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Study on flow behavior of polymer solutions in microchannels

Dong-Hak Kim[1*], Guojun Xu[2], Kurt W. Koelling[2] and L. James Lee[2]

미세구조 내에서의 사출성형 흐름에 관한 연구

김동학[1*], Guojun Xu[2], Kurt W. Koelling[2], L. James Lee[2]

Abstract Filling the microchannels is very important in designing micro-injection molding, microdevices, etc. In this paper, flow dynamics was studied in injection molding with microchannels. A transparent PMMA mold was designed and the flow dynamics was observed. The experiment was performed using poly (ethylene oxide) (PEO) and polyacrylamide (PA) aqueous solutions. The transient dynamic flow and flow competition between the base plate and the microchannels were observed. The flow observation was used to explain previous filling length results in microchannels during micro-injection molding.

Key words: flow dynamics, micro-injection molding, microchannel

요 약 랩온어칩(Lab-on-a-chip) 등 미세구조를 갖는 다양한 장치들의 대량 생산이 가능한 사출성형공정 내에서의 미세 흐름 거동의 이해는 매우 중요하다. 본 논문에서는 마이크로 채널 구조 내에서의 사출성형 흐름에 관하여 연구하였다. 흐름 현상을 관찰하기 위하여 투명한 PMMA를 사용하여 가시화 금형(visual mold)을 제작하였다. 실험 대상 물질로는 고분자 용액인 PEO (poly (ethylene oxide)) 와 PA (polyacrylamide) 용액을 선정하였는데, 이는 고분자 용융체의 특징인 높은 점성과 탄성을 갖도록 설계한 것이다. 시간에 따른 흐름현상과 주 채널과 마이크로 채널과의 경쟁적인 흐름 현상을 관찰하였다. 이로부터 마이크로 사출성형 흐름에서 나타나는 마이크로 채널 내의 충전길이에 대한 해석이 가능하였다.

Introduction

The demand for high-precision miniature devices and efficient processing technologies for micro-/nano-fabrication has been growing rapidly in recent years. Potential applications may include chemical- and medical-devices, telecommunication components, optical components, automotive crash, acceleration and distance sensors, camera and watch components, and mechanical devices [1,2]. Most of these devices are currently built on single crystal and polycrystalline silicon materials. The main reason for choosing Si-based materials is that micro-fabrication methods for these materials have been extensively developed for the micro-electronics industry over the last four decades. However, for many applications (particularly in the biomedical field) these materials and the associated production methods are too expensive, or the material properties often induce problems such as lack of optical clarity, low impact strength and poor bio-compatibility. Therefore, non-silicon materials such as specialty polymers are gaining more attentions, since polymeric materials offer a wide range of physical and chemical properties, low cost, and good processibility for mass production, and are recyclable.

A number of polymer-based micro-components have been fabricated for demonstration in academia and

Dong Hak Kim acknowledges the support given by Soonchunhyang University during a 2004-2005 research year.
[1]Department of Chemical Engineering, Soonchunhyang University
[2]Department of Chemical and Biomolecular Engineering, Ohio State University
[*]Corresponding author: Dong Hak Kim(dhkim@sch.ac.kr)

industry by combining various surface machining techniques and conventional manufacturing methods. Micro-injection molding has the potential for economical mass-production. Here we are interested in regular parts with microfeatures. Observation of the flow in the microchannel helps to understand the filling and thus design and development of micro injection molding.

Kim et al. [3] observed the characteristics of transient filling flow in microchannel by using a flow visualization method. The five microchannels were made of SU-8 on the silicon substrate. Theirchannels are 40 m thick and 100m to 500 m wide. They investigated the effects of surface tension on the transient filling flow and predicted the experimental results by numerical simulation. They reported the flow blockage and hindrance in narrower channels, but did not observe the flow pattern or streamline in the microchannels. The viscoelastic effect was not considered either. There are many studies regarding the visualization and measurement of flows in microchannels. Santiago et al. [4] and Meinhart et al. [5] developed methods to measure steady fluid velocities in microchannel by using micro-PIV (Particle Image Velocinetry). To measure the unsteady flow, Yamamoto et al. [6] proposed a laser induced molecular tagging (LIMT) technique to measure electroosmatic flow using micro-PIV.

