Optics and Lasers in Engineering 53 (2014) 98–103

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

An integrated solution for mold shape modification in precision glass molding to compensate refractive index change and geometric deviation

Lijuan Su [a,c], Fei Wang [b], Peng He [a], Olaf Dambon [b], Fritz Klocke [b], Allen Y. Yi [a,*]

[a] Department of Integrated Systems Engineering, The Ohio State University, 210 Baker Systems Building, 1971 Neil Avenue, Columbus, OH 43210, USA
[b] Fraunhofer Institute for Production Technology, IPT, Aachen, Germany
[c] School of Instrumentation Science and Opto-electronics Engineering, Beihang University, 37 Xueyuanlu, Beijing 100083, China

A R T I C L E I N F O

Article history:
Received 22 May 2013
Received in revised form
12 August 2013
Accepted 23 August 2013
Available online 19 September 2013

Keywords:
Finite element method
Numerical simulation
Precision glass molding
Refractive index
Curve compensation

A B S T R A C T

In precision glass molding, refractive index change and geometric deviation (or curve change as often referred to in industry) occurred during molding process can result in substantial amount of aberrations. Previously, refractive index change and geometric deviation were investigated in separate studies by the authors. However, optical performance of a molded glass lens depends on both refractive index and geometry. In order to mold lenses with optimal performance, both refractive index change and geometric deviation have to be taken into consideration simultaneously and compensated. This paper presented an integrated compensation procedure for modifying molds to compensate both refractive index change and geometric deviation. Group refractive index change predicted by the finite element method simulation was used to provide a modified geometry design for a desired lens. Geometric deviations of molded glass lenses with the modified design were analyzed with a previously developed numerical simulation approach, which is used to modify the mold shape. This procedure was validated by molding a generic aspherical glass lens. Both geometry and optical measurement results confirmed that the molded lens performed as specified by the original design. It also demonstrated that finite element method assisted compensation procedure can be used to predict the final optical performance of compression molded glass components. This research provided an opportunity for optics manufacturers to achieve better performance lens while maintaining lower cost and a shorter cycle time.

1. Introduction

In recent years, growing demands for small size, high performance optical devices have boosted the development of lenses with nonconventional shapes. Yi and Jain [1] investigated the compression molding technique of aspherical glass lens by both numerical analysis and experimental approach. Then a process of molding 3-dimensional microstructure glass optics was developed by Chen et al. [2]. He et al. [3] further developed a process for fabricating hybrid aspherical diffractive glass lenses. These studies proved that precision glass molding process is a fast and cost effective method for fabricating these lenses with complicated geometries, including aspherical, freeform and diffractive hybrid shapes.

In a typical glass molding process, glass blanks undergo three stages: fast heating stage, compression molding stage and controlled cooling stage. During the controlled cooling stage, dramatic changes of temperature in a range of several hundreds of degree within a short time affect the performance of molded lenses, and introduce unexpected aberrations in the optical system where molded glass lenses are employed. On the glass properties, both the report from Schott [4] and the research of Fotheringham et al. [5] showed that the refractive index of an optical glass typically becomes smaller after molding due to glass relaxation during cooling. Another issue is with the geometry accuracy of molded lenses. After pressing, the shape of glass lens continuously changes during cooling as a result of thermal shrinkage, which causes curves of the molded lens to deviate from the design form.

Previously, Dambon et al. [6] investigated geometry error of glass lenses from thermal shrinkage and glass structural relaxation. In that study, an FEM (finite element method) assisted mold manufacturing process with efficient geometry compensation was developed. Su et al. [7] presented a numerical method to predict refractive index changes of optical glass after precision molding. Fotheringham el al. [5] verified the empirical logarithm equation on the relationship between refractive index of glass and cooling rate. The experiments were however based on a relatively low cooling rate compared to normal practice in glass molding [4].

However, both refractive index change and geometric deviation are coupled with heating, molding and cooling parameters in glass

* Corresponding author. Tel.: +1 614 292 9984; fax: +1 614 292 7852.
E-mail address: yi.71@osu.edu (A.Y. Yi).

0143-8166/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.optlaseng.2013.08.016

molding process and could not be compensated alone. Therefore, a combined compensation solution is required to fabricate high performance molded lenses. In this paper, an integrated scheme for designing the mold contours is presented to compensate for both refractive index change and geometrical deviation. Based on previous studies, two FEM predications, i.e. refractive index prediction based on Tool–Narayanaswamy–Moynihan (TNM) model and curvature prediction based on a generalized Maxwell model, are integrated for the first time to solve the problem discussed above. The optical performance of compensated lens is analyzed by using ZEMAX (3001 112th Avenue NE, Suite 202, Bellevue, WA 98004-8017). Experiments were performed to mold an aspherical lens and test the performance. The results verified that proper geometry and optical performances were achieved.

