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THERMAL REFLOW PROCESS FOR GLASS MICROLENS MANUFACTURING

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1. ABSTRACT

This fabrication process includes three major steps, i.e., fabrication of glassy carbon molds with arrays of micro size holes, glass compression molding to create micro cylinders on glass substrate, and reheating to form microlens arrays. As compared to traditional polymer microlens arrays, glass microlens arrays are more reliable and therefore could be used in more critical applications. In this research, microlens arrays with different surface geometries were successfully fabricated on P-SK57 (T_g = 493 ºC) glass substrate using a combination of compression molding and thermal reflow process. The major parameters that influence the final lens shape, including reheating temperature and holding time, were studied to establish a suitable fabrication process. A numerical simulation method was developed to evaluate the fabrication process.

2. INTRODUCTION

In recent years, interest in microlens arrays fabrication has increased dramatically for their wide applications in optoelectronics and optical communication [1]. Different methods have been developed for fabricating microlens arrays, such as photoresist thermal reflow [2], polymer replication hot embossing [3] and roller embossing [4], excimer laser ablation [5], direct reactive ion etching (RIE) [6], mechanical ultraprecision machining [7] and glass compression molding [8]. Compared with these fabrication processes, glass compression molding is an emerging technique that can be adopted for high volume fabrication of precision glass optical elements [9].

Glass compression molding is a hot forming process in which a heated raw glass blank is pressed by optically polished molds with micro patterns to create the finished glass optical components. As compared with other glass micro fabrication techniques (e.g., etching, laser ablation), glass molding is an environmentally benign and net shape or near net shape high volume fabrication process. The glass molding process has previously also been evaluated for fabricating glass diffractive optics [10].

Thermal reflow is used for fabricating polymer microlens arrays for its low cost nature, high productivity and simplicity [2]. In this process glass material is melted when processing temperature reaches a level above its transition temperature and surface tension of the molten material forces the formation of spherical geometry of the microlenses.

3. FABRICATION PROCESS

There are three major steps involved in fabrication of glass microlens arrays in this research: mold fabrication, glass compression molding and thermal reflow (as shown in figure 1). First of all, glassy carbon molds with arrays of micro holes were fabricated in a cleanroom lithography-etching process. Secondly, compression molding was performed to replicate the micro cylinders on a glass substrate. Finally, a reflow process was applied to thermally form the micro cylinders into microlens arrays.

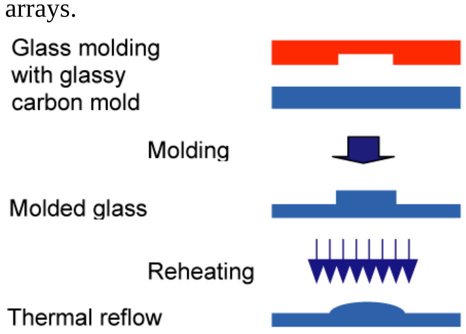

Figure 1: Illustration of the glass microlens array fabrication process, including three major steps i.e., fabrication of molds, glass compression molding, and reheating

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In this research, glassy carbon was used as mold material for its excellent chemical stability at high temperature (up to 2,000 ºC) and its good optical polishability. In addition, glassy carbon can be easily fabricated using lithography and RIE process due to its amorphous structure. These properties make glassy carbon suitable as a mold material for fabricating microlens arrays using glasses with high transition temperatures. To start, molds were fabricated on glassy carbon wafers using lithography process and followed with RIE. To fabricate the microlens arrays used in this research, glassy carbon molds with 100 μm diameter micro holes were etched to 10 μm deep as shown in figure 2. The pitch distance was also 100 μm in this mold design.

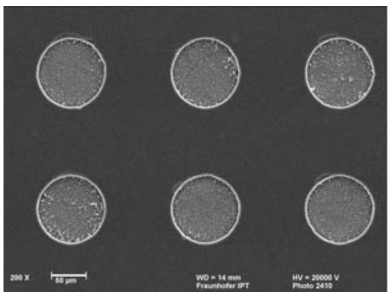

Figure 2: Fabricated glassy carbon molds measured by Scanning Electron Microscope (SEM), shows a pattern of the micro holes array with 100 μm diameter and 100 μm pitch distance,

After the glassy carbon molds were completed, the glass compression molding experiments for micro glass optical components were performed on a Toshiba GMP 211V machine at Fraunhofer Institute for Production Technology (IPT), Aachen. The major parameters of compression molding process could be found in figure 3. A thermocouple was inserted into the lower mold to measure the mold temperature as shown in figure 3. The detail of glass compression molding could be found in reference [10].

