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Numerical Simulation of Glass Molding

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Abstract. Glass molding is a mass fabrication method for precision glass lenses. Residual stresses induced during cooling process were inevitable reserved in molded glass lenses, and can cause the quality deterioration. Control of the cooling rate is one of the methods to keep residual stresses at a required level. In this research, glass molding of a blank glass cylinder and an aspherical glass lens were simulated by Finite Element Method. The residual stresses were simulated. Then the residual stresses under different cooling rates were also simulated to provide a proper cooling rate for glass molding.

Introduction

Glass molding is a thermal forming process and an ideal fabrication method for precision glass lenses because of its high volume and net-shape fabrication capability [1, 2]. A heated glass blank is pressed by a pair of optically polished molds to create desired geometries in glass molding process. The pressed glass is then maintained at the molding temperature for a preset time in order to release the stresses induced by pressing. Then cooling process is followed. And the cooling rate is controlled to keep residual stresses and thermal shrinkage at or below the required levels.

Residual stresses are important criteria for evaluating optical glasses [3, 4]. Residual stresses were generated during cooling and eventually frozen in the molded lenses when the glass completely solidified. Residual stresses can induce refractive index variation, resulting unwanted light path deviation as well as intensity change that may cause image quality deterioration.

In this research, Finite element method (FEM) was employed to study the glass molding process [5-10]. A glass cylinder under heat treatment and a glass molded aspherical glass lens were studied. Residual stresses were calculated by the numerical simulation. Then the impact of cooling rates of glass molding of aspherical glass lenses was also studied.

Numerical Simulation

Numerical simulations of the glass molding of BK7 glass were performed by using a commercial FEM software MSC/MARC. Two different samples: a glass cylinder and an aspherical glass lens, were studied. Taking advantage of the rotational symmetrical geometry of the samples and experiment settings, two dimensional (2D) axisymmetric models were established. A four-node isoparametric quadrilateral element was employed to mesh the samples.

FEM Model of a Glass Cylinder. The glass cylinder, with a diameter of 7 mm, is 7 mm high. In experiment, the glass cylinder was placed on a ceramic plane with 4 mm height and 15 mm diameter. The glass cylinder was meshed into 3,500 elements, and the lower ceramic supporter was meshed into 381 elements, shown in Fig. 1(a).

The time-temperature history of the heat treatment process is plotted in Fig. 1(b). First, the glass cylinder and ceramic plane were heated to the temperature of 490 ℃ at a rate of 7.68 ℃/min and kept for 30 minutes. Then the temperature was increased to 680 ℃ at a rate of 3.17 ℃/min and kept for 30 minutes. Then cooling was performed at a rate of 11.17 ℃/min to room temperature.

