

Predictive Molding of Precision Glass Optics

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ABSTRACT

Precision glass molding process is an attractive approach to manufacture small precision optical lenses in large volume over traditional manufacturing techniques because of its advantages such as low cost, fast 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. A 2D axisymmetric finite element model is developed to model the glass molding process. The proposed modeling technique is more efficient than the all-in-one modeling technique. The molds are assumed to be rigid, except for thermal expansion, at all time and glass treated as a flexible body during the compression. 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.

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 multi-step process which requires a series of material removal processes [1] [2]. Although, there have been recent advances in optical fabrication techniques such as magnetorehological finishing and ion beam polishing [3], the complexity of these processes is such that the overall costs are high for medium to high volume production of aspheric optics. Furthermore, the process incurs environmental issues because of the use of grinding fluids and polishing slurries.

A potential low-cost and fast method to produce precision glass optics is a *compression molding process* [4]. In a lens molding process a glass gob is heated to a temperature above the glass transition temperature and is pressed between two mold halves having the required aspheric profile. The formed lens is then either cooled naturally or by forced convection to a 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. The flowchart in Figure 1 shows the use of a numerical simulation tool to produce the final product without the conventional iterative mold design.

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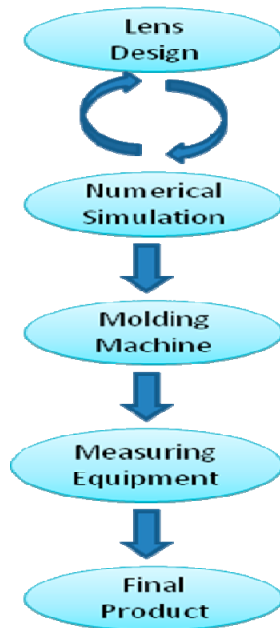


Fig 1: Production flow of aspherical lenses using a numerical simulation tool

Numerical simulation of the entire glass molding process is a complex process. Performing an all-in-one simulation of entire molding process would not only be computationally expensive, but would incur modeling a lot of unnecessary complex processes. In addition, all-in-one modeling prevents from understanding important aspects of each process and fails to provide physical insights of the problem at hand.

In this paper we aim to analyze each sub-process that goes into the molding process and to create a computationally simplified model using engineering judgment and assumptions that would give results accurate enough for manufacturing purposes and simple enough for use for design purpose. We analyze and segregate the vital phenomenon that affect the quality of the final optical element and treat them quantitatively.

Yi *et al.* [5] showed that it is possible to use the finite element method to predict the glass molding process by using commercial software. However, there is no commercial software available customized for simulating multi-step molding processes. A more sophisticated model is required to accurately predict the manufacturing of aspheric lenses by molding and a simplified model is desired for computational expense.

Hence, in this paper we aim to

1. Understand the physics of a compression glass molding process and create a simplified numerical model

2. Develop a computational tool using finite elements to simulate the glass molding process for the above model

Using the above tool, one would be able to predict the final geometry of the glass after the compression molding.

From the predicted geometry of the glass, the reverse engineering of the molding process can be performed to determine the initial conditions such as, the mold profile, operating temperature, and other process parameters that would result in the desired profile of an optical element. This would be achieved by executing the tool through an optimization routine to produce the desired profile of element by treating the above quantities as design variables and minimizing the error between the desired and the resulting geometries.

The following section explains the glass molding process. Then the physics-based model for glass molding process is proposed, followed by the finite element model of the simulation of the process. Optimization to predict the mold geometry and results are discussed towards the end.

MOLDING PROCESS OF GLASS OPTICS

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 and cooling processes. 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 is difficult. As a result, the process of creating molds is inherently iterative. Figure 2 outlines the basic steps in a compression glass molding process:

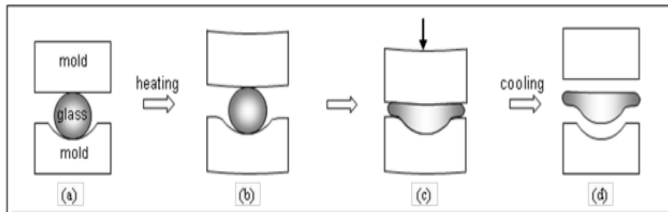


Fig 2: Glass Molding Process

- Initial shape of the glass and the molds at room temperature
- Heating process: Both glass and molds are deformed due to thermal expansion
- Compression process: Glass is pressed on thermally deformed mold surfaces
- Cooling process: Molds recover their original shapes, but final geometry of glass is different from that of molds due to thermal contraction and residual stress

DETAILED STEPS IN A GLASS MOLDING PROCESS

The typical glass molding process can be conducted in the following steps [6]:

- Heating:** Heating is the first step in the glass compression process. During this process, the molds and the glass gob are heated above the glass transition temperature. During the heating process the system is continuously purged with Nitrogen to prevent oxidation on the molds. The molds are heated to the commanded temperature by an induction heating system around the molds
- Soaking:** Soaking is necessary to achieve the steady state of constant temperature between the molds and the glass. The controller maintains the commanded temperature for the duration of soaking cycle time. On large sized molds and glasses, the soaking times can be of the order of few minutes to ensure uniform temperature
- Pressing:** The pressing process commences at the end of soaking cycle. Maintaining the temperature constant, the upper mold is pressed uniformly to deform the glass according to the mold profile
- Gradual cooling:** The temperature of the glass and the molds are reduced gradually till the annealing temperature of glass. The gradual cooling is done by injecting heat continuously to maintain the rate of cooling and using Nitrogen gas to cool. If needed force can be applied in this cycle

- Steep cooling:** Once the glass annealing temperature has been attained, the glass and the molds are cooled to room temperature using a high flow of Nitrogen gas. After this cycle has been completed, the glass is unloaded from the molds and a new gob loaded

Figures 3 and 4 show the glass molding apparatus along with induction heating/cooling system.

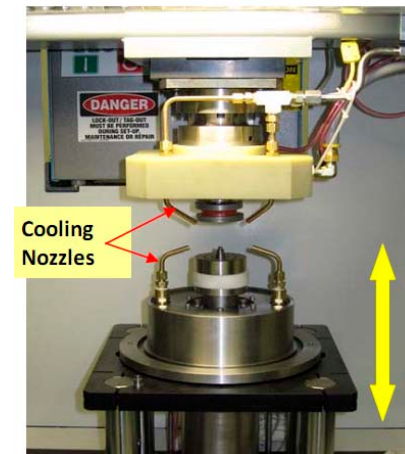


Fig 3: Molding Setup

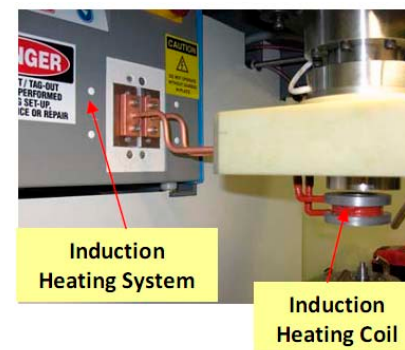


Fig 4: The Induction Heating System

The graph in Figure 5 outlines the temperature profile for the glass pressing cycle. The uniform force for pressing is applied in the pressing cycle which occurs at time T_3