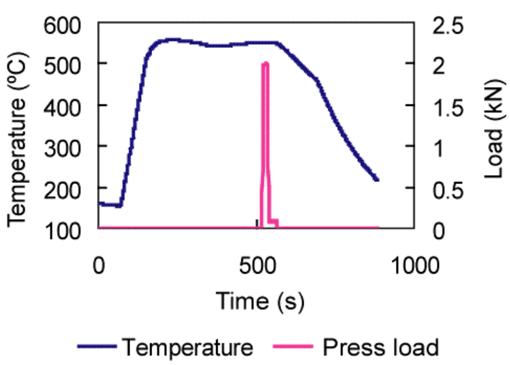

Figure 3: Molding temperature and press load time history for glass microlens array, with 565 ºC molding temperature, 300 seconds soaking time, 2 kN molding force.

After the molding process was completed, the glass workpiece with micro cylinders was re-heated to temperature that was higher than its glass transition temperature and was kept at this temperature for a pre-determined amount of time (400 s in the experiment performed at 600 ºC) to achieve the desired surface curve shape. A controlled cooling was performed (same as in molding process). At the soaking temperature, glass behaves as a viscoelastic material [11], which is strongly time and temperature dependent. Microlenses with precise surface geometry could be created at different soaking temperatures and soaking times.

4. NUMERICAL SIMULATION OF REFLOW PROCESS

Reflow of a molten glass article can be driven by gravity and/or surface tension. The relative importance of each factor depends on the size of the flow domain. To compare the two effects, one may conduct an order of magnitude analysis of a fluid domain with a characteristic dimension of D. The work done by surface tension can be estimated to be

$$\Delta S = D^2\gamma\,, \qquad (1)$$

where γ is surface tension, and the work done by gravity can be estimated to be

$$\Delta G = D^4\rho g \qquad (2)$$

where ρ is density and g is gravitational acceleration. Therefore the relative importance of these effects can be compared using a dimensionless group defined as

$$\mathrm{Sg} = \frac{\Delta S}{\Delta G} = \frac{\gamma}{D^2\rho g} \qquad (3)$$

In microlens molding, the characteristic dimension is on the order of 10 μm, resulting in an Sg on the order of 10^5.Therefore only surface tension needs to be considered in the reflow process for microlens.

Isothermal surface tension driven flow can be approximated using a creep flow model. In this case, the material is considered to be a purely viscous material, and compressibility is neglected. The simplified conservation equations are:

$$\nabla\cdot\underline{v} = 0\,, \qquad (4a)$$

$$-\nabla p + \nabla\cdot[\eta(\nabla\underline{v} + \nabla\underline{v}^T)] = 0\,, \qquad (4b)$$

where p is pressure, η is viscosity and $\underline{v}$ is a velocity vector. The geometry and the boundary conditions used in the reflow model are shown in figure 4. It is assumed that the surface tension induced deformation is local to the microlens. The fluid domain (i.e., glass) is axisymmetric. Due to this axisymmetry, only half a cross-section is shown in the model. The boundary conditions on the symmetries are zero normal velocity and zero tangential stress, where $\hat{n}$ and $\hat{s}$ are unit normal and tangential vectors. On the free surface, surface tension causes a net normal stress on the surface, where $\nabla\cdot\hat{n}$ is curvature. The governing equations and boundary conditions were implemented using Polyflow, a commercially available finite element analysis software package for polymer/glass molding

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and forming. The mesh size and time step used were 1 μm and 0.01 s.

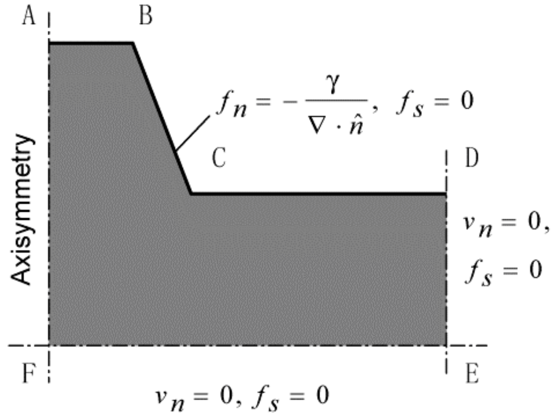

Figure 4: Surface tension driven reflow model. The dimensions along the *x* and *y* axes have different scales; along the *x* axis, FE = 150 μm, and along the *y* axis, AF = 20 μm.

