morphology, and thus a product’s properties.

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Nan Zhang is a Senior Postdoctoral Research Fellow at University College Dublin. His research focuses on microinjection molding, prototyping polymer microfluidic devices, and manufacturing of microstructure tool inserts.

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**Reference:**

Table 1. Comparison of process and thickness dependent mechanical properties of miniature tensile specimens to the conventional 4mm thick standard tensile specimen from material supplier.

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<tr>
<th></th>
<th>Young’s Modulus (MPa)</th>
<th>Strain at break</th>
<th>Yield stress (MPa)</th>
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<tbody>
<tr>
<td>µIM(Process dependent)</td>
<td>247-275</td>
<td>1.5-2.60</td>
<td>33-39</td>
</tr>
<tr>
<td>µIM (thickness dependent)</td>
<td>249-319</td>
<td>1.2-1.5</td>
<td>29-38</td>
</tr>
<tr>
<td>Arkema (ISO 527-1/-2)</td>
<td>522</td>
<td>&gt;3</td>
<td>26</td>
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