Precise Micro Pattern Replication by Hot Embossing∗

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The LIGA (Lithografie, Galvanoformung, Abformung [German: lithography, electro-plating, and molding]) process is one of the promising techniques for fabrication of microstructures having high aspect ratios. Microstructures as high as a few hundred µm or more are widely used for various devices, such as micro-actuators, micro-mechanisms, and micro-sensors. The key to reducing the microstructure fabrication cost of the LIGA process is by using micro replication technology. Hot embossing is attracting the attention of engineers as one such technology for economically mass-fabricating microstructures on thin plastic sheets. This technology is especially effective for precisely replicating micro patterns on relatively large sheets. This paper describes the results of research the authors recently carried out to find the optimal conditions for hot embossing in the atmosphere and in a vacuum. For a series of experiments, we prepared two types of Ni molds each containing an area of 33 × 33 mm² distributed with hole or column patterns 60 µm in diameter and 1.0 in aspect ratio. The LIGA process using synchrotron radiation fabricated these patterns. From the experiments, we could determine the optimal conditions for replicating these patterns on PMMA sheets in a normal-atmosphere and vacuum environments.

Key Words: LIGA Process, X-Ray Lithography, Nickel Electroforming, Hot Embossing, Vacuum

1. Introduction

The need for cost-effective, large aspect ratio microstructure fabrication and micro system integration technologies has grown in the field of cutting-edge technologies such as IT, energy-saving technologies, and biotechnology. The LIGA process using synchrotron radiation[1,2] is a typical example of such technologies attracting the attention of engineers. This process utilizes nano-/micro-molding technology to economically fabricate microstructures.

We have been engaged in research to apply synchrotron radiation for microstructure fabrication. Our research results include the development of a vacuum hot embossing machine that can mold microstructures with high aspect ratios[3]−[5]. Consisting of a high-precision alignment mechanism and high efficiency cooling system, this machine can efficiently fabricate microstructures by embossing on one or both sides of a sheet.

In our research, we applied the LIGA process to electroform Ni molds in which micro patterns were densely distributed over a relatively large area. Using these molds, we performed hot embossing of the micro patterns in both a normal atmosphere and vacuum environments, in order to find the optimal mold configuration and hot embossing conditions for microstructure fabrication.

2. Vacuum Hot Embossing Machine

The vacuum hot embossing machine that we developed is shown in Fig. 1. The machine consists of a vacuum chamber, top and bottom heaters, pressurizer, vertical position alignment mechanism, and cooling system. The pressurizer is equipped with a servomotor to control the position with a high degree of precision. The vertical position alignment mechanism enables a micro mold to be embossed on both surfaces. The cooling system uses a combination of a very low temperature/pressure air nozzle and chiller to efficiently cool the mold. The machine can heat the mold to 400°C, thereby allowing most thermoplastic resins and low melting glass to be embossed.
Major specifications:
- Manufacturer: ACCESS Engineering Co., Ltd.
- Pressure load: 50 kN (servomotor)
- Heating temperature: 400°C
- Sheet size: 80 × 80 mm
- Vacuum: 1 Pa
- Cooling system: air cooling, water cooling
- Alignment accuracy: ±5 μm
- Mold release force measurement system

3. Fabrication of Electroformed Molds

We spin-coated PMMA resist over a 4-inch Si substrate to a thickness of 60 μm to make an X-ray mask on which φ60 μm micro dot patterns are densely distributed. We made a master electroformed mold by processing this X-ray mask with X-ray lithography in the synchrotron radiation beam line BL 11 of the New SUBARU (a research laboratory at the University of Hyogo).

The pattern distribution of the X-ray mask is shown in Fig. 2. As can be seen from this figure, φ60 μm micro dot patterns distribute continuously along the diagonal at a density of several to 150 dots per an area of 1 mm². There are approximately 6,500 dots in a square with a side of 33 mm.

Using the master molds we made as described above, we electroformed two types of Ni molds in a sulfamic acid Ni electroforming solution. Measuring 3 mm in thickness and 80 mm in diameter, each mold contained an area of 33 × 33 mm square at the center where φ60 μm hole or column patterns with an aspect ratio of 1.0 were distributed. For mounting the molds on the embossing machine, holes were machine-cut along a circle with a diameter of 60 mm. To concentrate the pressure load in the pattern area, we ground to a depth of 0.25 mm the area outside the periphery of a 40 × 40 mm square in the center of each mold. From a preliminary experiment, we found that the PMMA sheets were warped or deformed when the above molds were used. To eliminate this defective condition, we additionally ground the area 3 mm outside the 40 × 40 mm square to a depth of another 0.25 mm, so that each mold would be released in a two-step manner. The new mold configuration now reinforced the sheets, reducing the warping of the sheets to practically zero.

