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Dong-kil Lee
Jun-girl Oh
Won-Gun Jang
Yang-gyu Kim
Kwanghoon Lee
Anjin Park
Young-Soo Yang

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Dong-kil Lee,^{a,b} Jun-girl Oh,^{a,b} Won-Gun Jang,^a Yang-gyu Kim,^a Kwanghoon Lee,^a Anjin Park,^a and Young-Soo Yang^{b,*}

^aKorea Photonics Technology Institute, 3D Convergence Center, Chumdan venture-ro 108 beon-gil 9 (WolChul-Dong), Buk-gu, Gwangju 500-779, Republic of Korea

^bChonnam National University, School of Mechanical Systems Engineering, 300 Yongbong-dong, Buk-gu, Gwangju 500-779, Republic of Korea

Abstract. Generally, aspheric glass lenses are manufactured using a glass molding press (GMP) method and a tungsten carbide mold core. This study analyzes the thermal deformation that occurs during the GMP process, and the results were applied to compensate an aspheric glass lens. After the compensation process, the form accuracy of aspheric glass lenses improved from ~ 3.7 to $\sim 0.35 \mu\text{m}$. The compensated lens complied with the actual specifications. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: 10.1117/1.OE.53.6.065106]

Keywords: aspheric glass lens; glass molding press; form accuracy; compensation algorithm; ultraprecision grinding.

Paper 140322 received Feb. 26, 2014; revised manuscript received May 9, 2014; accepted for publication May 23, 2014; published online Jun. 25, 2014.

1 Introduction

Due to the tremendous growth in media technology in recent times, the demand for ultraprecision optical components^{1,2} has increased rapidly. In addition, there has been a corresponding increase in the demand for improvement in optical performance, e.g., higher resolution and brightness. Thus, there is a growing need for precise aspheric glass lenses and ultraprecision grinding of the mold core^{3,4,5} and molding techniques⁶ that are able to mass-produce the aspheric glass lenses are needed. Nowadays, the glass molding press (GMP) method⁶ is favored as the molding technique for aspheric glass lenses because fabrication through conventional glass grinding techniques is not only difficult but also gives a low mass production.

Aspheric glass lenses, produced using the GMP method, are molded by treating them by a process in which they are subjected sequentially to heating, pressing, and cooling. This leads to thermal deformation of the lenses, especially in the cooling process. The thermal deformation changes the radii of curvature of the lenses and lowers the performance of the optical system.

In this study, the thermal deformation of aspheric glass lenses during the cooling process in the GMP technique was analyzed and the results were applied to the ultraprecision grinding of the mold core in order to improve the performance of lenses used in closed-circuit televisions (CCTVs).

2 Aspheric Glass Lens

2.1 Design of an Aspheric Glass Lens

Aspheric surfaces can be represented by a specific equation, Eq. (1), obtained by adding the conic section and the aspheric shape factor

$$z = \frac{C \cdot x^2}{1 + \sqrt{1 - (1 + K) \cdot C^2 \cdot x^2}} + \sum_{i=1}^n A_i \cdot x, \quad (1)$$

where C is the inverse of the radius of curvature, K is the conic constant, and A is the aspheric coefficient. In this case, the surface has a hyperbola, a parabola, an ellipse, and a sphere—various forms of a conic section—rotated about the optic axis, whose form is determined by the conic constant.

Figure 1 shows a schematic diagram of an aspheric glass lens for a CCTV optical system.

2.2 Thermal Deformation in the Molding of Aspheric Glass Lenses

In general, the GMP process is used for the mass production of aspheric glass lenses. In this study, progressive-type molding was applied to the GMP method. Progressive-type molding is carried out sequentially in the following three stages: heating, pressing, and cooling. This molding technique is suitable for the mass production of uniform aspheric glass lenses. Figure 2 shows a schematic of the progressive-type molding⁶ used in this study.

In the GMP process, glass lenses are molded by heating them above the yield point (at 559°C), followed by pressing and cooling of the glass lenses, after a preform of the glass is loaded in the mold core. During the transition from the pressing stage at high temperature to the cooling stage at room temperature, molded lenses are thermally deformed due to the creation of thermal stress inside the lenses. Thermal stress is caused by the difference in the cooling rate due to the difference in the thickness of a lens. The thermal deformation varies according to the shape and the size of the lenses, leading to errors in the value of the designed lenses' form accuracy. This further leads to lower optical performance of aspheric glass lenses. Figure 3 schematically describes the thermal deformation during the GMP process.

