Finte Element Analysis of PMMA Microfluidic Chip Based on Hot Embossing Technique

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Abstract. Using creep experiment to characterize the mechanical property of PMMA has been studied in this paper. Polynomial and first order exponential decay function have been used to fit the data to get creep curve of PMMA. With the finite element analysis method and based on the creep and viscoelastic material models, simulation of the hot embossing process is carried out. Time influence on hot embossing has been emphasized. The simulation result is proved by experiments. It is shown that simulation based on viscoelastic model represents more compliance with experiments, and can describe the process of polymer deformation during hot embossing.

1. Introduction

Hot embossing is especially well suited for manufacturing small and medium-volume series, because the mold insert can be exchanged within a rather short period of time. Another advantage is the discrete material supply. In this way, polymers can be changed from one molding cycle to the next without any hardware modification being required [1]. A number of studies have been conducted in recent years to investigate the technique of hot embossing, the equipment and process gained a lot development [2-4]. However most research groups still rely on a series of experiments to obtain hot embossing parameters, not much effects have been attempted in trying to understand or characterize the mechanics of the hot embossing process in fabricating micro structure, it brings some disadvantages, such as the great workload, high expense of materials and so on. Since the selection of process parameters is not based on the material’s mechanical properties, it cannot reach the aim of process optimization actually.

Wen-Bin Young et al. used a viscous model to predict the polymer flow behavior during the imprinting [5]. K.F.Lei et al. describes the mechanism of using molds with microfeature to hot emboss PMMA substrates. The paper also shows that numerical prediction on wall profiles compare favorably with actual experimental results for channel widths, pressures and temperatures [6]. Seldom research group has studied the time influence on hot embossing.

With a better understanding of the polymer behaviour, the embossing conditions can be optimised, and good replication fidelity for the fabrication of micro devices can be ensured. It is difficult to model the viscoelastic behavior of polymer in hot embossing process. In this paper, the problem is solved by
creep experiment. The mechanical property of PMMA has been characterized by creep curves based on creep experiment and numerical fitting. Model for hot embossing is established by creep and viscoelastic model. We use the finite element analysis method to study the influence of time in hot embossing process.

2. Finite element analysis
The mechanical behavior of PMMA is depended on time largely. The strain is a function of time when a constant stress is applied to sample [7]. The modulus is also the function of time. In hot embossing process, the relationship between stress and strain cannot simply described by elasticity, time influence has to be considered in deformation. Creep and relaxation are two main mechanical behaviors of viscoelastic materials, and also are two main experimental methods for study viscoelastic materials. In this paper, creep experiment has been done to describe the mechanical behavior of PMMA.

2.1. Creep experiment
The creep experiment with PMMA (from ATOGLAS, Korea) is carried out on RYJ-Ⅱ hot embossing equipment, which is designed and developed at Research Center for Micro System Technology, Dalian University of Technology, the process is shown as follows:

1) Two PMMA substrates (50mm×50mm×2mm) are heated to 120°C (the actual hot embossing temperature), and then hold at this temperature for 10 min to reach the heat balance.

2) A sudden pressure $\sigma_0=3.14\times10^6$N/m$^2$ (the actual hot embossing pressure) is applied on PMMA substrates, holding this pressure, collect the data of the displacement change along with time.

The strain vs. time curve under unit stress is shown in figure 1, it is creep curve.

![Figure 1. The creep curve of PMMA](image)

The relationship between strain and time under unit stress is fit by third order polynomial formula, the result is:

$$\varepsilon(t) = 1.166 + 0.02t - 4.87\times10^{-5}t^2 + 4.27\times10^{-8}t^3$$

(1)

The relationship between strain and time under unit stress is fit by first order exponential decay formula:

$$y = y_0 + A_1e^{(-x/t)}$$

(2)

We obtain the parameters:
Fitting curves are shown in figure 1.

2.2. Finite element simulation

With the data obtained by creep experiment, the simulation of hot embossing on PMMA is carried out with MSC. Marc.

