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Effects of Different Backing Materials of Hybrid Rapid Tooling on the Demolding Time in the Hot Embossing Process

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Fresnel lenses are becoming more and more important because they are widely used as optical elements for concentrating solar power. Micro-hot embossing is a promising approach to fabricate Fresnel lenses. Precision optical elements must be more quickly and cheaply introduced to the market due to the pressure of global competition. The thermal conductivity of Aluminum (Al)-filled epoxy resins is lower than that of conventional mold steel materials. This work demonstrates a technique for fabricating hybrid rapid tooling with different backing materials to investigate the demolding efficiency in the hot embossing process. It was found that the Al was strongly recommended as backing material for fabricating hybrid rapid tooling due to cost, demolding time efficiency and dimensional accuracy of the embossed parts. Demolding efficiencies for the hot embossing mold with backing materials of copper, aluminum and steel about 78 %, 68 % and 50 % can be enhanced compared to that of the conventional rapid tooling. The replication rate exceeding 96 % in the hot embossing mold manufacturing process can be reached. The transcription rate exceeding 93 % in the hot embossing process can be obtained.

Keywords: hot embossing, Fresnel lenses, demolding efficiencies, backing materials.

1. INTRODUCTION

The precision mold and die industry continued to suffer pressure due to both time and expense for manufacturing a mold or die are two main issues in the new product development phase. To solve this issue, additive manufacturing (AM) [1] and rapid tooling technique (RTT) [2 – 4] was proposed to reduce the manufacturing cost and manufacturing time to market. The physical prototypes could be fabricated swiftly by AM technique compared to long lead times taken by conventional machining. Rapid tooling is capable of replacing conventional mold making to reduce manufacturing cost and development time to market [5]. Direct RTT has played important role in the new product development phase [6]. Wang et al. [7] demonstrated an automatic method to design the conformal cooling circuits used for rapid tooling. Iftikhar et al. [8] developed an innovative turbine blade by using RTT. Yang and Hannul [9] used a precision spray forming to fabricate a rapid tooling. Nandi et al. [10] proposed a new composite mold material to enhance the solidification efficiency in the soft tooling process. Gill and Kaplas [11] proposed a rapid casting technology to fabricate a rapid tooling.

Mohan and Kanny [12] employed the recycled epoxy as reinforcement in an epoxy composite. In general, the Al-filled epoxy resins mold is used as the tentative mold for pilot runs due to it own good mechanical properties and high temperature resistance [13]. However, the demolding time in the hot embossing process is longer due to the poor thermal conductivity of the Al-filled epoxy resin compared to metal. Therefore, enhancing the efficiency of demolding time during the hot embossing in the development phase of a new optical element is an important issue. In this study, hot embossing molds with different backing materials were fabricated to investigate the demolding efficiency in the hot embossing process. The effects of different backing materials on the demolding time are investigated. The replication rates of the four hot embossing molds were examined. The Fresnel lens was fabricated using hot embossing molding. The transcription rates of the embossed parts were also investigated using an optical microscopy.

2. EXPERIMENT

The Al-filled epoxy resins (174 A, Jasdi Chemicals) and silicone rubber (KE-1310ST, Shin Etsu) were chosen as mold making materials. The master model is a Fresnel lens with dimensions of 3 cm in length and 3 cm in width. The detailed manufacturing processes of hot embossing mold are described in the previous study [14]. The copper (1100, Poki Metal), steel (Nak-80, Daido Steel) and Al (6061, Nikko Metals) were first machined as backing materials to fabricate hybrid rapid tooling using a universal milling machine. The backing material thickness is 15 mm. The vacuum machine was used to eliminate air bubbles from the molding materials [15]. Firstly, the positive silicone rubber mold was manufactured by pouring the mixed silicone rubber over the master model. The master model was not adversely affected due to no heat was generated during the curing process. Silicone rubber was mixed with a curing agent with a 10:1 mass ratio. Spraying release agent to the surface of the positive silicone rubber mold is necessary before fabricating the negative rubber mold. The negative rubber mold was then created from a positive silicone rubber mold. Finally, the hot embossing

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mold was created by pouring the mixed epoxy resin composites over the positive silicone rubber mold. The hot embossing mold was then cured in a convection oven (DH400, Deng Yag) to reach the mechanical properties required. After post cure, the fabricated hot embossing mold possesses adequate mechanical strength for hot embossing molding. The replication rates of the four fabricated hot embossing molds and the transcription rates of the embossed Fresnel lenses were analyzed.

