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Experimental study of polymer microlens fabrication using partial-filling hot embossing technique

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ABSTRACT

A method to fabricate microlens arrays in polymer substrates via hot embossing is presented in this paper. The partial-filling hot embossing technique of micro cavities on a mold insert through surface tension and capillary action is proven to be an effective means of limiting imperfections on the surface of microlens arrays. The effects of the investigated process parameters including temperature, embossing pressure, and holding time are analyzed via Taguchi method to identify effective processing conditions for microlens arrays of varying heights and diameters. Signal-to-noise (S/N) ratios are calculated for the focal length of the fabricated microlens arrays to identify key individual parameters and their interactions for a streamlined fabrication process. Experimental data indicates that the holding time in the embossing process has the most significant impact on lens focal length followed by embossing temperature and pressure. This study identifies a reliable means of microlens production and demonstrates the effects of varying process parameters in the partial-filling method of micro hot embossing for the production of lens arrays.

1. Introduction

Microlenses and microlens arrays have been used in the biomedical, optical communication, and optoelectronics fields [1–5]. Used in fiber optic applications, the addition of microlens arrays at the objective and relay ends of a fiber bundle increases the fill factor of the bundle, as well as improves its coupling efficiency [2]. Microlenses have also been commonly employed in endoscopic applications for tissue and cellular imaging [1,5]. In response to growing demand, a variety of microlens manufacturing methods have been investigated. The most common methods include laser ablation, reflow techniques, ink jet molding, injection molding, and hot embossing [6–9]. While laser ablation techniques allow for later phase fabrication of micro-optics in established devices, they offer no versatility in lens height or diameter due to masking requirements [10]. Polymer reflow and ink jet molding techniques are effective for large aperture lenses. However, the processing parameters required are difficult to control in micro scale production [11]. The thermal and flow induced stresses introduced into small, thin profiles negate the mass production volumes that characterize injection molding processes.

In contrast, a hot embossing technique offers advantages in regard to simplicity, operating cost, and replication accuracy for microstructures. The capability to fabricate microlens arrays with hot embossing has been demonstrated with two techniques: partial-cavity filling and full-cavity filling [12,13]. Full-cavity filling uses mold inserts with the desired microlens geometry that facilitate the complete filling of the mold cavity generating microlenses with limited variation. While this method does produce repeatable batch-to-batch outcomes, the polymer makes contact with the mold insert often resulting in surface defects that scatter incident light [14]. The partial-filling technique alleviates this issue by capitalizing on surface tension and capillary action to generate the lens structure thereby minimizing contact with mold surfaces and achieving optical surface characteristics [12]. Partial-filling is initiated with surface tension generated from the mold making contact with the polymer substrate under embossing pressure. The surface tension is a result of the elevated energy levels on the surface of the polymer opposed to its interior. In combination with polymer temperatures above glass transition temperature, this surface tension leads to a capillary action forcing the polymer into the recesses of the mold. The hemispherical convex lens formation of the polymer is a result of a reduction in surface tension as the center of the mold cavity allows the polymer to flow with less restriction [15].

Usable microlens fabrication requires an embossing temperature, an embossing pressure, and a holding time to be applied in the proper configuration. An effective combination of these parameters promotes the

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partial filling of the mold cavities in a hemispherical fashion without contacting the mold sidewalls. During embossing, the flow front of the polymer substrate flows into the mold cavity at a higher velocity in comparison to the flow at the sidewalls due to the pressure differential between the hole edge and its center [12]. Furthermore, alteration of process parameters facilitates the filling of the microholes at varying heights resulting in changes in focal length. Thus, microlens arrays of varying focal lengths can be achieved with the adjustment of processing parameters using only one mold insert. Despite these advantages, the partial-filling method is difficult to control with variations from lens-to-lens and batch-to batch reproducibility being the primary concerns.

In this study, polymer microlens arrays are demonstrated with polymethyl methacrylate (PMMA) substrates, commonly used in hot embossing to form a variety of microstructures [16–18]. To improve replication reliability, the effects of major processing parameters are systematically investigated in this paper. Three processing parameters including an embossing temperature, an embossing pressure, and holding time are considered with three levels arranged in the L_9 orthogonal configuration of Taguchi method, a statistics based experimental design, which is beneficial in identifying significant impacts of individual processing parameters in addition to parameter interactions [19]. The focal length of the fabricated microlens arrays is measured and compared with the calculated value using the dimensions of the radius of curvature (ROC), sag height, and diameter to determine the effects of process parameters on the microlens array.

2. Design of microlens mold insert

Hot embossing uses a patterned mold insert to transfer microstructures inherent to the mold onto polymer substrates. Effective fabrication of microstructures demands accurate mold patterns that are capable of generating high-resolution replications in polymer substrates. A variety of metallic materials have been implemented in the fabrication of mold inserts including nickel, stainless steel, and brass [20–22]. A brass alloy is selected for this study as it demonstrates the capability to withstand repetitions of high pressure and temperature variations present in hot embossing [14]. A HAAS MiniMill, a vertical CNC milling machine, is used to form microhole arrays in the brass. The design and fabrication of the mold insert is critical for defining the diameter of individual microlenses within an array, which determines the ROC and focal length of the microlenses.