2. Compensation procedures for the mold shape

In order to reduce the aberrations of a molded lens due to refractive index and geometry changes, optical design of the lens is compensated by curvature modification of the molds. In the process of establishing the compensation scheme, both refractive index change and geometric deviation are modeled by finite element analysis. Su et al. [7] established a methodology for predicting final refractive index, while Wang et al. [8] presented a methodology for designing of the molds for compression molding process. Both the refractive index and lens shape changes should be compensated to ensure the optical performance of a compression molded lens from a particular heating–molding–cooling condition. Fig. 1 illustrates the flow chart of the integrated compensation scheme.

First, the refractive index analysis is conducted to predict the refractive change. Second, the lens shape is modified to compensate

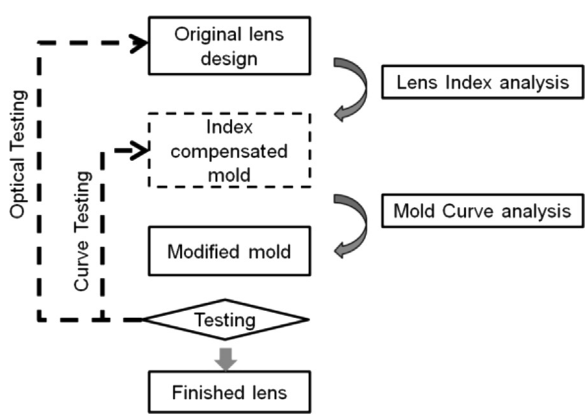

Fig. 1. Flow chart for the integrated compensate scheme.

for the optical performance degradation caused by the refractive index change. An index compensated mold design is obtained afterwards. Third, the shrinkage of lens using "index compensated mold" is predicted. A corresponding amount of alteration is made to mold to obtain a modified mold design. After the lens is molded using the modified mold, both its geometry and optical performance will be tested. Process parameters might be adjusted and additional compensation cycles are needed if the geometry and optical performance do not satisfy the requirements. Ideally, the finished lens, which has different refractive index from initial glass material, can fulfill optical performance requirement as long as the final lens shape matches the "index compensated mold."

2.1. Original lens design

In order to demonstrate the compensation procedure proposed in this research, the design and molding of an aspherical lens is presented in details for an arbitrarily selected double convex lens design. The presented compensation procedures can be easily applied to other glass lenses. In this paper, the original design is a double convex aspherical lens with 25 mm in diameter and 4.8 mm thickness at the center, as shown in Fig. 2(a). It has two identical surfaces with a radius of 60 mm and conic coefficient k_0 of -3.916735. Glass material is P-SK57, a special optical glass material formulated for precision glass molding. The back focal length of this lens is $f_{b,0}=50.52054$ mm at $\lambda=632.8$ nm, which is considered to be the original lens design in this paper.

Wavefront coming from a lens is often used to evaluate the lens performance. Placing a point light source in front of a lens, the distance between the point source and front surface of the lens is defined as d. If the point light source is placed at the front focal point of the original designed lens, where $d=f_{b,0}$, the wavefront coming from the back surface of the original lens is simulated in ZEMAX and as shown in Fig. 2(b). The light in all simulation and measurement is based on He–Ne laser at wavelength of 632.8 nm.

Refractive index of this lens is $n_d=1.58700$, which is the listed value from glass catalog. Mechanical and thermal properties of P-SK57 glass and mold, tungsten carbide (WC), are listed in Table 1. In Table 1, liquid linear coefficient of thermal expansion (CTE) is chosen as three times of solid linear CTE. The viscosity of T_{ref} is based on the definition of T_g.

2.2. Refractive index analysis and compensation

In glass molding, the volume of a glass blank changes during the heating, molding, and cooling (or annealing) process. The refractive index of a molded glass usually shows a lower value than glass blanks. This "index drop" depends on the cooling rate

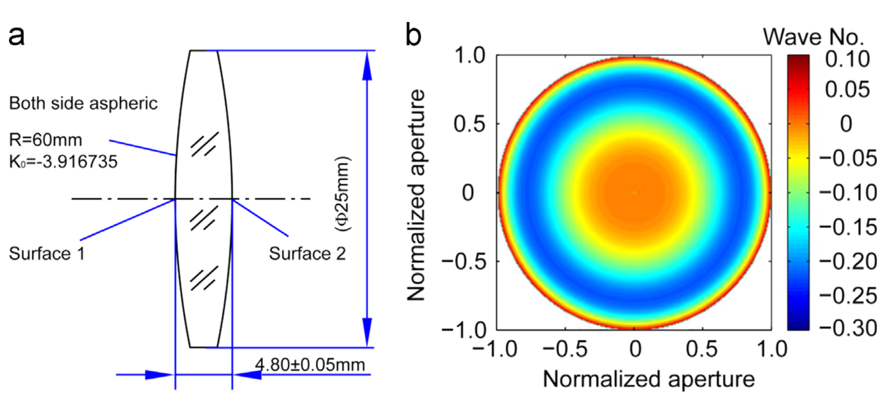

Fig. 2. (a) Geometry of the original lens design. (b) Simulated wavefront of the original lens when a point light source is placed at focal point, $d=f_{b,0}$.