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Microplastic embossing process: experimental and theoretical characterizations☆

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Abstract

A microplastic hot embossing process is characterized by measuring both the height and radius of curvature of hot-embossed cylindrical microlenses with various process conditions, including processing pressure, temperature and time. Polycarbonate is used as the plastic material and silicon mold inserts with circular openings of 100–200 μm in diameter are used to fabricate plastic microlenses. Experimentally, the processing pressure has little effect on the radius of curvature of microlens under a fixed processing temperature. The relationship between the height of the microlens and the applied pressure can be modeled linearly and the interfacial stress is derived empirically. The height and radius of curvature of microlenses with respect to temperature changes is modeled by the Arrhenius function and empirical formulae are derived. It is found that the activation energy is a constant independent of processing temperature or size of opening holes on the mold insert. Furthermore, the processing time constants for both the height and radius of curvature of microlenses are the same that implies both parameters reach steady state simultaneously.

Keywords: Hot embossing; Plastic; Microlens; Modeling

1. Introduction

The behavior of polymer flow in combination of the geometrical shape of the mold insert determines the final configuration of plastic structures in a hot embossing process. Hot embossing conditions, such as pressure, temperature, processing time and procedure, affect the polymer flow behavior and should be characterized. Previously, various macroscale investigations have reported models and simulation results on the flow of polymer melt. For example, a complex model dealing with transient flow behavior is proposed and simulated [1]. A pseudo-concentration method is used to track the melt flow front and to predict the forming process of plastic structures [2]. A one-dimensional model has been used to simplify basic polymer processing operations [3]. Surface tension is one of the important factors in the hot embossing process but is generally ignored or simplified in the macroscale models because surface tension changes with temperature [4] and there are no sufficient temperature-related data available for various polymer materials. However, in the micro hot embossing process, surface tension effect becomes the dominant force due to the large surface-to-volume ratio and must be carefully considered in models or simulations.

In contrast to the macroscale hot embossing processes, little work can be found in the modeling and experimental characterization of microplastic hot embossing process. Difficulties in dealing with the behavior of polymer melt flow under pressure at a temperature above the glass transition point of polymer materials may have hindered the full scale investigation. This paper presents the experimental study of the polymer melt behavior in a micro hot embossing process and preliminary models that include effects of temperature and surface tension. Possible applications of these hot-embossed cylindrical microlenses are in the optical fiber coupling or switch systems and micro-objectives for medical applications.

2. Experimental setup and results

The experimental setup of the micro hot embossing process is described previously [5]. A 500 μm thick polycarbonate substrate is hot embossed by using a silicon mold insert with circular openings of 100, 120 and 200 μm in diameter as shown in Fig. 1. These holes are fabricated by

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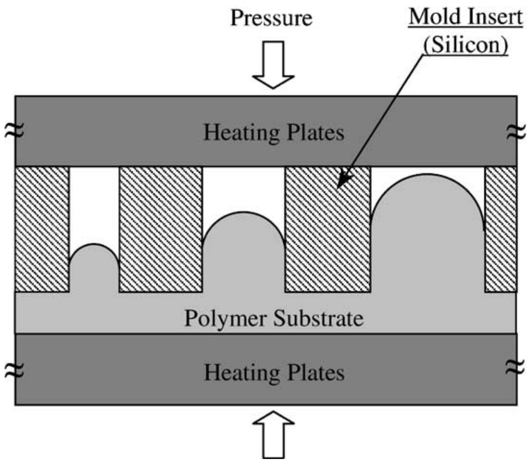

Fig. 1. The experimental setup of the microhot embossing process.

using a deep reactive ion etching process. When an external pressure is applied at an elevated temperature above the glass transition point of 150 °C of polycarbonate, microlens of various heights and curvatures can be constructed. It is expected that holes with larger openings will have deeper plastic penetration as shown. Heaters are placed on both sides of the testing specimen to achieve uniform heating and a thermal couple is used to monitor the local temperature. Unlike previous experiments [5], the applied pressure is kept constant through the hot embossing process and the typical temperature history is shown in Fig. 2. The processing temperature is set at T_1, that is above 150 °C and below 200 °C. The processing time is defined as the time period between t_1 and t_2 as shown in Fig. 2 when the processing temperature is maintained at T_1. The heating power is controlled such that the desired processing temperature is achieved in 15 min during the heating process. During the demolding process, temperature drops to T_2 at 80 °C through a naturally cooling process.