Fig. 1(a) shows the design and the dimension of the microhole array on the brass mold insert. A 10 × 10 array of 508 μm (0.02 in.) microholes is arranged in a rectangular configuration with a pitch of 711 μm (0.028 in.) and a 203 μm (0.008 in.) spacing between each hole. Fig. 1(b) is a cross-section view of A–A′ indicated on Fig. 1(a). Optical defects due to machining traces present on the mold insert are avoided using the partial-filling method. As the polymer substrate does not contact the sidewalls or bottom of the microholes during the embossing process, the length of the microholes is insignificant and set at 508 μm, a 1:1 depth to diameter ratio. Fig. 1(c) shows a schematic of the partial-cavity filling hot embossing technique.

Fig. 2 illustrates the micro-milled mold insert on brass, (353 engravers brass, McMaster Carr) and a microscopic image of the microholes. Machining tolerances in conjunction with limitations inherent to end mill fabrication resulted in a deviation of hole diameter from mold design to fabrication. The measured diameter of fabricated microholes is 512 μm. The microhole array is placed in the center of the mold insert to mitigate thermal stresses created in the embossing process.

3. Fabrication of microlens array

A 3 mm thick PMMA substrate is selected due to its appropriate optical transparency, and mechanical durability. A Carver Thermal Press (3893 4NE18, Carver Inc., Wabash, IN) is employed for the hot embossing process. The mold insert is mounted on the upper platen while a secondary brass stage is mounted to the lower platen. The lower stage, polished to mitigate surface roughness, is used to limit the transfer of surface artifacts to the polymer substrate. An oil-based cooling system is implemented to reduce thermal stress and its effects during cooling and demolding and to reduce process cycle time. The cooling system consists of an oil transfer pump, used to circulate a heat transfer fluid throughout the heating and cooling platens paired with a condenser that serves as a heatsink for the thermal fluid.

In hot embossing, the polymer substrate is heated to an embossing temperature prior to molding. The glass transition temperature (T_g) of PMMA is 105 °C. The applied embossing pressure forces the heated polymer to flow into the microhole. The hot embossing process

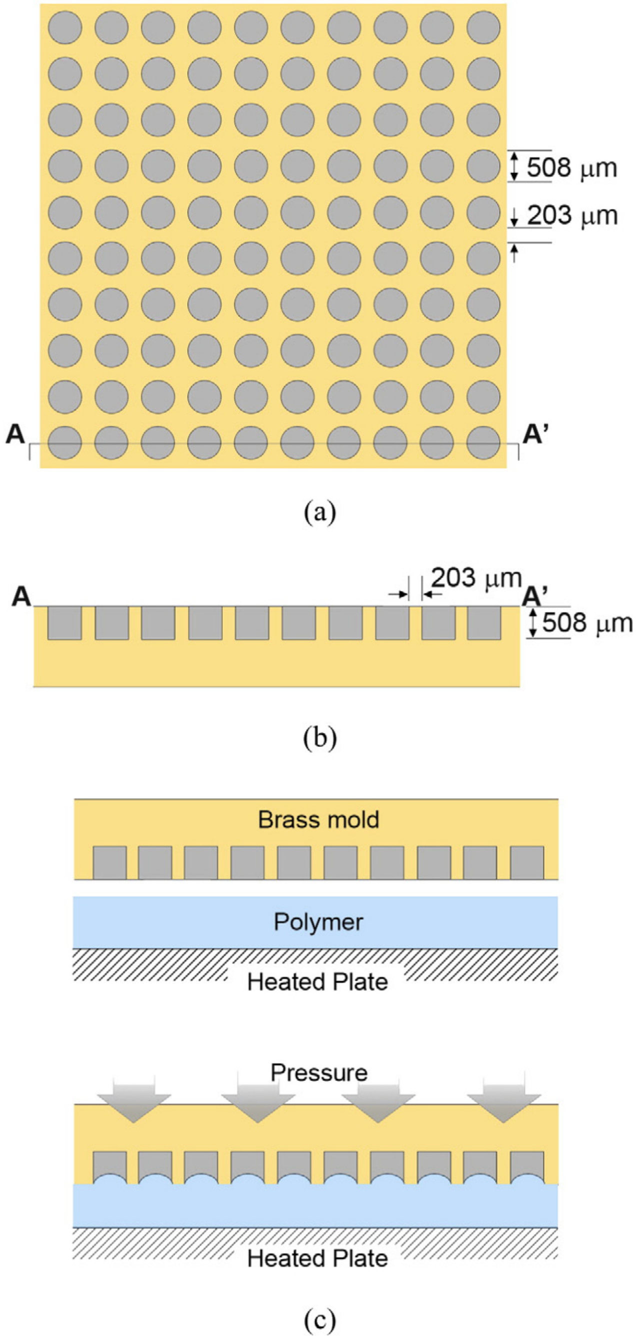

Fig. 1. (a) A schematic representation of the microlens array design. (b) The cross-section view of A–A′ illustrated in panel (a) with a 1:1 depth to width ratio. (c) Illustration of partial-filling hot embossing process.