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SHAPE TRANSFERABILITY AND MICROSCOPIC DEFORMATION OF MOLDING DIES IN ASPHERICAL GLASS LENS MOLDING PRESS

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ABSTRACT

Glass molding press (GMP) experiments have been performed to fabricate aspherical glass lenses. Shape transferability of the GMP process was evaluated by examining and comparing the form accuracy and surface roughness of the molding dies and the molded lenses. Nanometric surface roughness and submicron level form accuracy have been confirmed on the resulting lenses. It was also found that the molding dies underwent microscopic deformation and topographical change, and the durability of the molding die was strongly dependent on their curvature radii. To clarify this effect, finite element analysis of glass deformation in the GMP process was conducted, and a strong location-dependence of material flow and stress/strain distribution in the molded lens were observed. Based on the simulation results and the experimental data, possible approaches to improve the service life of the molding dies were discussed.

Keywords: Glass molding press, aspherical optical lens, molding die, finite element method, shape transferability.

1. INTRODUCTION

Glass lens has many predominant advantages over the plastic counterpart on aspects of hardness, refractive index, light permeability, stability to environmental change in terms of temperature and humidity, and so on. For these reasons, glass lenses have been needed increasingly in the field of high-resolution digital cameras, mobile phone cameras, and Blu-

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ray disk players and recorders. Conventionally, glass lenses have been fabricated by a series of material removal processes, such as grinding, lapping and polishing, which require a long production cycle and result in very high production cost (Nicholas and Boon, 1981; Johnson and Michael, 2005; Venkatesh et al., 2005). As an alternative approach, glass molding press (GMP) process has been accepted as a promising way to efficiently produce precision aspherical lenses (Yi and Jain, 2005; Katsuki, 2006; Masuda et al., 2007; Zhou et al, 2007; Chang et al., 2008). The GMP process is a technique to replicate the shape of the molding die to the glass lens. A glass ball with a volume equal to that of the designed lens is heated to the molding temperature above the glass transition temperature (T_g) in the heating stage, and then the softened glass ball is pressed between a pair of molds to form a lens in the pressing stage. After that, the formed hot lens is slowly cooled down to a specific temperature to anneal the internal stress, and finally, cooled to room temperature rapidly in the cooling stage.

Two aspects are always taken into account in the GMP process: one is the quality of the molded lens, and the other is the cost of lens manufacturing. In other words, to fabricate the aspherical lens with a high accuracy at a low cost is the aim in this field. Shape transferability from the molding dies to the heated glass ball is a key issue in the GMP process to improve the form accuracy of final aspherical lens. It is essential that by optimizing the molding conditions, the shape of the molding dies can be precisely transferred to the glass lens. As for the reduction of lens manufacturing cost, an effective way is to prolong the service life of molding dies. From this point of view, the microscopic deformation of the molding dies during GMP is another important issue.

In the present work, we investigated the shape transferability between the molding dies and glass and the microscopic deformation of the molding dies through both experimental and simulation approaches. First, GMP experiments were conducted, and after pressing, the resulting glass lenses and the molding dies were evaluated in terms of form accuracy and surface roughness. Then, to illustrate the material flow mechanism and stress/strain distribution in glass, finite element method (FEM) simulations of the GMP process were conducted.

2. GMP EXPERIMENTS

Experiments were carried out using an ultraprecision glass molding machine, GMP-0204V-TS, developed by Toshiba Machine Corp. (Shizuoka, Japan). The main structure of the GMP machine is schematically shown in Figure 1. First, a glass ball is placed onto the lower mold, then the molding chamber is 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 reaches the molding temperature, the chamber is vacuumed again, and then the lower mold is driven upward to close the molds, while the upper mold remains stationary. In this way, an aspherical glass lens is formed. Then, annealing is conducted to release the internal stress. Finally, the lens is rapidly cooled to room temperature.

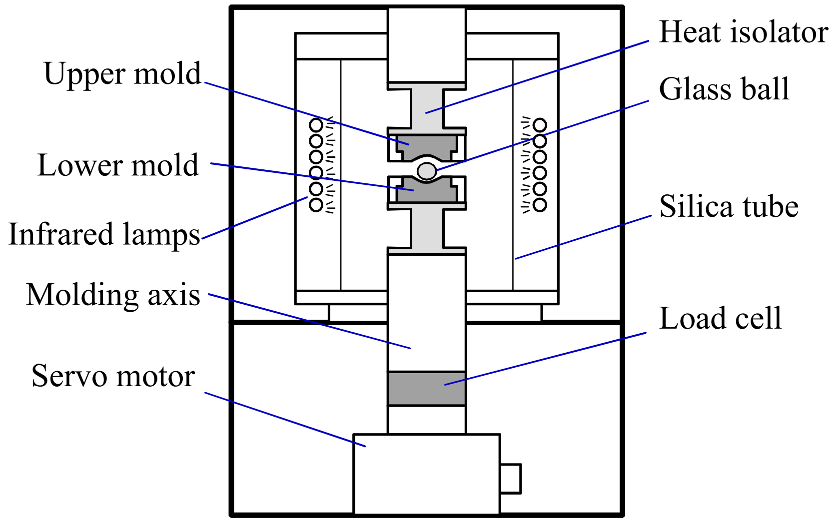


Figure 1. Schematic of the configuration of the ultraprecision glass molding machine.

During the press stage, the temperature of the molding dies is kept the same as that of the glass ball, and thus this kind of GMP is an "isothermal" process.