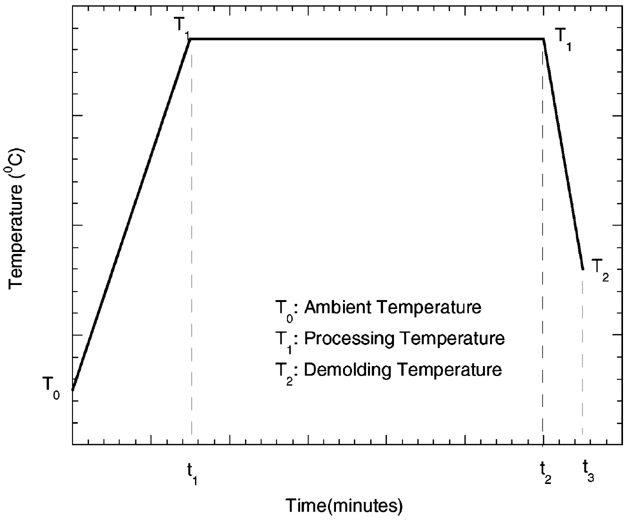

Fig. 2. Hot embossing processing temperature history.

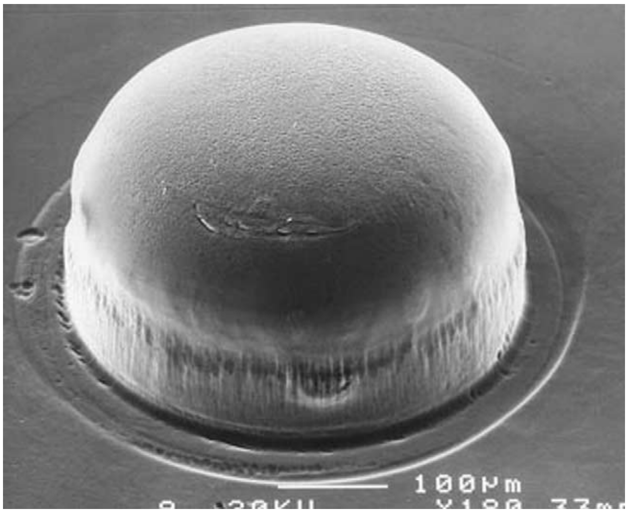

Fig. 3. SEM of a microlens fabricated by the hot embossing process.

If the processing pressure and temperature are kept low, the polymer melt will not reach the other end of the mold insert. As a result, microlenses with specific height and curvature can be constructed as shown in the SEM photograph in Fig. 3. During experiments, processing pressure, temperature and time are recorded and characterized. Fig. 4 shows a group of three fabricated microlenses taken from the side view. The height of the microlens is measured by using focus/defocus method from the top of the hemispherical lens to the bottom of the plastic plate under an optical microscope and the estimated measurement error is $+3$ µm. The radius of curvature of the microlens is measured under an interferometer Zygo Newview 5000 and the scanned surface profiles are put into MATLAB for curve-fitting. The best-fitted equation is used to calculate the curvature at each points and the mean radius of curvature is calculated afterwards. By using this method, the estimated error is $+6$ µm.

