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Study on Nonisothermal Glass Molding Press for Aspherical Lens*

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Abstract
Nonisothermal glass molding press (NGMP) was proposed to fabricate aspherical lenses, and its characteristics were studied by both experiments and finite element method (FEM) simulations in comparison with the traditional isothermal glass molding press (IGMP). The cycle time, form accuracy, surface roughness, stress/strain distributions of the aspherical lenses made by IGMP and NGMP were examined and compared. Experimental results and simulation results show that NGMP is an effective way to improve the molding efficiency and prolong the service life of the molding dies.

Key words: Glass Molding Press, Aspherical Lens, Finite Element Method, Nonisothermal Forming

1. Introduction

Glass lens has many predominant advantages over the plastic counterpart on aspects of hardness, refractive index, light permeability, stability to environmental changes in terms of temperature and humidity, and so on. For this reason, glass lenses have been needed increasingly in the field of high-resolution digital cameras, cell phone cameras, and blue ray DVD players and recorders. Conventionally, glass lens has been fabricated by a series of material removal processes, such as grinding, lapping and polishing, which requires a long production cycle and results in very high production cost [1, 2]. As an alternative approach, glass molding press (GMP) has been accepted as a promising way to efficiently produce precision optical elements with complex shapes, like aspherical lenses, Fresnel lenses, diffractive optical elements (DOEs), micro lens arrays, and so on [3, 4].

In GMP, a lens is fabricated by pressing a glass ball at a high temperature above the glass transition temperature. Conventionally, pressing is performed when the temperature of glass becomes the same as that of the molding dies. This method is termed as “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, which have been described in one of our previous papers [5]. First, the glass ball is placed on the lower mold, and an inert gas (usually nitrogen, N_2) is flowed into the machine chamber to purge the air, then the molds and glass ball are heated to the molding temperature (usually by infrared lamps). Second, the glass ball is pressed to form a lens between the two mold halves. Third, the pressing load is decreased to a lower level and is maintained and the formed lens is cooled slowly to release the internal stress, namely, annealing. Finally, the glass lens is cooled rapidly to ambient temperature and released from the molds. Through these four stages, the shapes of the molding dies are replicated to the glass lens. As all of the four stages are controlled successively in the time sequence, the total time needed for a molding cycle is the sum of time for heating, pressing, annealing and cooling.

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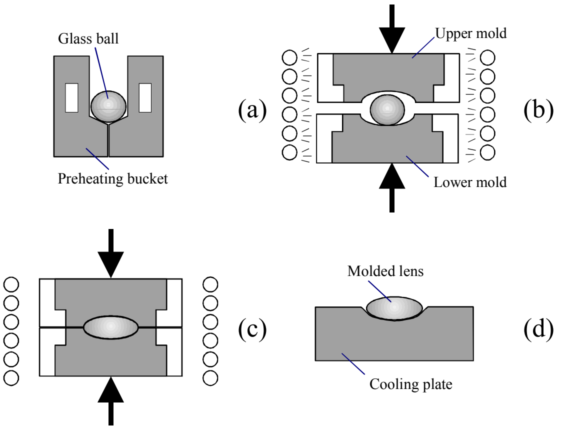


Fig.1. Process flowchart of the NGMP process: (a) preheating, (b) pressing, (c) annealing and (d) cooling.

In this work, a new method, namely “nonisothermal glass molding press (NGMP)” is proposed for fabricating aspherical lens. It is expected that NGMP can reduce the molding cycle time and prolong the mold life. In the NGMP process, the temperature control of the glass ball is separated from that of the molding dies. Fig. 1 schematically shows the process flow of the NGMP method. First, the glass ball is preheated to a temperature above the molding temperature in a preheating bucket, while the molding dies are held at a relative lower temperature than the molding temperature (Fig. 1(a)). Second, the preheated glass ball is moved into the molding chamber and pressed to form a lens by the molding dies, the temperature of which is lower than that of the glass ball (Fig. 1(b)). Third, the formed glass lens is annealed to release the internal stress (Fig. 1(c)). Finally, the annealed lens is taken out from the molding chamber and cooled down separately on a cooling plate to the room temperature (Fig. 1(d)). In the NGMP method, when a glass ball is in the molding chamber for pressing and annealing, the next glass ball is being heated in the preheating unit, and the last molded lens is being cooled in the cooling unit. By controlling these stages in a parallel way, the average cycle time can be remarkably reduced. Additionally, the temperature change of the molding dies in NGMP is smaller than that in IGMP, so the service life of the molding dies can be prolonged.

