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Prediction of birefringence distribution for optical glass lens

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Abstract

Based on the viscoelastic theory, simulations were carried out on glass-lens forming processes. In addition, the birefringence distribution was calculated by stress-optic relation. First, to verify this viscoelastic simulation, FEM analysis was performed with the same material properties and process conditions used in the Bruckner's experiment. The result of the analysis was compared with Nadai's and Bruckner's results. The simulation results were in good agreement with the deformation and birefringence distribution in the experimental results. Finally, the FEM simulation technique was applied to actual LD-lens. The simulation was performed for each different cooling rate and the results were compared to each other in terms of birefringence. To investigate the effect of initial preform shape to optical property, a simulation was performed by using the new-proposed-shape-preform and the results were compared to the present shape in terms of birefringence.

Keywords: Viscoelasticity; Birefringence; Residual stress; Optical glass lens; Preform

1. Introduction

Following remarkable advancement in the IT and display industry and the high integration of mechanical components in the optical device, the glass product, which has demonstrated good optical performance and environmental reliability over plastics, is being used increasingly in the optic industry.

Due to no grinding or polishing process, the glass press forming method has advantage over conventional glass-forming method in terms of production rate and geometry of glass product [1].

In the press forming method, it is very important to avoid not only the occurrence of geometrical defects of final products, but also optical defects, such as birefringence. Birefringence is caused by optical anisotropy which originate from residual stress due to thermal history and deformation in glass-forming process [2]. Thus, it is also essential to predict the residual stress distribution of final product accurately.

Many works [3–5] have been published in the area of glass-forming simulation using computer-based analysis. Most of those researches have been performed using the viscous fluid model for conducting the simulation of conventional glass forming at high temperature. However, the glass press forming has been performed in relatively low temperature, and the proper constitutive equations are required for a given temperature range. Glass is known to show viscoelastic behavior between the transition temperature and softening temperature, where forming and the first cooling stage occur.

In this paper, simulations of glass-lens forming processes were carried out based on the viscoelastic theory and were performed for each process stage: heating, pressing and cooling. The FEM simulation technique was verified with experiment and then applied to actual lens with each different cooling rate. Simulation results were compared to each other case in terms of birefringence.

2. Numerical modeling

The glass material usually behaves as an elastic solid at low temperatures and as Newtonian liquids at extremely high temperature. On the other hand, the forming and the first cooling processes are generally performed at intermediate temperatures and under moderate stresses where the mechanical behavior can be described with a linear viscoelastic law [6]. The viscoelastic constitutive equations, which are deduced from the Boltzmann superposition principle, are given as follows:

$$\sigma(t) = \int_{-\infty}^{t} G(t-s)\dot{\varepsilon}(s)\,\mathrm{d}s \quad (1)$$

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where G is called the relaxation modulus. Through the normalization method, G are given as follows:

$$g(t) := \gamma_\infty + \sum_{i=1}^{N} \gamma_i \exp\left[\frac{-t}{\tau_i}\right] \tag{2}$$

Several contributions from literature show that most silica glasses are thermorheologically simple material over a range of temperatures near the glass transition [7]. So, the master curve is constructed by calculating the shift function.

Eq. (3) calculates the birefringence with stress distribution calculated from Eq. (1):

$$n_i - n_j = C(\sigma_i - \sigma_j) \quad (i, j = 1, 2, 3) \tag{3}$$

$n_i - n_j$ represents the difference of the orthogonal refractive index on the plane which is perpendicular to the light path. It represents the birefringence or path difference when the orthogonal rays pass through the unit thickness. $i - j$ represents the difference in stress that is applied along the direction of the refractive index. Here, birefringence is calculated by multiplying stress-optic coefficient C [2].