Fig. 1. shows the experimental setup for thermal conductivity measurement of different backing materials according to ASTM D5470 [16]. Temperature measurements were made using six K-type thermocouples (C071009-079, Cheng Tay) for calculating thermal conductivity. Note that the Th and Tc indicate temperatures at the interfaces of cold and hot ends. The dimensions of the test sample are 13 mm in length and 25 mm in diameter. A test sample was mounted under load of 360 N between two Al terminals in order to minimize air gaps between Al terminal and the test sample. The dimensions of the cylinder Al terminal are 30 mm in length and 25 mm in diameter. A heat flux of 10 W was supplied at the hot end. Cooling was performed by water circulating at a rate of 400 cc/min in the cold end. In order to investigate the demolding time in the hot embossing process, temperature histories of the embossing process were measured using a k-type thermocouple and a data collection system (MRD-8002L, Acqview). The ANSYS Icepak software was used to predict the demolding time in the hot embossing process. A series of experiments were performed to optimize the embossing parameters. The process parameters for hot embossing molding are embossing temperature of 120 °C, embossing force of 900 N, and holding time of 10 min. The home-made hot embossing machine was used for hot embossing molding. The 0.8 mm thick polymethylmethacrylate (PMMA) films (MH, Meihan Shinku Kogyo) were used as molding material. The replication rates of the four fabricated hot embossing molds and the transcription rates of the embossed parts were examined using an optical microscopy (M835, Microtech).

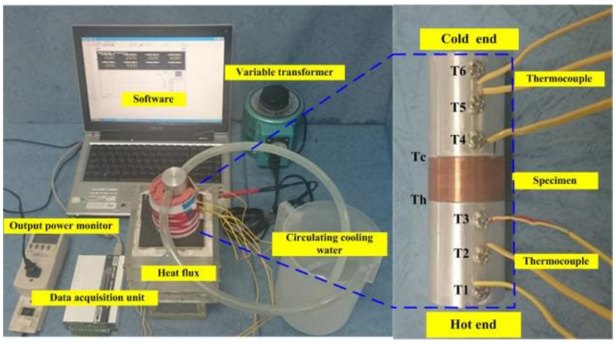


Fig. 1. Experimental setup for thermal conductivity measurement of different backing materials. The temperature histories were recorded by six thermocouples referred to as $T1$, $T2$, $T3$, $T4$, $T5$, and $T6$. Temperatures Th and Tc can be determined by the extrapolation method form the temperature values measured

The solid model preparation was carried out with the software Solidworks. Hexagonal 3D quadratic stress elements, SOLID 95, were used for mashing the part [10]. The Young's modulus and the Poisson's ratio of the epoxy resin were determined from the results of mechanical testing using a universal testing machine (Insight 5 SL, MTS system Inc.).The Young's modulus for the new epoxy resins and recycled epoxy resins are about 9.9 GPa and 3.7 GPa, respectively. The Poisson's ratio for the new epoxy resins and recycled epoxy resins are about 0.32 and 0.27, respectively. Boundary conditions were applied to the embossed areas. The applied load is about 650 N. Maximum stresses of a large-area hot embossing mold were investigated by finite element method using ANSYS software.

3. RESULTS AND DISCUSSION

Fig. 2. presents the thermal distributions over the length of Al-filled epoxy resins, Al, Cu, and steel. Temperature readings were recorded every 30 minutes. The thermal conductivity can be determined when the temperature reaches the steady-state conditions. For the sample of Al-filled epoxy resins, the thermal conductivity slightly goes down from 2.73 W/m-K to 1.94 W/m-K as the measurement time arises and saturates at thermal conductivity of 1.94 W/m-K. The same phenomena are observed for Al, Cu, and steel. Thus, the calculated thermal conductivity values for Al-filled epoxy resins, Al, Cu, and steel are estimated to be 1.94 W/m-K, 162.23 W/m-K, 397.45 W/m-K and 47.04 W/m-K, respectively. To understand the experimental error of the thermal conductivity measured, a series of five tests were carried out on each sample. All the experimental results are shown in Fig. 3. These results show that the reproducibility of the results is in agreement with previous measurement. It is worth pointing out that the maximum standard variation of the thermal conductivity of Cu is estimated to be 8.46 W/m-K.