A general view of the molds electroformed with micro hole and column patterns is shown in Fig. 3 and SEM images of the hole and column patterns are shown in Fig. 4. As can be seen from these figures, both the hole and column patterns were sharply formed with smooth surfaces, showing that the configuration of the master mold was accurately replicated on these micro molds.

4. Hot Embossing Experiment

4.1 Hot embossing in the atmosphere

Using the hole pattern and column pattern molds, we hot embossed 1 mm and 2 mm thick, 70 × 70 mm PMMA sheets in the atmosphere. At first, we set one of the molds on the bottom of the embossing machine. In this installation, the sheet adhered to the pattern surface of the mold, hence the knockout pins provided along the outer edge of
Table 1  Hot embossing conditions in the atmosphere

| Parameter             | Conditions          |
|-----------------------|---------------------|
| Molding temperature   | 140°C, 150°C, 160°C, 170°C |
| Heating time          | 5 min.              |
| Pressure load         | 5 kN, 6 kN, 8 kN    |
| Pressing time         | 60 sec.             |
| Mold release temperature | 60°C, 80°C          |

the pattern area were unable to release the mold. Next, we set the mold on the top of the embossing machine. We also arranged 16 undercut knockout pins in the pattern area at intervals of 10 mm. With the above-described setup, we then carried out a series of embossing experiments under the following conditions of Table 1.

In the case of hot embossing 1 mm thick PMMA sheets under the above conditions, they adhered to the molds. Various other defective conditions occurred when each mold was released, including breakdown of the knockout pins at the undercut portion, tearing of the sheet, and breakage of micro patterns into pieces and accumulation in each mold. Our analysis showed that these defective conditions mainly came from the following causes: (1) Softened PMMA sheets could not flow deeply into the undercut portions of the knockout pins and this made it difficult to fix the sheets on the bottom of the embossing machine; and (2) the sheets were not rigid enough for hot embossing. Though we sprayed a mold lubricant over the molds or sheets, we could not completely remove these abnormal conditions. To make softened resin sheets easier to flow into the undercut portions, we rounded the inlet edge of each undercut. We also increased the depth of each undercut so that the rigidity of the sheet would increase during hot embossing. After modifying the experimental setup as described above, we carried out another experiment using 2 mm thick PMMA sheets. In this experiment, the knockout pin did not break at the undercut. However, the knockout pins were lifted since the springs used for fixing the knockout pins could not hold the mold release force. We replaced the springs with those of a higher spring constant. As a result, the sheets themselves did not tear. However, the pattern surface was scratched when the mold was released and part of the patterns broke into pieces and remained in the mold. We were able to eliminate these abnormal conditions by spraying a mold lubricant over the PMMA sheet or mold. As a result, lubricating the sheet or mold one time allowed about 10 consecutive molding operations with no damage to the patterns and knockout pins.

From our series of experiments, we obtained the following hot embossing conditions that allow relatively accurate pattern replication with smooth mold release (Table 2). The optimal mold release temperature for both types of molds was found to be 80°C.

When the same molding temperature was used, the pattern replication performance did not differ greatly between the two different molds, though the replication performance enhanced as the heating temperature increased. When compared with the mold with hole patterns, the mold with column patterns yielded hot embossing of higher replication quality at a lower pressure load. Our investigation showed that the reason for this was because, for a mold with hole patterns, it was difficult for the softened resin to reach to the bottom of each hole due to flow resistance of the resin, in addition to air resistance due to hot embossing in the atmosphere.

SEM images of the hole patterns and column patterns we replicated under the above optimal hot embossing conditions are shown in Fig. 5. When compared with the sharp-edged patterns of the molds, the edges of the replicated holes and columns are slightly rounded. We estimate that such configuration was due to the effects of mold lubricant, pressure load, and air. Identification of the true causes has been left for future research, together with improvement of the molds themselves.

4.2 Vacuum hot embossing

After taking into account the results of the series of hot embossing experiments in the atmosphere, we carried out another experiment under the following conditions of Table 3.