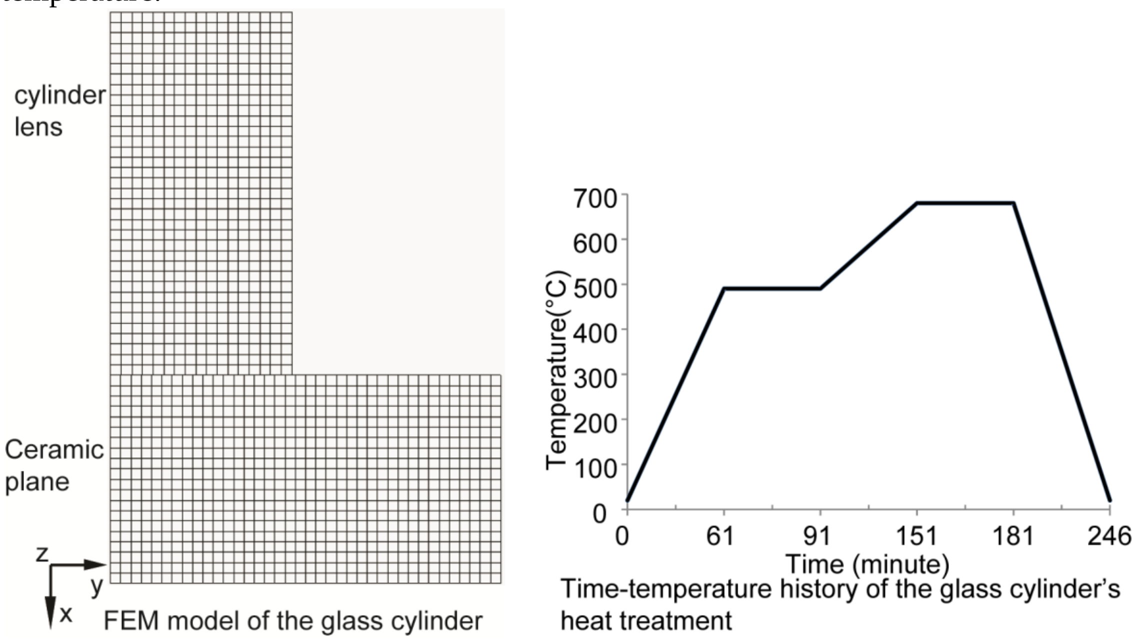

Figure 1. (a) FEM model of the glass cylinder, (b) Time-temperature history of the glass cylinder's heat treatment.

FEM Model of a Aspherical Glass Lens. The design of the aspherical glass lens is shown in Fig. 2. The aspherical surface is described by the flowing equation:

$$Z = \frac{-Cx^2}{1+\sqrt{1-(1+K)C^2x^2}} \tag{1}$$

Where x is the coordinate of the optical surface, K (4.3666) is the conic constant. C is surface curvature ($C = 1/R_1$, R_1 is the vertex radius of the aspherical surface).

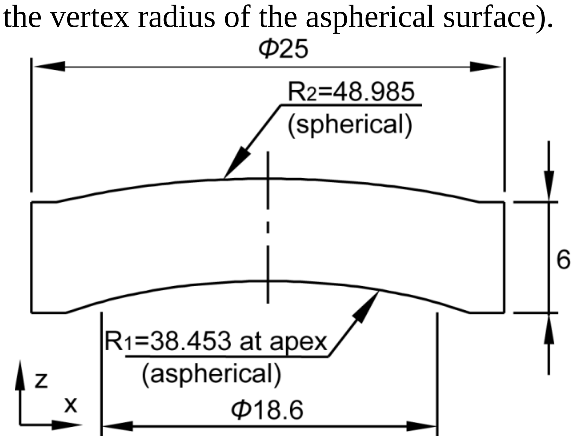

Figure 2. Schematic of aspherical lens (unit: mm).

The glass blank was meshed into 3,500 elements. Upper and lower molds were meshed into 381 and 365 elements, respectively. The deformed aspherical lens at the end of molding is shown in Fig. 3 (a). The material for upper and lower molds is Tungsten carbide (WC, Fujilloy J05).

The simulation was conducted in two steps: (1) First, the glass blank and molds were heated to the molding temperature of 684 ℃. When the glass blank reached its steady–state temperature distribution, molding was carried out. The lower mold moved up with a speed of 0.145 mm/s until the two molds made contact. Then temperature was maintained until stresses in glass from pressing were completely released. (2) Second, two steps cooling were conducted: cooled to 520 ℃ at an initial rate of 0.8 ℃/s and then to 200 ℃ at a rate of 1.6 ℃/s. Once the temperature was reduced to around 200 ℃, the lens was released and cooled to room temperature by natural cooling. Fig. 3 (b) shows the time-temperature history of the glass molding process.