However, many researchers dealt with purely viscous fluid where surface tension is dominant in the microchannel system. On the other hand, there are few research reports on the transient viscoelastic flow in the microchannel with regular sized base platethat is important in mass production of micro/nano parts using micromolding techniques.

Experimental

Two molds were tested for flow visualization. One was made of stainless steel-insert and the other was PMMA-insert, as shown in Fig. 1.

The PMMA-insert was made using soft lithography.

The microchannel was 100 ㎛ in width and 500 ㎛ in depth. For the metal mold, the base plate was 24 mm long, 8 mm wide and 1 mm thick. The base plate of the PMMA mold was 17 mm long, 1 mm thick and 200 ㎛ wide. There were one single channel and three adjacent channels. The three adjacent channels are next to each other with distance of a channel width.

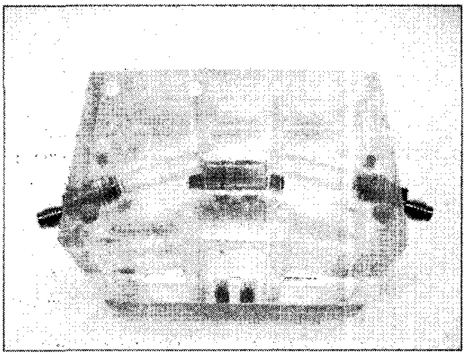


Fig 1. (a) Metal-insert mold.

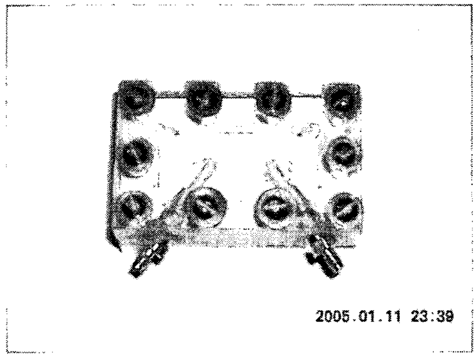


Fig 1. (b) PMMA-insert Mold

Spherical aluminum powder (Aldrich 26,651-5) of 20 ㎛ in diameter was used as the tracing particles with concentration of 0.01wt%. PS fluorescence spheres with 3 ㎛ in diameter were also tried. A strong fiber light was used to illuminate the microdevices. A high-resolution CCD camera was applied to collect the weak light reflected from the tracing particles. An image analyzing software, MetaMorph, was used to record and analyze the movies and images. 2% PEO and 1% PA aqueous solutions were used. The viscosity and first normal force difference of these solutions were measured by MCR300.

Results and Discussion

The viscosity of PEO and PA solutions is shown in

Fig. 2. The PEO and PA solutions are typical shear thinning fluids. The first normal stress difference was also measured (Fig. 3) and the relaxation time can be calculated at a certain shear rate. PA solution shows more viscous and elastic than PEO solution. But, both of solutions are adequate model fluids for polymer melt in micro-injection mold process.

