Numerical Simulation of Glass molding Process for Large Diameter Aspherical Glass Lens

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Abstract. In order to obtain the approximate precision molding process parameters of large diameter aspheric glass lens and predict the residual stress of the lens, a thermodynamic coupling model was established by using FEM software—ABAQUS. Meanwhile, we obtained the filling ratios of large diameter aspheric glass lens at different temperatures and pressures. Furthermore, the work analyzed the different process parameters effecting distribution of residual stress. In the large aspherical glass molding process, the annealing rate has a great influence on residual stress, and the molding velocity and pressure effect the stress inside glass in the forming stage. The more important, mathematical optimization of the temperature of molding and annealing for different glasses can improve the production efficiency. It is expected that the simulation of large diameter aspherical glass lens is a meaningful way to investigate the isothermal glass molding process.

1. Introduction

There are more and more demands for aspherical optical elements, including telescope, cameras, projectors etc. The conventional glass lens fabricating process involves complicated procedure of grinding, lapping and polishing which is time-consuming and difficult for the worker. Furthermore, the resin rapid injection technique has a high efficiency and low costs, but the physical performance of lens of the injection is poorer than that of glass lens.

Precision glass molding, called non-grinding briquetting method, is a promising manufacturing technology that can produce high precision optical components, such as aspherical lens, micro-lens array and Fresnel Lens[1,2].

There are many factors that affect the optical quality of the glass lens, such as the temperature gradient of the glass lens during the cooling stage[3], thermal expansion coefficient of the glass and molds[4], internal stress of the molded glass lens[5], characteristic of the glass material[6]and the molding parameters[7]. It is a effective way to optimize the processing parameters by using the FEM software.

Jain and Yi et al.[8-13] studied the high temperature viscosity and temperature dependence of elastic modulus of glass by using a commercial molding machine to finish cylindrical compression test as well as the technique of Brillouin light-scattering to measure, respectively. The obtained data that using cylindrical compression test to measure are input to the FEM software to simulate the molding process. The structural relaxation and stress relaxation phenomenon of the glass are researched by compression simulations and experiment. In order to study residual stress inside lens during the cooling stage, the birefringence method assisted by the FEM is used to optimize the molding process.
Zhou et al.[14-16] simulated cylindrical glass compression at different temperature by viscoelastic models (Maxwell, Kelvin and Burger) to obtain the viscoelastic parameters. Moreover, based on experimental measurement of the glass, thermo-mechanical coupling model is performed to study heat transfer phenomenon and shape transferability of the glass.

The work simulated the whole molding process of large diameter aspherical glass lens. Moreover, with the optimal molding process parameters were required, we analyzed the stress change and stress distribution of the molding process were analyzed. The suitable molding process parameters were obtained to guide the practice of production.

2. The simulation of large diamater aspherical glass lenses

As shown in Fig.1(a)-(d), the whole molding process consists of four stages: heating, pressing, annealing and cooling. In the large aspherical lens molding process, a well-defined glass sample was firstly loaded into a precision mold assembly, and then heated up to the above transition temperature in the anaerobic conditions. Furthermore, a special pressure was given to the precision mold, with the glass copied into designed shape (see Fig.1(e)). Finally, the lens cooled to room temperature and removed out of mold assembly.

In this paper, numerical simulation of the whole molding of a big diameter plano-convex aspheric lens were conducted using the finite element simulation software ABAQUS, which has a powerful non-linear function and accurate calculation for the analysis of large deformation. The model is axisymmetric two-dimensional thermodynamic or thermal-displacement.

![Figure 1](image.png)

**Figure 1.** The whole molding process (a) heating (b) pressing (c) annealing (d) cooling and taking (e) the molded shape of aspherical lens

The curve equation of aspherical lens is denoted as:

$$Z = \frac{-x^2}{R + \sqrt{1 - (1 + K)x^2 / R^2}}$$  \hspace{1cm} (1)

The characteristics of glass material have a great dependence with temperature, and the glass under high temperature conditions is viscoelastic. The viscosity of OHARA optical glass LBAL-35 is in 10^{13.5} Pa.s when the glass is at the strain point (497°C). The glass LBAL-35’s viscosity lies in 10^{12} Pa.s when the temperature of glass is at annealing point (520°C).

