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Development of a Large-Area Hot Embossing Mold with Micro-Sized Structures

Chil-Chyuan KUO *, Min-Hsiang WU

Department of Mechanical Engineering, Ming Chi University of Technology, No. 84, Gungjuan Road, New Taipei City 243, Taiwan

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Microtechnology is a core technology in the 21st century. Microfabrication plays an important role in the precision machinery industry. Two major troublesome issues in the mold industry are the time and expense needed for producing a mold for the pilot run in the new product development phase. The aim of this study was to propose a cost-efficient method for fabricating a large-area hot embossing mold with micro-sized structures. The advantages of this method include short manufacturing leading times, simple manufacturing processes, low manufacturing cost, and short processing time. A large-area hot embossing mold with areas of 250 mm × 350 mm was fabricated. Cost savings about 61.3 % can be reached. The manufacturing processes developed in this work possess a significant industrial application value because a new 3C product with surface texture could be reached with a large-area epoxy resin mold using hot embossing molding.

Keywords: mold, polymeric, manufacturing, aluminum.

1. INTRODUCTION

Microfabrication is the processes used in making micro-scale components or devices. Microfabrication has been successfully employed in precision instruments and microelectronics [1]. As the increase in the number of industries relies on microfabrication, many methods have been demonstrated for making dies or molds with micro-sized structures. These methods include silicon-based micromachining technology [2], lithography galvanoformung abformung (LIGA) [3], laser micromachining [4], micro-electro discharge machining (μ-EDM) [5, 6], micro machining [7], deep-reactive ion etching [8], electrochemical micromachining [9], and focused ion beam [10]. However, these methods have many associated disadvantages. For example, silicon mold service life was limited due to its high brittleness. As a result, it is important to develop a cost-effective method for fabricating a large-area hot embossing mold with micro-sized structures for microfabrication.

In many industries, surface texture is an important aspect of product design because it allows a company to influence user's tactile impression of their product [11]. Surface texturing can be accomplished in a number of methods, including shot blasting [12], laser surface texturing [13], 5-axis computer numerical control (CNC) micromaching [14] and chemical etching [15]. In general, laser is known as a highly powerful tool for precision machining. Thus, laser surface texturing technique is one of the most widely employed methods of creating surface texturing because it possesses many distinct advantages, such as high spatial resolution, good flexibility and non-contact. However, processing is very costly and time consuming because it requires precision beam delivery and focusing optical systems. Among them, wet chemical texturing technique would be the best choice because processing is very inexpensive. Unfortunately, the waste liquid of this method has an environmental impact. In this study, a cost-effective, fast and simple method was proposed to fabricate a large-area precision mold with surface textures for microfabrication. Replication accuracy of the fabricated molds was investigated. Hot embossing was used to produce micro-sized structures. Dimensional accuracy of the embossed parts and molds were investigated. The surface roughnesses of hot-embossed parts were also evaluated.

2. EXPERIMENT

A room temperature vulcanization silicone rubber (KE-1310ST, Shin Etsu) and aluminum (Al)-filled epoxy resins (70-3810R, Epoxies) were used to manufacture a large-area epoxy resin mold [16]. Fig. 1 shows the schematic illustration of manufacturing process flows to fabricate a large-area epoxy resin mold with micro-sized structures. The Al 6061 alloy was first machined using precision universal milling machines to fabricate the plate of cell mold. In this study, two types of methods were employed of creating surface texturing. Surface textures were fabricated using both Rockwell (DRH-M, Matsuzawa) and Vickers (MV-1, Matsuzawa) hardness indenters. The micro-sized structures were prepared using a diamond pyramidal indenter having a square base and pyramid angle of 136° for Vickers method. The load of 10 kgf was applied to samples for 15 s. The applied loads ranging from 1 – 50 kgf of Vickers hardness tester was employed to fabricate micro-sized structures of a cell mold. The micro-sized structures were also prepared using a diamond cone indenter having 1/16" steel ball for Rockwell method. The indenter was forced to samples under a preliminary minor load of 10 kgf. The applied loads ranging from 60 – 150 kgf of Rockwell hardness tester was employed to fabricate micro-sized structures of

