High-Efficiency and Ultra-precision Glass Molding of Aspherical Lens and Microstructures

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***Abstract*:** Glass molding press (GMP) process was applied to produce aspherical glass lens in mass production. In the traditional isothermal glass molding press (IGMP), the four stages for aspherical lens fabrication, heating, pressing, annealing and cooling were carried out one by one in the molding chamber. As a result, the molding cycle is long and the mold life is short. In this paper, nonisothermal glass molding press (NGMP) was proposed to fabricate aspherical lenses at high productivity. The characteristics of NGMP were studied by comparing with the traditional IGMP. Furthermore, GMP process was extended to fabricate microstructures on the glass plate, including microgrooves and micropyramids. The molding condition was optimized to improve the forming accuracy of the molded microstructures. In this way, the high efficiency and the high precision are confirmed by the GMP experiments for fabricating glass optical elements.

***Key Words*:** Glass molding, Aspherical lens, Microstructure

1. Introduction of aspherical lens and microstructures

The optical lens is one of the most important parts in the electro-optic systems, such as digital camera, camera assisted driving system, blue ray DVD. The name of glass aspherical lens has already shown its two characteristics. One is that the surface is aspherical and the other is that the material is glass. The aspherical surface can suppress chromatic spherical aberration, which can achieve a clearer image. And also, a single aspherical lens can replace multi spherical lenses in an optical system, which can make the optical system more compact by reducing the number of lenses [1]. Glass material has many advantages over plastic. For example, the glass can endure the environmental change, because it is heat resistant and chemical resistant. What's more, the glass lens can increase the peripheral brightness because of a better light permeability.

Microgrooves and micropyramids are widely used in the optical system, biology equipment and so on. For example, microgrooves or micropyramids can improve the imaging quality and brightness as the backlight panels in the LCD monitor [2]. As the increasing needs of these kinds of optical elements, including aspherical lens and glass microstructures, we have to face the challenge: "How to fabricate them efficiently?"

2. Innovation of glass molding press for aspherical lens

In conventional GMP method, as shown in the process flow of Fig. 1, the glass ball is first placed onto the lower mold, and then, heated together with the mold. After that, the pressing is performed to form the aspherical lens. Finally, the formed lens is cooled to room temperature [3]. In this process, the temperature of the glass is the same as the temperature of the mold, so this method is termed "isothermal glass molding press (IGMP)". According to the thermal cycle, a typical IGMP process can be divided into four stages: heating, pressing, annealing and cooling. Because all the four molding stages are controlled successively in the time sequence in the same molding chamber, the molding cycle is long, and it leads to a low efficiency. Additionally, the temperature change of the molding dies is large, and it results in a short mold life.

In order to solve these problems, a new method, namely

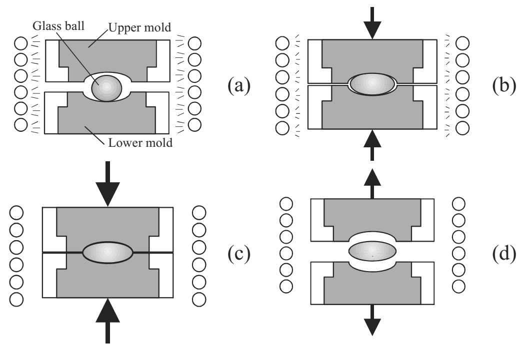


Fig. 1. Process flowchart of the IGMP process: (a) heating, (b) pressing, (c) annealing, (d) cooling.

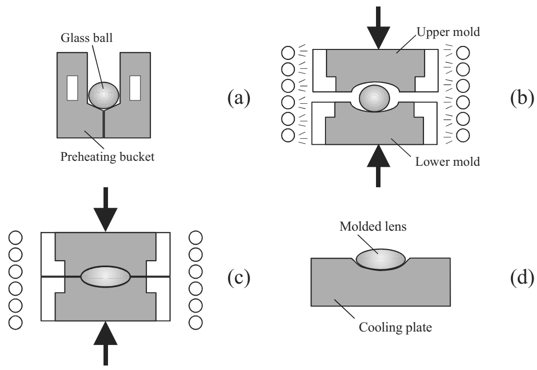


Fig. 2. Process flowchart of the NGMP process: (a) preheating, (b) pressing, (c) annealing, (d) cooling.