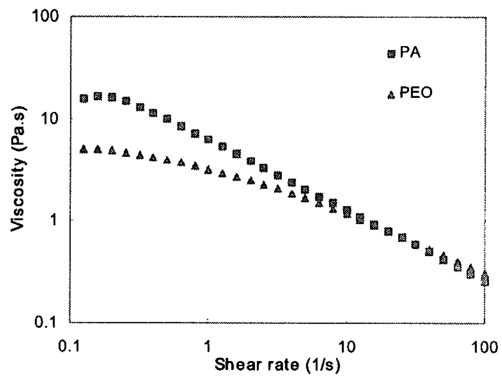


Fig 2. Viscosity of PEO and PA solutions

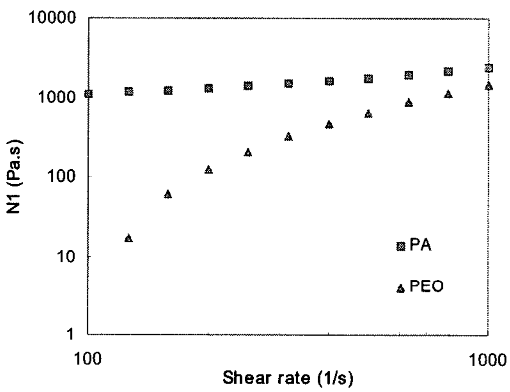


Fig 3. First normal force difference of PEO and PA solutions.

The experiment was initially performed on the metal-insert mold. It was found that it was very difficult to observe the dynamic flow patterns in the microchannel because the light intensity of the metal mold system was too low to illuminate the inside of the microchannel. So, we designed and made the PMMA-insert mold.

In previous result[7] with the melts in metal mold, even though the system is nonisothermal and steady state, the filling length in microchannel is affected by injection speed, mold temperature, micro-channel size and location. The filling stage and the packing stage both play important roles. Finally, a filling length results can be merged into a single master curve vs. Fourier number. But, they did not observe the transient flow.

Dynamic flow patterns can be observed in the transparent PMMA-insert mold. One example of the transient flow patterns in the single microchannel is shown in Fig. 4. It was found that the fluid started to flow into the microchannel once the main flow front reached the microchannel at a low flow rate. As soon as the main flow passed the whole microchannel, the fluid snapped due to surface tension effect. Then the flow stopped far away from the end of the microchannel. The reason is that the pressure drop is not high enough and the fluid does not have enough driving force to move further. Moreover, the air in the microchannel was compressed. Because the end of base plate was open to air, there was no packing stage and thus no pressure build-up.

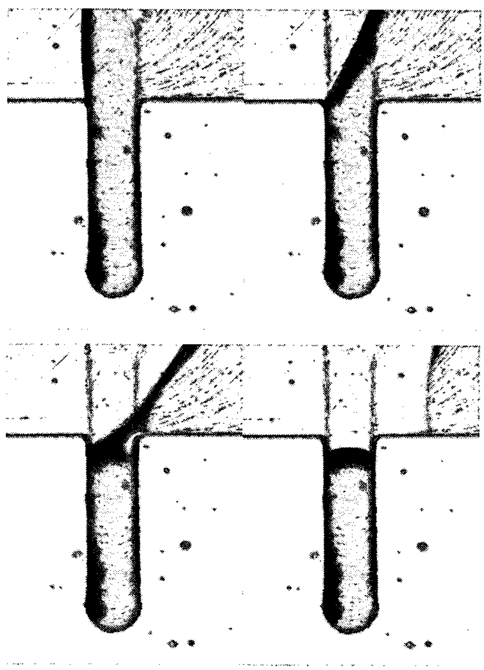


Fig 4. Flow pattern in the microchannel.

For these three adjacent microchannels, the fluid also moved into the microchannel once the fluid reached the microchannel. The flow moved abruptly once the fluid completely passed any one of these three microchannels. Then the fluid stopped and could not move forward any more. It is interesting to note that the flow front is concave and the filling lengths are almost same regardless of microchannel location. It seems that the surface tension played an important role and needs further study.