* Corresponding author. Tel. +886 2 29089899 (4524), fax: +886 2 29063269. E-mail: *jacksonk@mail.mcut.edu.tw* (C.C. Kuo)

a cell mold. According to the specifications of 3C products, the reference dimensions of the micro-sized structures are 835 µm in width, 90 µm in depth, and 4 mm in pitch length. The textured area was chosen to be 70 mm in length and 50 mm in width. The manufacturing process of a large-area epoxy resin mold includes a five-step microreplication technology. The cell mold was prepared in advance. The cell silicone rubber mold was manufactured by pouring the mixed silicone rubber resin over the cell mold. The dimensions of a large-area silicone rubber mold are 350 mm in length and 250 mm in width. As shown in Fig. 2, 25 cell silicone rubber molds were jointed to form a large-area silicone rubber mold. The purpose of this process was to make a large-area silicone rubber mold with positive shape by assembling 25 cell silicone rubber molds. Thus, a large-area silicone rubber mold with negative shape was fabricated by pouring the mixed silicone rubber resin over a large-area silicone rubber mold. Finally, a large-area epoxy resin mold was fabricated by pouring the mixed epoxy resin composites over a large-area silicone rubber mold. Thus, the epoxy resin mold has negative microfeatures of the master model. A vacuum casting machine was used to eliminate air-bubbles for manufacturing a bubble-free silicone rubber mold. The epoxy resin mold was cured in a convection oven (DH400, Deng Yag) at 79 °C for 2 h followed by 149 °C for 3 h. The epoxy resin mold is a clone of the large-area silicone rubber and has negative microfeatures of the master model. After post-cure heat treatment, the epoxy resin mold can be used for microfabrication using the micro-hot embossing molding. The polypropylene (PP) (TP423L, Semi Plastic) was used as the molding material since it can be easily patterned by hot embossing molding [17, 18]. The melting temperature of PP sheet is about 170 °C. The large sheet of the PP materials was cut into square pieces of 250 mm × 350 mm. The samples were cleaned in an ultrasonic cleaner with ethanol before hot embossing molding. The processing parameters for hot embossing molding are embossing temperature of 180 °C and press force of 350 N.

The dimensions of the produced micro-sized structures in the fabricated molds and hot-embossed parts were measured using an optical microscope. The surface roughnesses (Ra) of the fabricated molds and hot-embossed parts were examined using a white light interferometer (7502, Chroma). The chosen measurement dimensions of the sample were 250 µm × 250 µm. The form accuracies of a large-area epoxy resin mold before and after the post cure were also investigated using a coordinate measuring machine (LH 600, Wenzel).

In this study, two types of methods were employed to fabricate a large-area epoxy resin mold. In order to reduce the manufacturing cost, green manufacturing technology was employed to fabricate a large-area epoxy resin mold. Fig. 3 shows the manufacturing process flow to fabricate a large-area epoxy resin mold using green manufacturing technology. The recycled pieces of Al-filled epoxy resins were milled into powders using a precision universal milling machine. The recycled Al-filled epoxy resin powders were first mixed with new epoxy resins (174 A, Jasdi Chemicals) with a weight ratio of 1 : 1.33 and then poured into the mold frame as backing material for reducing the manufacturing cost of a large-area epoxy resin mold. In order to remove air air-bubbles inside the mixtures, all the processes were operated in a vacuum casting machine.

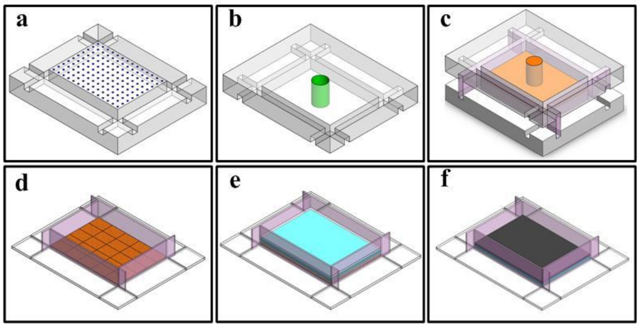

Fig. 1. Schematic illustration of manufacturing process flows to fabricate a large-area epoxy resin mold with micro-sized structures: a – cell mold machining; b – fabrication of a cell silicone rubber mold; c – repeated fabrication of 24 cell silicone rubber molds; d – joining 25 cell silicone rubber molds to a large-area silicone rubber mold; e – fabrication of a large-area silicone rubber mold with negative shape; f – fabrication of a large-area epoxy resin mold

