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Deformation behavior of solid polymer during hot embossing process

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ABSTRACT

Though hot embossing is a well known technique for the fabrication of polymer based micro-device, the deformation behavior of solid polymer during hot embossing process is not investigated clearly. In this paper, the deformation behavior of solid polymer was observed by two methods, synchronous observation and asynchronous analysis. A finite element simulation and a phenomenological model were used to evaluate the deformation behavior of solid polymer during hot embossing. Results showed that the deformation of solid polymer during embossing process included two stages. One was a stress concentration and strain hardening stage, which occurred during the heating and applying pressure process. The "swallowtails" induced by incomplete filling generate at this stage. The other was a stress relaxation and deformation recovery stage, which occurred during the remaining temperature and pressure process. The "swallowtails" were eliminated at this stage. The second stage was significant for improving replication precision, but it had not been reported before.

1. Introduction

Hot embossing is a technique to fabricate high precision and high quality plastic microstructures [1]. Hot embossing means replicating the microstructures of the mold into the polymer substrate at proper pressure and temperature. Most of hot embossing processes include three steps, the first is heating and applying pressure step, the second is remaining temperature and pressure step and the third is de-molding step [2]. Hot embossing can be performed isothermally or non-isothermally. The isothermal hot embossing means the substrate and mold will be heated to the same temperature during embossing process. In contrast, the non-isothermal embossing means the mold and the substrate will be heated to different temperature [3]. Isothermal method is the most popular process for the hot embossing of solid polymer. Here, "solid polymer" refers to the polymer under glassy state and hyperelastic state, "molten polymer" refers to the polymer fluid under molten state. Some groups have reported their studies of embossing polymer under solid-state or molten state. Heyderman et al. [4] reported their research results on the flow behavior of molten PMMA into micro-cavities during hot embossing lithography. The mechanism of the filling behavior was observed through a series of asynchronous experiments. Because the temperature used in their experiments was higher than T_g +100 °C (near viscous flow temperature), at which temperature the polymer exhibited viscous property, the filling behavior of polymer was viscous flow which differed from the deformation behavior of solid polymer. Juang et al. [5] investigated the solid polymer deformation behavior near glass transition temperature. The deformation of polymer during male die pressing was studied through a series of hot embossing experiments. The relationship between hot embossing parameters and parts qualities were established. The polymer deformation behavior for isothermal condition reported in Juang'-paper accorded with the results reported in other paper [6,7], which didn't show the difference of deformation between heating and applying pressure step and remaining temperature and pressure step.

In summary, the topics of most reported embossing papers emphasize on "molten polymer flow behavior". Though there are some reports discussed the polymer embossing near glass transition temperature, most of which only emphasize on how to achieve high replication precision by optimizing embossing parameters. The real deformation behavior and mechanism of solid polymer have not been studied clearly. We also have found several reports give some FEA results to explain the deformation process of solid polymer during hot embossing process. However, their simulation results haven't been supported by any experimental observations, and then their results can't show the real deformation process of solid polymer.

In this paper, a male die was used to emboss polymer substrate under isothermal condition. The deformation of solid polymer during embossing process was recorded synchronously by a SLM (stereo light microscope) system. The deformations of solid polymer during heating and applying pressure process and remaining temperature and pressure process were observed. Asynchronous

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experiments were also conducted. The microchannels fabricated without remaining temperature step were compared with the microchannels fabricated with remaining step. Base on these experiments, the solid polymer deformation behavior during hot embossing process, especially the formation and elimination of "swallowtail" was investigated. For our knowledge, the formation of "swallowtail", which is a ubiquitous defect formed during solid polymer embossing, hasn't been reported until now. A phenomenological model was used to evaluate the deformation mechanism of polymer in hot embossing. Finite element analysis (FEA) was also designed to evaluate the deformation behavior, the strain and the stress of polymer during heating and applying step and remaining temperature and pressure step.

2. Experiments

2.1. Material

The PMMA plates used for experiments were purchased from Asahi Kasei Corporation, with glass transition temperature of approximately 105 °C. PMMA substrates were cut to 1 mm thick and 51 mm × 51 mm square pieces by CO_2 laser cutting. Some material properties of this PMMA were also proposed by Asahi Kasei Corporation and were used in FEA simulation.

2.2. Mold insert

A nickel mold fabricated by UV-LIGA method, which is a 5 mm thick and 63 mm × 63 mm square plate, was used for hot embossing. The micro-protrusions on mold plate with double "T" features were 40 μm high, 70 μm wide and 55 mm long and were fabricated by electroforming. Buffing machine was used to make the mold surface smooth.