The ANSYS Icepak software was used to predict the transient heat transfer of the hot embossing process [17]. Fig. 4. illustrates the temperature as a function of predicted demolding time in the hot embossing process using the ANSYS Icepak software. The predicted demolding time can be determined when the temperature of mold surface reached the demolding temperature. As can be seen, the predicted demolding times for the hot embossing molds with backing materials of Al-filled epoxy resins, Al, Cu, and steel are 130 min, 25 min, 20 min, and 55 min, respectively. To obtain the actual demolding time, Al-filled epoxy resins, Al, Cu, and steel were employed as backing materials to fabricate embossing molds for hot embossing molding, as shown in Fig. 5.

The embossing molds exhibit superior dimensional accuracy due to very little shrinkage during the curing process. The width and depth of a master model are 67 µm and 400 µm, respectively. The averages of width and depth for the hot embossing molds with backing materials of steel are 65 µm and 397 µm, respectively. Hence, the transcription rates in the width and depth are 97 % and 96.7 %, respectively. The averages of the width and depth for the hot embossing molds with backing materials of Al are 66 µm and 398 µm, respectively. Hence, the transcription rates in the width and depth are 98.5 % and 99.5 %, respectively.

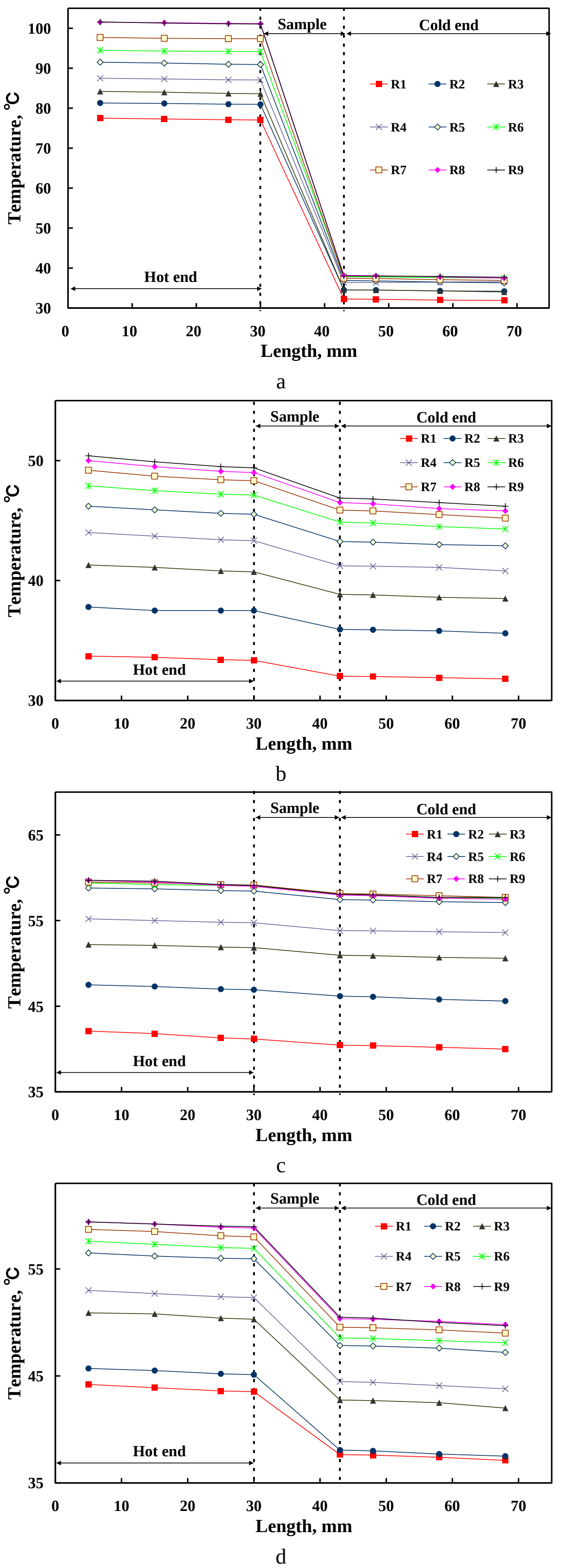


Fig. 2. Thermal distributions over the length of: a – Al-filled epoxy resins; b – Al; c – Cu; d – steel

The averages of the width and depth for the hot embossing molds with backing material of Cu are 65 µm and 397 µm, respectively.