In the present paper, experiments and finite element method (FEM) simulations were carried out to study the molding cycles of both IGMP and NGMP, and a comparison of the two methods was made. FEM simulation was performed by coupling the mechanical and thermal aspects of glass deformation [6]. By analyzing of the experimental results and the simulation results, the merits of NGMP were demonstrated.

2. Experiments

2.1. Lens geometry

A biconvex lens having two aspherical surfaces, ASP1 and ASP2, was designed as shown in Fig. 2. The cross-sectional curves of the aspherical surfaces are defined by Eq. (1).

$$z = \frac{x^2}{R\left(1+\sqrt{1-(1+k)x^2/R^2}\right)} + B_4x^4 + B_6x^6 + B_8x^8 + B_{10}x^{10} \tag{1}$$

where x is the coordinate across clear aperture of the optical surface, and z is the sagittal value as a function of x; R is the vertex radius of curvature; K is the conic constant; and B_4, B_6, B_8, B_{10} are the corresponding aspheric coefficients. The upper surface ASP1 has a vertex radius of 10.75341 mm, and the lower surface ASP2 has a vertex radius of 2.194511 mm. In other words, ASP2 has a bigger curvature than ASP1. Detailed parameters for the aspherical surface ASP1 are: R=–10.75341 mm, K=0, $B_4=8.621796\times10^{-3}$, $B_6=-2.561791\times10^{-3}$, $B_8=3.037140\times10^{-4}$, and $B_{10}=-1.80822\times10^{-5}$, and those for ASP2 are: R=2.194511 mm, K=–2.6379, $B_4=2.468082\times10^{-3}$, $B_6=-2.852381\times10^{-3}$, $B_8=4.228797\times10^{-4}$, and $B_{10}=-4.749531\times10^{-5}$.

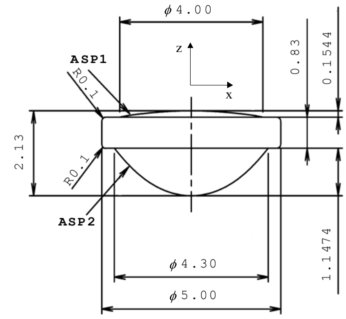


Fig. 2. Shape of the designed biconvex aspherical lens.

2.2. Molding machine

Both of the IGMP and the NGMP experiments were carried out by using a newly developed glass molding press machine, GMP-0204V-TS, the general structure of which is schematically shown in Fig. 3. For performing the NGMP experiments, a preheating unit and a cooling unit were equipped. A robotic arm was used to transport the preheated glass ball from the preheating unit to the molding unit before pressing, then after annealing, handle the molded lens from the molding chamber to the cooling unit. When performing the IGMP experiments, only the molding unit was used.

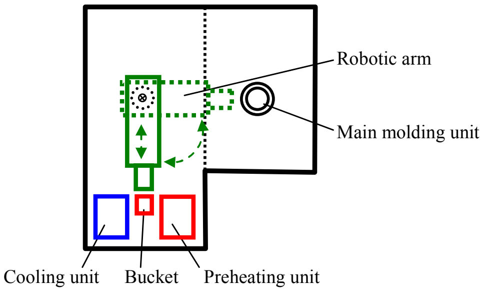


Fig. 3. Schematic diagram of the general structure of the developed ultraprecision high-efficiency glass molding machine.

2.3. Molds

Both the IGMP and the NGMP experiments were carried out using the same set of aspherical molds. The molds were made of tungsten carbide (WC), which has high strength, high hardness and low expansion at high temperature. The thermo-mechanical properties of the WC molds are given in Table 1. Mold surface coating, alternatively referred to release agent coating, is important in GMP [7] to prevent high-temperature glass from adhering to the bare molding dies and to prolong the service life of the molding dies. In the present study, a thin film of diamond like carbon (DLC) of 1 μm thickness was coated onto the WC molding dies. The cross-sectional curves of the molding dies were defined by Eq. (1). Both the upper die and the lower die were assembled in a pair of die bases, and guided by two location pins to minimize decentration. The diameter of the die base is 40 mm. Photographs of the assembled molds are shown in Fig. 4.