Fig. 5 shows the measured height of the microlens with respect to the processing time from 0 to 55 min under the

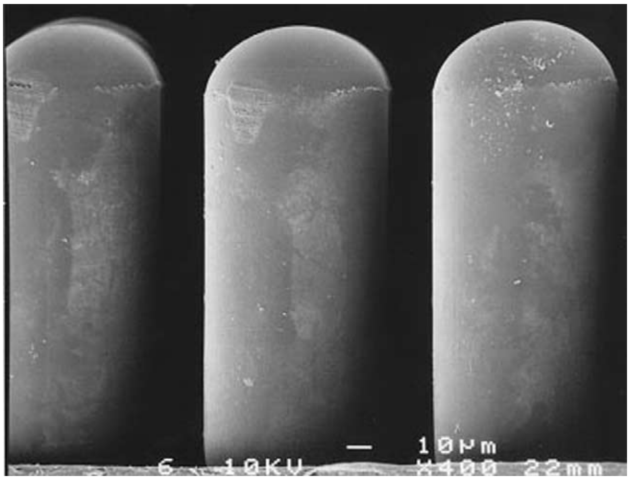

Fig. 4. An array of microlenses seen from the side view.

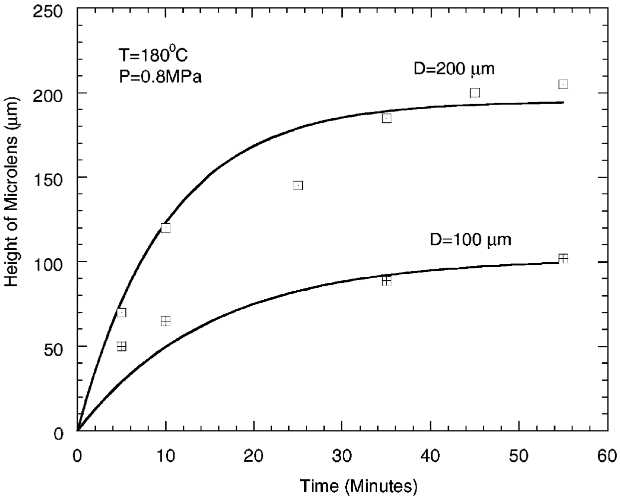

Fig. 5. Height of microlens under various processing time periods in the hot embossing process.

processing pressure of 0.8 MPa and temperature of 180 °C. This measurement reveals that the height of the microlens increases with time and gradually reaches a steady-state height. Under the same processing time period, the mold insert with the mold opening of 200 μm in diameter can produce higher microlenses than the mold insert with the mold opening of 100 μm in diameter. These experimental data can be approximated by the following equation:

$$h = h_{\mathrm{steady}}\left(1 - \exp\left(-\frac{t}{t_{\mathrm{c}}}\right)\right) \tag{1}$$

where h_{steady} is the steady-state height and t_{c} the time constant for the transient height growth. It is found that h_{steady} and t_{c} for the mold openings of 100 and 200 μm in diameter are 102 and 195 μm, and 15 and 10 min, respectively.

Fig. 6 shows the measured curvature of the microlenses with respect to the processing time under the same processing pressure and temperature as those in Fig. 5. It is found that the curvature reduces from infinite (flat surface) to a finite value and gradually reaches steady state as suggested in the experimental results. For the smaller openings of 100 μm in diameter, the curvatures are smaller than those made by the larger openings of 200 μm in diameter under the same processing time. The experimental results can be approximated by the following empirical formula:

$$R = R_{\mathrm{steady}} + R_{\mathrm{ct}}\exp\left(-\frac{t}{t_{\mathrm{c}}}\right) \tag{2}$$

where R_{steady} is the steady-state radius of curvature, t_{c} the time constant and R_{ct} is an empirical constant. The steady-state radii of curvature for the mold openings of 100 and 200 μm in diameter are found to be 82 and 146 μm, and R_{ct} values are 113 and 170 μm, respectively. The time constants in this case are found the same as those from the transient response of height measurements in Fig. 5. This suggests that both height and radius of curvature may reach steady state simultaneously.