When the viscosity of the glass lies between 10^{8.5} and 10^{6.6} Pa.s, the glass is easily compressed to form a better shape without producing prodigious stress [17]. Importantly, the formed lens does not appear with gas pocket. The quality of lens forming quality is relatively good in the viscosity range. In the viscosity of 10^{13} to 10^{9} Pa.s, it can be expressed by Arrhenius equation as follow.

$$\eta = A_\eta \exp(E_\eta / RT)$$  \hspace{1cm} (2)

Where $A_\eta$ is a constant; $E_\eta / RT$ the ratio of activation energy to gas constant.

In the paper, the glass molding process was thought as general Maxwell model to understand the relationship between stress and strain, and representing the modulus of hook spring and viscosity of dashpot with Newtonian fluid[8,9]. The time-dependent response of Maxwell model can be expressed as:

$$\sigma(t) = \int_0^t G(t - \tau) \frac{d\varepsilon(t)}{d\tau} d\tau + G(t)\varepsilon(0)$$  \hspace{1cm} (3)

The glass can be treated as a thermally rhetorical simplicity (TRS) model using the Williams–Landel–Ferry (WLF) equation. The general function is denoted as:
When the temperature of glass changes abruptly in transition region, the volume change of glass is slower than the external temperature change, and the structural relaxation phenomenon occurs. The structural relaxation equation is as follows [6]

\[ M_v(t) = \frac{T_r(t) - T_x}{T_i - T_x} \]  

The molds are made of tungsten carbide (WC), with an excellent performance and low expansion at high temperature. Glass is a viscoelastic material at high temperatures. Table 1 shows the thermal-mechanical properties of Tungsten carbide and glass L-BAL35[18].

| Parameter                          | LBAL-35    | WC         | Stress relaxation |
|------------------------------------|------------|------------|-------------------|
| Elastic Modulus (Mpa)              | 100800     | 570000     | g_i               |
| Poisson ratio                      | 0.247      | 0.2        | t_i               |
| Density (kg/m^3)                   | 2820       | 14650      | 0.363             |
| Specific heat (J/kg.K)             | 858        | 314        | 0.028             |
| Thermal expansion                  | ---        | 4.9×10^{-6} | 0.57              |
| Transition temperature(℃)          | 527        | -----      | Structural relaxation |
| Thermal conductivity (W/m².K)       | 1.126      | 63         | g_i               |
|                                    |            |            | 0.45              |
|                                    |            |            | 0.36              |
|                                    |            |            | 0.04              |
|                                    |            |            | 0.149             |

3. The analysis of simulation results

The processing parameters were compared with different values of molded lenses for each simulation, showing that how the volume and profile of the lenses change to process parameters. To study the effect of molding temperature on the stress and geometry of formed lens, the molding force was set to 10MPa; the keep pressure 1MPa, and the cooling rate 0.15 °C/s; while the temperature varied from 550 to 600°C.

Fig.2 shows the residual stress distribution predicted by FEM at six different temperatures. It can be found that the maximum stress appear at edge and center of lens. Fig.2(a) shows the glass cannot fill the cavity completely, and the edge of lens appears large stress. Higher stress may cause lens rupture easily. Due to the large dimension and low molding temperature, the molded lens of Fig.2(a) was not successful forming. From Fig.2(b) to 2(f) show that residual stress of molded glass lens decreases as the molding temperature rises.

**Figure2.** Comparison of residual stresses distribution at different molding temperature

(a)550°C (b)560°C (c)570°C (d)580°C (e)590°C (f)600°C

As shown in Fig. 3, due to the geometry and flow ability of glass, the glass is not fully filled in the cavity when the molding temperature was at 560°C, but when the temperature is at 570°C, the glass can form completely. With the increased temperature increasing, the filling ratio increases.
The residual stress of glass lens leads to the refractive index, which affects imaging quality. With the increased temperature, the maximum residual stress of lens decreases obviously. The higher temperature leads to the better flow ability and lower viscosity of glass. The stress relaxation is faster at higher temperature.

