RELATIONSHIP OF SHEAR HISTROY, MORPHOLOGY – MICROSTRUCTURE AND MECHANICAL PROPERTIES OF MICRO INJECTION MOLDED PARTS

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Abstract

The relationship of shear history, morphology-microstructure and mechanical properties of the micro-scale parts was investigated based on the polypropylene parts with thickness 0.2mm and 0.5mm molded under varied injection speed. Shear rate was analyzed using Moldflow. 0.5 mm parts showed skin-core structure in the thickness direction with imperfect shish-kebab structure appeared in the transition layer between skin layer and core layer, however, the transition layer of 0.2 mm parts shows columnar crystal. The whole shear level in shear history increased with injection speed increasing for all the parts with two thicknesses. The ratio of skin layer of 0.5 mm parts decreased as the injection speed increased, which result in the decreasing of yield stress, modulus, breaking strength and elongation at break. The ratio of skin layer of 0.2 mm parts increased with injection speed increasing, and results in increasing of yield stress, modulus and breaking strength, and decreasing of elongation at break.

Introduction

The micro injection molding process appears as one of the most suitable processes for fabricating complex micro plastic parts accurately at one process. The melt experienced a highly complex shear history in micro injection molding compared to conventional injection molding especially for semi-crystalline polymer. The shear history will influence the crystalline structure, the morphology and microstructure of the micro parts, and subsequently affect the mechanical properties of the parts. In order to obtain high quality micro injection molding parts, it is necessary to investigate the relationship of the molding processes, morphology and the mechanical properties.

The conventional injection molded parts show typical ‘skin–core’ structure within the cross-section. Ito et al. [1] found relative thickness of the microstructure layers were different between thin-wall injection (0.3 mm) and conventional injection molding. Julien et al. [2] reported no spherulite was present within the thickness of the high-density polyethylene (HDPE) micro molded part, and the reason was supposed to that large fraction of molten polymer contacted with the mold wall and promoted its heterogeneous nucleation in the thin-wall geometry. Liu [3-5] et al found large fraction of shear layer through-the-thickness-morphology of isotactic polypropylene (iPP) micropart with 200 mm thickness, and highly oriented shish-kebab structure was present in the shear layer of the microparts. The reason for the formation of highly oriented structures with large fraction was the reduced thickness which normally generated higher shear rates and faster cooling speeds during injection molding process. Li Shuang et al.[6-8] investigated the influence of mold temperature, melt temperature and injection speed on the morphology of the micro parts. A typical skin-core structure was found in the parts with thickness of 1mm, while almost no core layer and obvious shish-kebab structure showed in the parts with thickness of 0.2mm. Kamal et al[9-10] identified a five-layer skin core structure for micro molded polyoxymethylene and the thickness of each layer varied with the processing parameters and the location along the flow direction, and yield stress and elastic modulus of the parts decreased with the increase of injection velocity. The influence of the thickness of shear layer and the orientation of molecular chain on the mechanical properties of the micro injection molded parts was higher than that of the traditional injection molded parts. Other scholars[11-12] indicated that the modulus and yield stress decreased with the decreasing of the size of the micro parts. However, when the size is smaller than a critical value, the modulus and yield stress began to increase with the decrease of the part size, and the reason is that the micro scale effect makes the increase of the shear layer and crystallinity. Baldi et al.[13]investigated the relationships among the processing conditions, the mechanical properties and the microstructural characteristics of polyoxymethylene miniaturized specimens, and the material ductility in the miniaturized specimens depends on the microstructure which is significantly affected by the mould temperature. There were many attempts at understanding the correlation between mechanical properties and dimension of the micro parts. A systematic study of the relationship between processing parameters, morphology and mechanical properties of microinjection molding parts, and analysis of the formation mechanism of the
morphology and microstructure of the micro parts is needed.

In this work, single-factor experiments were conducted by varying the injection speed systematically to mold the test specimens, the shear history of the melt in the molding process was analyzed and the relationships among the shear history, morphology and microstructure, and the mechanical properties of the specimens were investigated.

**Experimental**

**Material**
The experimental material was polypropylene (iPP T30S, China Petroleum Chemical Co) with an isotactic index larger than 97%, melt flow rate of 3.5 g (10 min)$^{-1}$, tensile yield strength of 355 kg·cm$^{-2}$.

**Sample preparation and characterization**
The microparts were molded on an Eagel Victory 28 high speed Injection Molding System, which has maximum injection speed of 600 mm·s$^{-1}$, maximum injection pressure of 220 MPa and screw diameter of 18 mm. Two different thickness microparts (0.5 and 0.2 mm) were injection molded to investigate the impact of shear history on morphology and mechanical properties of the parts. Two-cavity mold were used to fabricate all the samples shown as shown in Figure 1.

The mold temperatures, melt temperatures and the packing pressure were 120 °C, 260 °C and 160 MPa respectively and they all kept constant during the experiments. The injection speed varied as shown as in Table 1.