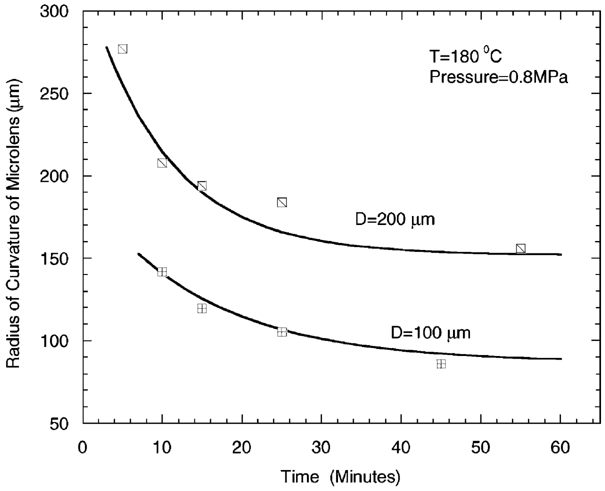

Fig. 6. Radius of curvature of microlens under various processing time periods in the hot embossing process.

In the second test, temperature is altered while the processing time is kept at 55 min and processing pressure is kept at 0.8 MPa to investigate the height and curvature relationships with respect to temperature. Fig. 7 shows the temperature-dependent radius of curvature of microlens from 170 to 190 °C. The general trend is that the radius of curvature reduces as the viscosity and surface tension of polymer melt decreases at high temperature. For different opening sizes, the same trend holds, but for a larger opening, the radius of curvature is larger. The following function is proposed to describe the temperature-dependent radius of curvature as an analogy to the viscosity and surface tension changes with temperature [6]:

$$R = R_0 + R_{\mathrm{ct}}\exp\left(\frac{\Delta H_{\mathrm{R}}}{R_{\mathrm{G}}T}\right) \tag{3}$$

where R_{G} is the universal gas constant (8.31 J/K mol) and $\Delta H_{\mathrm{R}} = 5.18$ kJ/mol is determined experimentally by

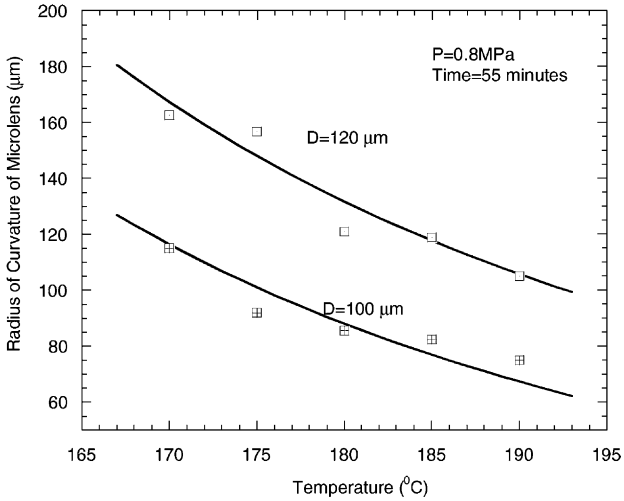

Fig. 7. Radius of curvature of microlens under various processing temperature in the hot embossing process.

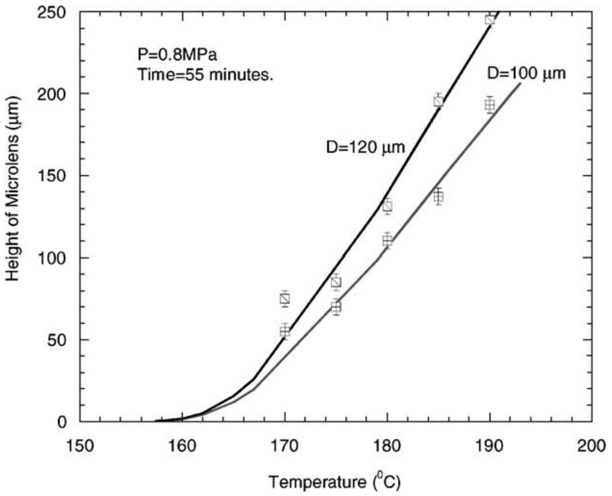

Fig. 8. Height of microlens under various processing temperature in the hot embossing process.

