Fabrication of large area resin microlens arrays using gas-assisted ultraviolet embossing

Po-Hsun Huang1, Tzu-Chien Huang1, Yi-Ting Sun2, and Sen-Yeu Yang*1
1Department of Mechanical Engineering, National Taiwan University, Taipei 106, Taiwan
2Mechanical and Systems Research Laboratories, Industrial Technology Research Institute, Hsinchu 310, Taiwan
*Corresponding author: syyang@ntu.edu.tw

Abstract: Large-area microlens arrays are becoming important components in many applications such as LCD-TV diffusers. This paper reports a uniform pressure, low temperature process for their fabrication. The process integrates gas-assisted embossing and UV-curing embossing. During the process, the 230mm x 203mm PMMA substrate is pressed against the stainless-steel stamper coated with UV-curable resin. Under the gas pressuring and UV irradiating, a large array of microlens can be formed. By using this process, high embossing temperature and high embossing pressure can be avoided. Little residual stress is observed in the embossed PMMA substrate. The uniformity of large-area fabrication and optical properties of fabricated resin microlens array have been verified. This study has successfully shown the potential of this gas-assisted UV embossing process for the replication of large-area microstructures.

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References and links
1. Introduction

Recently, microlens arrays have been used in many electro-optical applications such as micro-scanning systems, fiber-coupling, optical data storage, optical communication, and diffusing plate in LCD backlight unit. Many methods for fabricating microlens arrays have been presented, e.g., thermal reflow [1-2], UV proximity printing [3], gray-scale photolithography [4-5], micro-transfer molding [6], reactive ion etching [7], 3-D diffuser lithography [8], and two photon photopolymerization [9]. Most of these methods involve complicated processes and require expensive equipment, resulting in high cost and low productivity. To improve the productivity, several replication methods for manufacture of plastic microlens arrays have been used, including injection molding [10], hot embossing [11], hot intrusion [12], and extrusion rolling embossing [13]. In recent years, ultra-thin and large-size LCD-TVs are becoming popular due to their greater viewable screen area and reasonable price. Accordingly, fabricating the large-area optical elements for use in large-size LCD-TVs is important. There is an increasing demand for developing an efficient method for the fabrication of large-area optical elements with low cost and high throughput. In addition, large-area production is an alternative way to enhance the productivity. However, large-area production means higher cost. Among the forementioned fabrication methods, extrusion rolling embossing could effectively raise the productivity. However, the roller mold fabrication and process control are challenging issues. Though injection molding can fabricate precise plastic products, molding large area thin parts is difficult due to the large flow resistance. Significant flow- and thermal-induced residual stresses are induced in the molded parts. Hot embossing is comparatively inexpensive. But it is difficult to achieve uniform pressure distribution over large area using hot plates. Thus the embossing area is limited. A gas-assisted hot embossing process has been proposed [14]. With gas pressurizing method, uniform embossing pressure throughout the whole area can be achieved. Another problem with hot embossing is the long heating/cooling time of the plastic substrates. The substrates are usually the ready-made plastic substrates. Reheating is not only time and energy consuming, but also will release the residual stress, resulting in warpage. In order to avoid the reheating, we have presented the UV-molding method for fabricating microlens arrays [15].

This study is devoted to developing a process for effective fabrication of large-area microlens arrays at room temperature and with low pressure. This process integrates the gas-assisted embossing process and the UV-curing embossing process. The gas-assisted embossing provides the uniform pressing pressure over the whole large area, while the UV-curing embossing enables the process to perform without heating and cooling and under low pressure. By using gas-assisted and UV-curing mechanisms, the high temperature and high pressure can be avoided. Moreover, the problems of non-uniform pressure and residual stress can be addressed.