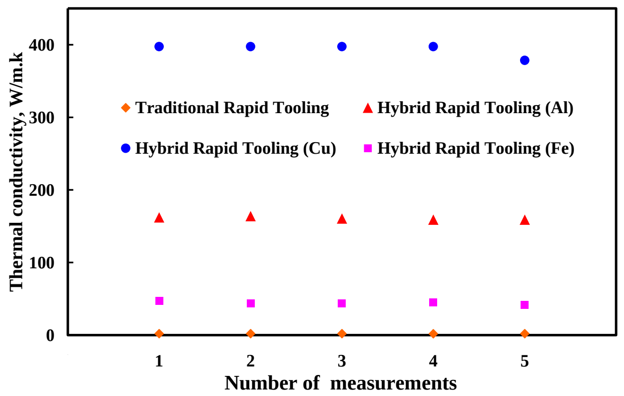


Fig. 3. Variations of thermal conductivity measurement for Al-filled epoxy resins, Al, Cu, and steel

Hence, the transcription rates in the width and depth are 97 % and 99.2 %, respectively. The averages of the width and depth for the conventional hot embossing molds are 66 µm and 397 µm, respectively. The transcription rates in the width and depth are 98.5 % and 99.2 %, respectively. Thus, the replication rate of the fabricated embossing molds exceeding 96 % can be obtained.

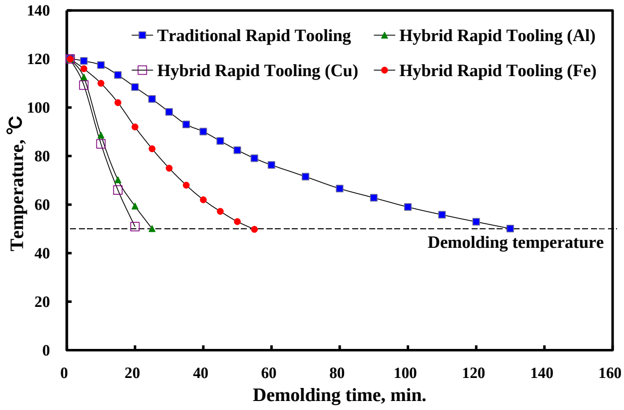


Fig. 4. Temperature as a function of predicted demolding time in the hot embossing process using the ANSYS Icepak software

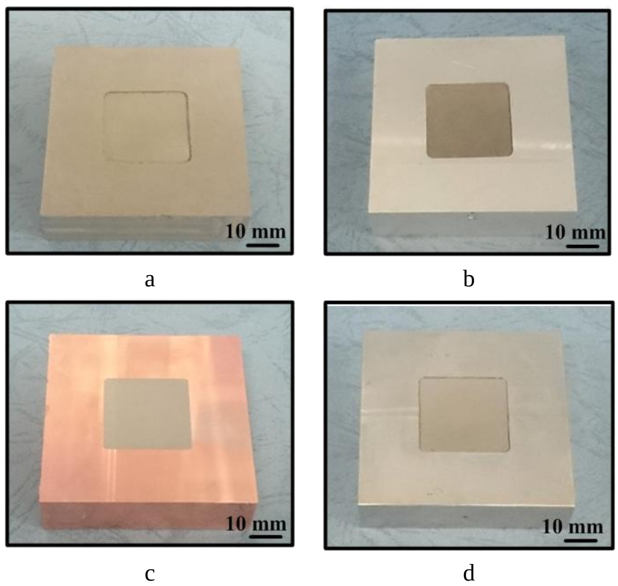


Fig. 5. Hot embossing molds with backing materials of: a – Al-filled epoxy resins; b – Al; c – Cu; d – steel

Hot embossing is a promising method to fabricate Fresnel lens to be used as optical elements for concentrating solar power. Long cycle time is related to the time interval from the embossing temperature to demolding temperature. To enhance the efficiencies of hot embossing process, shortening this time interval is critical. Fig. 6. shows the temperature as a function of the actual demolding time in the hot embossing process. The actual demolding times for the hot embossing molds with backing materials of Al-filled epoxy resins, Al, Cu, and steel are 140 min, 45 min, 30 min, and 70 min, respectively. To understand the experimental error of the actual demolding time, a series of ten tests were carried out. All the experimental results are shown in Fig. 7. showing that the reproducibility of the results is in agreement with previous measurement. The mean actual demolding times for the hot embossing molds with backing materials of Al-filled epoxy resins, Al, Cu, and steel are 140.8 min, 45.1 min, 30.4 min, and 70.6 min, respectively. It was found that the trend of demolding efficiency from experimental data was in good agreement with those predicted by numerical simulations. The maximum standard variation of the demolding time of steel is estimated to be 1.6 min. Thus, the demolding time efficiencies for hot embossing mold with backing materials of copper, aluminum and steel about 78 %, 68 % and 50 % can be enhanced compared to that of the conventional rapid tooling. The result meets the concept of fast fabrication [18, 19].