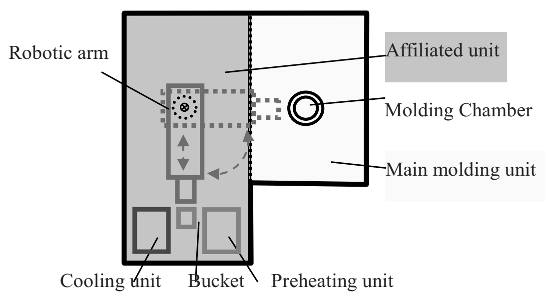


Fig. 3. Schematic diagram of the general structure of the high-efficiency and ultra-precision glass molding machine

"nonisothermal glass molding press (NGMP)" for aspherical lens is proposed. In the NGMP process, as shown in Fig. 2, the temperature control of the glass ball is separated from that of the molding dies. First, the glass ball is heated to a temperature above the molding temperature in a preheating bucket. Second, the high-temperature glass ball is pressed to form a lens by the low-temperature molding dies. Third, the formed glass lens is annealed in the molding dies to release the internal stress. Finally, the annealed formed lens is taken out from the molding dies and cooled separately down to the room temperature on the cooling plate.

In the NGMP method, when one glass ball is in the pressing stage and annealing stage, next glass ball is being heated in the preheating stage, and last molded lens is being cooled in the cooling stage. By controlling these stages in a parallel way, the average cycle time is remarkably reduced. Additionally, the temperature change of the molding dies in NGMP is smaller than that in IGMP, so the mold life will be prolonged.

3. Experiments of IGMP and NGMP

Both the isothermal and nonisothermal experiments were carried out by using a newly developed glass molding press machine, and the general structure is schematically shown in Fig. 3. From top to bottom, the main molding unit is assembled by the upper axis, the upper mold, the lower mold, the lower axis, the load cell and the servo motor. In the NGMP experiments, a preheating unit and a cooling unit were used, at the same time, and a robot arm was added to transport the preheated glass from the preheating unit to the molds and move the molded lens from the molds to the cooling unit. While in the IGMP experiments, only the main molding unit was used.

A biconvex lens with two aspherical surfaces, ASP1 and ASP2, was designed as shown in Fig. 4. Fig. 5 is the photographs of the assembled molds. The aspherical surfaces of the upper die and the lower die, made of tungsten carbide (WC), was generated by the diamond grinding, and coated with diamond-like-carbon (DLC) film. Both the upper die and the lower die were assembled in a pair of die bases (molds), and guided by two location pins to minimize the decentration. The diameter of the mold is 40 mm.

The time sequences of temperature, pressing load and lower mold position are plotted in Fig. 6. The time sequences of temperature, pressing load and lower mold position in NGMP are plotted in Fig. 7. By comparing Fig. 6 with Fig. 7, first, we can find that the molding cycle time has been shortened from 6 minutes to 2 minutes. Therefore, the productivity of the NGMP method is three times that of the IGMP method for aspherical lens fabrication. Second, the temperature change of the molds in IGMP is in the range of 150ºC ~ 580ºC, while the temperature change of the molds in NGMP is ranging from 500ºC to 580ºC, which is much smaller than that in IGMP. From the temperature changes of the molds, we can make a simple prediction that the mold life will be longer in NGMP.

Fig. 8 is the photograph of the molded aspherical lenses. Figs. 9(a) and (b) show the measurement results of form errors (including the upper surface and the lower surface) of a molded lens fabricated by the IGMP and NGMP. For the lens molded by IGMP method, except for the measurement error on the rim of the lens, the form error of the upper surface (ASP1) is within ±0.1 μm, where a slight negative

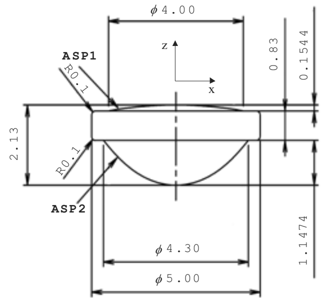
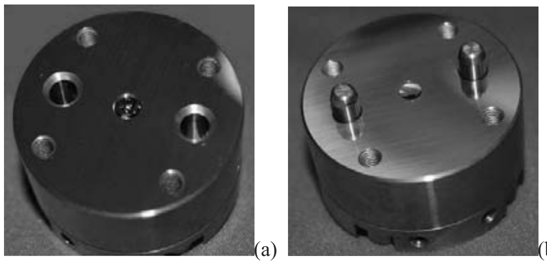


Fig. 4. Designed biconvex aspherical lens.