5. RESULTS AND DISCUSSION

5.1 Geometry Measurement

Figure 5 shows the SEM images of the microlens array after the thermal reflow step and figure 6 shows the geometry of a microlens after reflow for a specific period.

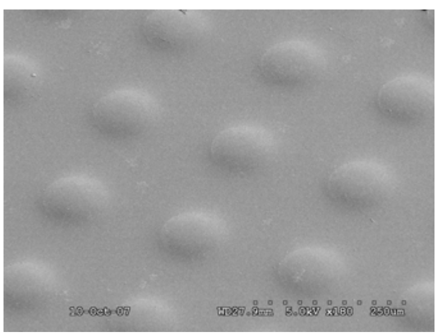

Figure 5: SEM images for fabricated microlens array on glass substrate, after thermal reflow at 610 ºC with 400 s soaking time

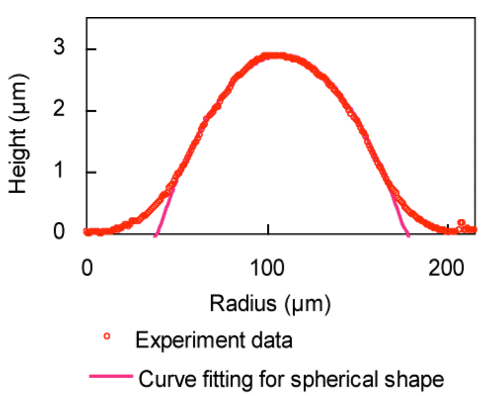

Figure 6: Surface geometry of a microlens after thermal reflow (610 ºC and 400 s). The red dotted line is the measured data from Veeco scan, and the solid line is the curve fitting for spherical shape of 830 μm radius.

Since the viscosity of glass material is strongly temperature dependent, different thermal reflow temperatures were tested to study the influence of temperature on surface curve change. At a higher reheating temperature, glass material had a lower viscosity. Therefore a lower height of microlens array (sagittal value) was expected as in figure 7. When the reflow temperature was 560 ºC or lower, there was almost no change in the surface shape from the molded glass micro cylinders. On the other hand, when the reflow temperature was more than 620 ºC, the shape of the microlenses became effectively flat.

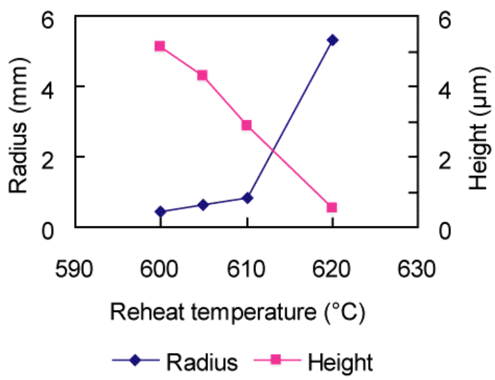

Figure 7: Radius and height of microlenses at different thermal reflow temperature.

5.2 Reflow Simulation Results

The dimensions of the compression molded micro cylinders, about 10 μm in height and 100 μm in diameter with a slope on the side, were taken as the dimensions for the initial geometry in the model. The typical surface tension of molten glass is approximately 0.3 N/m [12]. The viscosity of molten P-SK57 glass was previously characterized [13], governed by the following equation:

$$\log\eta(T) = A + \frac{B}{T - T_0} \tag{5}$$

where *A*, *B*, and T_0 are model coefficients and for this material are -3.556, 2917.3, and 306.4, respectively. The calculated viscosity at 610 °C is 10^6 Pa-s. However, the simulation results with these parameters did not agree with the experimental observations. Instead, a good agreement was obtained at a slightly lower viscosity of $3\text{x}10^5$ Pa-s. The simulated reflow for η = $3\text{x}10^5$ Pa-s and γ = 0.3 N/m at different time is shown in figure 8. At these parameters, reflow would occur at a similar time scale as observed in the experiments, as shown in Figure 12 for a reflow process at 610 °C and 400 seconds holding time. This discrepancy may be explained considering the deviation of the actual temperature inside the mold, i.e., the temperature measured outside the mold

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cavity could be significantly lower than the actual molding temperature. Furthermore, the surface tension used in the simulation was an estimate from the literature and therefore could bring in additional calculation errors.

