

Reducing Refractive Index Variations in Compression Molded Lenses by Annealing

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ABSTRACT

Compression molding of glass optics is gradually becoming a viable fabrication technique for high precision optical lenses. However, refractive index variation was observed in compression molded glass lenses, which would contribute to image quality degradation. In this research, annealing experiments were applied to control the refractive index variation in molded glass lenses. The refractive index variations pre and post annealing experiment in molded lenses were measured by an experiment setup based on Mach-Zehnder interferometer. The experimental results showed that the refractive index variation can be controlled providing that a proper cooling process is applied during cooling.

Keywords: Refractive Index; Mach-Zehnder Interferometer; Optical; Annealing; Compression Molding

1. Introduction

Compression molding is a thermal forming process for precision glass optics [1, 2]. However, refractive index variation was induced in glass during cooling when the glass material went through its glass transition region [3-5]. On the other hand, the variation of refractive index in a molded glass lens will introduce distortion to the wave-front passing through the glass lens, which leads to image quality degradation. In order to ensure a proper optical performance of thermally formed glass lens, it is important to reduce the degree of refractive index variation in the molded glass lens.

Annealing has been studied for improving the quality of glass [6-9]. Through annealing, glass can achieve homogeneous refractive index. Annealing of the compression molding of glass lenses was investigated in this research. In order to identify the effects of annealing on refractive index variations, computer tomography method was employed to measure the refractive index distribution in the glass lenses. The measurement was conducted by using an optical setup based on Mach-Zehnder interferometer [4, 10]. By comparing experimental results of the glass lens pre and post annealing, the results showed that refractive index variation was reduced.

2. Design of Experiments

Glass lenses studied in this research were molded in a commercial glass molding machine (GMP-211V). Ther-

mal forming was carried out at 684 °C. After forming, the temperature was maintained until stresses in glass caused by pressing were completely released. Two steps cooling process was followed: the glass lens was cooled to 520 °C at a rate of 0.8 °C/s and then to 200 °C at a rate of 1.6 °C/s. When the glass lens was cooled to 200 °C, the lens was taken out of the molding machine and cooled naturally at room temperature. **Figure 1** is the illustration of the glass lens. BK7 was chosen as the glass material. The properties of BK7 are shown in **Table 1**.

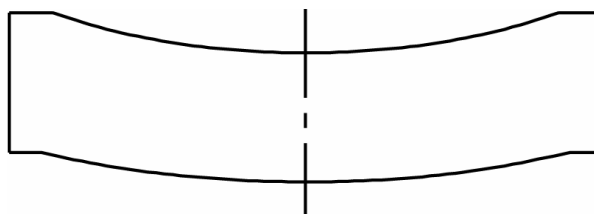


Figure 1. Illustration of the compression molded glass lens.

Table 1. Properties of BK7 glass [11].

Material Properties	BK7
Elastic modulus, E [MPa]	82,500
Poisson's ratio, ν	0.206
Transition temperature, T_g [°C]	557
Refractive index, n	1.5148

2.1. Refractive Index Measurement

Figure 2 shows a schematic of the experiment setup used to measure the refractive index in glass lenses. To avoid refraction, tested lens was placed in a box filled with refractive index matching liquid of BK7. He-Ne laser was used as the light source. In the experiment setup, beam splitter 1 divides the laser beam into two. One is used as reference beam, the other one goes through the lens under test. These two beams interfere with each other at beam splitter 2. Fringe pattern carried with refractive index distribution in the lens was captured by a CCD camera.

Figure 3 is the fringe pattern of the molded glass lens at one direction. The fringe pattern was analyzed by a 2D Fourier transform technique [12] and a least-square phase unwrapping method [13] for unwrapped phase. Because of the axisymmetric property of the glass lens, it is sufficient to reconstruct the refractive index distribution in the glass lens through only one fringe pattern. With the unwrapped phase, 3 dimensional (3D) refractive index distribution of the glass lens relative to the refractive index of matching liquid can be reconstructed using the filtered back-projection method [14].