In this paper, the facility and process for fabrication of large-area microlens arrays based on gas-assisted UV-curing embossing principle is implemented and tested. Using photolithography and wet etching, the micro-holes array is first formed on a stainless-steel plate of 0.8mm thickness, which is used as the stamper. During the gas-assisted UV-curing embossing process, the PMMA substrate is pressed against the stainless-steel stamper coated with UV-curable resin. Under the gas pressuring and UV irradiating, a large array of microlens can be formed. The uniformity and optical properties of the microlenses array over whole substrate are verified with an optical microscope, a surface profiler, a strain viewer, and a light focusing system.
2. Experiment setup

Figure 1 schematically shows the apparatus and fabrication procedure of the gas-assisted UV embossing apparatus for fabricating large-area of microlens array. The embossing apparatus is composed of a upper chamber, a lower chamber, a UV-LED lamp, and a seal film. For upper chamber, nitrogen gas can be introduced to produce a pressing pressure. The lower chamber is vacuumed to reduce air bubble during embossing. Since the traditional UV-lamp is a linear light source and is difficult to provide a uniform irradiation over large-area, a UV-LED array (14x9) lamp as shown in Fig. 2 has been designed and implemented for completely covering, irradiating, and curing a large-area. The wavelength of the UV-LED lamp is between 375–395nm. Poly(ethylene terephthalate) (PET) film with a thickness of 180μm is used as the seal film. The seal film is needed to separate the nitrogen gas in the upper and lower chambers and to pressurize the stamper/substrate stack. 0.8mm-thick PMMA plates (230mm x 203mm) are used as the substrates in the experiment. An ultraviolet-curable resin with a refractive index of 1.56 is employed.

In this study, the large-area stainless-steel stamper (270mm x 195mm) with a micro-holes array is supplied by Industrial Technology Research Institute of Taiwan. The stainless-steel stamper has a very large array (over 1500x1500) of holes and is fabricated by photolithography and wet etching. As shown in Fig. 3, the average diameter of the micro-holes is 120.5μm. The shapes of the etched micro-holes are varying and not uniform. The average depth of the micro-holes is 7.95μm.

The gas-assisted UV-curing embossing process is composed of five steps:
(a) The stainless-steel stamper with micro-holes array cavity is coated with the UV-curable liquid resin using a scraper and is fixed on the holder of lower chamber.
(b) The upper and lower chambers are closed. At the same time, the PMMA substrate is brought into contact with the UV-curable resin coated on the stainless-steel stamper. Subsequently, the lower chamber is vacuumed and the nitrogen gas is introduced into upper chamber to produce a pressing pressure. The stack of stamper and substrate is pressed for a specific duration.
(c) The liquid resin is transferred onto the PMMA substrate and is cured by the UV irradiation at room temperature.
(d) After curing, the nitrogen gas is introduced into lower chamber to separate the stamper and substrate.
(e) The upper and lower chambers are opened. The stainless-steel stamper is removed from the PMMA substrate, and the PMMA substrate with microlens array on its surface can be obtained.
Fig. 1. Schematic of the gas-assisted UV-curing embossing process for the fabrication of large area microlens array.

Fig. 2. Photograph of the UV-LED array lamp.

Fig. 3. OM image of the micro-holes array on the stainless steel stamper.
3. Results and discussion

3.1 Observation of residual stress for the fabricated large area microlens arrays

To observe and inspect the residual stress, a strain viewer (Compact, Sharples, UK), based on the polarized light and birefringence, was employed. Figure 4 shows the observation of photoelastic stress. There is little residual stress observed. The result demonstrates that negligible residual stress is induced in the large-area PMMA substrate using proposed process. By using proposed process in this study, the high temperature and high pressure can be avoided due to gas-assisted and UV-curing mechanisms. Accordingly, the substrate is expected to be free of residual stress.