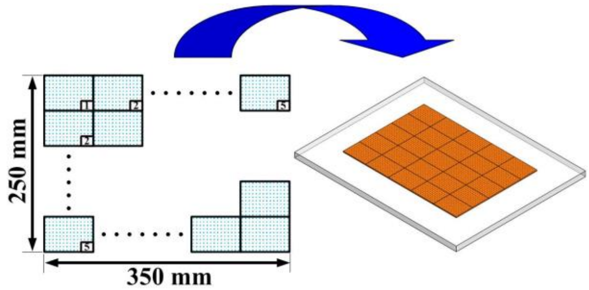

Fig. 2. Schematic illustration of the formation of a large-area silicone rubber mold

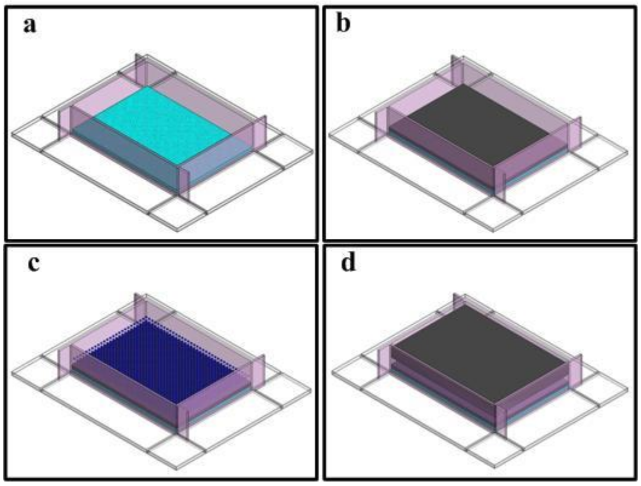

Fig. 3. Schematic illustration of a cost-effective approach for manufacturing a large-area epoxy resin mold using green manufacturing technology: a – placing the large-area silicone rubber mold with negative shape; b – shell mold fabrication by pouring new Al-filled epoxy resins; c – pouring the mixtures of recycled Al-filled epoxy resin powers and new epoxy resins into the mold frame as backing materials; d – pouring new Al-filled epoxy resins

3. RESULTS AND DISCUSSION

Fig. 4 shows the micro-sized structures fabricated by Vickers hardness indenters with six different loads. The average widths of the fabricated micro-sized structures are 115.5 µm, 284.8 µm, 364.3 µm, 374.6 µm, 442 µm, and 529.3 µm, respectively.

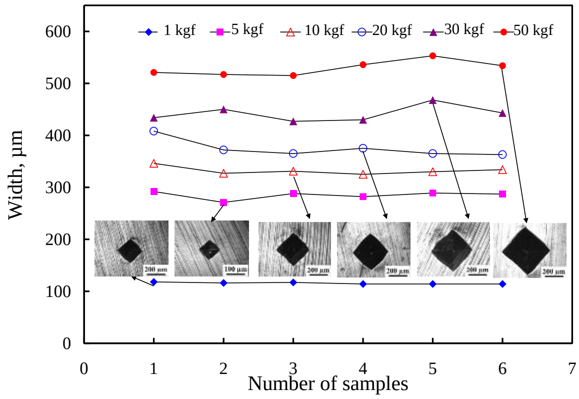

Fig. 4. Micro-sized structures fabricated by Vickers hardness indenters with six different loads

The widths of these micro-sized structures are smaller than the reference dimension, indicating that this is not an appropriate method for fabricating micro-sized structures. The variations in the width of micro-sized structures fabricated by Rockwell hardness indenters with three different loads are plotted in Fig. 5.