$$n(x, y, z) = \frac{p(x, y, z)\lambda}{2\pi d} \tag{1}$$

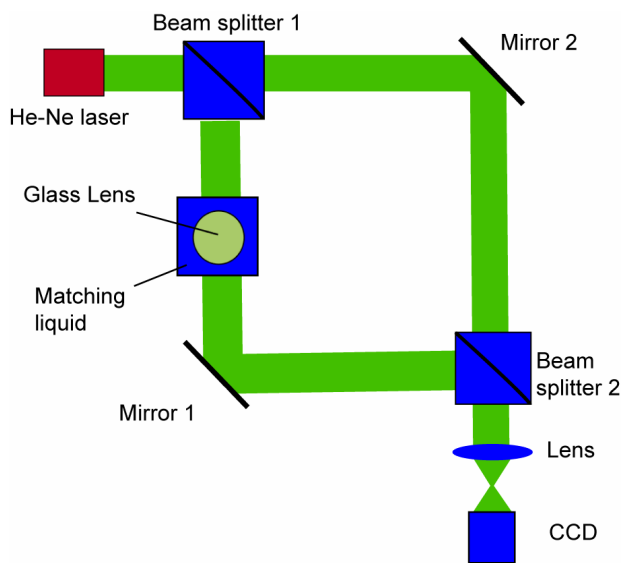


Figure 2. Schematic of the experiment setup for refractive index measurement.

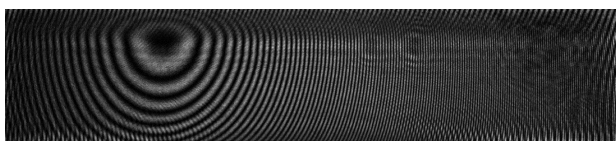


Figure 3. Fringe pattern of the compression molded glass lens before annealing at one direction.

where, $p(x,y,z)$ is the reconstructed phase distribution at point (x,y,z) , d is the pixel size in the test lens of the interferogram. The reconstructed refractive index in the middle section of the compression molded lens relative to the matching liquid is shown in Figure 4.

2.2. Annealing

Annealing experiments were conducted in a commercial furnace (Grieve, BF-12128-HT). Figure 5 illustrates the time-temperature history of the annealing experiments.

At first, the molded glass lens was heated to 560 °C, slightly higher than the glass’s transition temperature, and soaked for 10 minutes. After soaking, the glass lens was cooled to 500 °C at a rate of 1 °C/min. Then the furnace was turned off. The maximum cooling rate was about 1.29 °C/min after turning off the furnace, because there was no force cooling system. Once the temperature decreased to 150 °C, the glass lens was taken out of the furnace and cooled to room temperature naturally. In the experiments, the glass lens under thermal treatment was placed on a ceramic plate in the furnace with the concave side facing down.

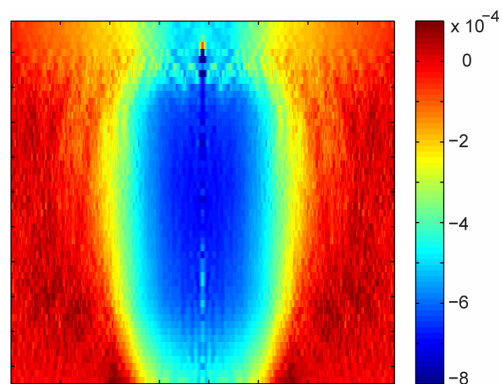


Figure 4. Refractive index distribution of middle section of the molded glass lens relative to the matching liquid.

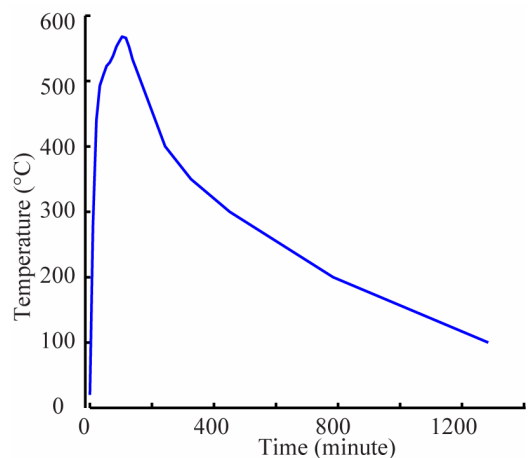


Figure 5. Time-temperature history of annealing.

3. Results and Discussion

Refractive index variations of the molded glass lens pre and post annealing were both measured. **Figure 6** shows the average refractive index variations in the middle section of the glass lens along radial direction pre and post annealing experiment. The maximum refractive index variation was reduced about 4×10^{-4} which was more than half of the maximum variation before annealing.

