NUMERICAL SIMULATION AND MOLDABILITY INVESTIGATION OF MICRO-FEATURES
Shia-Chung Chen¹², Li-Chi Su¹², Cheng-Yi Chang³, Hsin-Wei Hung³ and Wen-Hsien Yang³

1. Department of Mechanical Engineering, Chung Yuan Christian University Taiwan.
2. R&D Center for Membrane Technology, Chung Yuan Christian University Taiwan.
3. CoreTech System Co., Ltd., Hsinchu, Taiwan.

Abstract
In micro-injection molding, the preservation of precise micro-feature is one of the most important indications to ensure proper functionality and quality. A new technique, "Induction Heating", which is advanced in heating up the mold quickly and accurately, is adopted to control mold temperature during filling phase. This paper aims to analyze the technique specifically for a part with micro-feature of a high aspect ratio. Meanwhile, it probes into the result of numerical simulation and actual experimental investigation. The result shows that some critical factors have a dominant effect on the molding mechanism, and this result will be beneficial to the development of micro-injection molding technology.

Introduction
Micro-injection molding can be classified into two categories. One is a micro part which is entirely small; the other is a part with tiny features on a relatively large body. Nowadays, with the advancement of manufacturing technique and economics, products with micro-features, such as light guide plate of LCD, DVD and so on, have been widely prevailed all over the world. However, it is still a challenge for engineers to ensure proper functionality and quality by correctly preserving the micro-feature.

To preserve the micro-feature as complete as possible, variotherm technique is often introduced into the molding process. With the technique, the mold surface with the micro-feature is allowed to be heated up to a temperature higher than general recommended mold temperature to keep the polymer from solidification in micro-features during injection. The extra benefit of the technology is that molders can heat up the mold surface efficiently and accurately to achieve the required temperature [3-6].

This paper aims to analyze the moldability of a micro-feature vs. its surface temperature, meanwhile comparing the experiment with the 3D simulated results, in order to identify a proper heat transfer coefficient (HTC) that would be suitable for simulations of micro-injection with similar micro-feature.

Numerical modeling
The polymer melt is assumed to behave as Generalized Newtonian Fluid (GNF). Hence the non-isothermal 3D flow motion can be mathematically described by the followings:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 \]  
(1) Conservation of Mass

(2) Conservation of Momentum
\[ \frac{\partial}{\partial t}(\rho u) + \nabla \cdot (\rho uu - \sigma) = \rho g \]

where \( \sigma = -pI + \eta \left( \nabla u + \nabla u^T \right) \)

(3) Conservation of Energy

\[ \rho C_p \left( \frac{\partial T}{\partial t} + u \cdot \nabla T \right) = \nabla \cdot (k \nabla T) + \eta \dot{\gamma}^2 \]

where \( u \) is the velocity vector, \( T \) the temperature, \( t \) the time, \( \rho \) the pressure, \( \sigma \) the total stress tensor, \( \rho \) the density, \( \eta \) the viscosity, \( k \) the thermal conductivity, \( C_p \) the specific heat and \( \dot{\gamma} \) is the shear rate. In this work, the modified-Cross model with Arrhenius temperature dependence is employed to describe the viscosity of polymer melt:

(4) Modified-Cross model

\[ \eta(T, \dot{\gamma}) = \frac{\eta_0(T)}{1 + \left( \eta_0^{\dot{\gamma}} / \dot{\gamma}^* \right)^n} \]

with

\[ \eta_0(T) = B \exp \left( \frac{T_c}{T} \right) \]

where \( n \) is the power law index, \( \eta_0 \) the zero shear viscosity, and \( \dot{\gamma}^* \) is the parameter that describes the transition region between zero shear rate and the power law region of the viscosity curve. A volume fraction function \( f \) is introduced to track the evolution of the melt front. Here, \( f=0 \) is defined as the air phase, \( f=1 \) as the polymer melt phase, and then the melt front is located within cells with \( 0<f<1 \). The advancement of \( f \) over time is governed by the following transport equation:

(5) Transport Equation

\[ \frac{\partial f}{\partial t} + \nabla \cdot (uf) = 0 \]

The flow rate or injection pressure is prescribed at mold inlet. No slip is assumed at mold wall. Note that only inlet boundary condition is necessary for the hyperbolic transport equation of volume fraction function.

