Micro-molding of microlens array using electroformed mold insert

NAMSUK LEE, SU-DONG MOON, and SHINILL KANG

Center for Information Storage Device, Yonsei University, Korea

Key Words : Micro-molding, Microlens, Micro-mold insert, Electroforming, Replication quality

Abstract

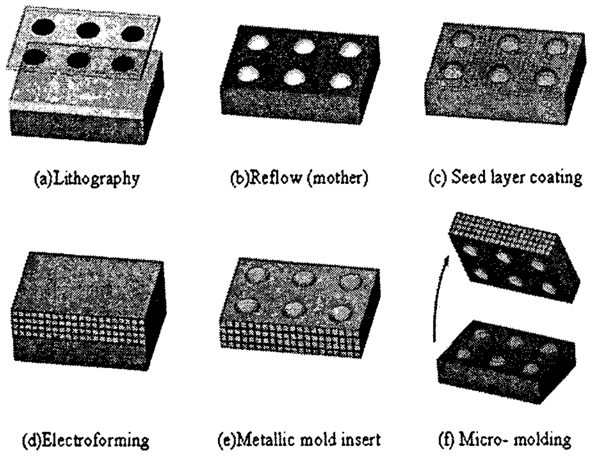
Polymeric microlens arrays with diameters of 13~96 μm fabricated using the micro-compression molding with electroformed mold inserts. In the present study, the electroforming process was used to make the metallic micro-mold insert for micro-molding of microlens array. The wettability property of the fabricated mold insert was examined by measuring the contact angle of the polymer melt on the mold insert. Microlenses were compression-molded with the fabricated mold insert. The effects of the molding temperature and wettability property on the replication quality of the molded lenses were analyzed experimentally.

1. Introduction

The increasing demand for micro-optical elements, in the fields of optical data storage, optical communication, and digital display, has required advanced mass fabrication technology for polymeric microlens and lens array. Micro-molding, including injection molding, compression molding and hot embossing, is regarded as the most suitable process for replicating and mass producing the micro-plastic products because it offers high repeatability, mass productivity with low cost, and versatility in selecting polymers. In micro-molding, the micro-mold insert, which contains the micro-patterns, is required, and the quality of the mold inserts determines the success of molding. A silicon micro-mold insert was frequently used due to its ease of manufacturing[1]. However, it is too brittle to be used for compression molding for mass production, where high-pressure shock is applied to the mold cavity repeatedly. A metallic mold insert can provide a solution to this problem, and either mechanical machining or electroforming can be used to make micro-patterns on the metallic mold insert. However, lens-shaped patterns are difficult to make on a metallic mold insert by mechanical machining if the lens diameter is less than 300 ㎛[2]. Electroforming provides a good alternative to the mechanical machining process because metal structures can be generated with a good surface quality. Additionally, electroforming is a more suitable pattern transfer process for areas with a high density of small features. So electroforming process is regarded as the most suitable fabrication method to make micro-patterns on the metallic mold insert [3-7].

But many technical problems have to be overcome to mass-produce the plastic micro product by using micro-mold insert at low cost. For example, as the features of the micro-patterns on the micro-mold become smaller, one needs increase the mold temperature and pressure to make the polymer melt more fluid. And when the polymer melt becomes more fluid, the replication quality of the micro-pattern in the micro-mold improves. However, when one increased the mold temperature excessively, the polymer melt may stick to the micro-mold cavity, deteriorating the surface quality of the molded micro-patterns, as described in detail by Kang et al. [6]. Therefore, we need to study the effects of the molding temperature on the replication quality of the molded lenses.

The main objective of this work is to fabricate microlens array by micro-compression molding with metallic mold insert. Figure 1 shows the fabrication procedure of micro-mold insert and microlens array. The electroforming process was used to make the metallic micro-mold insert. The wettability property of the mold insert was examined by measuring the contact angle of the polymer melt on the mold insert. Microlenses were compression-molded with the fabricated mold insert. The effects of the molding temperature and wettability property on the replication quality of the molded lenses were analyzed experimentally.


