NUMERICAL SIMULATION AND MOLDABILITY INVESTIGATION OF MICRO-FEATURES

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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.

The true 3D numerical approach developed in the past few years [1-2] is applied to the simulation. Hele-Shaw approach method is not suitable for the simulation because it lacks transverse flow information and the fountain flow effect around the flow advancement. Under the circumstances, the thermal history of a polymer particle could be not fully characterized; it might lead to a significant influence on the temperature estimation.

Experiment

An experiment of micro-feature molding whose purpose is to get a good reference data regarding the subject had been conducted. The schematic of the experimental part is shown as Fig. 1. The thickness of the part is 1.2 mm. The picture of the mold is shown as Fig. 2.

To control the temperature of mold surface which containing the micro-feature, a variotherm technique, "Induction Heating", is introduced to the project. The device is composed of a rectifier, a frequency converter, a transformer and a coil. Following Faraday's and Lenz's Law, having an AC current passing through a heating coil, an alternating magnetic field will be created. Simply by placing the coil near by the mold surface, the difference in magnetic flux through the mold surface will result in Eddie current flow through it. The Eddie current flow in the mold will cause the object to heat up due to the electrical resistance, thus achieving the goal of heating mold surface.

The detailed molding conditions are shown in Table 1. Fig. 3 shows the schematics of the mold surface with the micro-feature and induction-heating coil. Before filling, the mold temperature of side surface had always been kept as 60 °C, meanwhile the temperature of the core side containing the micro-feature varied from 70 °C ~140 °C. The experiment is performed with 2 conditions, with and without vacuum.

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:

(1) Conservation of Mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0$$

(2) Conservation of Momentum

$$\frac{\partial}{\partial t}(\rho\mathbf{u})+\nabla\cdot(\rho\mathbf{uu}-\boldsymbol{\sigma})=\rho\mathbf{g}$$

where $\boldsymbol{\sigma}=-p\mathbf{I}+\eta\left(\nabla\mathbf{u}+\nabla\mathbf{u}^{T}\right)$

(3) Conservation of Energy

$$\rho C_{P}\left(\frac{\partial T}{\partial t}+\mathbf{u}\cdot\nabla T\right)=\nabla(\mathrm{k}\nabla T)+\eta\dot{\gamma}^{2}$$

where $\mathbf{u}$ is the velocity vector, T the temperature, t the time, p the pressure, $\boldsymbol{\sigma}$ the total stress tensor, ρ the density, η 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

$$\eta(T,\dot{\gamma})=\frac{\eta_{o}(T)}{1+\left(\eta_{o}\dot{\gamma}/\tau^{*}\right)^{1-n}}$$

with

$$\eta_{o}(T)=BExp\left(\frac{T_{b}}{T}\right)$$

where n is the power law index, η_o the zero shear viscosity, and τ^* 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

$$\frac{\partial f}{\partial t}+\nabla\cdot(\mathbf{u}f)=0$$

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 ºC. Also, when the surface is heated up to 110 ºC, 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 induction-heating temperature, where the deep blue color indicates the unfilled area. Fig.12, the X-Y plot of the filling altitude with HTC =1250, shows a very good agreement with the experimental result. Fig.13 shows the simulation results with HTC = 25000, 5000 and 750. The correlations with experiment are not as good as HTC=1250 at all.

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.

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Keywords

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

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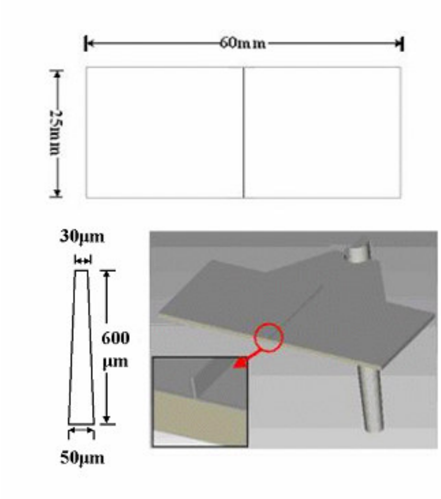


