대면적 미세패턴 사출성형에서의 전산 모사
Multi-scale simulation of injection mold filling with micro featured parts

*박 시환 [1], #이 우일 [1], 유 영은 [2], 최 두선 [2]
*Si Hwan Park[1], #Woo Il Lee[1] (wilee@snu.ac.kr), Yeong Eun Yoo[2] and Doo-Sun Choi[2]
[1] 서울대학교 기계공항공공학부, [2] 한국기계연구원 나노공정팀

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1. INTRODUCTION

In recent years, the fabrication of polymer-based micro-components for optical and biomedical applications has gained increasing attention [1]. And micro-injection molding of polymer materials is one of the key technologies for micro-manufacturing because of the probability for mass production. Components manufactured by micro-injection molding fall into one of the following two categories: Micro-sized parts and regular-sized parts with micro features. Due to the presence of two distinctively different length dimensions, it is a challenge to simulate micro-injection molding processes.

In this paper, a two-step method (macro-micro filling) is adopted for an efficient filling analysis of a part with micro-surface features with reasonable number of elements. The transcription depth in micro-channels is simulated and compared with the experiment's results.

2. EXPERIMENTAL

A conventional injection machine(Sumitomo SE550D) was used in the experiment. A prism pattern, with V grooves with a pitch of 50 ㎛ and a right angle, was adopted. The cavity size was 400X400mm^2, with a thickness of 1.0mm (Fig. 1). A pressure sensor made by Kistler (6190A) was mounted, and the material used is a polymethyl methacrylate (PMMA) from Asahi (Grade 80NA). The detailed processing conditions applied in the present micro-injection molding experiments are listed in Tables 1 and 2.

Table 1 Injection molding operational conditions

	Injection time(sec)	Packing pressure(kgf/c)	The growth rate of the cavity pressure(Mpa/sec)
Case 1	1.33	350	300(measured)
Case 2	1.33	1250	300(measured)
Case 3	0.89	350	600(measured)
Case 3	0.89	1250	600(measured)

Table 2 Injection molding operational conditions

	Mold temperature(oC)	Other conditions
Case 5	70	Injection time : 0.89sec Packing pressure:1250(kgf/c)
Case 6	90	
Case 7	110	
Case 8	130	

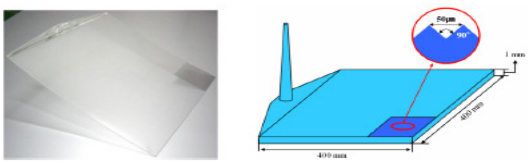

Fig. 1 Product resulting from injection molding and the shape of micro-patterns

3. NUMERICAL PROCEDURE

In order to understand the flow pattern, a numerical simulation was performed. The governing equations of the two-dimensional system are as follows:

Conservation of Mass

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

Conservation of Momentum

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right) = \nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{S} \tag{2}$$

Constitutive Equations

$$\boldsymbol{\sigma} = \boldsymbol{\tau} - p\mathbf{I} \ ; \ \boldsymbol{\tau} = 2\mu \mathbf{D}$$
$$\mathbf{D} = \frac{1}{2}\left[(\nabla \mathbf{u}) + (\nabla \mathbf{u})^T\right] \tag{3}$$

where u , ρ , σ , S , τ , p and D are the velocity vector, density, total stress tensor, body forces, viscous stress tensor, pressure, and rate of deformation tensor respectively.

In order to handle the incompressible constraint, the penalty method was used since the computational cost can be saved [2-4].

$$p = -\lambda \nabla \cdot \mathbf{u} \tag{4}$$

where λ is a large, positive penalty parameter (10^8~10^{12}), which numerically enforces the mass conservation.

In order to deal with the moving boundary problem, the volume of fluid (VOF) method was used to trace the free surface. The fractional volume is then computed and updated at each time step using the following advection equation:

$$\frac{\partial C}{\partial t} + u_i \frac{\partial C}{\partial x_i} \tag{5}$$

In the above equation,where C is the color function (fractional volume).

In order to consider the effect of surface tension in the Eulerian grid system, we adopted Brackbill's CSF model formulation [5], which converts surface force to body force: as

$$F = \frac{\gamma}{[C]}\kappa \nabla C, \quad \kappa = -(\nabla \cdot n), \quad \mathrm{n} = \frac{\nabla \mathrm{C}}{|\nabla \mathrm{C}|} \tag{6}$$

The 3D problem has been conventionally simplified to a 2D problem based on a Hele-Shaw approximation [6,7]. Commercial 2.5D codes provide good results with flat and thin, so-called standard (i.e., flat and thin) injection modeled parts. However, standard injection molding simulation packages are not able to describe all of the effects in micro-molding [8]. A 3D fine mesh may have too many nodal unknowns to make the simulation practical. On the other hand, the simplified 2.5D mesh may not be accurate enough. Therefore, we conducted a step by step analysis from global to local. The global analysis is important as it allows us to predict with confidence the characteristics of the final product. Furthermore, in this study, the global analysis is also performed in order to obtain the boundary condition for the local analysis. Then, using the boundary condition from the global analysis, the local area is analyzed to observe the filling length and predict the defects of the pattern. In the global analysis (including the micro-pattern) the flow behavior is almost same as the global analysis without the micro-pattern [9]. When the polymer melt flows near the micro-feature, it tends to bridge over instead of flowing in, since the pressure at the flow front is too low for it to enter the micro-feature

(Fig. 2). The two-step method mentioned above can be used to analyze the micro-flow with appropriate boundary conditions.