Using the feedback system of the molding machine, the pressing load, pressing velocity, mold position and temperature can be precisely monitored and controlled. Temperatures of the upper and lower molds are monitored by two thermocouples beneath their surfaces with a measurement accuracy of ±1°C. The position of the lower mold is recorded by an encoder with a resolution of 0.1 μm. A load cell is placed beneath the lower axis as a feedback of the pressing load with a resolution of 0.1 N.

A biconvex lens with two aspherical surfaces, ASP1 and ASP2, was designed as shown in Figure 2. The cross-sectional curves of both 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. Therefore, ASP2 has a bigger curvature than ASP1. Detailed parameters for surface ASP1 are: R=–10.75341 mm, K=0, B_4=8.621796×10^{-3}, B_6=–2.561791×10^{-3}, B_8=3.037140×10^{-4}, B_{10} =–1.80822×10^{-5}, and those for ASP2 are: R=2.194511 mm, K=–2.6379, B_4=2.468082×10^{-3}, B_6=–2.852381×10^{-3}, B_8=4.228797×10^{-4}, B_{10}=–4.749531×10^{-5}.

The volume of the biconvex aspherical lens can be calculated by the volume integration of the curve equations. Assuming that the volume of the glass ball is equal to the volume of the molded glass lens, the diameter of the glass ball (3.66 mm) then can be determined. A typical low transition temperature glass, L-BAL35, produced by Ohara Corp., Japan, was selected as the test material. The glass balls were finely polished with a diametrical error less than 0.2 μm. The thermo-mechanical properties of the glass material are listed in Table 1.

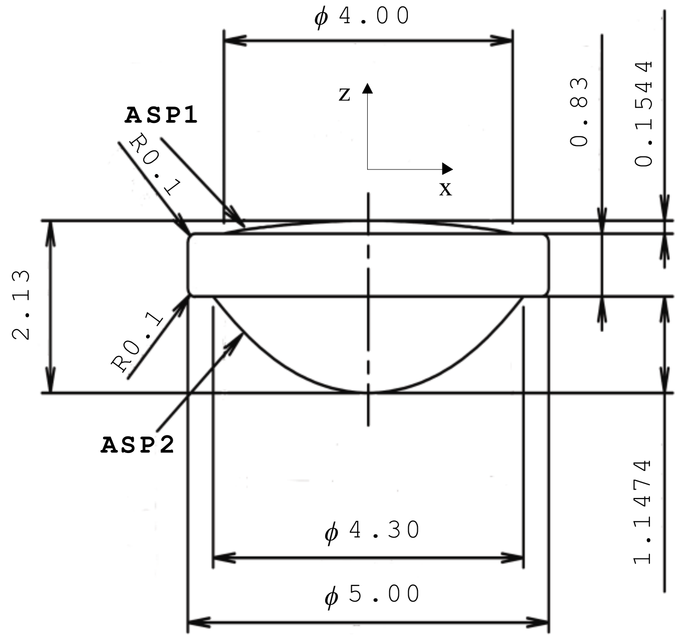


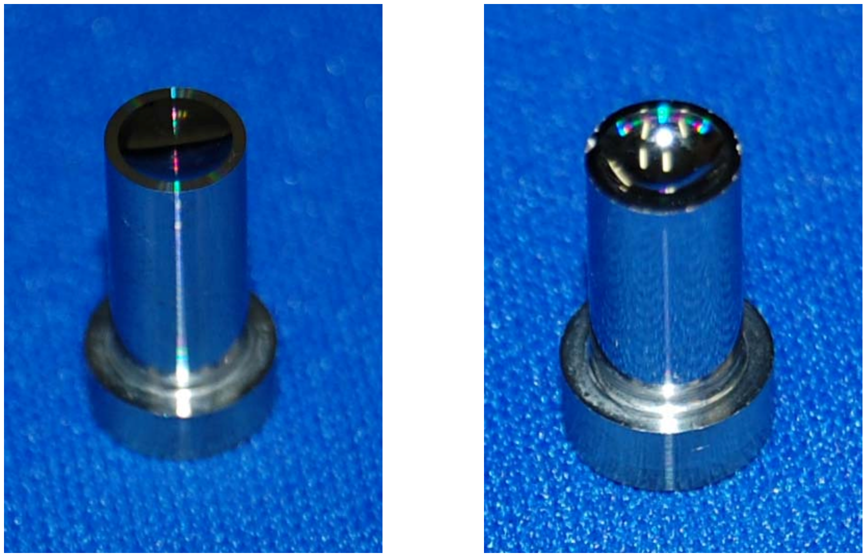
Figure 2. Shape of the objective biconvex aspherical glass lens.

Table 1. Thermomechanical properties of glass L-BAL35

Property	Value
Thermal expansion α ($\times10^{-6}$/°C)	8.1
Thermal conductivity k (W/(m·K))	1.126
Specific gravity d	2.82
Module of elasticity E ($\times10^{8}$ N/m^2)	1008
Module of rigidity G ($\times10^{8}$ N/m^2)	403
Poisson's ratio ν	0.252
Transition temperature T_g (°C)	527
Yielding temperature A_t (°C)	567
Softening point SP (°C)	619

A pair of molding dies made of tungsten carbide (WC) was used. WC has high strength, high hardness and low expansion at high temperature, thus is a popular material for optical molds. Figure 3 is photographs of the molding dies. The cross-sectional curves of the molding dies were also defined by Eq. (1). The molding dies were firstly ground to the aspherical shape, and then polished to a mirror surface. After surface finishing of the bare WC molding dies, diamond-like carbon (DLC) coatings were deposited on the die surfaces to protect them from wear and chemical reactions with glass. The thickness of the DLC coating is about 1 μm.