Table 1. Thermo-mechanical properties of the WC molding dies

Property item	Property value
Thermal expansion α ($\times10^{-6}$/°C)	4.1 (0~400°C) 4.9 (400~600°C)
Thermal conductivity k (W/(m×K))	97
Specific gravity d	15.2
Module of elasticity E ($\times10^{9}$ N/m^{2})	650
Module of rigidity G ($\times10^{9}$ N/m^{2})	270
Poisson's ratio ν	0.2

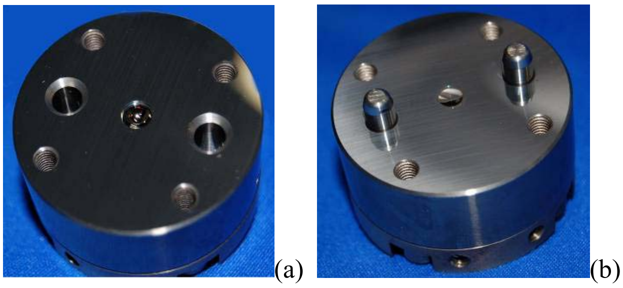


Fig. 4. Photographs of the assembled molds: (a) upper mold, (b) lower mold.

2.4. Glass

A typical low transition temperature glass, L-BAL35, produced by Ohara Corporation, was selected for molding glass lenses. The thermo-mechanical properties of the glass material are listed in Table 2. The volume of the biconvex aspherical lens can be calculated by the volume integration of the curve equation. Assuming that the volume of the glass ball is equal to the volume of the molded glass lens, the necessary diameter of the glass ball can be calculated. Accordingly, glass balls with a diameter of 3.66 mm were used in the experiments. The balls were finely polished to control the form error to be less than 0.2 μm.

Table 2. Thermo-mechanical properties of glass L-BAL35

Property	Property value
Transition temperature T_g (°C)	527
Yield temperature A_t (°C)	567
Softening point *SP* (°C)	619
Thermal expansion α ($\times 10^{-6}$/°C)	6.6 (–30~70°C) 8.1 (100~300°C)
Thermal conductivity *k* (W/(m×K))	1.126
Specific gravity *d*	2.82
Module of elasticity *E* ($\times 10^9$ N/m^2)	100.8
Module of rigidity *G* ($\times 10^9$ N/m^2)	40.3
Poisson's ratio ν	0.247

2.5. IGMP molding conditions

In the IGMP experiment, first, a glass ball was placed onto the lower mold, then the molding chamber was closed and vacuumed by a vacuum pump; and then, nitrogen gas was flowed to prevent the molds from oxidation during heating. The molding chamber was covered by a transparent silica glass tube, which can let in the infrared rays from the infrared lamps and separate the nitrogen gas from the air outside. After the glass ball reached the molding temperature, the chamber was vacuumed again so as to reduce the oxygen concentration remained in the N_2 gas. Then, the lower mold was driven upward to close the molds, while the upper mold remained stationary. In this way, an aspherical glass lens was formed. After that, annealing was conducted to release the internal stress. Finally, the lens was rapidly cooled to room temperature by fast flowing of nitrogen gas. The time sequences of temperature, lower mold position and pressing load are plotted in Fig. 5.

2.6. NGMP molding conditions

In the NGMP experiment, first, a glass ball was preheated to 590°C in the preheating unit before being loaded onto the lower mold. At this time, the upper and lower molds were maintained at a lower temperature of 560°C. After the glass was loaded onto the lower mold, pressing was conducted to form the lens. After pressing, the glass was annealed slowly in the molds to 500°C. Finally, the lens was rapidly cooled to room temperature in the cooling unit. The time sequences of temperature, lower mold position and pressing load in NGMP are plotted in Fig. 6.