2.2.1. Geometrical model. As the analysis time is dependent on the element number in finite element analysis largely, the geometrical model is simplified:

(1) Suppose the part of material far from the microchannel makes no difference for hot embossing, we use a part of the PMMA and mold to simulate;

(2) It is can be supposed as plane strain analysis as the PMMA substrate is under vertical pressure;

(3) Both the material and load are symmetrical, the model can be build with the half of the material.

The geometrical model is shown in figure 2.

![Geometrical model of hot embossing](image)

2.2.2. Material model. The elastic property of PMMA at 120°C is inputted by elastic module as 2e6, and poisson’s ratio is 0.35. The strain of polymer is changed along with time under a constant stress, the time dependent material property should also be inputted.

Based on the result of polynomial fitting and first order exponential decay fitting, the creep model and viscoelastic model are used to simulate the flow behavior in hot embossing.

(1) Creep model

The first order differential coefficient of the polynomial formula describes the relationship between strain rate and time:

\[
\varepsilon'(t) = 0.02 - 9.74 \times 10^{-5} t + 1.28 \times 10^{-7} t^2
\]  

This strain rate formula is input in the creep option to describe the material property.

(2) Viscoelastic model

Kelvin-Voigt [8] model is a parallel connection of a spring and a damper, the creep equation is described with the following formula:

\[
\varepsilon(t) = \frac{\sigma_0}{E} (1 - e^{-t/\tau_d})
\]  

\[
J(t) = \frac{1}{E} (1 - e^{-t/\tau_d})
\]

First order exponential decay fitting can be used in the viscoelastic analysis, because it has the similar form with Kelvin-Voigt model and their curves have the same shape.
2.2.3. Loading method. The hot embossing experiment is carried out at 120°C under pressure of 800kgf to collect the displacement-time data, figure 3 shows the first order exponential decay fitting of the experiment data, the result is:

\[ y = 166 - 190e^{-t/55.74} \]  

(6)

The displacement load is applied on the rigid body, and simulation results with two material models are shown in figure 4.

2.3. Results and discussion

The polynomial fitting has good compliance with collected experiment data, but the shape of the polynomial curve decides that it cannot describe the long time mechanical property of polymer. However, the first order exponential decay fitting is accordant with the creep curve, it is a better fitting method.

The finite element analysis with viscoelastic model in hot embossing gained the follow conclusion:

If the hot embossing time less than 180 s, the material can not fill the micro structure completely;

If the hot embossing time is 300s, the filling of the material reach to 98.4%, it satisfies the request of product quality;

Figure 3. The displacement load curve.

Figure 4. Simulation results with two material models. (a) creep model at 300s. (b) viscoelastic model at 180s. (c)viscoelastic model at 300s.(d) viscoelastic model at 600s.
If the hot embossing time is longer than 600s, the filling of the material reach to 98.5%, it increases 0.1% in 300s.

Considering efficiency and quality, 300s is the optimized hot embossing time.

3. Experiments
The hot embossing experiment is carried out under the condition of 120°C and 800kgf, the hot embossing time is 180s, 300s, 600s respectively. Experiments show that the trend of micro channel’s shaping in hot embossing is accord with the simulation with viscoelastic material model. The profile of micro channel under condition of 120°C, 800kgf and 300s is shown in figure 5.

![Figure 5. The profile of micro channel under condition of 120°C, 800kgf and 300s.](image)

4. Conclusion
According to polynomial and first order exponent decay formula fitting, creep mechanism of PMMA in hot embossing has been established. It is shown that the polynomial fitting can not be extrapolated to describe the polymer property and the first order exponential decay curve has the same shape with creep curve for long time, it is more accurate than polynomial.

Viscoelastic model is based on first order exponent decay fitting, it has more advantages than creep model which is based on polynomial fitting: Firstly, the computational error of first order exponent decay fitting is less than polynomial fitting; Secondly, viscoelastic model take both elastic and viscosity property to account, it is more suitable for describing polymer mechanical property.

The hot embossing simulation with viscoelastic model shows that the profile of micro structure of PMMA depended on time largely. When embossing time is more than 300s profile of the micro structure satisfies the request of product quality, this is consistent with experiment. The hot embossing time can be established by this time.

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