Surface coating, alternatively referred to "release agent coating", is very important in GPM. To prevent high-temperature glass from adhering to the bare WC molding dies and to prolong the service life of the molding dies, surface coatings are always necessary.



a b

Figure 3. Photographs of the molding dies for GMP tests: (a) upper die, (b) lower die.

Various types of coatings have been attempted in industry, although available literature on this issue is very limited. For example, Re-Ir coating has been used by Kim, S.S. et al. (2007), Ir-Pt coating has been attempted by Masuda et al. (2008), and DLC coating has been used by Holmberg et al. (2007). It is said that DLC may be widely accepted as an excellent coating material to replace the rare metal coatings (Kim, H.U. et al., 2008). The surface coating not only affects the performance of the molding does, but also determines the surface quality of the molded lenses.

Both the upper die and the lower die are assembled in a pair of die bases, and guided by two location pins to minimize decentration. The glass balls were pressed at a molding temperature of 570°C between the transition temperature T_g and the softening point *SP*. The details of the GMP process conditions are summarized in Table 2.

Table 2. GMP experimental conditions

GMP process condition	Value
Heating time (s)	180
Soaking time (s)	60
Molding temperature (°C)	570
Pressing velocity (mm/min)	15
Maximum pressing load (N)	1000
Annealing temperature (°C)	400
Slow cooling rate (°C/s)	1.2
Fast cooling rate (°C/s)	2.8
Releasing temperature (°C)	220

In most previously reported GMP experiments, the evaluation of the molded lens has not been mentioned, and the microscopic deformation of the molding dies has not been clarified.

In this work, the form error and the surface roughness of the molded lenses were measured, and the microscopic deformation of the molding dies was examined in detail. The form accuracy of molded lenses was measured by an ultraprecision three-dimensional profilometer, UA3P, produced by Matsushita Electric Industrial Co., Ltd. Japan. The resolution of the profilometer in depth direction is 3 nm. The surface roughness and surface topography of the molded lenses were measured by a laser interferometer, NewView 5000, produced by Zygo Corp., USA. This interferometer has a resolution of 0.1 nm and a repetitive accuracy within 0.4 nm in root-mean-square (RMS).

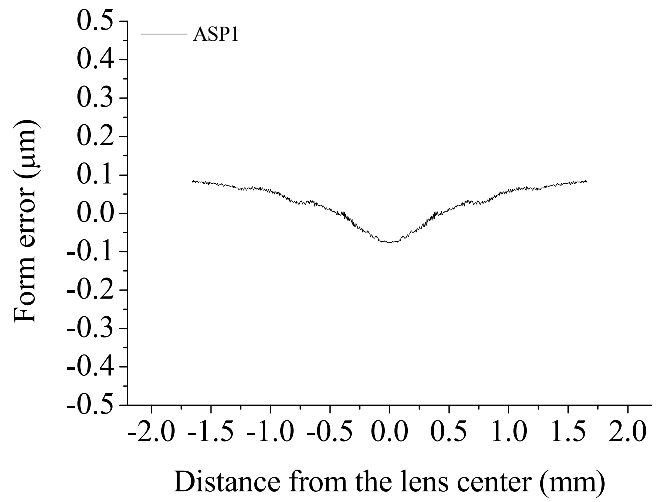
3. EXPERIMENTAL RESULTS

3.1. Form Accuracy and Surface Roughness of the Molded Lens

Figure 4 shows the photograph of a few molded aspherical lenses. Figure 5 shows the measurement results of form error of a molded 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. 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. The form errors of the molded lens might be caused by 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.

Figure 6 shows three-dimensional measurement results of the centers of the upper surface ASP1 and the lower surface ASP2 of a molded lens. The measured area is 141 μm×106 μm. Note that the vertical scale of Figure 6 (a) is different from that of Figure 6 (b). Next, to reveal the microscopic topography of the lens surface, the measurement data was processed by removing the aspherical curvature. Figures 7 (a) and (b) are microscopic topographies of the lens centers after removing the aspherical components. The peak-to-valley (P-V) values of ASP1 and ASP2 are both 41 nm, and the RMS values are 3 nm for ASP1 and 4 nm for ASP2, respectively.

Figure 4. Photograph of molded glass lens samples.



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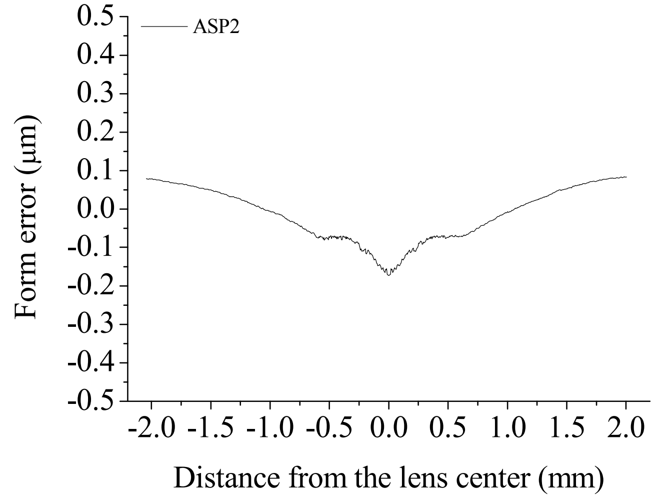

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Figure 5. Form error profiles of a molded lens: (a) upper surface ASP1, (b) lower surface ASP2.