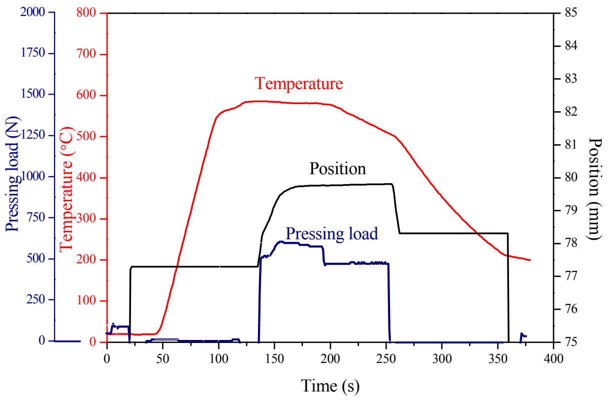


Fig. 5. Time sequence of temperature, lower mold position and pressing load in a molding cycle of IGMP.

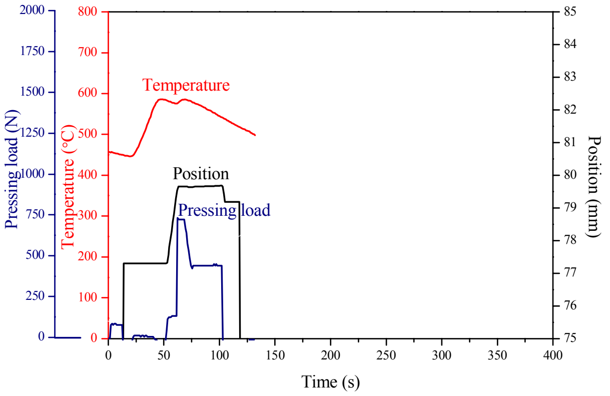


Fig. 6. Time sequence of temperature, lower mold position and pressing load in a molding cycle of NGMP.

3. Experimental Results

3.1. Measurement results of molded lenses

Fig. 7 is a photograph of three of molded aspherical lenses, one of which (A) was made by IGMP and two (B and C) were made by NGMP. The form error of the molding dies and molded lenses were measured by an ultrahigh accuracy 3D profilometer (UA3P), produced by Matsushita Electric Industrial Co., Ltd. Japan. The resolution of the profilometer is 3 nm in Z axis. The surface roughness of the molded lenses was measured by a laser interferometer, NewView 5000, produced by Zygo Corp., USA. The interferometer has a resolution of 0.1 nm and a repetitive accuracy within 0.4 nm in root-mean-square (RMS).

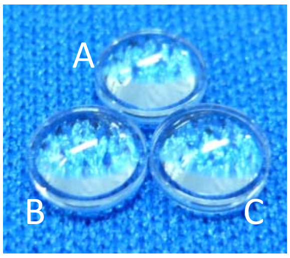
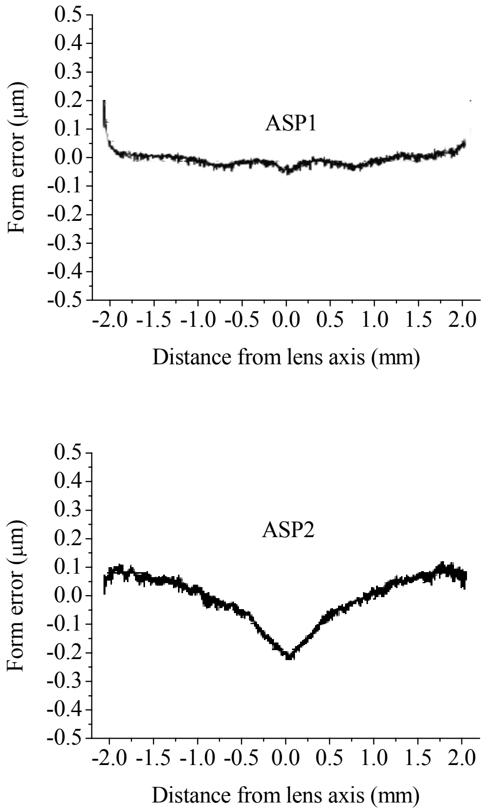