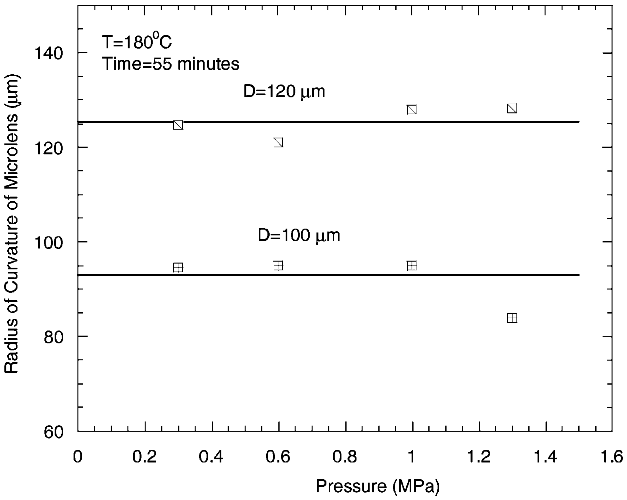

Fig. 10. Radius of curvature of microlens under different pressure.

curve-fitting and its value is the same for the mold openings of 100 and 200 μm in diameter because it is a material-related property. R_0 and R_{ct} depend on the size of the mold opening with $R_0 = -27$ μm and $R_{ct} = 2.68$ μm for the mold opening of 100 μm in diameter, and $R_0 = -8.87$ μm and $R_{ct} = 2.97$ μm for the mold opening of 120 μm in diameter.

Fig. 8 shows the heights of microlens with respect to different processing temperatures. An empirical formula is proposed as an Arrhenius function:

$$h = h_c \exp\left(\frac{-\Delta H_h}{R_G(T-150)}\right) \quad (4)$$

where h_c is a height constant and is found to be 957 and 1254 μm for microlenses made by opening holes of 100 and 120 μm in diameter, respectively. The value of ΔH_h is related to material properties similar to the function of activation energy and is independent of temperature. From the experimental results, this value is found to be 548.5 J/mol for both opening sizes.

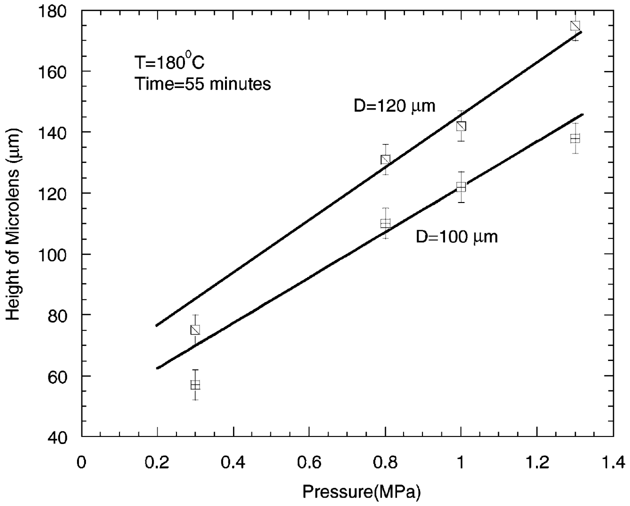

Fig. 9. Heights of microlens under different applied pressure.

The third test deals with the effect of pressure variations with respect to the height and radius of curvature when the processing temperature is fixed at 180 °C and processing time is fixed at 55 min as shown in Figs. 9 and 10, respectively. In Fig. 9, the height of microlenses increases as the applied pressure increases. On the other hand, the radius of curvature seems to remain the same with a variation of less than 5 μm under various levels of applied pressure as shown in Fig. 10. Therefore, the experimental results imply that pressure plays a minor role in forming the radius of curvature of spherical microlens and the radius of curvature is mainly controlled by the processing temperature.