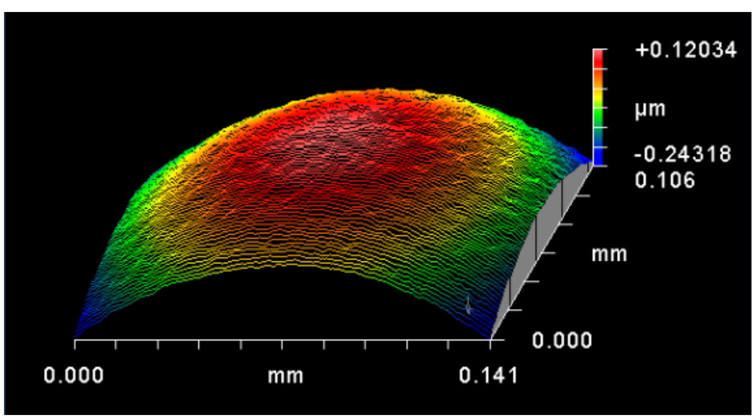

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Figure 6. (Continued).

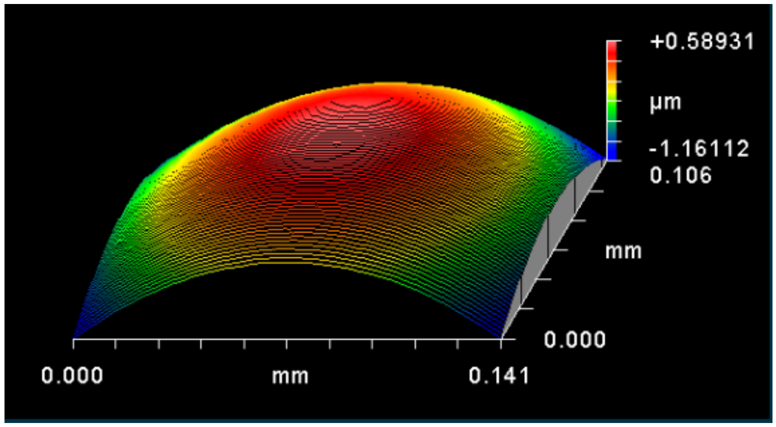

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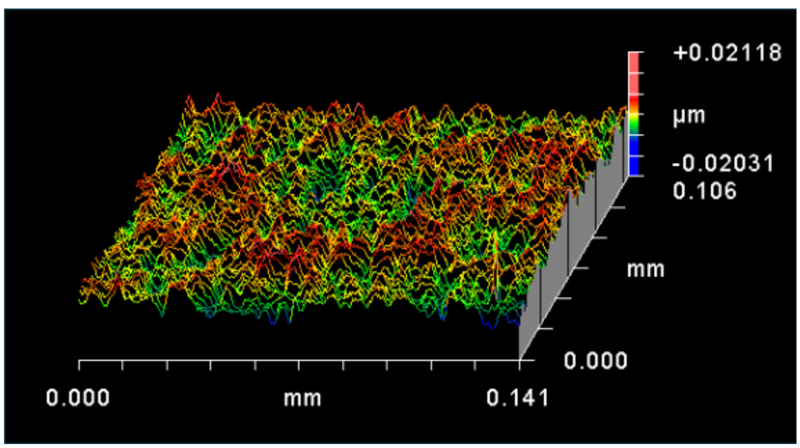
Figure 6. Three-dimensional measurement results of the center region of a molded lens: (a) upper surface ASP1, (b) lower surface ASP2.



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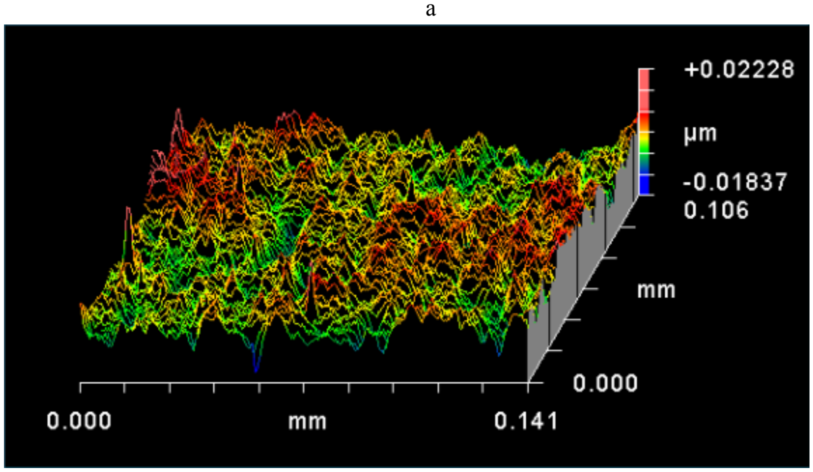

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Figure 7. Microscopic topographies of the molded aspherical lens after removing the aspherical curvature: (a) upper surface ASP1, (b) lower surface ASP2.

The surface roughness data of the two lens surfaces and the corresponding molding die surfaces before and after GMP is listed in Table 3. By comparing the results of the molded lens with those of the molding dies, we can find that the P-V values of the molded lens are a little bigger than that of the mold, while the RMS and Ra values are more or less the same. Therefore, we can conclude that fine surface microstructures in the ten nanometer level can be transferred to glass in the GMP process, and the form accuracy of the molded lens is in the submicron level.