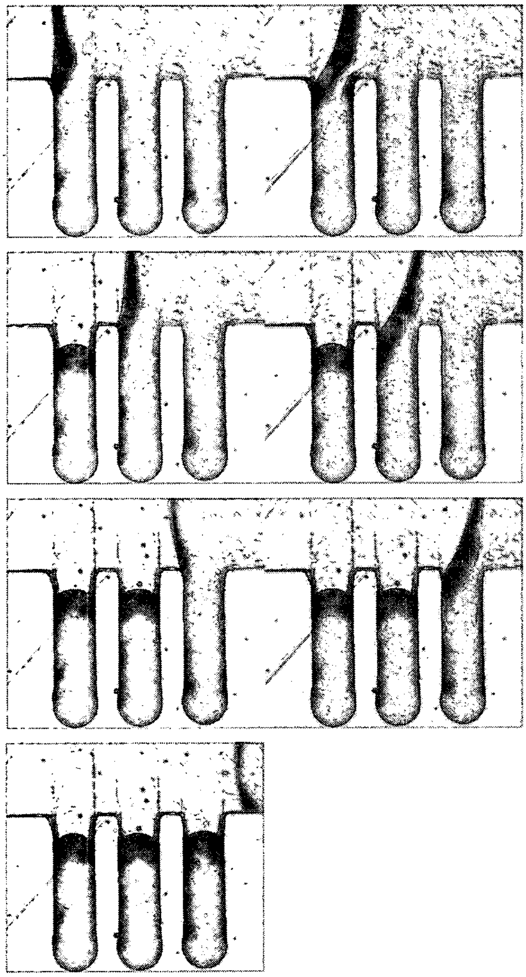


Fig 5. Flow pattern in the microchannels

Conclusion and Future Work

We have investigated transient flow dynamics in injection molding with microfeatures experimentally. The effect of velocity and elasticity on the flow pattern and flow competition between the base plate and the microchannels was observed. Different solutions with various viscosities will be used to study the effect of viscoelasticity. Further, there was an outlet at the end of the base plate in the current mold. We will block the end or leave small vents to investigate the effect of packing phase because it was found that the filling stage and the packing stage both play important roles. The microchannel was sealed in this study and a tiny vent channel will be created in future tests. Further tests will conducted with poly(caprolactone) melt instead of polymer solutions. Finally, simulation will be conducted and comparison will be made between the experimental and simulation results.

References

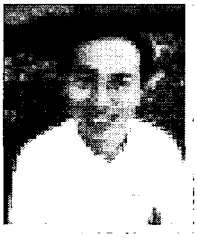
[1] Salamon, B. A., Koppi, K. A. and J. Little, SPE Antec. Tech. Papers, 515 (1998).
[2] Weber L. and Ehrfeld W., Kunststoffe 89, 10, 192 (1999).
[3] Kim, Dong Sung, Lee, Kwang-Cheol, Kwon, Tai Hun and Lee, Seung S., J. of Micromechanics and Microengineering, 12, 236 (2002).
[4] Santiago, J. G., Werely, S. T., Meinhart, C. D., Beebe, D. J. and Adrian, R. J., Exp. Fluids, 25, 316 (1989).
[5] Meinhart, C. D., Wereley, S. T. and Santiago, J. G., Exp. Fluids, 27, 414(1989).
[6] http://in3.dem.ist.utl.pt/lxlaser2002/papers/paper 12_5.pdf
[7] Liyong Yu, Ohio State University Dissertation(2004)

김 동 학(Dong Hak Kim) [Regular Member]

- 1986년: 서울대학교 화학공학과 (공학사)
- 1988년: KAIST 화학공학과(공학석사)
- 1993년: KAIST 화학공학과(공학박사)

<관심분야>
고분자가공, 유변학 및 이동현상

Guojun Xu [Regular Member]



- 2004 년: Ohio State University (Ph.D.)

<관심분야>
micro-injection molding, rheology, polymer processing

L. James Lee [Regular Member]

- 1972년: National Taiwan University (B.S.)
- 1979년: University of Minnesota (Ph. D.)

<관심분야>
BioMEMS, polymer processing, nano-technology

Kurt. W. Koelling [Regular Member]

- 1988년: University of Missouri -Rolla (B.S.)
- 1992년: Princeton University (Ph.D.)

<관심분야>
polymer processing, rheology, flow dynamics