The relations between refractive index n and density ρ of the glass material can be described by Lorentz–Lorenz equation [15]:

$$\frac{n^2 - 1}{n^2 + 2} = \frac{4\pi N_A \rho \alpha}{3 M} \quad (2)$$

where N_A is the Avogadro number, α is the mean polarization and M is the molar weight. Differentiating Equation (2), the relations between refractive index change dn and density change $d\rho$ can be obtained by:

$$\frac{dn}{d\rho} = \frac{(n^2 - 1)(n^2 + 2)}{6n\rho} \quad (3)$$

Substituting volume for the density, refractive index change Δn can be calculated from the volume change ΔV and the original volume V_0 :

$$\Delta n = \frac{(n^2 - 1)(n^2 + 2)}{6n} \left(\frac{-\Delta V}{V_0 + \Delta V} \right) \quad (4)$$

After annealing, residual stresses inside the glass lens were released. Values of the coefficient of thermal expansion (CTE) of the glass lens were different at different cooling rates due to the behavior of structural relaxation when the glass went through its glass transition region. As such, the volume change was imported by both stresses relaxation and the changes of CTE [16]:

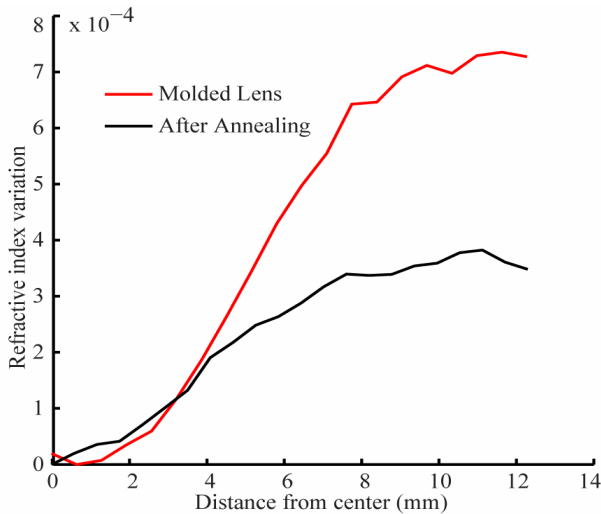


Figure 6. Comparison of the refractive index variations in a molded glass lens pre and post annealing.

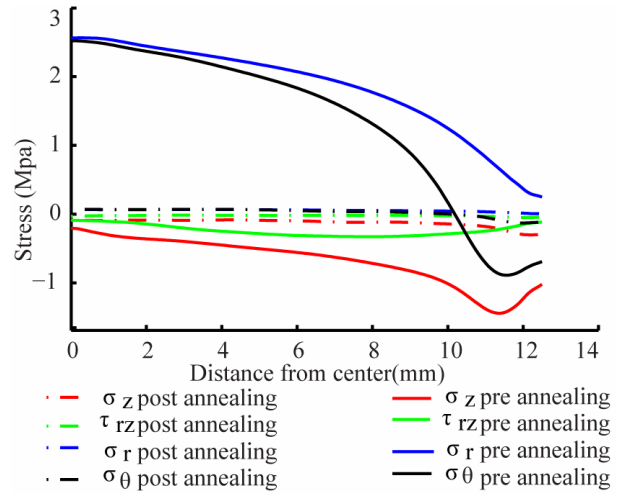


Figure 7. Residual stresses in the glass lens pre and post annealing in cylindrical coordinate.

$$\Delta V = V_o [3\beta_h - 3\beta_c] + V_o \left[\frac{1-2\nu}{E} (\sigma_{11} + \sigma_{22} + \sigma_{33}) \right] \quad (5)$$

where, $\beta_h = \int_{T_1}^{T_2} \alpha_h(T) dT$ and $\beta_c = \int_{T_2}^{T_1} \alpha_c(T) dT$.

α_h and α_c are CTE during heating and cooling, respectively. T_1 is room temperature and T_2 is soaking temperature. ν is Poisson's ratio and E is elastic modulus. σ_{11} , σ_{22} and σ_{33} are the changes of normal stresses along the axes.

The residual stresses inside the glass lens can be measured by a circular polariscope based on the property of birefringence when the glass is stressed [17-19]. The maximum residual stress in the compression molded glass lens was about 3 Mpa in cylindrical coordinate system. **Figure 7** shows residual stresses in the middle section of the glass lens pre and post annealing. The residual stresses were significantly released after annealing. Substituting the maximum changes of residual stresses, E and ν of the glass lens into Equation (5), the volume change induced by stress relaxation can be calculated, $\Delta V = 6 \times 10^{-5} V_o$. The maximum refractive index change induced by stresses relaxation was 4×10^{-5} .

Therefore the refractive index change was mainly caused by the changes of CTE. Basically, slower cooling rates yield lower volumes. In order to get lower refractive index variation, lower cooling rate should be applied.

4. Conclusions

Refractive index variations in compression molded glass lenses were investigated using an experiment setup. The refractive index variation was induced during the cooling due to structural relaxation of the glass material. Conse-

quently the refractive index variation in the glass lens can induce wave-front distortion. To control the refractive index variation, annealing of the glass lenses were conducted and the results demonstrated that the refractive index variations were significantly reduced. This research demonstrated that CTE played a critical role in process optimization for precision compression molded glass optics.

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