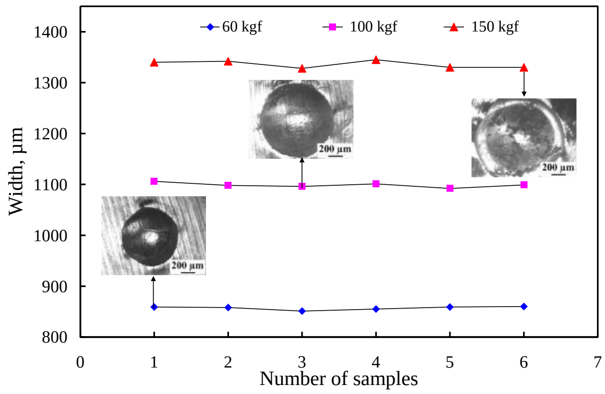

Fig. 5. Variations of the width of micro-sized structures fabricated by Rockwell hardness indenters with three different loads

The widths of the micro-sized structures increase gradually with increasing the applied load. The average widths of the fabricated micro-sized structures are 857 µm, 1098.7 µm, and 1335.8 µm, respectively. It can be seen that the widths of microstructure fabricated by the applied load of 60 kgf is close to the reference dimension. The standard deviation in width of the fabricated micro-sized structures is about 3.4 µm. The variations in the depth of micro-sized structures fabricated by Rockwell hardness indenters with three different loads are plotted in Fig. 6. The depths of the micro-sized structures increase gradually with increasing the applied load. The average depths of the fabricated micro-sized structures are 103 µm, 209.3 µm, and 357.2 µm, respectively. This clearly indicates that the depth of microstructure fabricated by the applied load of 60 kgf is close to the reference dimension. The standard deviation in the depth of the fabricated micro-sized structures is about 2.1 µm. Micro-sized structures with minimal burrs are observed. In addition, micro-sized structures with thermal damage were not observed [19, 20]. In this respect, Rockwell hardness indenter with the applied load of 60 kgf was recommended to create surface texturing of cell molds. Apparently, it is a cost-effective method for surface texturing since it requires no special equipment.

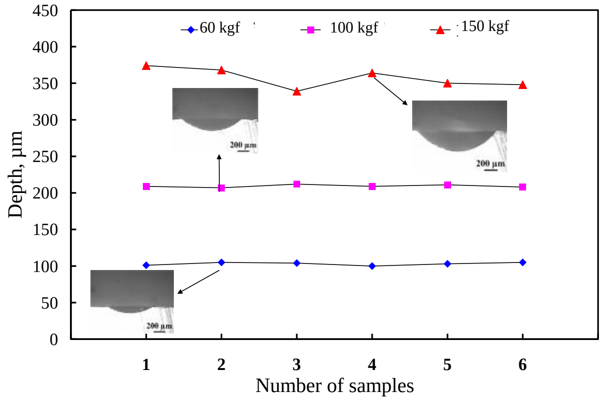

Fig. 6. Variations in the depth of micro-sized structures fabricated by Rockwell hardness indenters with three different loads

Fig. 7 demonstrates the results of the manufacturing processes of a large-area epoxy resin mold. As can be seen, a hot embossing mold with micro-sized structures can be fabricated using rapid tooling technology.