3. Theoretical investigations and discussions

Based on the experimental results in Fig. 9, a simplified steady-state model for the height of the microlens with a diameter of D is proposed by using a first-order force balance relationship between applied pressure, surface tension force on the top surface of the lens and interfacial shear force between the cylindrical part of the lens and the silicon wall:

$$P\pi\left(\frac{D}{2}\right)^2 = \pi D f_s + \pi D h_{\text{steady}} f_{\text{int}} \quad (5)$$

where P is the applied pressure, f_s the surface tension at the processing temperature and f_{int} the interfacial shear stress between the lens and the silicon wall. Therefore

$$h_{\text{steady}} = \frac{1}{f_{\text{int}}}\left(\frac{PD}{4} - f_s\right) \quad (6)$$

It is found that a critical pressure is needed to overcome surface tension in order for the polymer to flow:

$$P_{\text{cr}} = \frac{4f_s}{D} \quad (7)$$

The surface tension for polycarbonate fluid [7] is reported as 0.046 N/m at 250 °C; therefore, the critical pressure for polycarbonate fluid is 1840 Pa for the holes with 100 μm in diameter opening and 920 Pa for the holes with 200 μm in diameter opening at 250 °C. The numbers of critical pressure are expected to be higher for the processing temperature range used in this work. On the other hand, the experimental parameters used in this work (the combination of pressure and opening diameter) are at least two orders of magnitude larger than the surface tension effect in Eq. (6). Therefore, surface tension effect plays a minor role in determining the height of the lens. Furthermore, this linear equation of Eq. (6) predicts the height of the microlens will increase proportionally to the applied pressure and the slope is proportional to the opening size under a fixed processing temperature (f_{int} is fixed). This trend seems to be observed experimentally in Fig. 9. However, more experimental data have to be collected and analyzed to draw a concrete conclusion.

By examining Eqs. (4) and (6), the interfacial stress, f_{int}, is characterized as

$$f_{\mathrm{int}} = f_{\mathrm{c}} \exp\left(\frac{\Delta H_{\mathrm{h}}}{R_{\mathrm{G}}(T - 150)}\right) \tag{8}$$

and f_{c} is found to be 0.02 MPa by using the parameters gathered from Fig. 8. This constant is useful in Eq. (6) to predict the heights of microlenses under various processing pressure and temperature.

Another important characteristic of the process is the reliability and reproducibility issues. On a run of 32 microlenses [5], it is found that the average radius of curvature is 56.1 μm and the standard deviation is 0.46 μm. The small deviation as measured indicates good reproducibility of the process.

4. Conclusions

Experimental characterizations of a microlens forming process of polymer melt are demonstrated, including various possible effects such as processing pressure, temperature and time. The results show that temperature-dependent viscosity and surface tension play important roles in the forming process to determine the curvature and height of the microlens. The effect of applied pressure on the radius of curvature of microlens is minimum but the height of the lens seems to increase linearly with the applied pressure according to the experimental results. Processing temperature greatly affects both the radius of curvature and the height of the lens with complicated relationships. For first-order approximation, this work uses the concept of ΔH (the activation energy) and Arrhenius relationship. It is found experimentally that ΔH_{R} is 5.18 kJ/mol for polycarbonate in the radius of curvature experiment and ΔH_{h} is 548.5 J/mol in the height experiment. Finally, the processing time constants for the height and radius of curvature of microlens are the same with 15 and 10 min for the 100 and 200 μm in diameter openings, respectively.

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Biographies

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Li-Wei Pan was born in Taiwan, ROC. He received his MS and PhD degrees in mechanical engineering from The University of Michigan at Ann Arbor in 1996 and 2001, respectively. Presently he is a postdoctoral researcher of Berkeley Sensor and Actuator Center of University of California at Berkeley. His research interests include electroplating bonding, IC and MEMS integration, LIGA microsensors, and microactuators and microfluidics. His current research focuses on the microfluidic systems for biological applications.

Liwei Lin received his MS and PhD degrees in mechanical engineering from the University of California, Berkeley, in 1991 and 1993, respectively. He joined BEI Electronics, Inc., USA, from 1993 to 1994 in research and development of microsensors. From 1994 to 1996, he was an Associate Professor in the Institute of Applied Mechanics, National Taiwan University, Taiwan. From 1996 to 1999, he was an Assistant Professor at the Mechanical Engineering and Applied Mechanics Department at the University of Michigan. He joined the University of California at Berkeley in 1999 and is now an Associate Professor at

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