*Address all correspondence to: Young-Soo Yang, E-mail: ysyang@jnu.ac.kr

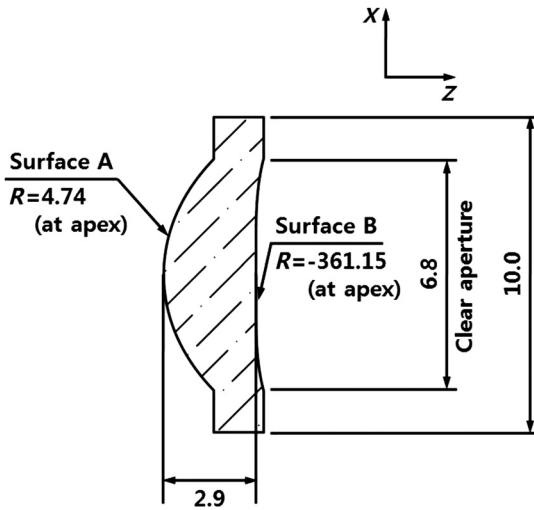


Fig. 1 Schematic optical design of aspheric glass lens.

3 Experimental Equipment and Condition

3.1 Experimental Equipment

In this study, the mold core of an aspheric glass lens was processed using an ultraprecision nonaxisymmetric generator (ASP01, developed by Japan-based Nachi-Fujikoshi Co., Tokyo, Japan). This generator is a tri-axial processing machine equipped with *x*- and *y*-axes tables that are orthogonally driven by two oil hydrostatic pressure slides. An air turbine spindle in the B-axis rotary table, which is driven with an oil hydrostatic pressure bearing, is an ultraprecision machine that is capable of grinding the aspheric surface. Its guide way has a positioning accuracy of 1 nm and is capable of dealing with a structure with a maximum diameter of 150 mm. To mold the aspheric glass lens using a mold core, a progressive type molding machine GMP 54-5s, developed by Japan-based Toshiba Machine Co., (Ooka, Japan) was used. The form accuracy values of the mold core and the molded lenses were measured by an ultrahigh accurate 3D profilometer, UA3P, developed by Japan-based Panasonic Co. (Osaka, Japan) The specifications of the ultrahigh accurate 3D profilometer are listed in Table 1.

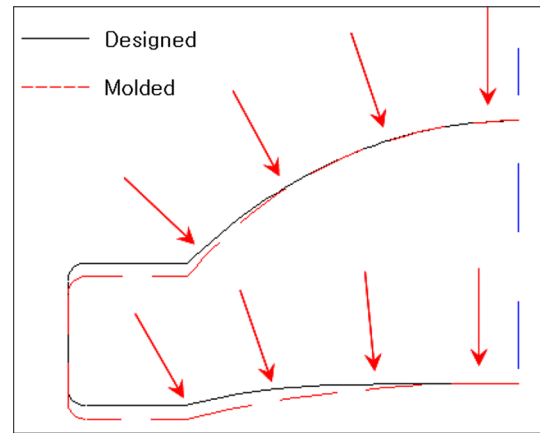


Fig. 3 Schematic description of thermal deformation during glass molding press processing.

3.2 Experimental Condition

The mold core of the aspheric glass lens was made by the parallel grinding of tungsten-carbide TJF03 devised by Japan-based Fujidie Co., (Tokyo, Japan) using a diamond-grinding wheel of particle-size #2,000. The specific conditions for grinding the mold core are listed in Table 2.

In the molding of aspheric glass lens ball-type glass L-BAL42, manufactured by Japan-based Ohara Co., (Oyama, Japan) was used, taking into consideration the volume of the designed lens. Table 3 lists the mold conditions of the aspheric glass lens used in this study. To minimize the influence of not only the shrinkage due to the molding of the aspheric glass lenses, but also disturbances caused before and after compensation, the mold core was made as per the grinding conditions listed in Table 2 and 10 aspheric glass lenses were molded as per the molding conditions listed in Table 3.