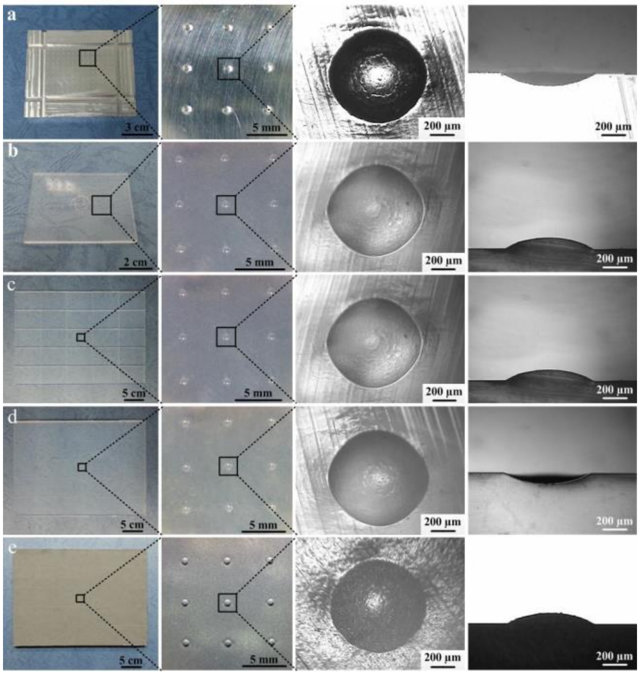

Fig. 7. Results of the manufacturing processes of a large-area epoxy resin mold: a – cell mold; b – cell silicone rubber mold; c – a large-area silicone rubber mold; d – a large-area silicone rubber mold with negative shape; e – a large-area epoxy resin mold

It is interesting to notice that the shrinkages of the silicone rubber, Al-filled epoxy resins can be compensated by the thickness of release agents sprayed. The thicknesses of the release agents sprayed were estimated to be approximately 1 – 3 μm. The dimensions in the width and depth of epoxy resin mold are 850 μm and 100 μm, respectively. Hence, the replication accuracies for both depth and width of a large-area epoxy resin mold are expected to be approximately 99.9 % because the reference dimensions in the width and depth of the cell mold are 851 μm and 101 μm, respectively. This indicates that the release agents sprayed are a key factor to affect the replication accuracy of a large-area epoxy resin mold. Silicone rubber is an excellent bridge tooling material because of high elasticity and low surface energy. Low surface energy provides a cell mold can be separated from the silicone rubber mold easily.

Experimentally, two types of approaches were used for fabricating the large-area epoxy resin mold. The total production costs associated with fabricating a large-area epoxy resin mold are listed in Table 1.

Table. 1. Manufacturing costs associated with fabricating of a large-area epoxy resin mold.

Cost (NT) \ Method / Manufacturing process	Traditional method	This work
Mold frame 1	133	133
First silicone rubber mold	368	368
Mold frame 2	462	462
Second silicone rubber mold	441	441
Al-filled epoxy resin	10.695	2.678
Epoxy resin	0	604
Total production costs (NT)	12.099	4.686

In principle, the major factor that affects the total production costs is the usage volume of new Al-filled epoxy resins. The total production costs of a large-area epoxy resin mold fabricated by the method proposed by this work is only NT 4.686, while that of a large-area epoxy resin mold fabricated by traditional method is NT 12.099. Consequently, a cost reduction up to 61.3 % can be reached using the proposed method. This is because a special step in the moldmaking processes is that the mixtures of recycled Al-filled epoxy resin powers and new epoxy resins were used as backing materials. Note that the method proposed in this work meet recycling objective and has industrial applications because the production cost reduction increases with increasing the sizes of the molds. Fig. 8 shows a large-area epoxy resin mold with areas of 25 cm × 35 cm was fabricated using green manufacturing technology. As can be seen, a large-area epoxy resin mold has smooth mold surfaces and can be fabricated about three days.

Fig. 9 shows the form accuracies of a large-area epoxy resin mold before and after post cure. The form accuracy of a large-area epoxy resin mold before the post cure is 147 μm whereas the form accuracy of a large-area epoxy resin mold after a post cure is approximately 264 μm. This phenomenon explains no significant global warpage of a large-area epoxy resin mold after a post cure was observed [21].

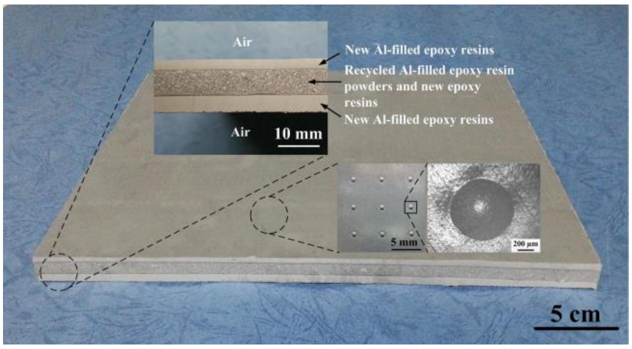

Fig. 8. A large-area epoxy resin mold with areas of 25 cm × 35 cm was fabricated using green manufacturing technology

Thus, a large-area epoxy resin mold after a post cure is suitable for hot embossing molding. Hot embossing molding is a simple method for fabricating microstructures because it has few processing steps and processing parameters. A large-area hot-embossed part with micro-sized structures can be fabricated using a hot embossing molding. The advantage of this approach includes high transcription fidelity because of low processing speed.