Table 3. Surface roughness results of the molded lens and the molding dies

	Surface	P-V (nm)	RMS (nm)	Ra (nm)
Molded lens	ASP1	41	3	2
	ASP2	41	4	3
Molding dies before GMP	ASP1	39	6	5
	ASP2	26	4	3
Molding dies after GMP	ASP1	716	11	5
	ASP2	688	6	4

3.2. Deformation of Molding Dies

Molding die deformation is one of the major reasons for the form errors of the molded lenses. As the pressing shot number increases, the shape of the molding dies changes gradually due to the repeated pressing forces at high temperature. In this study, we experimentally measured the form accuracy changes of the molding dies before and after GMP experiments for 100 shots.

Figure 8 (a) shows an example of the form error change of the upper molding die corresponding to lens surface ASP1. Before GMP experiments, the error profile was very flat, showing an extremely small form error (~0.01μm). However, after experiments, the profile became wavy with a P-V value of ~0.7μm. Figure 8 (b) shows the form error of the lower molding die corresponding to lens surface ASP2. In this case, the profile changed slightly with an increase in P-V value from 0.2 μm to 0.45 μm. From this result, we can say that the deformation of the lower molding die is smaller than that of the upper mold.

Measurements were also performed to evaluate the microscopic topography of the molding dies. Figure 9 is the three-dimensional topographical data of the upper and the lower molding dies before GMP experiments. It can be seen that both of the two molding dies are extremely smooth without any detectable damages. Figure 10 is the topographical data of the same molding dies after the GMP experiments. A few sharp spikes are clearly shown in the figure. From the figure, it is difficult to judge if the spikes are caused by micro projections or micro depressions on the surface, because they response similarly to the light beam of the interferometer. It is presumable that they are surface damages, namely micro pits, on the molding die coating layer, or glass adhesions on the damaged points of the molding die. It is these spikes that caused the distinct increase in the P-V value of surface roughness after GMP, as listed in Table 3.

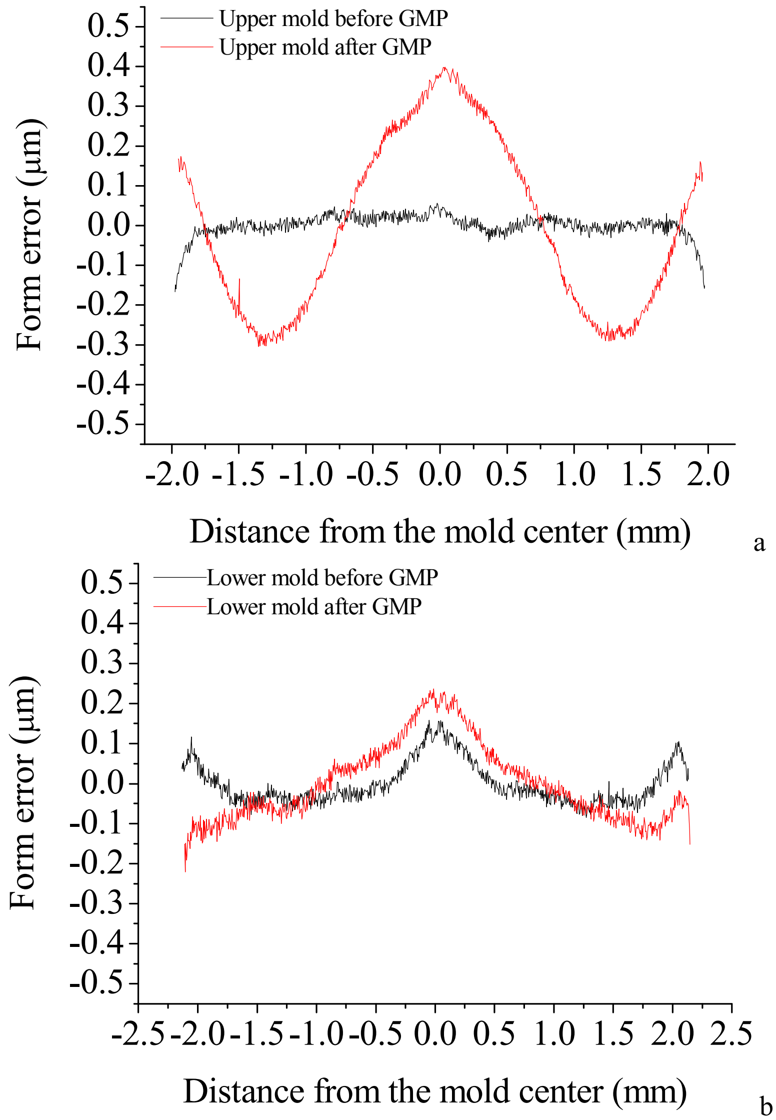

Figure 8. Changes in form error profile of the molding dies after 100 GMP shots: (a) upper die, (b) lower die.

By comparing Figure 10 (a) with (b), we can also find that the number of surface spikes on the upper molding die surface is more than that on the lower surface. This fact indicates that the durability of the upper die is shorter than that of the lower one. Next, in order to clarify the material flowing mechanism and the reasons for the differences in the durability between the upper and the lower molding dies, FEM simulations of the GMP process was performed.