In a vacuum, the molding temperature overshot the set temperature by approximately 30°C. In particular, when the molding temperature and pressure load were increased, the PMMA sheet melted and leaked out of the mold, making the hot embossing impracticable. From this we realized that the molding temperature control scheme

| Table 2  | Appropriate hot embossing conditions in the atmosphere |
|----------|--------------------------------------------------------|
| Molding temperature | Pressure load | Pressing time |
| Mold with column patterns | 160°C | 5 kN | 60 sec. |
| Mold with hole patterns | 160°C | 6 kN | 60 sec. |

Fig. 5  SEM images of replicated hole patterns (Left) and column patterns (Right)
Table 3  Vacuum hot embossing conditions

| Parameter          | Conditions                |
|--------------------|---------------------------|
| Degree of vacuum   | 20 Pa                     |
| Molding temperature| 140°C, 150°C, 160°C      |
| Heating time       | 5 min.                    |
| Pressure load      | 5 KN, 6 KN, 8 KN          |
| Pressing time      | 60 sec.                   |
| Mold release temp. | 80°C                      |

Table 4  Overshoot temperature for setting temperature at the PID ($P = 2^\circ C$, $I = 64$ sec., $D = 16$ sec.)

| Preset temperature ($^\circ$C) | 120 | 140 | 160 | 180 | 200 |
|---------------------------------|-----|-----|-----|-----|-----|
| Overshoot temperature of Top ($^\circ$C) | 5.4 | 4.4 | 3.0 | 2.5 | 1.4 |
| Overshoot temperature of Bottom ($^\circ$C) | 3.3 | 2.9 | 1.2 | 0.3 | 0.5 |

Table 5  Appropriate vacuum hot embossing conditions

|                  | Molding temperature | Pressure load | Pressing time |
|------------------|---------------------|---------------|---------------|
| Mold with column patterns | 140°C              | 5 KN          | 60 sec.       |
| Mold with hole patterns    | 150°C              | 5 KN          | 60 sec.       |

effective for hot embossing in the atmosphere was not effective for hot embossing in a vacuum.

To effectuate molding temperature control in a vacuum, we replaced the temperature controller for the heaters located on the top and bottom of the embossing machine with a PID parameter adjusting type controller. We determined the optimal PID parameters by carrying out a molding temperature control experiment in a vacuum. The temperatures overshot from each preset value under optimal PID parameters ($P = 2^\circ C$; range of proportion temperature, $I = 64$ sec.; Integration operation time, $D = 16$ sec.; Differentiation operation time) are given in Table 4.

After optimally setting the PID parameters, we carried out the hot embossing experiment. As a result, we found that the following embossing conditions produce relatively satisfactory replication results with smooth mold release performance (Table 5). Under the above hot embossing conditions, we were able to replicate micro patterns having the quality equivalent to that which we obtained in the atmosphere.

4.3 Double-sided hot embossing

Using the same hole and column pattern molds used for the previous experiments, we tried to emboss the patterns on both sides of a PMMA sheet. For the experiment, we located one mold on the top and the other mold on the bottom of the hot embossing machine. In this double-sided hot embossing process, knockout pins could not be used for releasing the PMMA sheet from the molds. Instead of the knockout pins, we used a suction pad. However, the pad did not work effectively because the sheet suffered various defects including deformation and flaws. It was difficult to hold the PMMA sheet in a fixed position during the hot embossing. The sheet broke when the molds were separated from each other and stuck to both mold faces. We repeated the hot embossing experiment in the atmosphere and a vacuum under various embossing conditions using a mold lubricant. As a result, we succeeded in obtaining the product of hot embossing that the patterns had excellently transcribed in both sides.

SEM images of the hole and column patterns on both sides of a sample sheet obtained from one of the experiments are shown in Fig. 6. The relation between the compacting pressure and the molding temperature of hot embossing obtained from the experiment is shown in Fig. 7.

5. Conclusion

In this research, we focused on high-precision replication of micro-patterns by hot embossing under both atmospheric and vacuum conditions. For our series of experiments we used relatively large molds with densely distributed micro patterns, in place of small test patterns that we had used in our previous study. For the embossing, we applied the LIGA process by using the BL2 beam line of the New SUBARU, a synchrotron radiation system installed in the University of Hyogo. As a result, we successfully embossed $\phi 60 \mu m$ micro hole and column patterns with an aspect ratio of 1.0 on PMMA sheets under both atmospheric and vacuum conditions. Moreover, we succeeded in hot embossing on both sides where both pattern...
terns had been used in obtaining an excellent experiment result. We found that, under the same pressure load, the molding temperature can be reduced by 10°C to 20°C in hot embossing in a vacuum than with that in the atmosphere. Through this series of experiments, we also verified that hot embossing in a vacuum is more effective for replicating micro-patterns with high aspect ratios than is hot embossing in the atmosphere.

We further found that a PID parameter adjusting type temperature control is essential for hot embossing in a vacuum to optimally control the heating temperature. We think that we can apply this experiment result to the production of the optical component (for instance, light guide and lens array, etc.) that needs micro shape pattern with the vacuum hot embossing molding. Our future tasks will include effectively using the findings from our research to improve the design and fabrication of molds, as well as finding the optimal mold release method and molding conditions for the embossing machine.

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