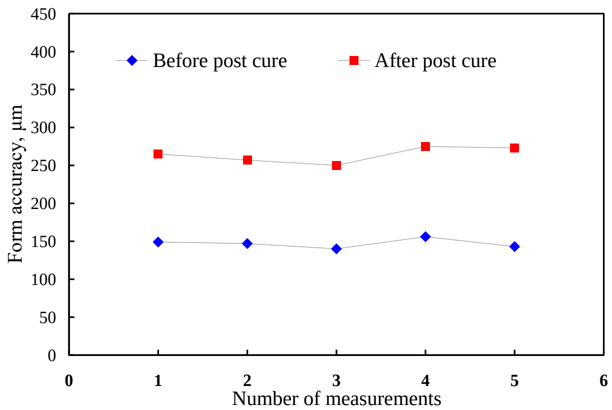

Fig. 9. Form accuracies of a large-area epoxy resin mold measured by a CMM

Fig. 10 shows the hot-embossed parts fabricated by a large-area epoxy resin mold.As can be seen, the micro-sized structures of surface texture can be fabricated with a large-area epoxy resin mold using hot embossing molding. Two phenomena can be observed from this figure. First, the microstructures on the edges of the hot-embossed parts were not replicated entirely because of the limitation of experimental apparatus employed. The completeness of the hot-embossed parts is about 70 %.This phenomenon can be observed commonly in large-area hot embossing molding because the molding area in the hot embossing machine is smaller than that of the large-area epoxy resin mold. This problem could be solved by gas-assisted hot embossing proposed by Hocheng et al [22]. Second, the hot-embossed parts with minimal warpage were observed. This problem could be solved when the embossed materials was changed to acrylonitrile butadiene styrene because of low glass transition temperature compared to PP. A large-area epoxy resin mold was then employed for short runs of parts using hot embossing molding. Fig. 11 shows the variations of dimensional accuracy of hot-embossed parts. The average dimensions in the width and depth of hot-embossed embossed parts are 847.3 μm and 98.7 μm, respectively. Hence, the transcription rates in the width and depth are 99.6 % and 98.7 % since the reference dimensions in the width and depth of epoxy resin mold are 851 μm and 100 μm, respectively.

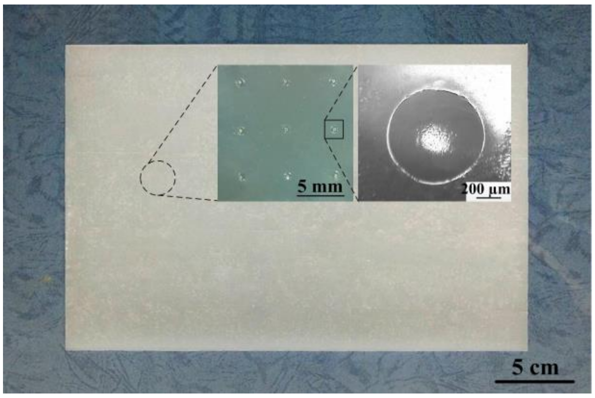

Fig. 10. Hot-embossed parts fabricated by a large-area epoxy resin mold

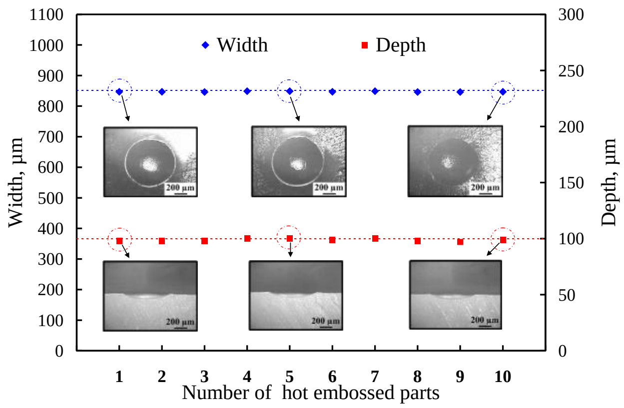

Fig. 11. Variations of dimension accuracy of hot-embossed parts. The dashed lines indicate the reference dimensions in the width and depth of the micro-sized structures

Fig. 12 shows the surface roughnesses (Ra) of a large-area epoxy resin mold and hot-embossed parts.