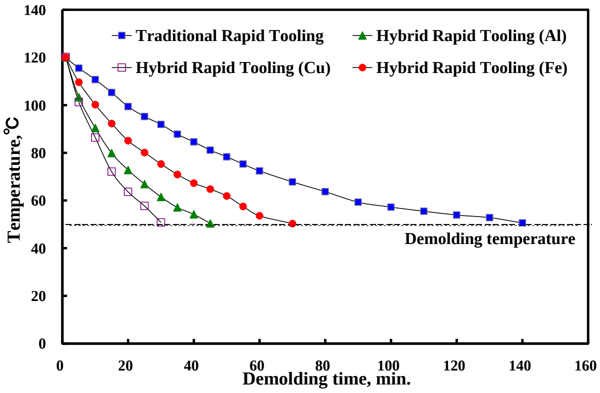


Fig. 6. Temperature as a function of the actual demolding time in the hot embossing process. The actual demolding time can be determined when the temperature of mold surface reached the demolding temperature

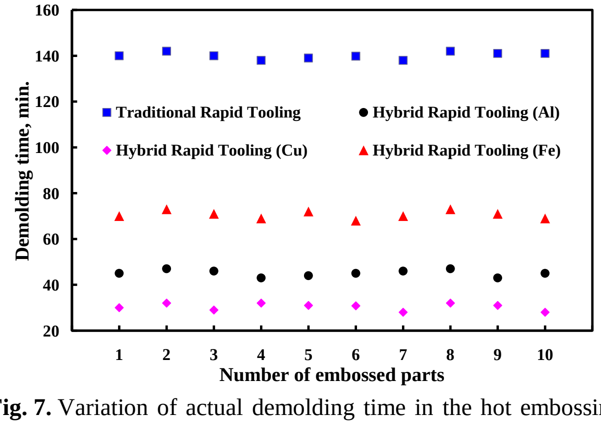


Fig. 7. Variation of actual demolding time in the hot embossing process

Fig. 8 and Fig. 9 shows the dimensional accuracy of the Fresnel lens fabricated by the hot embossing molds with different backing materials. The dimension variations of the width can be controlled from -4 μm to -1 μm. Besides, the dimension variations of the depth can be controlled from -11 μm to -1 μm. It must be mentioned that the dimensional variations of the Fresnel lens fabricated by the hot embossing molds with backing material of Cu are the largest due to shrinkage. One possible reason to cause this result is rapid heat transfer speed showing that the front Fresnel lenses solidify rapidly. Besides, the cost of Cu is higher than Al. This means that Al seems to be a good candidate as a backing material for fabricating hot embossing replication master [20] in terms of demolding efficiency and dimensional accuracy of the Fresnel lens. The transcription rates for hot embossing molds with backing materials of Al-filled epoxy resins, Al, Cu, and steel are about 97 %, 97 %, 93 %, and 96 %, respectively. Thus, the transcription rate exceeding 93 % can be obtained under the optimum embossing conditions. This means that precision diffractive optical elements can be fabricated by gas-assisted hot embossing molding [21], although the shrinkage of the PMMA is about 0.2 – 0.6 %. The proposed method for fabricating hot embossing mold needs no expensive equipment. Thus, the proposed method exhibits simplicity and economic due to without using the silicon-based micro-machining [22], ultrafast femtosecond laser micro-machining [23], micro-electro discharge machining [24], and electrochemical micro-machining [25]. Unfortunately, the lifetime of hybrid rapid tooling is limited because the mold surface is made from Al-filled epoxy resins.