2.3. Synchronous recording of polymer deformation

The device used for hot embossing consists of DC torque motor, lead screw, TEC (Thermal Electric Cooler) blocks, linear encoder and control system. The DC torque motor provides constant compression force during hot embossing process. Its control accuracy is about 0.5 N. Lead screw provides accurate displacement. TEC is a solid-state active heat pump capable of transferring heat from one side of the device to the other. It was used to heat and cool the mold insert and PET substrate. And the temperature control span is from room temperature to 200 °C. A linear encoder was mounted on the movable plate to monitor the displacement of the mold during embossing process. Temperature profiles were obtained by placing thermocouples in the TEC block. All results were recorded and processing by computer.

The SLM (stereo light microscope) system used to synchronously record the polymer deformation was composed of stereomicroscope, CCD and computer. The stereomicroscope has been modified for the purpose of recording. The scope body could move along the linear guide. To record the polymer deformation during hot embossing process, the SLM system was placed in front of the hot embossing device (Fig. 1). The object lens of the stereomicroscope must directly face to the side of the PMMA substrate. Clear photographs could be obtained by adjusting the knob of stereomicroscope.

2.4. Asynchronous analysis of polymer deformation

The polymer deformation also can be observed by choosing a short embossing time and de-molding when the microchannels are only partially fabricated [4]. The hot embossing profile has

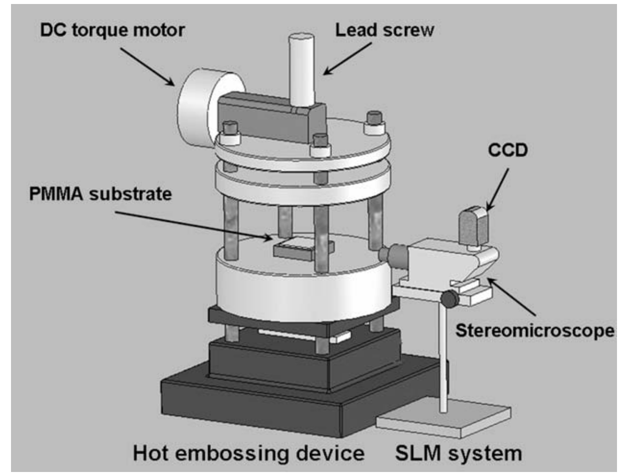

Fig. 1. The hot embossing device and stereo light microscope (SLM).

been shown in Fig. 2. In this study, we will study the deformation of polymer during heating and applying pressure stage and remaining temperature and pressure stage (Fig. 2). The asynchronous analysis was conducted as follows: firstly, the substrate and mold were heating to embossing temperature, subsequently applying pressure to maximum value, followed by cooling and de-molding. And the cross-sections of these substrates were recorded. These experiments were conducted without remaining temperature and pressure; secondly, the temperature and pressure were increased to maximum value and remained for several minutes, followed by cooling and de-molding. The cross-sections of these substrates were recorded; finally, the cross-sections of substrates fabricated without remaining temperature and pressure stage were compared with the cross-sections of substrates fabricated with remaining stage to reveal the effects of remaining temperature and pressure stage on polymer deformation.

3. Results and discussions

3.1. Solid polymer deformation in hot embossing

Fig. 3 shows the polymer deformation in the region between substrate surface and micro-protrusion, which are recorded synchronously using the method described in Section 2.3. Each image corresponds to a different stage of fabrication. The polymer deformations during heating and applying pressure step were shown in Fig. 3a, b and c. In contrast, the polymer deformations during remaining pressure and temperature step were shown in Fig. 3d, e and f. The deformation just before the temperature and pressure increasing to their maximum values (120 °C and 2.0 MPa) was shown in Fig. 3c. The deformations after remaining maximum temperature and pressure for 60–70 s, 150–180 s and 240–260 s are shown in Fig. 3d,e and f, respectively. In this paper, we called the regions, which were outlined with black lines in Fig. 4, as "swallowtails". The swallowtail, which could affect the replication precision of microchannel, is a main flaw in micro- or macro-embossing process. Though many simulation and experimental results reported had revealed the existences of swallowtails in hot embossing [6–9], no more attentions had been paid to it.

The swallowtails were found to generate between the mold protrusion and the mold surface during the step of heating and applying pressure (Fig. 3a–c). The swallowtails were found to be eliminated after remaining temperature and pressure for several minutes (Fig. 3d–f). In summary, from the synchronously observation, it was found that the deformations of polymer in hot embossing included two stages, the first formed the figure of microchannel