**Simulation**

Utilizing the simulation of injection molding to evaluate the moldability of micro-feature of part, the most difficult issue is to determine the heat transfer coefficient that can properly describe the non-continuous temperature distribution at both sides of the interface between the melt and the mold. Besides, because of the huge thickness difference between the micro-feature and the plate, the mesh modeling for sufficient resolution with a suitable element count for calculation becomes a challenge as well. To solve the problem, different element topologies were adopted to build the mesh model. Fig. 4 shows the cross section of the mesh in the joint of the plate and the micro-feature. The material used in this study is PMMA-CHIMEI CM205. Fig. 5 (a) and (b) are the viscosity and pvT curves for the material. The process condition of simulation is the same with the experiment, besides, various HTC (from 25000 to 500) were taken into simulation.

**Results and discussions**

To precisely measure the height of the micro-feature, a 3D laser digital microscope is applied to scan and measure it. Fig. 6 shows one of the scanning images of a molded micro-feature. Fig. 7 shows the location to measure the altitude of the micro-feature.

The experimental result is shown in Fig. 8, which shows that the vacuum condition doesn’t have a significant influence on the moldability. The most important phenomenon observed in the result is that the height of the microstructure increases quickly when the temperature of the induction-heated surface exceeds 100 °C. Also, when the surface is heated up to 110 °C, the altitude of the structure is drastically increased to more than 90 % of the height. Refer to [3] for the details of the experiments.

Simulations with the same process condition but different HTC were conducted for comparisons. The temperature boundary condition of the induction-heating surface is programmed to be the same to meet the experimental condition. Fig. 9 shows the surface with micro-feature where the boundary temperature is controlled to simulate the effect of induction heating. Fig. 10 shows the melt advancement of one of the simulations. With a series of simulations regarding different HTC, a set of simulations where HTC = 1250 is observed to have similar moldability tendency at the same temperature domain. Fig. 11 shows the filling status of the micro-feature with different HTC were conducted as well as the injection simulations. By comparing the results between simulations and experiments, a proper heat transfer coefficient is found in the simulation that shows the same physical tendency with the experiment. The coefficient found in the study will be a good reference for engineers who want to evaluate the moldability of a micro-feature part.

**Conclusion**

Heat transfer coefficient is used to describe the convection heat transfer between fluid and solid. In the study, the exact injection experiments have been conducted as well as the injection simulations. By comparing the results between simulations and experiments, a proper heat transfer coefficient is found in the simulation that shows the same physical tendency with the experiment. The coefficient found in the study will be a good reference for engineers who want to evaluate the moldability of a micro-feature part.
References


Keywords

micro injection, induction heating, heat transfer coefficient, 3D simulation

Acknowledgement

This work was partially supported by National Science Council NSC grant 94-2745-E-033-001-URD.

Table 1. Experimental molding conditions

<table>
<thead>
<tr>
<th>Experimental molding conditions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>PMMA-CHIMEI:CM205</td>
</tr>
<tr>
<td>Inject velocity</td>
<td>100 mm/s</td>
</tr>
<tr>
<td>Inject ratio</td>
<td>25.434 cm³/s</td>
</tr>
<tr>
<td>Packing pressure</td>
<td>140 MPa</td>
</tr>
<tr>
<td>Packing time</td>
<td>3 seconds</td>
</tr>
<tr>
<td>Melt temperature</td>
<td>250°C</td>
</tr>
<tr>
<td>Mold temperature</td>
<td>60.80.90.100.110.120.130.140(°C)</td>
</tr>
</tbody>
</table>
Fig. 4. Schematics of 3D mesh for micro-structure

Fig. 5. Material properties used in this analysis
(a) viscosity  (b) pvT

Fig. 6. Scanning image of the 3D laser digital microscope

Fig. 7. The location to measure the altitude of the micro-feature

Fig. 8. The altitude of micro-feature vs. various induction-heating temperature (experiment)

Fig. 9. The surface boundary used to simulate induction-heating effect.

Fig. 10. The simulated melt advancement

Fig. 11. Shows the filling status of the micro-feature with different induction-heating temperature with HTC=1250
Fig. 12. The simulated X-Y plot of the filling altitude with HTC = 1250

Fig. 13. The simulated X-Y plot of the filling altitude with the other HTC value