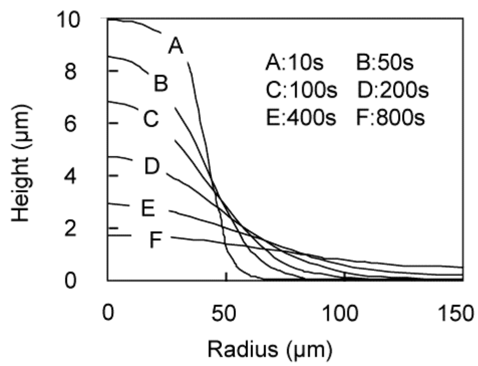

Figure 8: Simulation results showing the evolution of the microlens geometry during surface tension driven reflow.

5.3 Focal Length Measurement

To investigate the performance of the fabricated microlens arrays, the focal lengths of the microlenses were measured by using a system shown in Figure 9. In the test setup, a He-Ne laser (wavelength 632.8 nm) was employed as the light source and a charge coupled device (CCD) was used as an image collector. The fabricated microlens array was placed on a precision stage, which can be moved along the optical axis direction. First, the microlens array was manually moved to a position where the focus was on the flat surface of the microlens array workpiece. Then the stage was adjusted to move the microlens array away from the CCD camera until sharp focused spots were detected by the CCD camera. Figure 10 shows the image and focused light spots detected by the CCD camera for one of the glass microlens arrays, which was fabricated using thermal reflow at 610 ºC with 400 s holding time. The distance between these two positions gives the focal length of the microlens array.

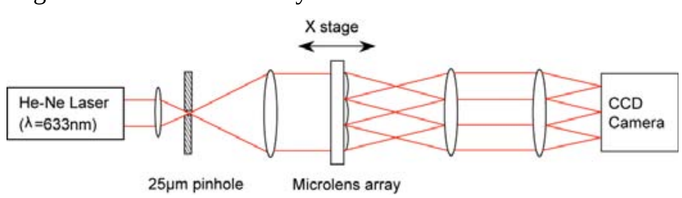

Figure 9: Optical test setup for measuring the focal length of a fabricated microlens array.

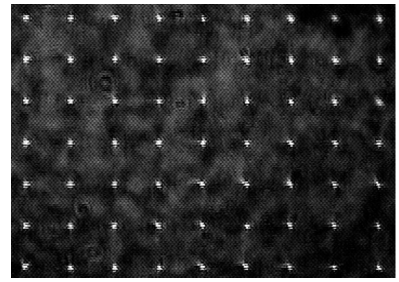

Figure 10: Images of light spots array produced by microlens array at focal plane.

The focal length of the microlens array can be determined approximately by using radius of curvature (*R*) and refractive index of P-SK57 glass with the equation below:

$$f = \frac{R}{n-1} \qquad (6)$$

The refractive index of P-SK57 for 632.8 nm wavelengths is 1.5849 according to the data sheet from Schott Glass [11]. The calculated radius of curvature after thermal reflow (610 ºC and 400 seconds) is 830 μm according to the curve fitting results as shown in Figure 8. Therefore, the focal length of this microlens was 1.42 mm by using the equation 6. The measurement result of focal length using above method is 1.75 mm.

6. CONCLUSIONS

From design, fabrication and measurement of P-SK57 glass microlens array, a new method for high volume production process was presented by combining glass compression molding and thermal reflow process. The quality of the glass surface geometry was measured using a mechanical stylus profilometer After thermal reflow at 610 ºC with 400 seconds soaking time, the microlens arrays with 150 μm in diameters and 2.89 μm heights were fabricated. By controlling reheating temperature and soaking time, microlens arrays with different radii and focal lengths were fabricated. Four different reheating temperatures from 600 ºC to 620 ºC were performed to research the relationship between reheating temperature and microlens curve shape. According to experiment results, a desirable microlens curve could be reached within the temperature range with 400 seconds holding time. At a higher reheating temperature, a lower height of microlens array (sagittal value) was expected. A numerical simulation was performed to evaluate and characterize the fabrication process that was driven by gravity and surface tension. According to the theoretical calculation, the gravity effect could be neglected compared with surface tension. The simulation results were compared with experimental data. The discrepancy between simulation and experiment could be explained by temperature measurement error and surface tension deviation. Finally, the focal lengths of fabricated glass microlens arrays were measured using an optical setup. The focal length of 1.75mm was measured. The experimental results matched well with the numerical simulation estimation. In summary, this method

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could be used for fabricating glass microlens arrays with controllable diameters and sagittal height with good optical performance. Furthermore that is based on glass compression molding therefore making it a very useful tool to mass produce various micro glass optical elements at a low cost.

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