To investigate the effect of molding pressure on the stress in lens, the molding temperature was set to 580°C constantly; the cooling rate was 0.20°C/s; the keeping pressure was 1MPa; the molding pressure were changed from 5 to 20MPa. The simulation results of residual stress at different molding pressures indicated the small relationship between molding pressure and residual stress (see Fig.4(a)). The effect of the pressure on the maximum residual stress is very small. But the molding pressure has a great influence on the stress of lens during forming stage. Fig.4(b) shows the stress of molded glass lens increases with the increasing molding velocity. Meanwhile, to study the influence of the keeping pressure on the residual stress in lens, the molding temperature was set at 580°C; the cooling rate was 0.20 °C/s; and the molding pressure was 5MPa, while the keeping pressures were set at 0.5, 1 and 1.5MPa. The relationship between the keeping pressure and the maximum residual is shown in Fig.4(c).

During the cooling stage, the residual stress in lens develops due to change of temperature. Since the thermal conductivity of glass is small, the internal glass has a temperature gradient during cooling stage. If the cooling rate is too fast, the temperature gradient of glass is bigger. Fig.4(d) shows the temperature gradient and stress of glass at different cooling rate. When the molding temperature is 580°C, the pressure is 5MPa, with the holding pressure of 0.5MPa. The residual stress of glass begins to largen when the glass shrinks due to tensile stress. The residual stress inside lens causes the lens variation of refractive index and residual birefringence, which degrades its optical properties[19]. In the transition region, the bigger cooling rate leads to the larger stress.

Fig.4(e) shows the maximum stress at four different molding velocities. The maximum stress occurs at the center of lens. With the increase of molding velocity, the maximum stress in lens increases. Higher stress makes lens rupture easily at the zone, so the molding velocity cannot be too quick. Fig.4(f) shows the maximum stress in glass during the cooling stage. The molding velocities have a little influence on residual stress inside lens.

![Figure 3](image3.png)  
**Figure 3.** The filling ratio of glass (a)The filling ratio of 560°C (b)The filled ratio of 570°C

![Figure 4](image4.png)  
**Figure 4.** (a) Residual stress and molding pressure (b) The forming stress and molding pressure (c) Residual stress and keeping pressure (d) Residual stress and annealing rate (e) The forming stress and molding velocity (f) Residual stress and molding velocity
Fig.5(a) shows the five different nodes in the forming lens are extracted as well as the curve of stress change. When the glass is in the forming stage, the internal stress is very small. During the annealing stage, the stress in lens increases rapidly until approaching to a certain temperature (the strain point of glass). In the rapid cooling stage, the internal stress in lens increases a little before temperature gets to a certain temperature. The maximum residual stress at the edge is about 3.3MPa. Though the molding pressures have small influence on residual stress in lens, it is a key factor to affect the profile accuracy (see Fig.5(b)).

Figure 5. (a) The stress change of five different nodes (b) The relationship between profile deviation and pressure

4. Conclusion

In this paper, the whole molding process of large diameter aspheric lens was analyzed. The conclusions were as follow:

1. The higher the molding temperature, the smaller the residual stress. The molding temperature is too low to fill the mold cavity. If the molding temperature is smaller than that strain point, the stress in lens will be enormous and the lens will break. For the big diameter aspheric lens of LBAL-35, the molding temperature of 580°C would be more suitable.

2. The effect of molding pressure and keeping pressure on the residual stress in lens is very small, but it has a great influence on stress in the glass during the forming stage. With the molding pressure increasing, the residual stress of molded glass lens changes little. However, the molding pressure has a great impact on the profile of the lens. In order to keep the quality of large diameter aspheric lens, the value of molding and keeping pressures are 10MPa and 1MPa respectively.

3. The annealing rate is the key factor to determine the residual stress inside lens. The slower annealing rate, the smaller the residual stress. If the residual is too large, the lens maybe broken and occur residual birefringence which effect the optical performance. In order to improve the molding efficiency and reduce the residual stress inside the molded glass lens, the annealing rate was determined to be 0.2 °C/s.

4. The molding velocity is not master factor on the residual stress, but it have a great influence on stress in the glass during the forming stage. The maximum stress increases with the increasing of molding velocity. The whole molding process, molding velocity of 0.1mm/s will be better for forming of large diameter aspheric lens.

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