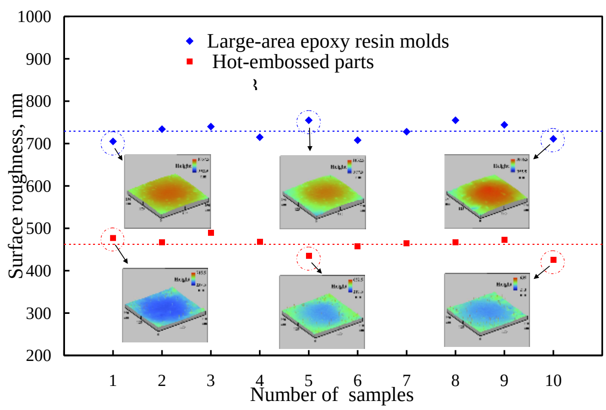

Fig. 12. Surface roughnesses: a – of large-area epoxy resin mold; b – of hot-embossed parts. Dashed lines stand the average value of the measured data

Generally, polishing mold surface in steel mold is very expensive and time consuming. It is worth mentioning that a large-area epoxy resin mold has good surface quality as steel molds machined by precision CNC grinding machines [23]. A relatively smooth mold surfaces can be reached without subsequent polishing. Thus, the hot-embossed parts with better surface roughness can be fabricated with a large-area epoxy resin mold using hot embossing molding. Surface roughnesses of the micro-scale structures of the hot-embossed part are better than that of the epoxy resin mold since the embossed material is in a semi-liquid state during hot embossing molding.

According to the results described above, the method proposed in this work for fabricating a large-area hot embossing mold with micro-sized structures [24, 25] is a cost-effective approach since this method requires no special skill or equipment compared to laser micromaching, 5-axis CNC micromaching, and electroforming [26]. The thermal conductivity of a large-area epoxy resin mold is an important issue in the hot embossing molding because higher thermal conductivity provides higher productivity during mass production. In principle, cycle times in the hot embossing molding relates to the thermal conductivity of the mold. The thermal conductivity of Al-filled epoxy resin mold is low compared to steel mold. Shortening the cycle times in mass production are really an important issue for a large-area epoxy resin mold. Thus, further study is required to equip with conformal cooling channels in a large-area epoxy resin mold for shortening the cycle time during hot embossing molding [27].

4. CONCLUSIONS

A manufacturing process for fabricating a large-area hot embossing mold with micro-sized structures has been demonstrated. The surface texturing of a cell mold has been fabricated by a hard indenter. Based on the results discussed in this study, the following conclusions can be drawn:

1. A high-precision hot embossing mold with areas of 250 mm × 350 mm has been fabricated using rapid tooling technology for increasing the speed of hot embossing mold development. The proposed manufacturing process provides a simple, cost-effective, rapid and efficient way of manufacturing a large-area precision epoxy resin mold with micro-sized structures. It has saved about 61.3 % of the manufacturing cost.
2. The release agents sprayed is a key factor to affect the replication accuracy of a large-area epoxy resin mold. A highly replication accuracy of a large-area epoxy resin mold about 99.9 % can be reached at the optimum embossing conditions.
3. The micro-scale structures of the hot-embossed parts with smooth surfaces can be fabricated with a large-area epoxy resin mold using hot embossing molding.
4. The recycled pieces of Al-filled epoxy resins have been employed for reducing the manufacturing cost of a large-area epoxy resin mold, indicating that the method proposed in this work has a significant industrial application value because the cost reduction increases with increasing the dimensions of the molds.

5. This method can be used for producing a mold for pilot run in the new product development phase.

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