(a)Lithography (b)Reflow (mother) (c) Seed layer coating

(d)Electroforming (e)Metallic mold insert (f) Micro- molding

Fig. 1 Schematic diagram of fabrication process of micro-mold insert and microlens array

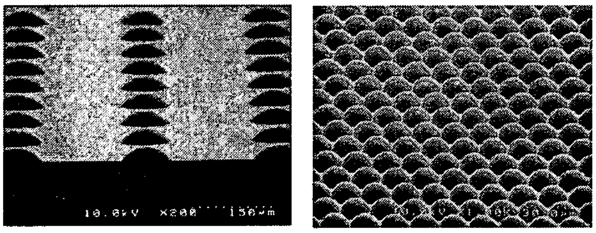

(a) (b)

Fig. 2 SEM images of mother lens array ((a) lens diameter of 96 μm, pitch of 250 μm and (b) lens diameter of 13 μm, pitch of 15 μm).

2. FABRICATION OF MICRO-MOLD INSERT

2.1 Fabrication of the master by reflow method

At first, we needed a master lens of the same shape as the final molded lens. Any of the established methods could be used to fabricate the master lens. The reflow method was used to make master lens in this study. The photoresist material was of the positive type with a propylene glycol monomethyl ether acetate (PGMEA) base. From the lens shape of desired diameter, height, and radius of curvature, we determined the diameter and height of the initial photoresist pattern. The photoresist patterns were made by standard photolithography, and then thermally treated on hot plate so that the surface tension converted the patterns into lens form. Figure 2 shows the SEM images of the master microlens array. The diameters of master lens surfaces were 96 μm and 13 μm, respectively, and the pitch of the array was 250 μm and 15 μm for each cases.

Table 1. Process parameters for evaporation

Parameter	Range of values
DC Kilovolts (KV)	8.5 ~ 8.53
DC Ampares (A)	0.98
DC Kilowatts (KW)	0.91
Deposition Rate (Å/s)	0.2
Pressure (Torr)	1.23×10^{-6}
Temperature (I⊢C)	57 ~ 61

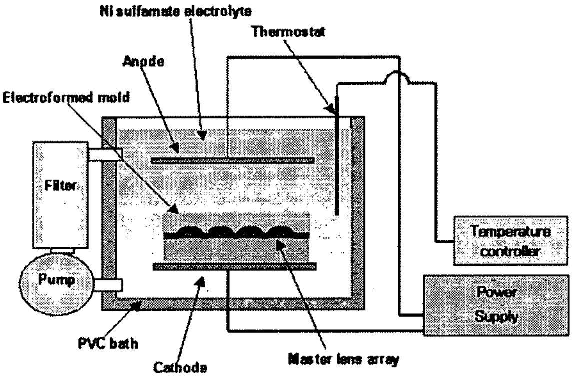


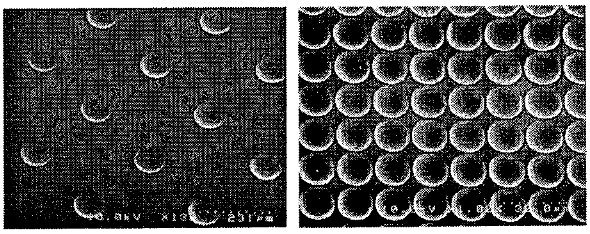
Fig. 3 Schematic diagram of electroforming system.

2.2 Fabrication of nickel mold insert by electroforming

An electron-beam (E-beam) evaporation system was used to deposit the seed layer on the master mold. As shown in Fig. 1, when the silicon wafer was removed from the micro-mold insert, nickel seed layer deposited on the mater mold was constructed the mold surface. Since the seed layer functions as the mold surface and the conduction layer in the electroforming process, the material of seed layer is important. Therefore, in selecting the material of seed layer, we should consider wear resistance, durability, thermal stability, conductivity and anti-adhesion property. Nickel was chosen as seed layer material because it contains desirable surface properties such as high hardness and thermal stability. Table 1 shows process parameters for E-beam evaporation of nickel seed layer. After the 1500Å–thick seed layer was deposited, the nickel was electroformed. Figure 3 shows the schematic diagram of electroforming system. Electroforming bath consisted of 66L PVC bath, power supply, air pump for agitation, filter, and thermostat for temperature control. Table 2 shows process parameters for nickel electroforming. Commercial nickel sulfamate solution was used as an electrolyte. The bath was maintained at 43~45 °C during electroforming by a current density of 10 ~ 20 mA/cm^2 yielding an approximate deposition rate of 1 ~ 2 μm /min; pH was maintained at 3.8 ~ 4.4. After finishing the