(a) (b)

Fig. 5. Photographs of the molds for aspherical lens: (a) upper mold, (b) lower mold.

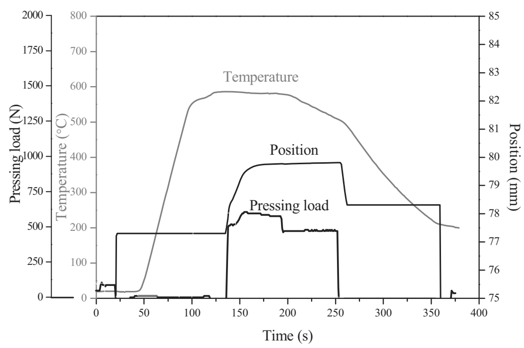


Fig. 6. Time sequence of temperature, lower mold position and pressing load in a molding cycle of IGMP.

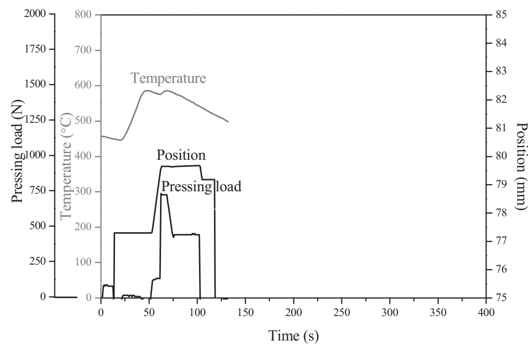


Fig. 7. Time sequence of temperature, lower mold position and pressing load in a molding cycle of NGMP.

Fig. 8. Photograph of the molded aspherical lenses.

deviation at the lens center is shown (Fig. 9(a)). The total form error of the lower surface (ASP2) is 0.26 μm, –0.18 μm in the center and +0.08 μm in the outer region (Fig. 9(b)). For the lens molded by NGMP method, the form error of the upper surface is almost the same as that by IGMP method (Fig. 9(a)), but the form error of the lower surface is in the range of +0.15 ~ –0.5 μm (Fig. 9(b)), which is a little larger than that by IGMP.

The form errors of the molded lens might be caused by the following three reasons: the manufacturing errors of the molding dies, the shrinkage of the lens during cooling and the deformation of the molding die during press. The form compensation of the shapes of the mold dies can improve the form accuracy of the molded aspherical glass lens.

4. Innovation of glass molding press for microstructures

As every one knows that the glass material is brittle and hard, and not easy to be machined directly. Traditionally, the microgrooves and micropyramids are made by the MEMS techniques, but sharp angle microgrooves are not easy to be fabricated. Micro cutting can produce sharp microgrooves, but this method is time consuming and is not suitable for mass production. Though micro injection molding and sheet nano imprinting can fabricate microgrooves and micropyramids in mass production, it is only suitable for plastic. In order to make the microgrooves and micropyramids on the glass plate efficiently, as shown in Figs. 10(a) and (b), glass molding press (GMP) was proposed to extend to fabricate the microstructures.

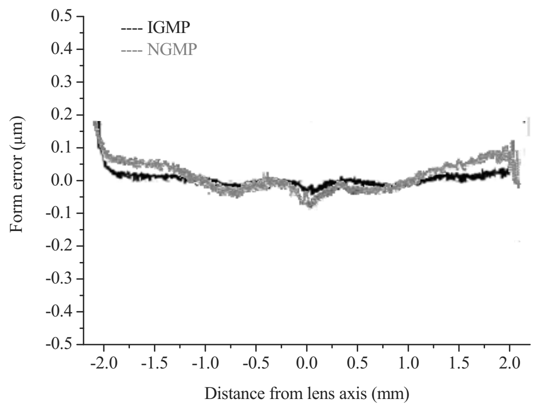
The mold with microstructures should be generated. WC is no doubt a good mold material in GMP, but it is too hard to be fabricated efficiently. Nickel phosphorus (Ni-P) has a good machinability in room temperature as well as a relative high hardness in high temperature pressing [4]. The microgrooves are cut by a sharp diamond cutting tool transversely fed in the horizontal direction while the depth of cut is kept constant. By periodically shifting the tool perpendicularly to the cutting direction, parallel microgroove arrays can be generated. While in the micropyramid cutting, the workpiece is then rotated for an angle of 90º after cutting an array of microgrooves, and the cross-grooving operation is performed. In this way, micropyramid arrays can be created on the mold surface.