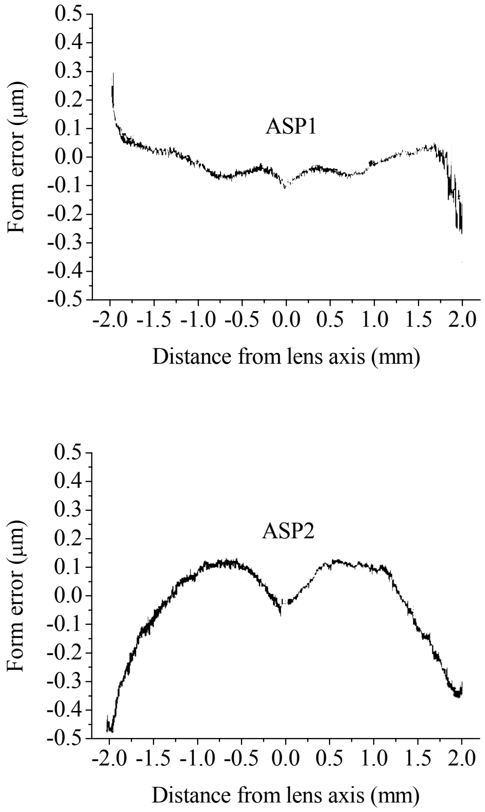
Fig. 7. Photograph of the molded aspherical lenses.



(a)

(b)

Fig. 8. Form accuracy of the molded lens by IGMP: (a) ASP1, (b) ASP2.



(a)

(b)

Fig. 9. Form accuracy of the molded lens by NGMP: (a) ASP1, (b) ASP2.

Fig. 8 shows measurement results for form accuracy of a molded lens fabricated by the 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 deviation at the lens center is shown (Fig. 8(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. 8(b)). The form errors of the molded lens might be caused by the following three reasons: (1) the manufacturing errors of the molding dies, (2) the shrinkage of the lens during cooling and (3) the deformation of the molding die during glass molding press. The surface roughness of ASP1 is 57 nm PV, and that of ASP2 is 42 nm PV.

Figs. 9(a) and (b) are the form errors of the upper and lower surfaces of the molded lens fabricated by the NGMP method. The form accuracy is in the range of +0.15 ~ –0.5 μm. The surface roughness of the upper surface is 31 nm PV, and that of the lower surface is 30 nm PV.

3.2. Comparison of NGMP with IGMP

By comparing Fig. 5 with Fig. 6, 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.

Next, we can see that in Fig. 5, the temperature change of the molds in IGMP is 430ºC (from 150ºC to 580ºC) while in Fig. 6, the temperature change of the molds in NGMP is only 80 ºC (from 500ºC to 580ºC). That is to say, the temperature change of the molds in NGMP is remarkably smaller than that in IGMP. From the temperature change of the molds, it is presumable that the mold life in NGMP will be longer than that in IGMP.

Finally, by comparing the form accuracy and surface roughness of the aspherical lenses fabricated by IGMP (Fig. 8) and NGMP (Fig. 9), we can find that although the two kinds of lenses both have submicron level form accuracy and ten nanometer level surface roughness, the form error of the lenses fabricated by NGMP method is a little bigger. Further work is needed to improve the lens form accuracy in the NGMP method.

4. FEM Simulation

An axisymmetric FEM model for GMP of aspherical lens was built in the simulation, as shown in Fig. 10. The dimensions of the glass ball, molding dies and molds in the model are the same as those used in the experiments. The material properties of the glass and the WC molds are given in Table 1 and Table 2, respectively.

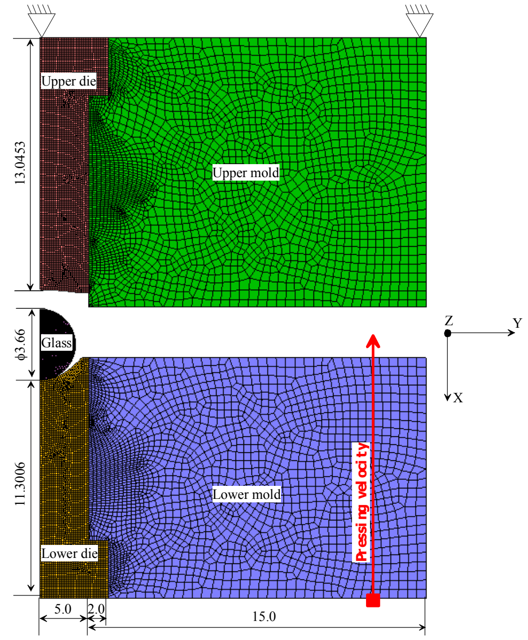


Fig. 10. FEM simulation model for GMP of aspherical lenses.