4 Molding Analysis and Compensation Process

The form accuracy of the mold core made using ultra precision grinding was found to be $0.213 \mu\text{m}$ peak to valley roughness height (P-V). Ten aspheric glass lenses molded

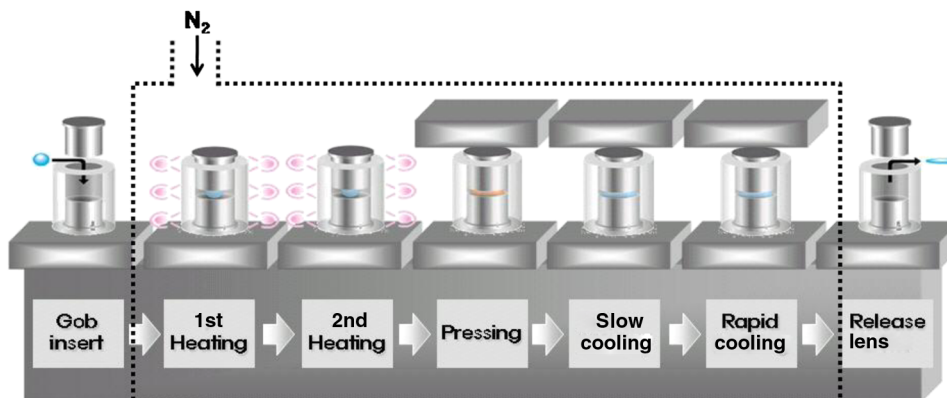


Fig. 2 Schematic of the progressive type molding.

Table 1 Specifications of ultrahigh accurate 3D profilometer (UA3P).

Items	Value
Measurement range (X, Y, Z-axes)	200 × 200 × 45 mm
Probe (diamond)	Atomic force probe—tip radius of curvature: 2 μm; measuring force: 0.3 mN
Probe measurement accuracy (diamond)	Measurement plane tilt angle ≤30 deg: up to 0.1 μm
Measurement errors by coordinate axis (measurement range of XY coordinate axes)	Up to 100 mm within 0.05 μm or less (repeatability within 0.05 μm)
Measuring speed	0.01 to 10 mm/s variable in multiple step

using the grinded mold core were made to have a form accuracy in the range of 3.6 to 3.8 μm (P-V), affected by thermal deformation that occurred during the molding process. It was observed that the values had deviated sharply from the standard specification [below 0.8 μm (P-V)] of the designed lens. Figures 4(a) and 4(b) respectively show the form accuracy of the mold core before the compensation process and an aspheric glass lens after molding.

To compensate for the form accuracy errors that occurred during the thermal deformation of the molded lenses, the compensation algorithm, which is given by Eqs. (2) and (3), was used.

$$Z_a = \sum_{i=4}^n A_i x^i = Z_{ap} + Z_{com} \cdot \alpha, \tag{2}$$

$$Z_n = Z_{sp} + Z_a. \tag{3}$$

Table 2 Grinding condition for mold core.

Items	Value
Work spindle	350 rpm
Turbine spindle	35,000 rpm
Feed rate	0.5 mm/min
Depth of cut	0.3 μm

Table 3 Molding condition for aspheric glass lens.

Items	Value
Unit processing time	75 s
Heating temperature	560°C
Slow cooling temperature	465°C
Press force	1000 N