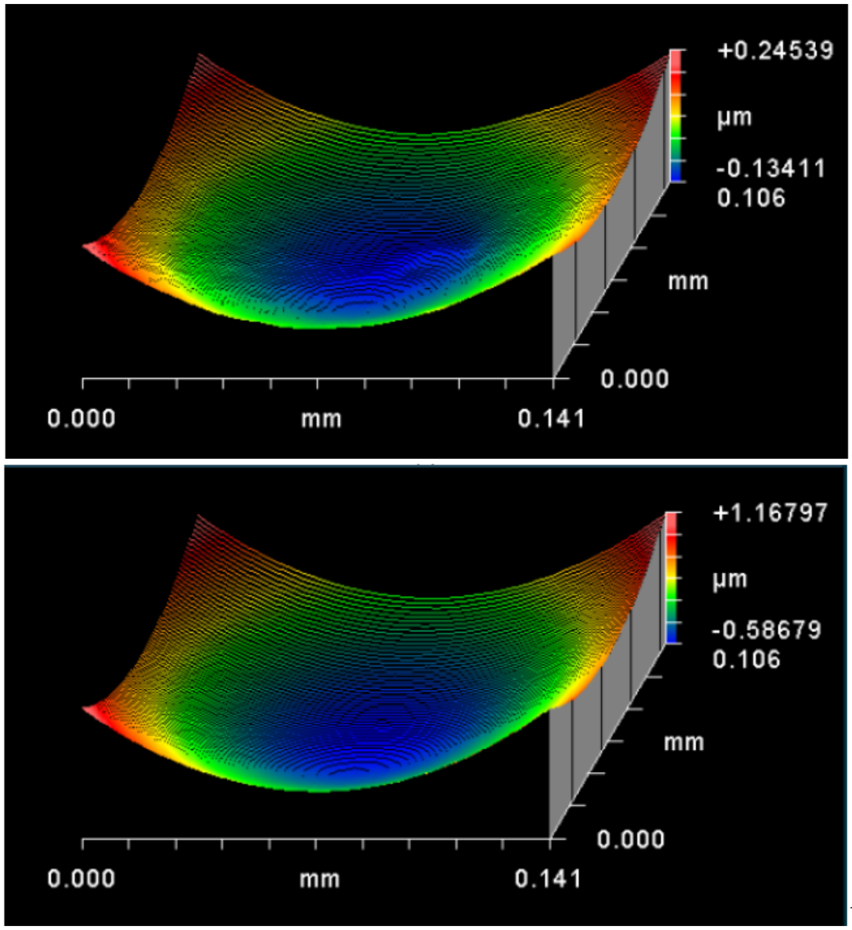

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Figure 9. Three-dimensional measurement results of the molding dies before GMP experiments: (a) upper die, (b) lower die.

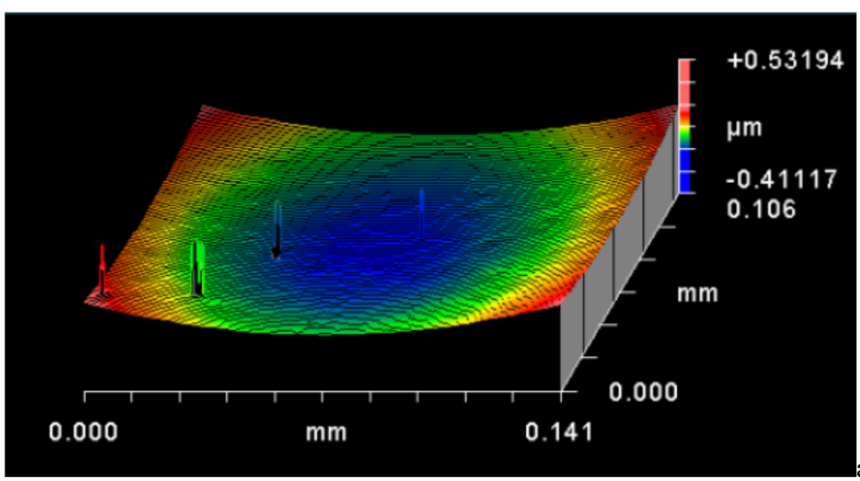

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Figure 10. (Continued).

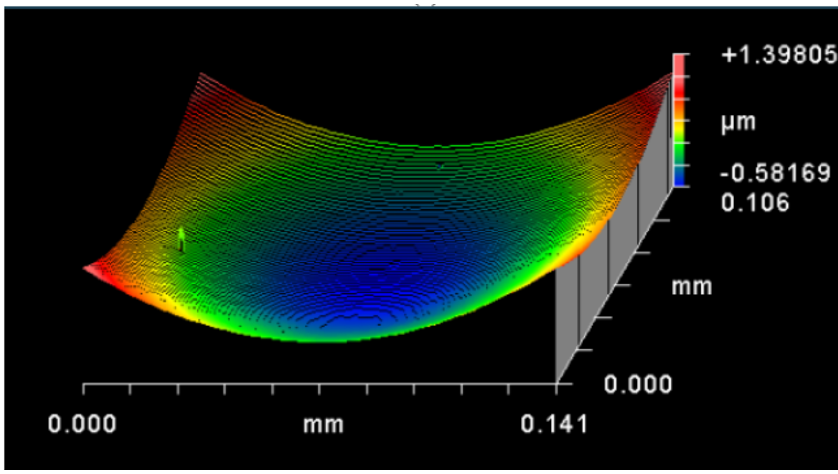

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Figure 10. Three-dimensional measurement results of the molding dies after 100 GMP shots: (a) upper die, (b) lower die.