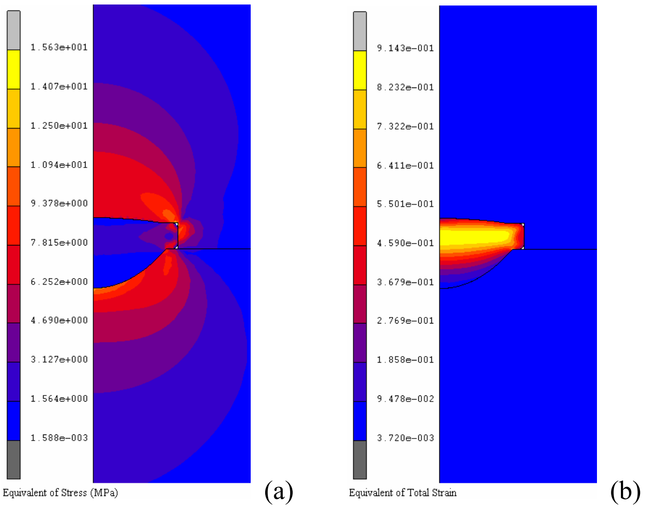


Fig. 11. (a) Stress distribution and (b) strain distribution at the end of pressing in IGMP.

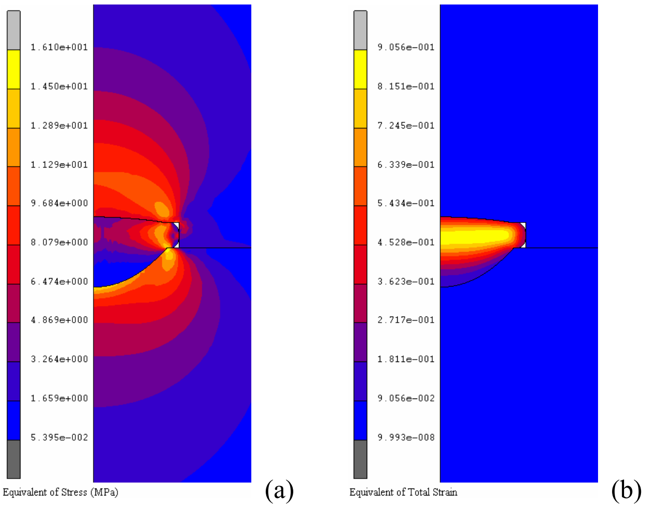


Fig. 12. (a) Stress distribution and (b) strain distribution at the end of pressing in NGMP.

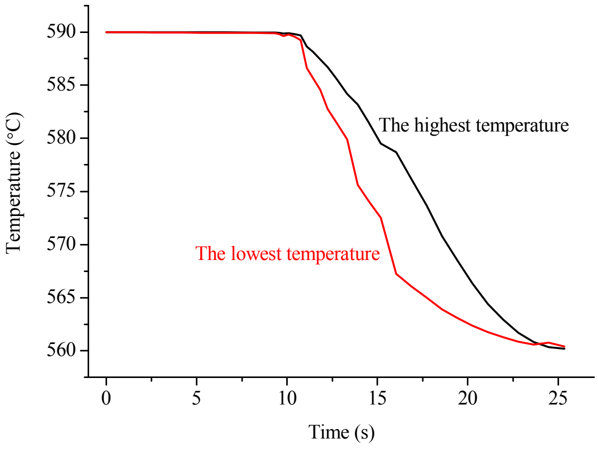


Fig. 13. Temperature change of glass during the pressing stage in NGMP.

4.1. Simulation of IGMP

Stress and strain distributions in IGMP were simulated during the molding process at a molding temperature of 570°C at a constant pressing velocity of 6 mm/min, and the simulation results are shown in Fig. 11. From Fig.11 (a), we can see that at the molding temperature (570°C), the glass material has been squeezed to fill up the whole cavity of the molds. The stress in the molding dies is very strong and distributes radially around the molded lens, and stress concentration takes place in the molding die near the fringe of the lens. Stress concentration is also found in the lens near the lens fringe, while in the center region of the lens bottom, the stress is extremely low.

From Fig. 11(b), it can be seen that the strain in the molding die is extremely small. The strain in the bottom of the lens is also very small, while the highest strain distributes in an arc shape in the top half of the lens. Therefore, we can deduce that most of the glass material flows through the top half part during the glass deformation from a spherical ball to an aspherical lens.