In the GMP for microstructures, first, microgrooves on the Ni-P layer are fabricated by micro cutting and used as the mold in the glass molding press. Second, a glass preform is heated and softened at high temperature, and then, it is pressed between a pair of molds. In this way, the shapes of microgrooves on the mold are replicated to the glass plate. The GMP method can produce microgrooves on the glass plate in high productivity at a low cost. Similarly, micropyramids can be molded by using the micropyramid mold.

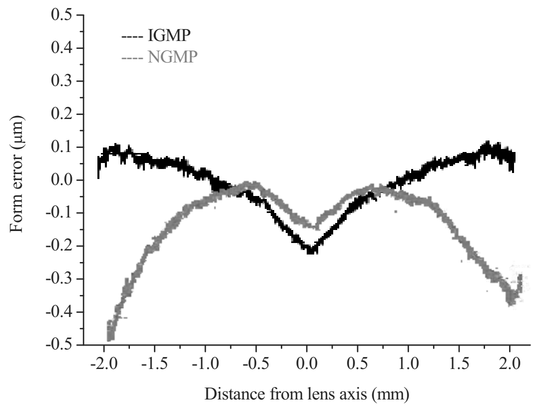
In the microstructure molding, the glass material will be difficult to fill up the tiny groove channel, and results in an incomplete replication of the mold shape. Therefore, the molding condition should be optimized.

5. Experiments of microstructure forming

Both the microgrooves and micropyramids have the same cross-section profile, which is schematically shown in Fig. 11. The depth is 5 μm, the pitch is 10 μm, and the cross section of a

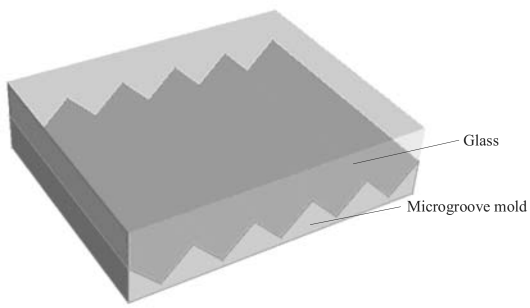


(a)

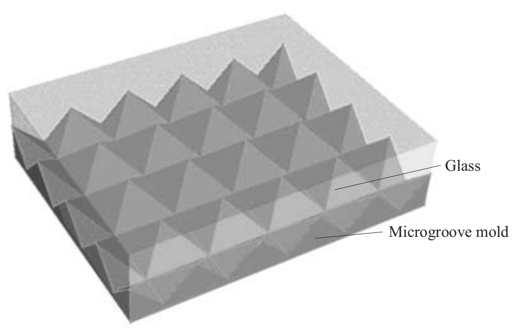


(b)

Fig. 9. Form accuracy of the molded lens by IGMP and NGMP: (a) upper surface, (b) lower surface.



(a)



(b)

Fig. 10. Schematic of glass molding for microstructures (a) microgrooves and (b) micropyramids.

microgroove or a micropyramid is isosceles right triangle. Fig. 12 is photograph of the mold for microstructures manufactured by single diamond cutting.

In the GMP experiments, the effects of the pressing velocity were investigated. When the molding temperature was fixed at 570ºC, the stress is found to be proportional to the pressing velocity. The stress, lower than 2 MPa, was adopted in the molding process. Therefore, the molding temperature of 570ºC and the pressing velocity of 6 mm/min is considered to be the optimum molding condition, and used in the experiments.