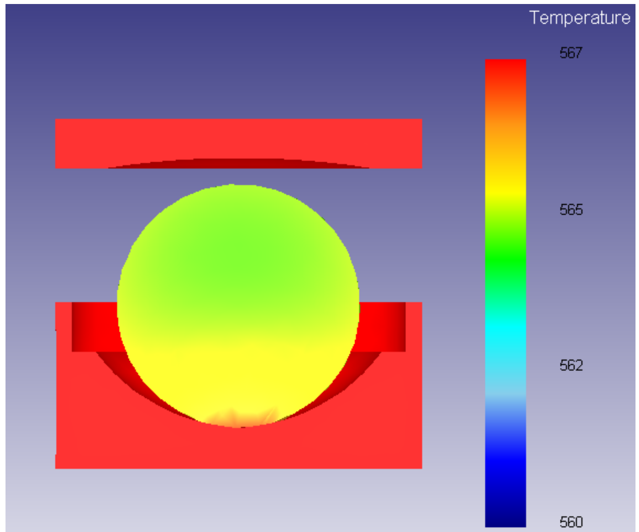
4. FEM SIMULATION OF GMP PROCESS

4.1. Temperature Distribution in Glass

In an actual GMP process of aspherical lenses, the temperature of the molds can be monitored directly by the thermocouples, but the temperature rise in glass can not. As pointed out in a previous paper of the present authors (Yan et al., 2008), there will be a delay between the temperature of glass and that of the molding die, because the transparent glass ball has a very low absorption rate of the infrared ray and most heat in glass is transferred from the lower mold through interfacial heat conduction. Therefore, modeling of the heat transfer phenomenon in GMP with considering the temperature dependence of specific heat and thermal conductivity of glass is important (Yan et al., 2008). Non-uniformity of the temperature in the glass ball will lead to a non-uniform material flow during the pressing, and result in a high strain which may bring down the optical quality of the molded lens (Na et al., 2007). Non-uniformity of the temperature may also cause an increase in pressing force, which gives rise to the mold deformation. As the temperature distribution in glass is affected by the heating time, determination of the heating time to soak the glass ball enough during the heating stage is a key step in the GMP process.

With the help of FEM simulation, the temperature distribution of the glass during heating can be visualized. Simulations of the glass molding process were conducted using a commercial FEM program DEFORM^{TM}-3D, which is suitable for simulating forging and molding of materials. The program is capable of simulating large deformation of material under isothermal and non-isothermal conditions (Walters et al., 1997). In the simulation, the initial temperature of the glass ball was set to 20°C, and during heating, the temperature was raised gradually to 570°C with a uniform distribution. The actual temperature rise of the lower mold, measured by experiment, was set as the temperature boundary condition of the glass ball during the heat transfer. As shown in Figure 11 (a), after heating for 180 s, the lowest temperature of the glass ball is 2°C lower than the temperature of the molding die.

However, after heating for 240 s, the whole glass ball has a uniformly distributed temperature of 570°C, as shown in Figure 11 (b).



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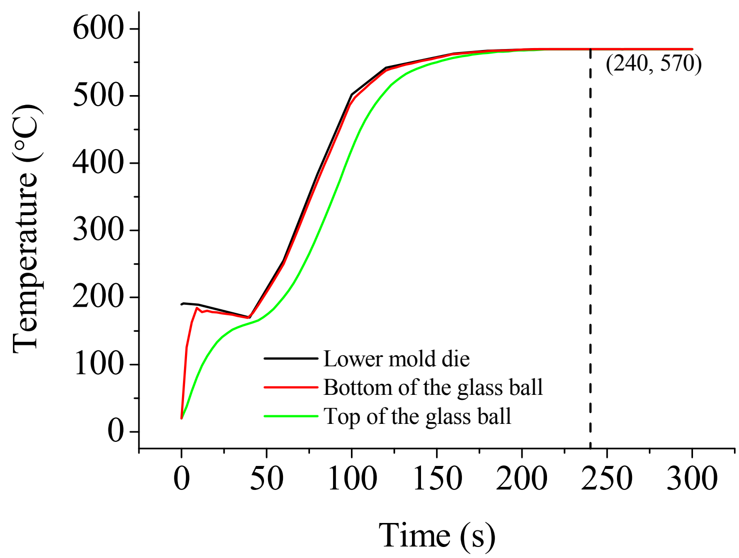


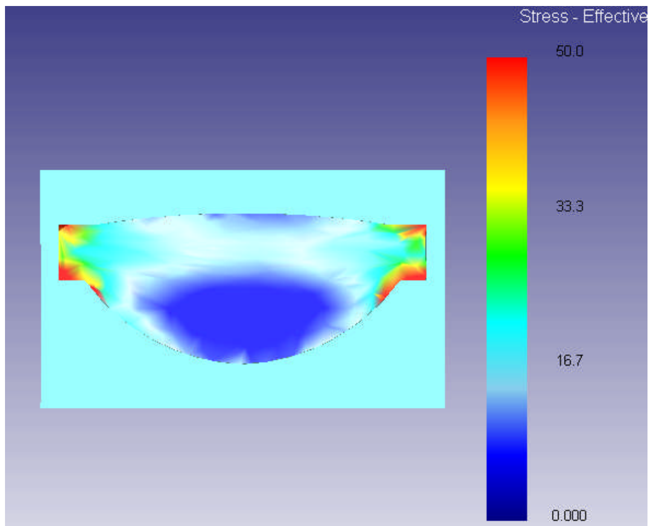
b

Figure 11. FEM simulation results of temperature distribution and temperature changes in the glass ball and the molding dies during heating: (a) temperature distribution, (b) temperature changes with time.

