Predictive Molding of Precision Glass Optics

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Abstract: Precision glass molding process is an attractive approach to manufacture small precision optics in large volume over traditional manufacturing techniques because of its advantages such as lower cost, faster time to market and being environment friendly. In this paper, we present a physics-based computational tool that predicts the final geometry of the glass element after molding process using the finite element method. Deformations of both glass and molds are considered at three different stages: heating, molding, and cooling. Details on identifying material parameters, modeling assumptions, and simplifications are discussed. The tool can be used to predict the final shape of the molded optic. This tool eventually can be used to design proper mold geometry that yields the correct shape of the final optical element, thereby eliminating the iterative procedure for designing the molds.

OCIS codes: (220.4610) Optical Design and Fabrication

1. Introduction

In the recent years, aspherical glass optics is widely chosen because of their superior optical properties, such as lesser aberration and lower birefringence, over plastics and spherical optics. The traditional lens manufacturing process is a complex and a multi-step process which requires a series of material removal processes [1, 2]. Although, there exist recent advances in optical fabrication techniques such as Magnetorehological finishing (MRF) and ion beam polishing, the complexity of these processes is such that the overall costs are high for medium to high volume production of asphere optics. Furthermore, the process incurs environmental issues because of the use of grinding fluids and polishing slurries.

A potential lower cost method and faster method to produce precision glass optics is by *compression molding process* [3]. In a lens molding process a glass gob is heated a temperature above the glass transition temperature and is pressed between two mold halves having the required asphere profile. The formed lens is then either cooled naturally or by forced convention to room temperature resulting in its final geometry. If this entire process is designed correctly, it can be easily adopted for high volume production of precision aspherical glass lenses.

Technology to produce glass optics via molding currently exists commercially, but it is not widely used. We believe the major difficulties encountered are quantifying and analyzing each process numerically that occur in the molding process and predicting the final shape of the glass element after molding. Another difficulty is to produce molds which will result in geometrically correct lens after the compression process. The reason for this is that, during the heating and cooling process, the dimensions of both the mold cavity and glass change due to thermal effects. Residual stresses exist during the cooling process due to the phenomena of structural relaxation which further affects the geometry of the molded glass. In addition, glass is an elastic solid at room temperature, but the primary deformation of glass occurs at high temperature (550 to 700 °C) where glass behaves as a viscoelastic material and hence the material properties change at the molding temperature. Due to the above challenges; a mold cavity that is geometrically perfect at room temperature will not produce a geometrically correct element; predicting the geometry of molded optics from the knowledge of mold geometry, processing parameters etc is difficult. As a result, the process of creating molds is inherently iterative.

Allen. Y. Yi [4] *et al*. showed that it is possible to use the finite element method to predict the glass molding process by using commercial software, and that a more sophisticated model is required to accurately predict the manufacturing of asphere lenses by molding.

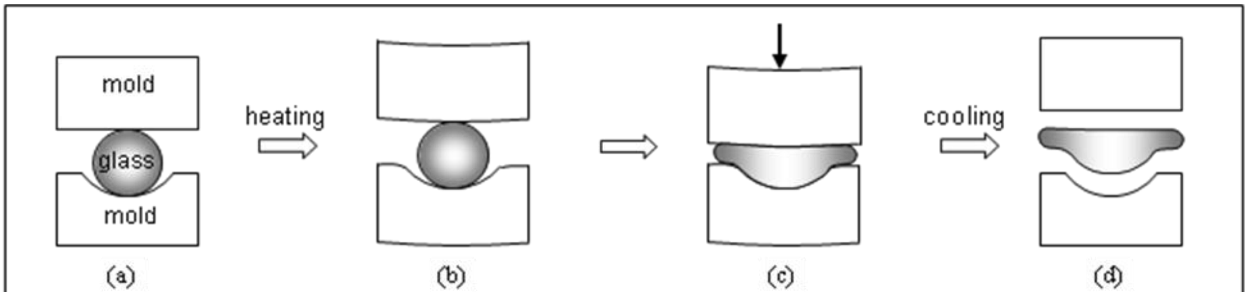
In this paper we aim to numerically simulate (using finite element method) the compression glass molding process by quantifying and analyzing each individual process that occurs in the molding process such as heating, compressing, and cooling, and hence be able to predict the final geometry of the glass lens. From the predicted geometry of the glass lens, the simulation process is run through an optimization routine to determine the mold geometry that would result the desired shape of the optical element. Details on identifying material parameters, modeling assumptions, and simplifications are discussed. This tool can be used to design proper mold geometry that can yield the correct shape of the final glass optics, without having to create molds by iterative design.

2. Model for Compression Molding Process

The molds are assumed to be elastic throughout the molding process. They deform elastically during the heating process and recover their original shapes after cooling. Because of their structural stiffness and inertness they are assumed to be a perfectly rigid body and that they do not incur any deformation due to the pressing process. For our purposes we used Extramet EMT 100 NG WC (Tungsten Carbide) mold.