Fig. 1. Schematics of micro-feature part

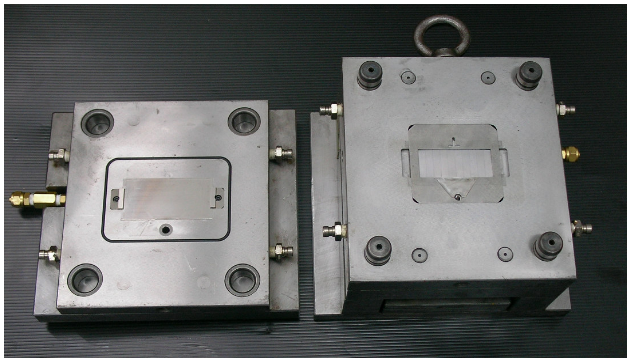


Fig. 2. Micro-feature mold for experiment

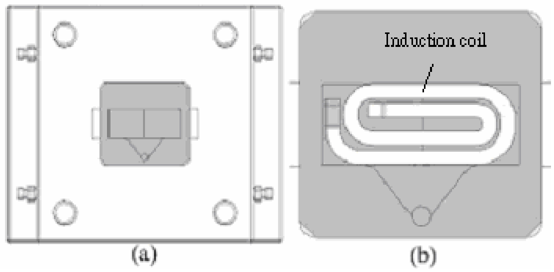


Fig. 3. Schematics of micro-feature part and the induction coil

Table 1. Experimental molding conditions

Experimental molding conditions	
Material	PMMA-CHIMEI:CM205
Inject velocity	100 mm/s
Inject ratio	25.434 cm^3/s
Packing pressure	140 MPa
Packing time	3 seconds
Melt temperature	250℃
Mold temperature	60.80.90.100.110.120.130.140(℃)

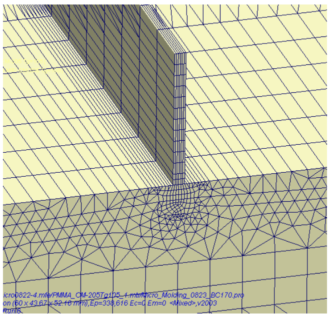
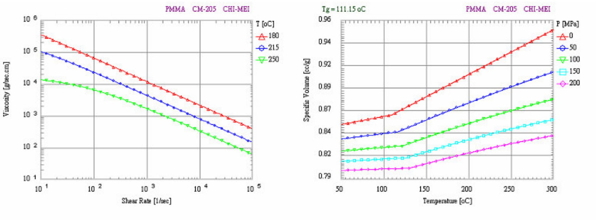


Fig. 4. Schematics of 3D mesh for micro-structure



(a)　　(b)

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

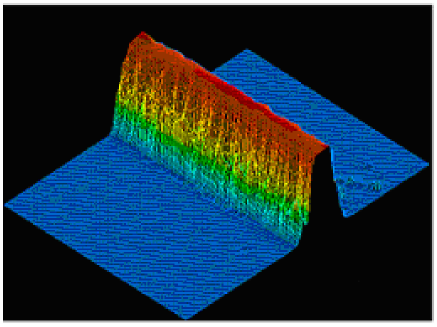


Fig. 6. Scanning image of the 3D laser digital microscope

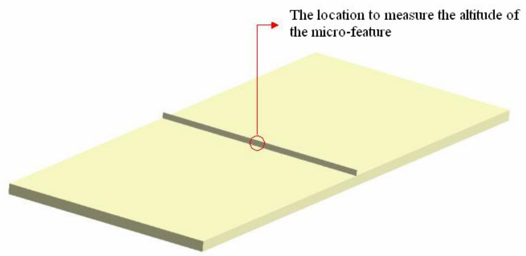


Fig. 7. The location to measure the altitude of the micro-feature

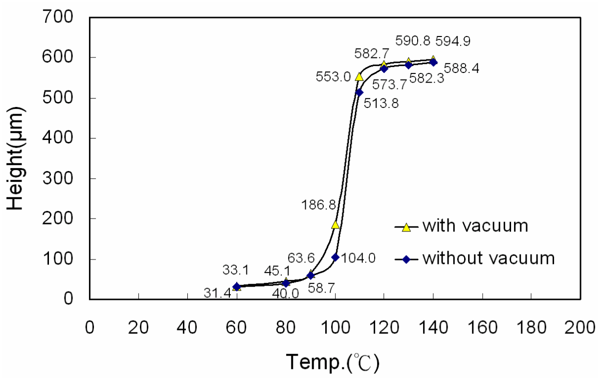


Fig. 8. The altitude of micro-feature vs. various induction-heating temperature (experiment)