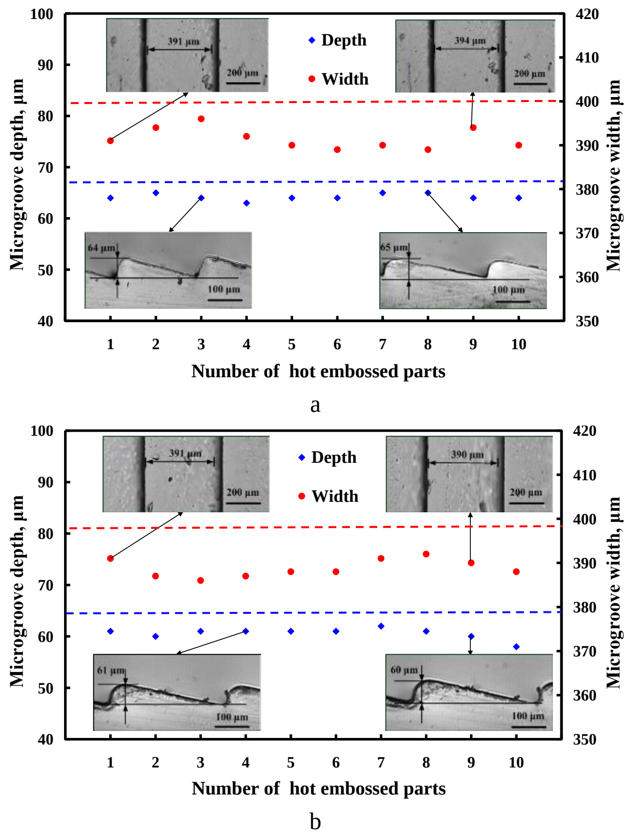
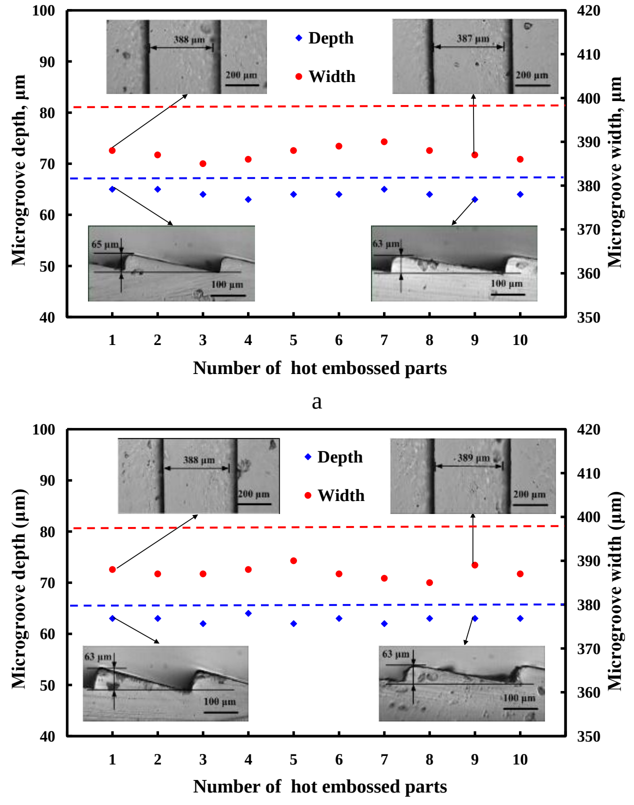


Fig. 8. Dimensional accuracy of the Fresnel lens fabricated by the hot embossing molds with backing materials of: a – Al-filled epoxy resins; b – Al. Dashed lines show the dimensions of width and depth of hot embossing mold



a

b

Fig. 9. Dimensional accuracy of the Fresnel lens fabricated by the hot embossing molds with backing materials of: a – Cu; b – steel. Dashed lines show the dimensions of width and depth of hot embossing mold

Further investigation on lengthening the mold life of hot embossing mold is required. In addition, optimization of the thickness of hot embossing molds is required by using ANSYS simulation software [26 – 29].

4. CONCLUSIONS

The aim of this study was to present four hybrid embossing molds with different backing materials. The thermal conductivities of four different backing materials have been measured experimentally. The effects of different backing materials on demolding time in the hot embossing process have been investigated. Based on the results discussed in this study, the following conclusions can be drawn:

1. The results of this study exhibit wide industrial application values because it can accelerate the development speed of a new precision optical element in the research and development phase. The hot embossing mold has the simplicity of the manufacturing process and cost-effective manufacturing cost.
2. Al seems to be a good candidate as a backing material for fabricating hot embossing mold in terms of cost, demolding time efficiency and dimensional accuracy of the embossed parts.
3. The hot embossing mold is rigid enough for short runs of precision optical elements using hot embossing technique.
4. The demolding time efficiencies for the hot embossing mold with backing materials of copper, aluminum and steel approximately 78 %, 68 % and 50 % can be enhanced.
5. The hot embossing mold can be fabricated without loss in detail. It has been verified that the replication rate exceeding 96 % can be reached.
6. The transcription rate of Fresnel lenses exceeding 93 % of the embossed parts can be obtained under the optimum embossing conditions.

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