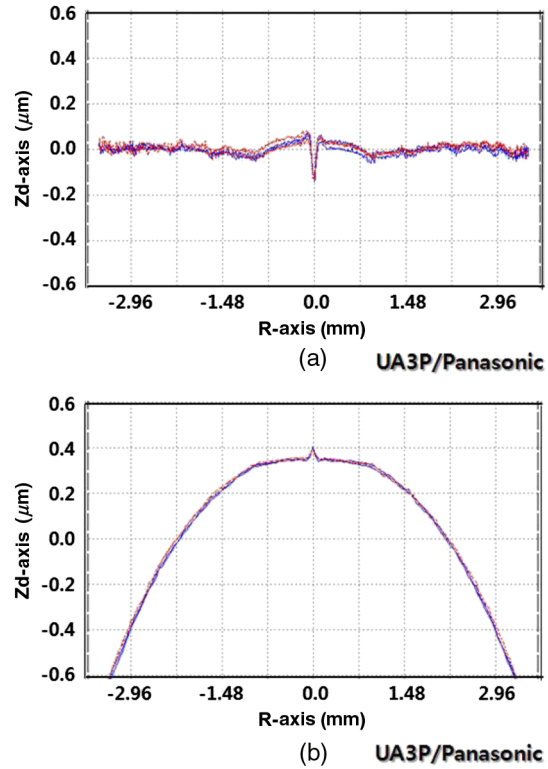


Fig. 4 Form accuracy of (a) mold core and (b) molded lens before compensation.

During the compensation process, the aspheric equation, Eq. (1), was divided into a spherical term Z_{sp} and an aspheric term/coefficient Z_a to reduce the parameters. The spherical term was made constant to determine the aspheric coefficient using the nonlinear curve-fitting method.⁷ A sag value Z_n of compensation in the aspheric equation was obtained by adding the spherical term Z_{sp} of the designed lens and the aspheric coefficient Z_a , which is the sum of the aspheric term of the designed aspheric surface and the compensation aspheric term Z_{com} that represents the thermal deformation. In this process, the compensation factor α is set at 0.85, and it reduces reshrinkage of the compensated mold core and influences the measurement of errors in lenses. Figure 5 shows the nonlinear curve-fitting results of the shrinkage-compensated aspheric coefficient Z_a .

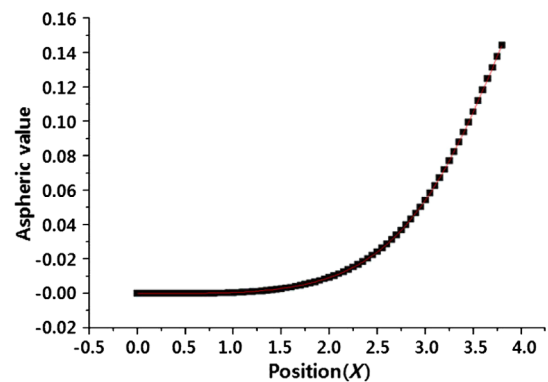


Fig. 5 Result of nonlinear curve-fitting.

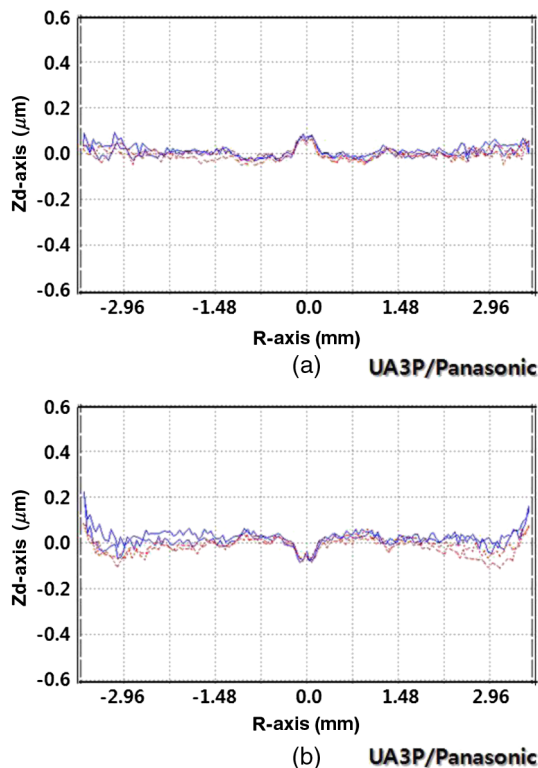


Fig. 6 Form accuracy of (a) mold core and (b) molded lens after compensation.

The form accuracy of the mold core reprocessed as the compensation shape by ultraprecision grinding was $0.157 \mu\text{m}$. The form accuracy of the 10 aspheric glass lenses remolded using the mold core made during the compensation process was found to be in the range 0.3 to $0.45 \mu\text{m}$. After the compensation process, the form accuracy of the aspheric glass lenses improved from 3.7 to $0.35 \mu\text{m}$. These results agreed with the standard specifications. Thus, it was proven that the compensation algorithm of thermal deformation is suited for molding aspheric glass lenses. Figure 6 shows the form accuracy of a mold core and a molded lens after the compensation process. Figure 7 shows pictures of the mold core and molded lenses.