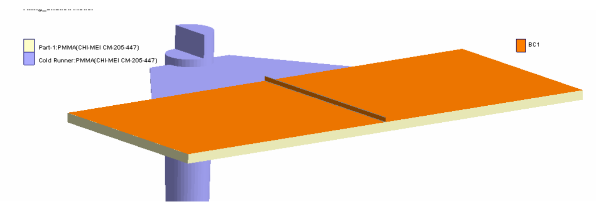


Fig. 9. The surface boundary used to simulate induction-heating effect.

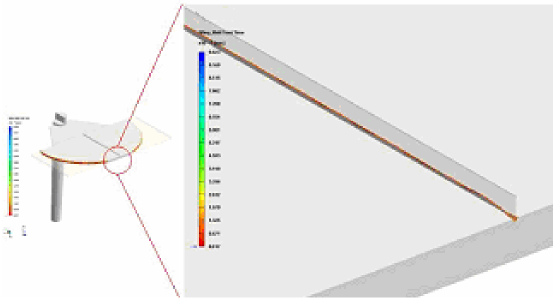


Fig. 10. The simulated melt advancement

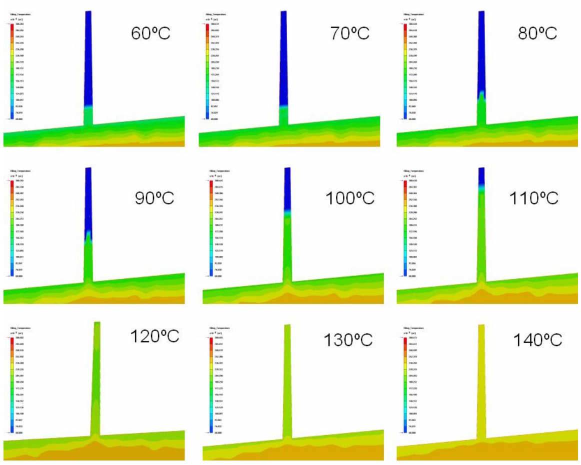


Fig. 11. Shows the filling status of the micro-feature with different induction-heating temperature with HTC=1250

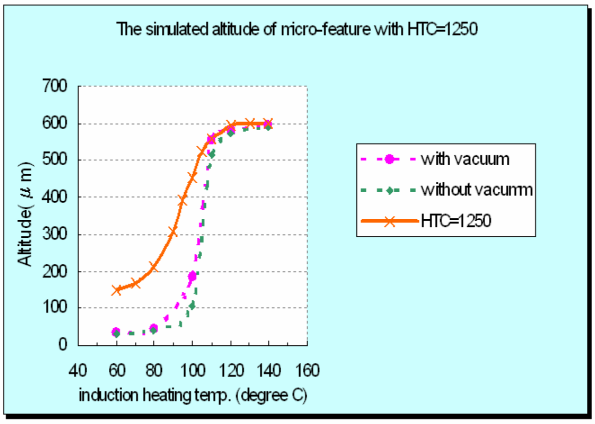


Fig. 12. The simulated X-Y plot of the filling altitude with HTC =1250

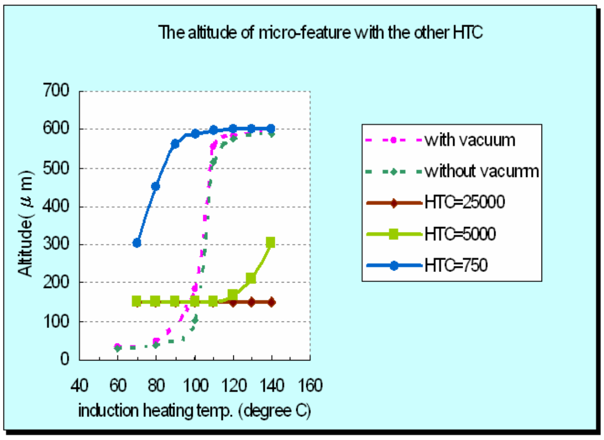


Fig. 13. The simulated X-Y plot of the filling altitude with the other HTC value