![Fig. 4. The observed photoelastic image from (a) central area and (b) side area of PMMA substrate.](image)

3.2 Profile of fabricated microlens and uniformity of large area fabrication

As shown in Fig. 5, a vary large array (over 1500 x 1500) of resin microlenses has been successfully fabricated onto a 203mm x 230mm PMMA substrate by gas-assisted UV-curing embossing process. The result demonstrates the capacity of this proposed process for large-area fabrication of microlens arrays. Figure 6 shows the optical microscope (OM) image and the surface profile of the fabricated microlens array under the processing conditions of 5 Kgf/cm² of pressing pressure, 60 seconds of pressing duration (including UV irradiating time), and 20 seconds of UV irradiating time. A large array of resin microlenses has been successfully fabricated over the whole PMMA substrate. To inspect and verify the fabrication uniformity of resin microlenses in large-area, the whole fabricated area was divided into nine areas as shown in Fig. 5. The surface profiles of 270 microlenses (30 microlenses were randomly selected in each area from nine areas) from a single process run are measured. Table 1 shows the average diameter and sag height of the fabricated microlenses measured from the nine areas. The average diameter is 119.77 μm with a standard deviation of 1.73 μm, while the average sag height is 7.89 μm with a standard deviation of 0.47 μm. The difference between averages and standard deviations in the nine areas must result from the non-uniformity of the micro-holes in the original stamper, not from the replication process. In the proposed process, the stamper is first coated and the micro-holes in it are completely filled with resin. The shape of the etched micro-holes is replicated with fidelity onto the PMMA substrate upon embossing.

Figure 6(c) shows the stylus scan of the five neighboring replicated microlenses. It is noted that the shape of lens is not identical and variation is observed especially at the lens vertices. Upgrading the uniformity of micro-holes in the stamper is needed to improve the quality of the microlenses produced.
Fig. 5. The PMMA substrate (203mm x 230mm x 0.8 mm) with fabricated microlens array.

Fig. 6. OM images and surface profile of the fabricated microlens array on PMMA substrate.
Table 1. Large-area uniformity of fabricated microlens array.

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<tr>
<th>Area</th>
<th>Diameter (μm)</th>
<th>Standard deviation (μm)</th>
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3.3 The optical property of the molded microlens arrays

In order to verify the optical property of the fabricated microlens array using this process, a light focusing system is employed. Figure 7(a) schematically shows the light focusing system which is composed of expanding lenses, an optical attenuator, a filter, a micrometer scale resolution Z-stage, a microscope, a CCD system and a 633 nm wavelength laser light source. The measured average focal length is 418μm for the fabricated resin microlens with an average diameter of 119.77μm and an average sag height of 7.89μm. Based on the geometry and optical theory, the theoretical radius of curvature (R), focal length (f), and numerical aperture (NA) can be calculated using the equations shown below:

\[ R = \frac{D^2 + 4h^2}{8h}, \quad f = \frac{R}{n-1}, \quad NA = \frac{D}{2f} \]

where D, h and n are the diameter, the sag height, and the refractive index of the UV-curable resin, respectively. The calculated average radius of curvature, the average focal length, and the average numerical aperture of the formed resin microlenses are 232.1μm, 414.46μm, and 0.145, respectively. The calculated average focal length agrees well with the measured average focal length. Results indicate good uniformity of the fabricated microlenses. Figure 7(b) shows a portion of the focused light spots observed by this system. The image reveals that the uniformity of pitch and intensity of the focused light spots are acceptable. Variation in the spot shape is caused by the non-uniformity in the replicated microlenses, which is due to the limitation in the uniformity of wet-etched micro-holes. To further improve the uniformity of spot pattern, the quality of the original stamper will be upgraded.
4. Conclusions

This paper reports a novel and effective process to fabricate large-area microlens arrays on thin PMMA substrates by gas-assisted UV-curing embossing with a stainless-steel stamper and a UV-LED lamp. This process takes advantage of the uniform pressing pressure of gas-assisted embossing and the low pressure and fast curing of the UV embossing. During this process, by pressing the PMMA substrate against the stainless-steel stamper coated with UV-curable resin, the resin microlens array can be fabricated. A large array (over 1500x1500) of microlenses has been successfully fabricated onto the whole PMMA substrate (203mm x 230mm) with 5Kgf/cm² of pressing pressure, 60 seconds of pressing duration, and 20 seconds of UV irradiating duration. With this process, no residual stress is observed in the embossed PMMA substrate. The uniformity of large-area fabrication and optical properties of fabricated resin microlens array have been proven. This process has proven its potential for the large-area fabrication of microstructures.

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