4.2. Simulation of NGMP

In NGMP, after the preheated glass ball is moved to the lower mold in the molding chamber, the initial temperature of the glass ball is 590°C, while the temperature of the molding dies is 560°C. For this reason, heat transfer continues during the deformation of the glass. As glass is a typical temperature-dependent material, the heat transfer will affect the glass deformation behavior. At the same time, deformation of glass will also change the heat transfer and temperature distribution in glass.

Fig. 12(a) shows the FEM simulated stress distribution in glass and in the molding dies at the end of pressing in NGMP. The shape of the contour map of the stress distribution is generally similar to that in Fig. 11(a), while the maximum stresses in both of the molding dies and the molded lens in Fig. 12(a) are higher than those in Fig. 11(a). Fig. 12(b) shows FEM simulated strain distribution corresponding to Fig. 11(a). The strain distribution in Fig. 12(b) is very similar to that in Fig. 11(b), indicating that glass deformation in both IGMP and NGMP is in the same level.

In order to find the reason for the increase of stress in Fig. 12(a), the temperature change of the glass ball during pressing was simulated. Fig. 13 shows the changes of the highest temperature and the lowest temperature. In the first 10 s, when the glass ball is driven upward by the lower mold, and has not contacted with the upper mold, the temperature of glass does not change noticeably and remains almost constant at 590°C. After the glass ball gets contact with the upper molding die and pressing begins, the lowest temperature of the glass ball (in the outer region) drops sharply and the highest temperature (in the center region) drops gradually. As a result, there is a temperature difference within the glass ball during pressing, which leads to non-uniform glass flow, and in turn, stress concentration. It should be noted that before the upper and lower molds were completely closed at 25 s, the highest temperature and the lowest temperature reached a balance at 560°C, namely, the temperature of the molding dies. From this meaning, we can say that by optimizing the mold closing speed, it is possible to control the heat transfer and the stress distribution in glass in the NGMP process.

4.3. Comparison of NGMP with IGMP

After comparing the simulation results of IGMP with those of NGMP, further differences between the two methods were indentified.

(1) In IGMP, the change of stress from the center to the fringe of the lens is monotonic. In NGMP, however, the change of stress is non-monotonic.

(2) In IGMP, the maximum stress takes place in the flat part of the lens fringe; while in NGMP, the maximum stress occurs near the juncture between the aspherical surface and the lens fringe.

(3) In IGMP, the cross section of the lens fringe is approximately rectangle, indicating that the glass flow and filling was almost complete. In NGMP, however, the lens fringe has round corners, indicating incomplete filling of glass. Although the lens fringe is not important for the optical performance of a glass lens, the premature solidification of the glass material in this region will hinder the material flow and increase the pressing load.

It should be mentioned that in the present study, for NGMP, the initial temperature of the molding dies was set to 560°C. This was to make the average molding temperature the same for both NGMP and IGMP (570°C). If the initial temperature of the molding dies is set to 570°C, the same as that for IGMP, the stress in the resulting lens of NGMP will be smaller than that of IGMP. In this case, the average molding temperature will be higher than 570°C. From this viewpoint, we can say that NGMP is beneficial to the mold life if the temperature of the molding dies is set to be the same as that of IGMP.

5. Conclusions

Nonisothermal glass molding press (NGMP) was proposed to fabricate aspherical lenses, and its characteristics were compared with the traditional IGMP method. The following conclusions have been obtained.

(1) In comparison with the IGMP method, the NGMP method can reduce the molding cycle time from 6 minutes to 2 minutes. The temperature change of the molding dies in NGMP (80°C) is remarkably smaller than that in IGMP (430°C), which will be beneficial to the service life of the molding dies.

(2) Aspherical lenses having submicron level form accuracy and ten nanometer level surface roughness have been obtained by both IGMP and NGMP. The form error of the aspherical lens fabricated by NGMP is slightly bigger than that by IGMP.

(3) FEM was used to simulate the stress and strain distributions in the glass lens and in the molding dies during pressing. Stress concentration occurs near the fringe of the lens, and the highest stress in NGMP is slightly higher than that in IGMP.

(4) Initial temperature of molding dies and mold closing speed are two important factors affecting the process performance in NGMP.

Acknowledgements

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