![Figure 1. Micro Part and Mold](image)

(a) Geometry of micro parts  (b) Runner system  (c) Micro injection mold

In order to compare the morphology of the micro parts with different thicknesses, thin slices located at point A were cut by means of a microtome as shown in Figure 2, and morphology of the thin slices was observed and analyzed by PLM. The shear histories of point A of the parts molded under different injection speeds were simulated by MOLDFLOW, and the influence of shear rate on morphology at point A of the microparts was also analyzed. The mechanical properties of the microparts were evaluated by Instron 5585 universal testing machine follow ASTM D882-02 standard at room temperature. Five specimens molded under each condition were tested and the average values and standard deviations were evaluated.

![Figure 2. Sample preparation methods and processes](image)

**Results and discussion**

**Simulation results of shear rate**
The shear histories of point A of the micro parts with two thicknesses molded under different injection speeds were simulated, and the results indicated the whole level of the shear rate increase with the increase of injection speed. The relationship between maximum shear rate of the parts and injection speed were shown in Figure 3. The maximum shear rate increased with the injection speed increasing. However, there exists a critical point, the maximum shear rate decreased with the increase of injection speed as the value higher than the critical point. This is attributed to large amount of shear heat generated by steep shear rate which will lower the melt viscosity and reduce the effect of shear subsequently. In addition, when the shear rate is too high, the wall shear stress comes up to the critical value and wall slip behavior will occur in the actual micro injection molding and lead to

<table>
<thead>
<tr>
<th>Thickness /mm</th>
<th>Injection speed /mm·s$^{-1}$</th>
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<tbody>
<tr>
<td>0.5</td>
<td>50 90 130 170 210 250</td>
</tr>
<tr>
<td>0.2</td>
<td>90 130 170 210 250 330</td>
</tr>
</tbody>
</table>
shear rate decreasing with the increase of the injection speed[10].

Figure 3. The maximum shear rate at position A of the micro parts with different thicknesses under different injection speeds

Crystalline morphology

Figure 4 shows optical micrographs of the complete thickness of the micro parts with thickness of 0.5 mm under different injection speeds. Several structural layers can be distinguished in all the parts, skin layer including frozen layer and shear layer created by a rapid cooling down and solidifying and shear effect, a large thickness fraction of special transition layer with imperfect shish-kebab crystals and a small fraction spherulitic core with essentially no preferred orientation.

The first layer, named amorphous frozen layer, is generated by a rapid cooling effect of the molten polymer which is in contact with the cold mold wall. The polymer flow approaching the frozen layer has a higher shear rate and a lower cooling rate. These effects favor the formation of highly oriented shish-kebab structure, often referred as shear layer (shown as inserts at higher magnification in Figure 4). The center of the flow has a higher temperature, a lower cooling rate and a lower shear rate, allowing the relaxation of previously oriented macromolecule chains, which favors formation of spherulites. Imperfect shish-kebab crystals can be observed in the transition layer between the shear layer and the core. It is because the shear effect is not high enough to restrict the polymer chains, oriented structure is hard to maintained, and the growth of the lamellae is not enough.

The thickness of different layers and their relative thickness (ratio between the thickness and the total thickness) of the parts with thickness 0.5mm molded under different injection speeds were also evaluated (as shown in Figure 5). It can be noted that the relative thickness of the shear layer decreases with the increase of injection speed and shear rate. During filling stage in injection molding process, large amount of shear heat generated by the effect of shear effect which could lead to melt temperature increasing, molecular chain relaxation and thus thickness of skin layer decreasing. Furthermore, wall slip was observed when the shear stress is larger than critical value. This would lower the alignment degree of the polymer chains, leading to a lower thickness of skin layer. Overall, the thickness of the skin layer depends on the comprehensive effect of the complex shear history and heat history in injection molding process. Additionally, the relative thickness of transition layer was found increased by increasing the shear rate. This is because that high shear rate approaching skin layer result in high orientation of the molecular chains, but more polymer chains relaxed due to the lower cooling rates of this area.

Figure 4. PLM figures in position A of the parts with thickness of 0.5 mm under different injection speeds

Figure 5. (a) Relationship between skin, core ratio, share rate and injection speed

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Figure 5. Percentage of skin layer of the parts with thickness of 0.5 mm under different injection speeds

PLM micrographs of the parts with thickness of 0.2 mm under different injection speeds can be seen in Figure 6. A similar skin–core structure was also found along the thickness direction. It can be seen that the relative thicknesses of the skin layer was more than 80%. Different from the parts of thickness 0.5 mm, columnar crystal was shown in the core layer of 0.2 mm parts. Due to the lower thickness 0.2 mm, the parts were molded under high temperature, high pressure and high shear rate, leading to a highly oriented shish-kebab structure, namely thick shear layer. Polymer chains highly aligned and featured fibrils structure along the flow direction approaching the shear layer. These fibrils structures play the roles of heterogeneous nucleation, and induced folded-chains growing along the oriented direction. Coupled with the impact of spatial limit effect, asymmetrical column crystals were formed toward the core layer.