Optical glasses show viscoelastic material behavior [5]. Glasses can be assumed to elastic solids at room temperature, but they exhibit non-Newtonian viscous properties at temperatures higher than the glass transition temperature [5]. Viscoelastic behavior is the time dependent response of a material to stress or strain. Under application of a sudden constant strain, there occurs an instantaneous stress (elastic effect) followed by continual relaxation of shear stress with time (viscous effect). N-BK7 [6] glass material was used for our purpose. The viscoelastic material parameters of the glass were identified by fitting the experimental data obtained from a simple ring compression test.

The compression molding process can be broken down into the following individual processes. The following figure shows each of the individual process. Each of these processes is treated individually to quantify their effects.



Molding process of precision glass optics; (a) Initial shape at room temperature; (b) Heating process: both glass and molds are deformed due to thermal expansion; (c) Compression process: glass is pressed on the thermally deformed mold surfaces; (d) Cooling process: the molds recover their initial shapes, but the final geometry of the glass is different from that of the molds due to thermal contraction and residual stress.

a. The glass and the molds are perfectly elastic at room temperature.
b. **Heating Process:** The molding setup is heated to the glass transition temperature. At this time, the molds and the glass deform elastically due to thermal expansion (550 – 700 ℃).
c. **Pressing Process:** Maintaining the temperature constant, the upper mold is pressed uniformly to deform the glass according to the mold profile. Glass is now deforms as a viscoelastic material and the molds are assumed to be rigid because of their high structural stiffness. At the end of the pressing process, all deviatoric stress components will be relaxed, while volumetric stressed will remain as residual stresses.
d. **Cooling Process:** The glass and the molds are cooled slowly to the room temperature. The molds will recover their initial shapes, but further deformation occurs in molded glass due to thermal contraction and due to the effect of residual stresses.

3. Finite Element Model and Implementation

Taking advantage of the symmetrical shapes of asphere glass lenses and the molds along their axis of revolution, the molding process was modeled as a 2D axisymmetric analysis. Four- node quadrilateral elements were implemented for the meshing of the glass and the molds. The performance of the program is verified using commercial software.

a. Heating: The spherical/elliptical glass shape is heated to the glass transition temperature. Since the glass gob has a simple shape we can obtain the change in its dimensions due to the heating analytically. The change in the dimension of the mold surface due to temperature change is calculated using the finite element method due to the temperature change. The surface of the mold is extracted for the pressing stage and is modeled as rigid surface.

b. Pressing: The viscoelastic behavior is described by the generalized Maxwell model which consists of springs and dashpots in series to model the viscous and the elastic response [7]. Since the upper and the lower mold surfaces are modeled as rigid surfaces, the pressing process is a contact problem with the glass being a flexible body and the molds being rigid. Newton-Raphson method was used to solve the non-linear finite element equations arising from the contact nature of the problem and viscoelastic material behavior.

After pressing, owing to the viscoelastic behavior of glass, the molds and glass are held at the glass transition temperature for a while (depending on the Maxwell coefficients) to allow stresses to dissipate though stress relaxation. However, there would still be shear stresses due to the elastic part which would contribute as residual stress.

c. **Cooling:** Elastic cooling analysis is performed on the deformed glass geometry to account for the thermal contraction of the lens due to the cooling process. Also, the residual stress after the pressing process is provided as presence of initial stress in the finite element analysis during the cooling and hence the deformation due to the residual stress is also taken into account. The resulting geometry is the final geometry of the lens after molding process.

4. Shape Optimization to Identify the Mold Geometry for Desired Optical Element

Using the final geometry of the lens that is obtained above, the mold geometry that would result in a given desired optical geometry can be obtained minimizing the error between the generated shape of the lens and the desired shape. This is achieved by setting up an optimization routine that would iteratively find the process parameters and the mold shape required to produce an optical element of desired profile.

5. Sample Lens Profile after Simulation

The following figure shows the final geometry of a compressed spherical N-BK7 glass with an aspheric lower mold and flat upper mold. The initial glass gob was spherical in shape with radius of 1 mm and was compressed by 1.2 mm at a uniform rate. The molding temperature was 550 ℃ and the ambient temperature was 25 ℃. At this time the authors are developing the experimental procedure to validate the results, which would be included in the future work of this project.

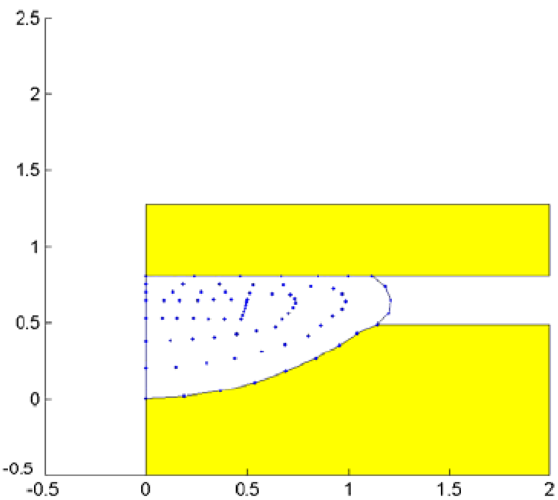


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Fig 1 Deformed lens geometry after pressing simulation

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