Fig. 7 Photograph of mold core and molded lens.

5 Conclusion

In this study, the thermal deformation phenomenon that occurs during the molding of aspheric glass lenses was analyzed for aspheric glass lenses used in CCTVs. The mold core was reprocessed by using the compensation aspheric coefficient determined by using the nonlinear curve-fitting method for the compensation of thermal deformation during the molding of aspheric glass lenses. The GMP technique was implemented using the reprocessed mold core and the progressive-type molding method, and the following results were obtained:

1. The compensation algorithm is used to compensate thermal deformation during the molding of aspheric glass lenses by analyzing the thermal deformation phenomenon.
2. After the compensation process, the form accuracy of aspheric glass lenses improved from $\sim 3.7 \mu\text{m}$ to $\sim 0.35 \mu\text{m}$. This complied with standard specifications of form accuracy [below $0.8 \mu\text{m}$ (P-V)].
3. The form accuracy of lenses molded by using the reprocessed mold core was confirmed on the basis of the compensation aspheric equation, and this proved the validity of the compensation algorithm for thermal deformation.

Acknowledgments

This study was performed by supporting of Small and Medium Business Administration Project "A Development of 4cc Laser Projector Engine for Mobile Application" of Small and Medium Business Administration. Thank you.

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Dong-kil Lee is a senior researcher at the 3D Convergence Research Center, Korea Photonics Technology Institute. He received his ME degree in mechanical engineering from the Yeungnam University of Mechanical Engineering in 2001. He is currently working toward his PhD degree in mechanical engineering from the Chonnam National University of Mechanical Engineering. He is the author of 28 journal papers. His research interests include optical components, optical applications, and precision mechanical engineering. He is a member of KSPE.

Jun-girl Oh is a researcher at the 3D Convergence Research Center, Korea Photonics Technology Institute. He received his BE degree in mechanical engineering from the Chonbuk National University of Mechanical Engineering, Jeonju, Republic of Korea in 2011. He is currently working toward his ME degree in mechanical engineering from the Chonnam National University of Mechanical Engineering,

Gwangju, Republic of Korea. His current research interests include optical components, optical applications, and precision mechanical engineering.

Won-Gun Jang is a senior researcher at the 3D Convergence Research Center of Korea Photonics Technology Institute. He received his PhD degree at the University of Colorado, Boulder, USA in 1998 in the field of soft-condensed matter physics. He was a postdoc at Liquid Crystal Institute of Kent State University in 1999. He is currently a senior researcher at KOPTI since 2001. His interests include organic displays, optical lens design, and optical components of concentrated photovoltaics.

Yang-gyu Kim is a senior researcher at the 3D Convergence Research Center, Korea Photonics Technology Institute. He received his master's degree in technology management from the Chonnam National University, Republic of Korea in 2011. His current research interests include 3D display applications and optical application engineering.

Kwanghoon Lee is senior research scientist at the 3D Convergence Research Center (3D-CRC) of Korea Photonics Technology Institute

(KOPTI), where he is responsible for R&D field in three-dimensional (3D) displays such super/multiview auto-stereoscopic 3D display, projection type of 3D display and pseudo and classical/digital holographic 3D display. Specially, he is one of the experts to 3D display system design and 3D optical property analysis based on human engineering.

Anjin Park received his MS and PhD degrees in computer engineering from Soongsil University in 2006 and 2009, respectively. He was at National Institute of Advanced Industrial Science and Technology, Japan, and Korea Institute of Science and Technology, Korea, as a postdoctoral research and is currently a senior research scientist at Korea Photonics Technology Institute in Gwangju, Republic of Korea. His research interests include 3D modeling, computer vision in 3D, and computer graphics.

Young-Soo Yang is a professor at the Chonnam National University of Mechanical Engineering. He received his PhD degree in mechanical engineering from the KAIST in 1991. He is the author of 40 journal papers. His research interests include the analysis of thermal stress and deformation.