4.2. Deformation of Glass During Pressing

FEM simulation is a powerful tool to visualize glass deformation in GMP process. In a few previous studies (Walters et al., 2000; Yi and Jain, 2005; Chang et al., 2007), the numerical model of glass has been built based on elastic-plastic or viscoelasitic models. However, in most cases the thermally induced material property changes of glass were not taken into account. For the fact that the viscosity of glass changes greatly above the transition temperature (Jain et al., 2005), material deformation in the pressing stage is strongly dependent on temperature. In previous studies of the present authors (Zhou et al., 2007; Zhou, et al., 2008; Yan et al., 2008), we investigated the fundamental thermal and mechanical properties of glass in the GMP process at the molding temperature by FEM simulation and experiments with flat molds.

In the present study, the Burgers model was used to describe the deformation during pressing (Zhou et al., 2008). The simulation was done at a temperature of 570°C at a constant pressing rate of 6 mm/min. Figure 12 shows stress and strain distributions within the glass lens after the molds have been closed.



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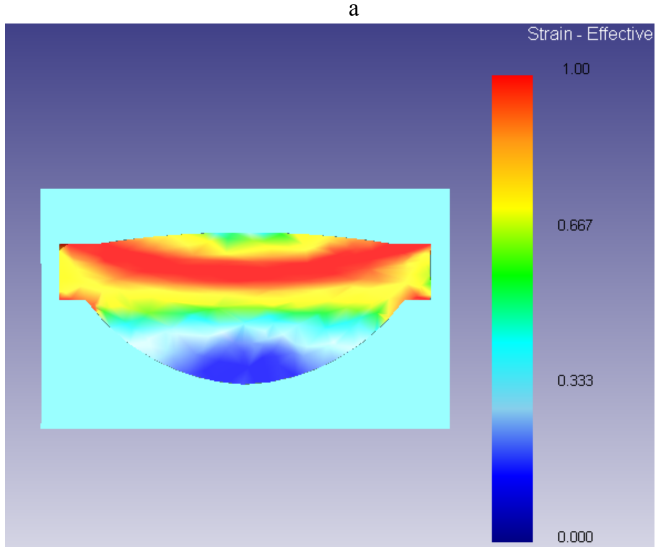

b

Figure 12. Distributions of (a) stress and (b) strain in the molded glass lens at a molding temperature of 570°C.

From Figure 12 (a), it can be seen that during press, stress at the outer region of the lens is higher than that in the center. The low stress region is located in the bottom of the lens. The stress distribution strongly affects the optical property of the lens as numerically studied by Doyle et al (2002), and influences the lens shape accuracy as pointed out by Jain and Yi (2006). Therefore, the residual stress must be completely relaxed in the annealing stage. In rapid molding cycles, however, the residual stress in the lens may not be completely released, and may cause form errors which must be get rid of by shape compensation of the molding dies. From Figure 12(b), we can see that the highest strain is located in a bow-shaped region at the upper half of the lens, while the strain in the lower half is almost zero. Therefore, we can deduce that most of the glass material flows near the upper molding die until forming an aspherical lens. It is this unbalance in stress/strain distribution between the upper side and the lower side that caused the differences in deformation and surface damages of the molding dies, as mentioned in Section 3.

5. Discussion

GMP is an "invisible" process, where the deformation mechanism of glass at a high temperature has not been completely clarified. A few important aspects in the GMP process, such as material flow and stress/strain distribution in glass, are strongly dependent on the geometries of the molding dies and the glass preforms, as well as other conditions like molding temperature and pressing rate. Generally speaking, a high molding temperature is helpful to obtain a low pressing force and low stress concentration during glass pressing. However, a high temperature will reduce the service life of the molding dies. The rapid changes in temperature induce thermal expansion during heating and shrinkage during cooling, thus cause thermal shocks to the molding dies. Chemical reactions among glass, molding dies and die coatings may also be accelerated at a high temperature. On the other hand, when molding at a low temperature, a high pressing load is needed to yield glass flow, which may lead to shape distortion of the mold or damages to the coating layers. Therefore, a proper molding temperature is essential for GMP, and FEM simulation is a useful tool for predicting the minimum heating time to achieve uniform temperature distribution.

The geometry of the glass preform is another important issue in the GMP of aspherical lenses. In the present study, spherical glass preforms were used, the radius of which was remarkably smaller than the curvature radius of the molding dies. The radius difference between the molding die and the glass ball was significantly bigger for surface ASP1 in comparison with surface ASP2. It is this curvature radius difference that caused the differences in material flow and stress/strain distribution, and in turn, the durability of molding dies between the upper side and the lower side. Therefore, in order to get rid of this effect, glass preforms with a similar curvature radius to the molding dies are preferable. The optimization of the preform geometry may also need the help of FEM simulation, which is a future task of this work. The effects of molding conditions on optical properties of the molded lens, such as refractive index and birefringence distribution, are also under investigation.

CONCLUSIONS

The GMP process of aspherical lenses has been investigated through both simulation and experimental approaches. The following conclusions have been obtained.

1. Shape transferability for aspherical glass lenses in GMP process has been evaluated. Under the present experimental conditions, aspherical lenses, having submicron level form accuracy and ten nanometer level surface roughness, have been successfully fabricated.
2. Microscopic deformation of the molding dies were measured after GMP experiments. When using a spherical glass preform, the upper molding die having a bigger curvature radius is less durable in repetitive GMP tests in terms of form error and surface damage.
3. The temperature distribution and temperature changes in glass have been visualized by FEM simulation. The minimum heating time for achieving a uniform temperature distribution in glass can also be predicted by FEM simulation.
4. Stress/strain distribution within glass lens in the pressing stage has been simulated. Stress concentration occurs at the outer region of the lens. A high strain takes place near the upper molding die where the curvature difference between the glass preform and the die surface is big.

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