Table 2 Process parameters for Ni electroforming

Parameter		Range of values
Temperature (° C) pH Current density (mA/cm^2)		43 ~ 45 4 ~ 4.2 10 ~ 20
Concentration of Electrolytes (g/l)	$Ni(NH_2SO_3)_2$ΠΠ$4H_2O$	300 ~ 450
	$NiCl_2$ΠΠ$6H_2O$	15
	H_3BO_3	45



(a) (b)

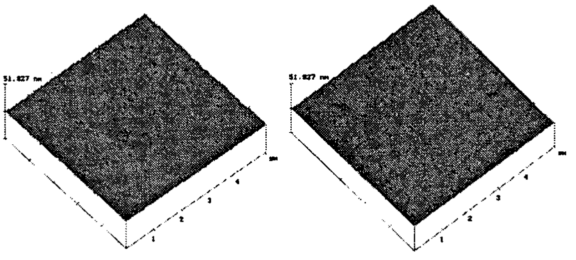
Fig. 4 SEM images of nickel electroformed micro-mold insert ((a) cavity diameter of 96 μm, pitch of 250 μm and (b) cavity diameter of 13 μm, pitch of 15 μm).

electroforming, we polished out the backside of electroformed mold insert to obtain the desired mold insert thickness and flatness. After the nickel mold insert was back-polished, the silicon wafer and photoresist were removed. Figure 4 shows the SEM images of electroformed nickel mold inserts.

The surface quality of the mold insert defines the final surface quality of the molded lens. An atomic force microscope (AFM) was used to measure the surface roughness of the mold insert. The specimens were randomly selected to avoid the possibility of systematic error infiltrating the system. Figure 5 shows AFM images of the mold cavity surface with diameters of convex surfaces were 96 μm and 13 μm, respectively. The average surface roughness (RMS) of metal mold cavities was 0.84 nm, which guarantee mirror-surface mold cavities.

2.3 Analysis of wettability of the mold insert

The wettability of micro-mold insert is an important factor which determines the surface quality of the molded micro-optics. For the analysis the wettability of the actual micro mold insert, the contact angle was measured under the identical temperature condition as the actual micro-molding process where the micro mold insert was heated above the glass transition temperature of the PMMA. Figure 6 shows the schematic diagram of the contact angle measurement system. This system consists of hot plate and thermal chamber, which are used to heat the air in the thermal chamber up to the temperature of the actual molding process. A microscope and CCD camera were used to record the images of polymer melt on the micro mold during measurement, and these images were analyzed to extract the contact angle by using an image analyzer.



(a) (b)

Fig. 5 AFM images of nickel mold inserts. ((a) cavity diameter of 96 μm , pitch of 250 μm and (b) cavity diameter of 13 μm, pitch of 15 μm).

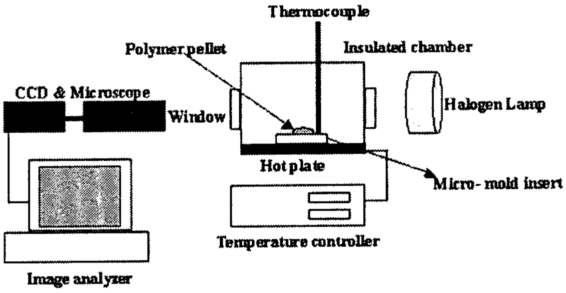


Fig. 6 Experimental setup for contact angle measurements

The contact angle was measured by using polymer melt at a temperature above the glass transition temperature of the PMMA. Considering the glass transition temperature of the PMMA, we determined 180 °C as the minimum temperature that could be used in measuring the contact angle by using polymer melt. Additionally, considering the mold temperature in the actual micro compression molding, the peak mold temperature was set to 180, 200, 210, 220, 230, and, 240 °C.