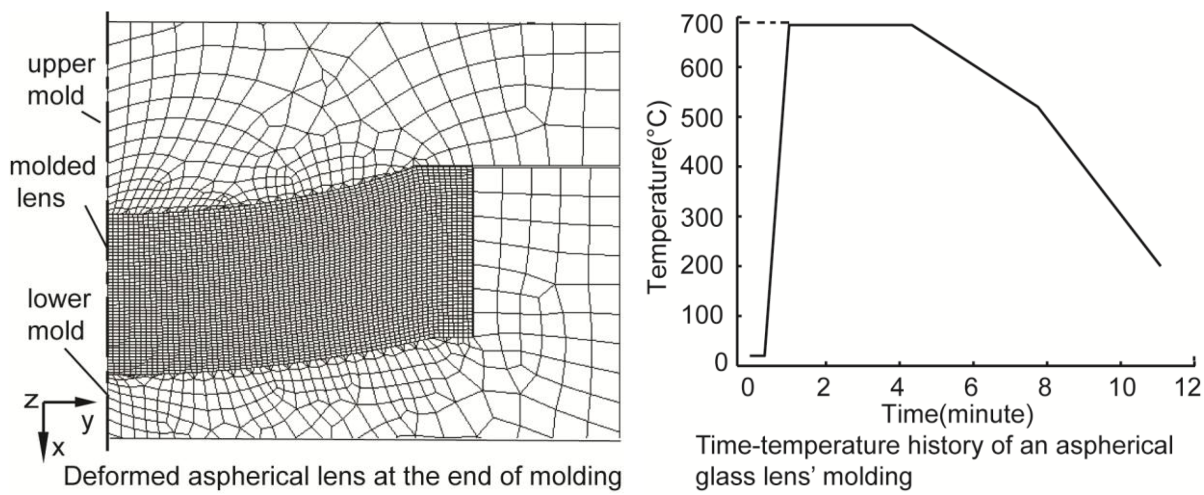

Figure 3. (a) Deformed aspherical lens at the end of molding, (b)Time-temperature history of an aspherical glass lens' molding.

The material properties of molds and lenses are summarized in Table 1. The parameters used in Tool-Narayanaswamy-Moynihan (TNM) model [7-9] during the cooling are summarized in Table 2.

Table 1 Mechanical and thermal properties of BK7 glass [10], ceramic [11] and Tungsten carbide [12]

Material Properties	BK7	ceramic	Tungsten carbide
Elastic modulus, E [MPa]	82,500	66900	570,000
Poisson's ratio, ν	0.206	0.29	0.22
Density, ρ [kg/m^3]	2,510	2520	14,650
Thermal conductivity, κ_c [W/m ℃]	1.1	1.46	63
Specific heat, C_p [J/kg ℃]	858	790	314
Transition temperature, T_g [℃]	557	--	
Solid coefficient of thermal expansion, α_g [/℃]	5.6×10^{-6}	1.26×10^{-5}	4.9×10^{-6}
Liquid coefficient of thermal expansion, α_l [/℃]	1.68×10^{-5}	--	--
Viscosity, η [MPa-sec] (at 685 ℃)	60	--	--

Table 2 Structural relaxation parameters [10]

Material properties	Value
Reference temperature, T_{ref} [℃]	685
Activation energy/gas constant, H/R [K]	47,750
Fraction parameter, μ	0.45
Weighting factor, w_g	1
Structural relaxation time, τ_v [sec] (at 685 ℃)	0.019
Stress relaxation time, τ_s [sec] at 685 ℃	0.0018

Results and Discussion

Simulated Residual Stresses. Fig. 4 shows the simulated distributions of residual stresses inside the glass cylinder in cylindrical coordinates. The stress distribution displays half of the cross section of the cylinder viewed in the normal direction. In these stress distribution figures, negative value means compressive stress and positive value means tensile stress.

Fig. 5 shows the simulated residual stresses distribution inside a molded aspherical glass lens under two-steps cooling in cylindrical coordinates. The stress distribution displays half of the cross section of the aspherical lens viewed in the normal direction. In Fig. 5, positive value means tensile stress, and negative value means compressive stress.

Based on the simulation results shown in Fig. 4 and 5, stresses σ_z and τ_{rz} show larger magnitude at the edge compared to the stresses in center. For σ_r and σ_θ, the lens is mainly under tensile stress in the center and compressive stress at the top and bottom surfaces. During the cooling, the center of the glass is cooled slower than the surfaces. Because that the glass lost heat from its surfaces due to conduction, convection, and radiation. Therefore, the center part will be under tensile stress as compared to the surface.

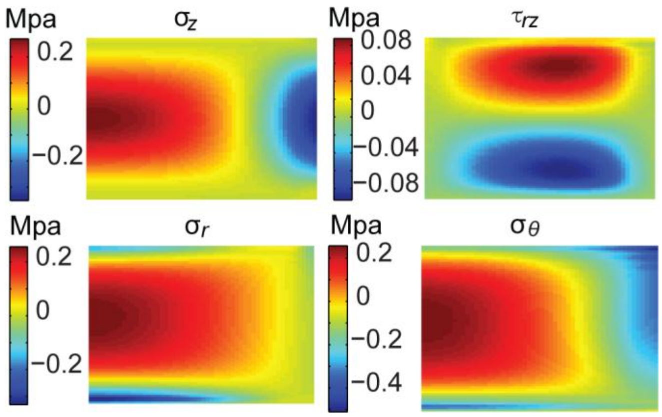

Figure 4. Simulated residual stresses distribution in a cylinder glass lens using structural relaxation model in cylindrical coordinates: axial stress σ_z, shear stress τ_{rz}, radial stress σ_r, circumferential stress σ_θ.