The relative thickness of the skin layer was also evaluated as illustrated in Figure 7. It can be seen that the relative thickness of skin layer increased and the relative thickness of core layer decreased with the injection speed increased for the 0.2mm parts, which is contrary to the results of 0.5mm. It can be explained by the balance of thermal dissipation and increasing orientation degree generated by the shear stress. The influence of thermal dissipation formed by shear had a dominant role for the parts with thickness 0.5 mm. However, orientation degree increasing is the main factor for the 0.2 mm parts.

Figure 6. PLM figures in position A of the parts with thickness of 0.2 mm under different injection speeds

Figure 7. Percentage of skin layer of the parts with the thickness of 0.2 mm under different injection speeds

Relationship between shear history, morphology and mechanical properties

The mechanical properties as a function of injection speed are evaluated in this section (Figure 8). Meanwhile, relationship between mechanical properties and skin layer ratio of micro parts are also discussed. The mechanical properties indexes including modulus, breaking strength, yield stress and elongation at break for two different
thickness (0.5 mm and 0.2 mm) parts under different injection speeds were illustrated in Figure 8 (a), (c) respectively. Relationship between mechanical properties and relative thickness of skin layer of the micro parts were shown in Figure 8 (b), (d) for 0.5 mm and 0.2 mm parts respectively.

The yield stress, modulus and breaking strength decreased as relative skin layer decreasing for 0.5 mm thick parts with the increase of injection speed (Figure 8 (a), (b)). This is because highly oriented molecular chains in the skin layer can stand greater force. Nevertheless, the arrangement of lamellae in the core layer with spherulites and in the transition layer with columnar crystals is irregular and unstable, and is easy to cause wall slip, leading to a lower strength.

Additionally, a relative thinner skin layer and higher amount of imperfect shish-kebab structure as the injection speed increasing will lead to the reduction of its ductility. Hence, for micro parts with thickness of 0.5 mm, the ratio of skin layer was higher under lower injection speed, leading to better strength and ductility performance. The modulus, yield stress and breaking strength for 0.2 mm parts became higher with the skin layer increasing as shown in Figure 8. However, the elongation at break decreased with the thickness of skin layer increasing.

The mechanical properties of the micro parts with different thicknesses were listed in table 2. Overall, yield stress, breaking strength and elastic modulus increased and the elongation at break decreased with thickness of the micro parts decreasing. All above-mentioned discussions of mechanical properties reveal that the processing parameters can remarkably change the mechanical performance due to the unique shear history in micro injection molding which induced different crystallization morphologies.

![Graph](image1)

(a) Mechanical properties vs injection speed of 0.5 mm parts

![Graph](image2)

(b) Mechanical properties vs skin layer ratio of 0.5 mm parts

![Graph](image3)

(c) Mechanical properties vs injection speed of 0.2 mm parts

![Graph](image4)

(d) Mechanical properties vs skin layer ratio of 0.2 mm parts

Figure 8. Relationship between mechanical properties and skin layer ratio of 0.5 mm parts

<table>
<thead>
<tr>
<th>Thickness/mm</th>
<th>ε/ %</th>
<th>σy/ Mpa</th>
<th>σb/ Mpa</th>
<th>E/ Mpa</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>440- 600</td>
<td>39-45</td>
<td>45-60</td>
<td>180-320</td>
</tr>
<tr>
<td>0.2</td>
<td>160-220</td>
<td>45-55</td>
<td>50-70</td>
<td>280-350</td>
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Table 2. Mechanical property of the micro parts with different thicknesses

Conclusions

Typical three structural layers can be distinguished in the parts with the thickness of 0.5 mm, including skin...
layer, transition layer and a core layer. Different structures were found in the 0.2 mm parts containing skin layer, core layer and columnar crystal structured layer between them. The relative thickness of each structural layer is related to the injection speed and the thickness of the parts. The ratio of skin layer decreased and the relative thickness of imperfect shish-kebab structured layer increased with the increasing of injection speed for 0.5mm parts. However, with the injection speed and shear rate increasing, the ratio of skin layer increased and the ratio of core layer decreased for 0.2 mm parts. The yield stress, breaking strength, elastic modulus and elongation at break decreased with the increasing of injection speed for the 0.5mm parts. Expect for elongation at break, the yield stress, breaking strength and elastic modulus increased with the increase of injection speed for the 0.2 mm parts. Overall, the morphology and structure of the parts depend on the complex shear history and thermal history of the melt, and the mechanical properties of the part are determined by its morphology and structure. The elastic modulus, yield stress and fracture strength of the parts increases with the decrease of the part thickness, and the elongation at break decreases with the decrease of the part thickness.

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