Figure 7 shows the dependence of the terminal contact angle on peak mold temperatures. As shown in Fig. 7, as the peak mold temperature increases, the terminal contact angle values decreases. When peak mold temperature was changed from 210 to 220 °C, the contact angle values decreased markedly. This temperature range includes the melting temperature of the PMMA. It indicates that when the mold temperature

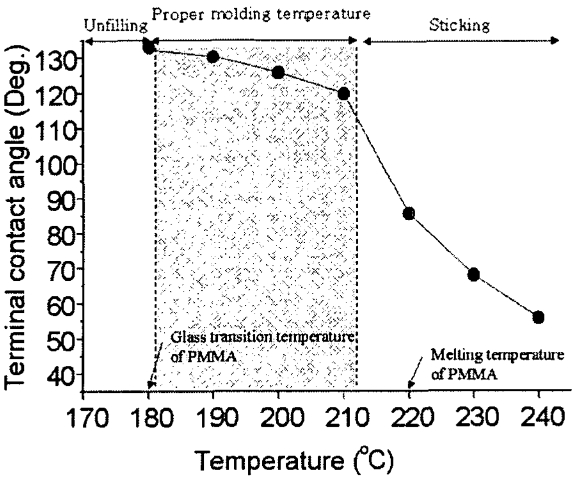


Fig. 7 Terminal contact angle for various peak mold temperatures.

increases over the melting temperature of PMMA, the wettability between the micro-mold cavity and the PMMA melt increases, and may adversely affect the surface quality of the molded micro-optics.

3. Micro-compression molding

A micro-compression molding with powdered optical polymer was used to fabricate polymeric microlens array. An optical grade PMMA(Polymethyl Methacrylate) powder, whose transparency was 93.0 % at 3.2 mm thickness, refractive index 1.489 at 655 nm wavelengths, haze 1.0 %, glass transition temperature 180 ℃, and melting temperature 220 ℃, was placed on the mold insert. Micro-compression molding process is similar to general molding process; powder filling, mold heating, pressing, cooling & pressure holding, and releasing [1]. In mold heating stage, the mold was heated above the glass transition temperature of PMMA. During heating, small pre-pressure was applied to maintain contact between the melting powder and the mold insert. The compression pressure was applied so that microlenses could be replicated when the mold temperature exceeded the glass transition temperature. The mold was then cooled while the compression pressure was maintained. Once the de-molding temperature had been reached, the molded microlenses were released from the metallic mold insert.

Figure 8 shows the SEM images of the molded microlens at different molding temperatures. The compression pressure was fixed as 24MPa. Figure 8 (a) shows that when the molding temperature was below the glass transition temperature, the molded lens did not replicate the mold insert cavity well. The elevation of the mold temperature over the glass transition temperature resulted in increasing the fluidity of the polymer melt, and the replication quality was improved, as shown in Fig. 8 (b). However, as shown in Fig. 8 (c), when the molding temperature was above the melting temperature, the sticking between the micro-mold and polymer melt produced serious surface defects in the molded lens. This shows that the excessive raise of the mold temperature resulted in increasing of wettability, which resulted in the sticking of the vitrified polymer. It agrees with the prediction by the wettability measurement.


(a) (b) (c)

Fig. 8 SEM images showing the effect of mold temperature and pressure : (a) molding temperature 180 °C, and molding pressure 24 MPa, (b) molding temperature 240 °C, and molding pressure 48 MPa.