3. Viscoelastic simulation of glass in simple compression case

3.1. Introduction

Bruckner's simple compression experiment was achieved by MTS. The material property of soda-lime silica glass is shown in Table 1. The geometrical change of glass deformation at high temperature was observed and compared by Eq. (4) which is based on viscous flow model, and the birefringence was calculated experimentally from 1 mm-thick rectangular specimen observed by photo-elastic stress measurement [9]. In this case, the same glass was compressed by 30% with 0.02 mm/s and its cooling rate is 2 K/min:

$$r(t) = R\left(\frac{h_0}{h(t)}\right)^{0.75} \exp\left[\frac{3}{8}\left(\frac{z^2}{h_0^2} - \frac{z^2}{h(t)^2}\right)\right] \tag{4}$$

In this study, two-dimensional axisymmetric simulations of simple compression were carried out with ABAQUS. To verify the viscoelastic simulation, FEM analysis was performed with the same material properties and process conditions used in Bruckner's experiment [8,9]. The specimen used was characterized by a cylindrical glass with a radius of 5 mm and a height of 10 mm. The result of the analysis was compared with the theoretical results and experimental results in terms of geometry of deformation and distribution of birefringence.

Table 1
Material properties of soda-lime-silica glass

Mechanical property	Value	Thermal property	Value
Mass density	2.2 g/cm^3	Thermal expansion coefficient	8.3E−06 °C
Poison ratio	0.22	Heat capacity	840 J/Kg K
Elastic modulus	6.2E + 01 GPa	Thermal conductivity	1.7 W/m K

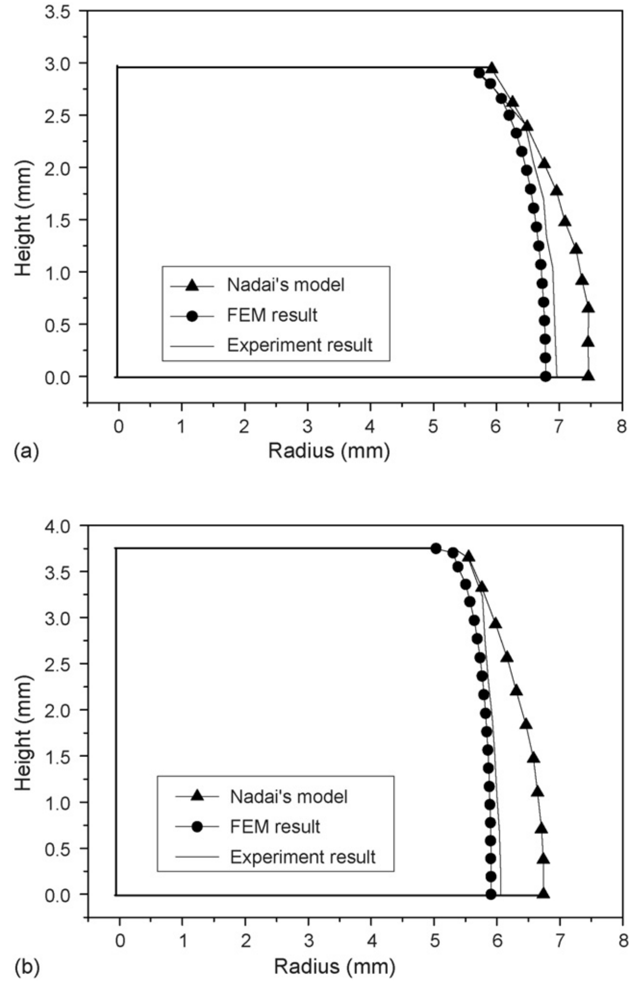

Fig. 1. Results of comparison data: (a) final shape after 42% reduction; (b) final shape after 35% reduction.

3.2. Verification of FEM analysis by comparing the geometry

After 25% reduction with 0.02 mm/s and 42% reduction with 0.06 mm/s at 600 °C (10^{10} Pa s), the results from the FEM analysis were compared with the Bruckner's experimental results and with Nadai equation, respectively.

Fig. 1(a and b) illustrate that the tendency of overall change obtained by FEM analysis is close to the tendency achieved through the experiment. Furthermore, it shows that it is more accurate than one calculated using Nadai's equation. It is because Nadai's theoretical equation is based on the viscous flow model and many assumptions. In case of 25% reduction of specimen, the maximum radius obtained by FEM analysis was 5.91 mm, 6.06 mm by the experiment, and 6.77 mm by Nadai's equation. Compared to the experimental results, the error by FEM analysis was calculated to as 2.5%, and error by Nadai's equation was calculated as 11.7%. Therefore, the FEM analysis produced more