The computational region and geometry are illustrated in Fig 2. A velocity boundary condition from global analysis was applied on both sides of the domain. a no-slip condition was imposed on the mold surface,. For micro-flow calculation, pressure obtained from the macro flow analysis was applied along the bottom of the domain (Fig 2).

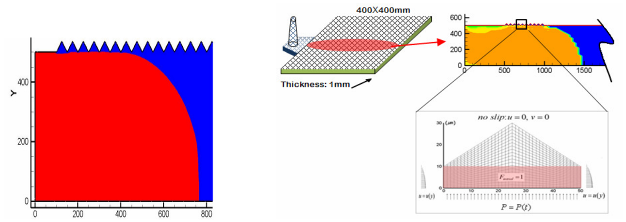

Fig. 2 Flow of liquid near the micro feature and Illustration of the macro and micro- flow domains

4. RESULTS AND DISCUSSION

First, the effect of the injection rate and packing pressure on the transcription fidelity was investigated. Fig. 3 shows four SEM images of the replicated surface of the samples, molded at a the mold temperature of 70°C, and the simulated results in with the similar processing conditions. As the growth rate of the cavity pressure is higher, the groove peak is sharper. Because the time span is shorter at the higher injection speed, athe more rapid increase of pressure can push more polymer melt into the micro-channels before the melt is cooled down andto be solidified. This result shows that the transcription fidelity is high around the gate and the edge [10], and this difference proves that a high injection speed is more effective in improving the transcription than a high packing pressure in case that the mold temperature is below the glass transition temperature.

Secondly, in the fabrication of micro-features, the cooling rate of the polymer melt is so quick that the flow length is limited to a very short distance under the usually mold temperature. The high mold temperature could prevent the polymer from being solidified rapidly and keep the viscosity of the polymer low.

Fig. 4 shows the relationships between the transcription ratio and the mold temperature. It is evident that the filling length tends to sharply increase with a high mold temperature. Although the others conditions are same, the groove peak of the sample that is fabricated above 110°C is shaper than those of the sample molded with lower mold temperatures.

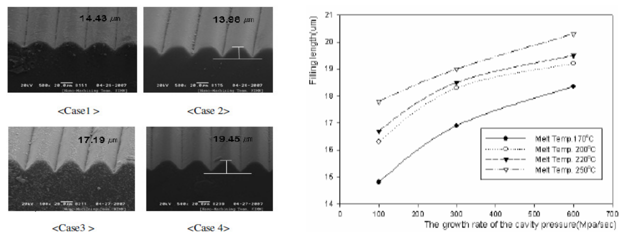

Fig.3 Variations of micro-patterns according to processing conditions

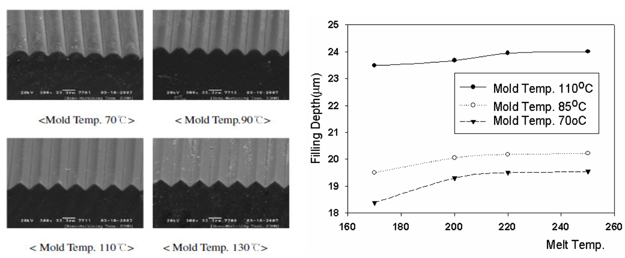

Fig. 4 Micro-patterns according to mold temperature

A three-dimensional plot of the transcription depths of V-grooves in the molded samples with processing conditions such as mold temperature and the growth rate of the cavity pressure are showed Fig. 5. The plotted upper surface and the lower surface represent the filling length with a mold temperature of 110°C and 70°C respectively. As showed in Fig. 5, the mold temperature was found to be the most important processing parameter of the transcription by microinjection molding. With regard to the mold temperature of 110°C, the filling lengths were above 23.4 ㎛.

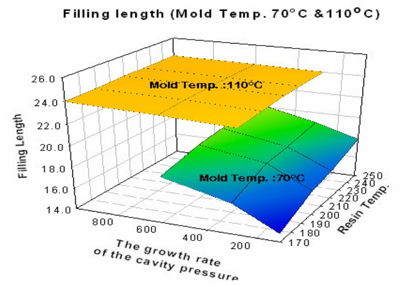

Fig. 5 Three-dimensional plots of the filling length for different processing conditions

5. CONCLUSION

In this paper, a numerical analysis has been conducted with the intent of studying the processing conditions during the micro-injection molding of regular-sized parts with micro-features. According to the numerical results, when the sample is fabricated below the glass transition temperature, the growth rate of the cavity pressure is higher and the fabricated groove peak is shaper at a higher main flow velocity. However, the transcription fidelity is more affected by the mold temperature than by any of the other processing conditions. The numerical method can be used to better understand flow behavior during micro-injection molding, and can thus be utilized in order to determine optimal processing conditions

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