Fig. 13 shows the photograph of one of the molded lenses. This is the picture of the mold with microgrooves and micropyramids on it. This is one of the molded microgrooves and micropyramids on the glass plate. The 3D sectional profiles of the molded microstructures were measured. As shown in Figs.14(a) and (b), the height of the molded microgrooves is 4.72589 μm, and the height of the molded micropyramids is 4.37375 μm. Therefore, the calculated filling ratio of the microgroove forming is 94.5%, and the filling ratio of the micropyramid forming is 87.5%. The forming error of the microgrooves between the molded lens and the mold can be controlled within 0.38 μm, and the forming error of the micropyramids is about 0.63 μm, which shows that the GMP method is can generate the microstructures at submicron meter level efficiently.

6. Conclusions

Aspherical lens are fabricated by using the WC mold, and microstructures are fabricated by using the Ni-P mold. In comparison of the aspherical lens forming with the microstructure forming, the GMP for aspherical lens molding concentrates on the smooth surface replication with a high efficiency, and the GMP for microstructure molding concentrates on the parallel microgroove and the periodic micropyramid replication with a high precision. The main conclusions drawn from this paper are as follows.

(1) NGMP was proposed to fabricate aspherical lenses, which can increase the productivity to 3 times and prolong the life of the molding dies.

(2) Although the aspherical lenses fabricated by IGMP and NGMP both have submicron level form accuracy, the form error of lenses fabricated by NGMP method is a little larger than that by IGMP.

(3) Microgrooves and micropyramids were successfully molded on the glass piece by using Ni-P mold. Microstructures on the glass piece can be obtained with form accuracy of several ten nanometers

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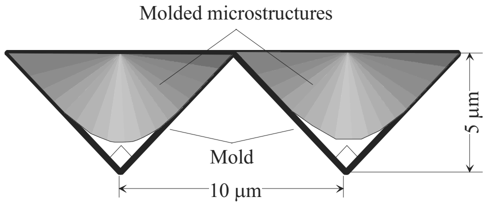

Fig. 11. Schematic diagram of the cross section of microgrooves and micropyramids.

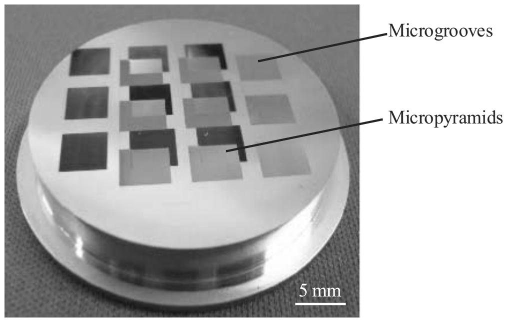

Fig. 12. Photograph of the mold for microstructures.

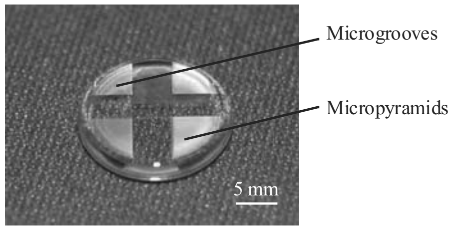

Fig. 13. Photograph of the molded microstructures on glass plate.

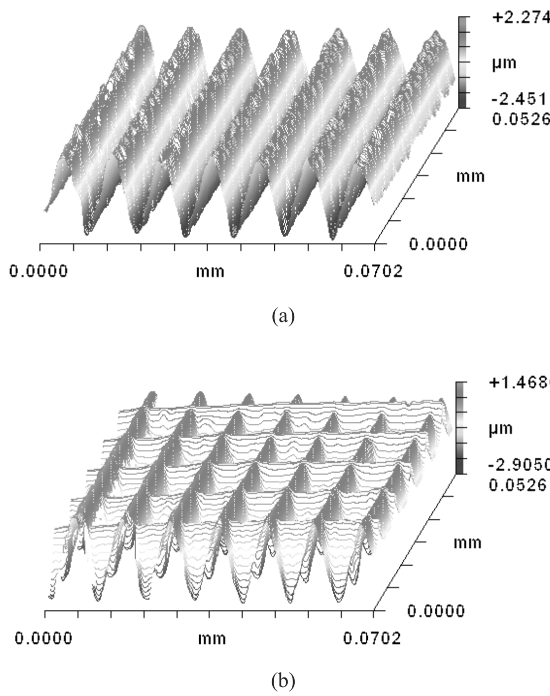

Fig. 14. 3D topographies of the molded microstructures on glass plate: (a) microgrooves and (b) micropyramids.