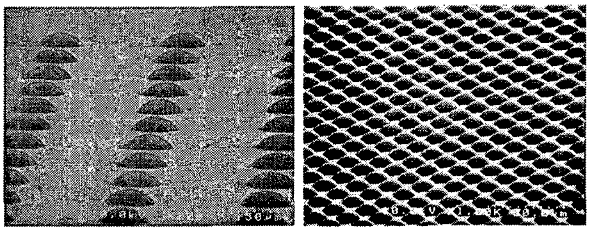

(a) (b)

Fig. 9 SEM images of molded microlens array ((a) lens diameter of 96 μm, pitch of 250 μm and (b) lens diameter of 13 μm, pitch of 15 μm).

Figure 9 shows the SEM images of the microlens array with diameters of 96 μm and 13 μm, respectively, which were molded with molding temperature of 190 °C and molding pressure 24 MPa. The surface profiles of mother lenses and the molded lenses were measured using the three dimensional optical profiler, mechanical profiler, and SEM to show the replication quality. Figure 10 shows the comparison between surface profiles of the master lenses and those of molded lenses with diameters of 96 μm and 36 μm. The average radius of curvature of the mother lenses with diameters of 96μm was 59.06 μm and that of molded lens was 58.29μm. The radius of curvature and sag height of the molded lenses deviated from those of the mother lenses by less than 0.8 μm and 0.2 μm, respectively. The surface roughness (RMS) of molded lens was 4.03 nm. These measurements show

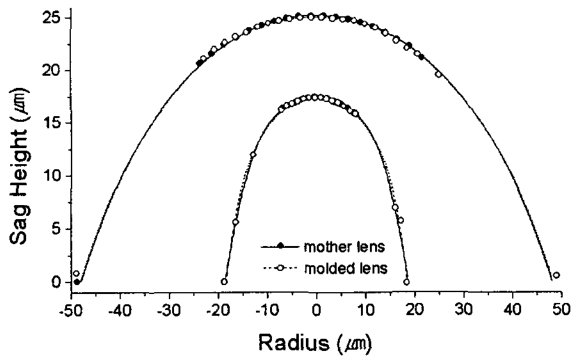


Fig. 10 Comparison between mother lens profile and molded lens profile.

the possibility of using the present molded lens for application areas such as data storage and optical communication, in which the wavelengths between 405 nm and 805 nm are used. It is because RMS of 4.03 nm for the present molded lens is about 0.011 for high-density optical data storage application (λ = 405 nm) and about 0.0051 for optical communication (λ = 805 nm).

4. CONCLUSION

Polymeric microlens arrays with diameters of 13~96 μm were fabricated using micro-compression molding with electroformed mold insert. The reflow method was used to make master lens patterns. The electroforming process was used to fabricate the metallic mold insert. The wettability property of the fabricated mold insert was examined by measuring the contact angle of the polymer melt on the mold insert. The wettability between the micro-mold cavity and the polymer melt increased rapidly as the molding temperature increased over the melting temperature range. A micro-compression molding with powdered optical polymer was used to fabricate polymeric microlens array. The effects of the molding temperature and the wettability property on the replication quality of the molded lenses were analyzed experimentally. Improvement of durability and anti-adhesion property of the mold insert is the subject of ongoing research.

Acknowledgement

This work was funded by the Korea Science and Engineering Foundation through Center for Information Storage Device (2002G0203) at Yonsei University.

References

(1) S. Moon, S. Kang and J Bu, Optical Engineering, Vol. 49 p. 2267, (2000)

(2) N. F. Borrelli: Microoptics technology, Marcel Dekker, New, (1999)

(3) T. S. Norris, G. A. C. Jones, and H. Ahmed: Microelectronic Engineering, Vol.3, p.85, (1985)

(4) E. W. Becker, W. Ehrfeld, P. Hagmann, A. Maner and D. Münchmeyer: Microelectronic Engineering, Vol.4, p. 35, (1980)

(5) L. J. Heyderman, H. Schift, C. David, B. Ketterer, M. Auf der Maur and J. Gobrecht: Microelectronic Engineering, Vol.57, p. 375, (2001)

(6) K. Seong, S. Moon and S. Kang: Journal of information Storage and Processing Systems, Vol.3 p. 1, (2001)

(7) S. Moon, N. Lee, and S. Kang, Journal of Micromechanics and Microengineering, Vol. 13, pp. 98, (2003)