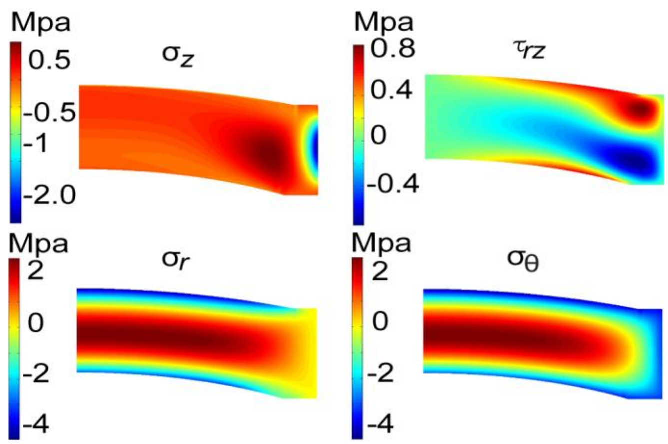

Figure 5. Simulated residual stresses distribution in a molded aspherical glass lens using structural relaxation model in cylindrical coordinates: axial stress σ_z, shear stress τ_{rz}, radial stress σ_r, circumferential stress σ_θ, (units:MPa).

Cooling Rate. Cooling rate is a key method to control the residual stresses. In general, higher cooling rate induces larger residual stresses. Fig. 6(a) shows the equivalent von Mises stress distribution at cooling rate of 0.43 ℃/s. And Fig. 6(b) shows the maximum von Mises stresses inside the glass lenses under different cooling rates: 0.00056 ℃/s, 0.03 ℃/s, 0.13 ℃/s, 0.43 ℃/s, 1 ℃/s, 2 ℃/s, 3 ℃/s, 5 ℃/s. Based on the results shown in Fig. 6, smaller residual stress was found associated with lower cooling rate and the residual stress appears to be roughly proportionally related to the cooling rate.

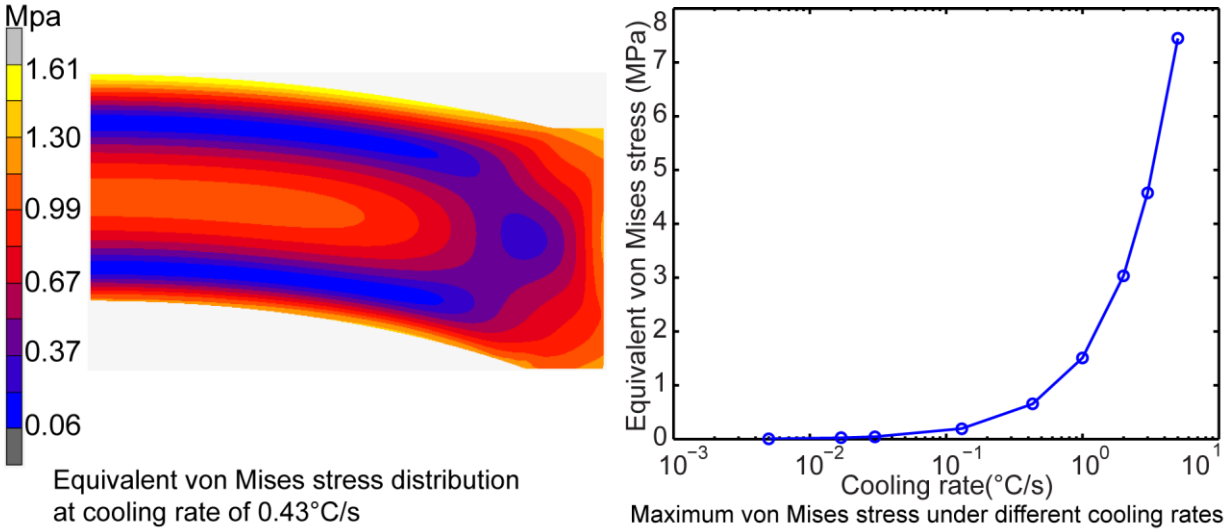

Figure 6. (a) Equivalent von Mises stress distribution at cooling rate of 0.43 ℃/s , (b) Maximum von Mises stress under different cooling rate.

Conclusions

By using FEM with a structural relaxation model, residual stresses were simulated. The simulation results show the existence and distribution of the residual stresses in molded glass lenses. For BK7 glass material, residual stresses become smaller at the lower cooling rate. However, for massive production, the cooling rate cannot be as low as possible. Therefore, in glass molding, the cooling rate is a trade off between residual stresses control and production rate.

Acknowledgments

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