Peng He\textsuperscript{1}, Fei Wang\textsuperscript{2}, Likai Li\textsuperscript{1}, Kyriakos Georgiadis\textsuperscript{2}, Fritz Klocke\textsuperscript{2} and Allen Y. Yi\textsuperscript{1}

\textsuperscript{1}Department of Integrated System Engineering
The Ohio State University, Columbus, OH, USA
\textsuperscript{2}Fraunhofer Institute for Production (IPT), Aachen, Germany

INTRODUCTION
Refractive and diffractive hybrid lenses have been designed and implemented for some industrial applications. These optical elements however are limited to low volume production or specific materials such as polymers. Although plastic lenses can be fabricated using injection molding into different geometries at high volume, these optics do not perform well under rigorous conditions of high temperature, pressure and humidity that are required for many precision applications (e.g., military applications). On the other hand, optical glasses have been and will continue to be the materials of choice for high precision imaging optics. Unfortunately, glass materials are extremely difficult to process using conventional methods. As an alternative to traditional glass lens manufacturing processes, compression molding of glass lenses can be a very attractive approach [1-3].

The aim of this research is to demonstrate a feasible glass diffractive optics molding process by integrating established precision mold making, heat transfer and rheological modeling of glass materials. The primary goal of this research is to verify proper glass and mold materials, and process parameters that will satisfy pre-defined design criteria for compression molding of diffractive glass aspherical optical elements thus resulting in lower cost and high quality products. In addition, numerical modeling software for optical efficiency simulation will also be evaluated. The proposed process is a net shape, high volume manufacturing method therefore it allows optical manufactures to design compact optical systems using optical glasses that were not available before. The results from this research can be integrated in optical design, fabrication and assembly therefore providing industry with the possibility of low cost, compact and high performance optical systems utilizing hybrid precision glass optics.

OPTICAL DESIGN
Optical Mold Preparation
In this research, a refractive-diffractive hybrid singlet lens aimed to compensate for chromatic aberrations in visible light range was designed using software Zemax (www.zemax.com). The features of the hybrid lenses are listed in Table 1.

\begin{table}[h]
\centering
\begin{tabular}{|l|l|}
\hline
F/# & 4 \\
Lens diameter & 18 mm \\
Center thickness & 3 mm \\
Glass type & P-SK57 \,(n_d=1.5870, \, \upsilon_d=59.6001) \\
Wavelength & F, D, C \,(486.1327, 587.5618, 656.2725) \, nm \\
\hline
\end{tabular}
\caption{Hybrid lens design features}
\end{table}

The DOEs (diffractive optical elements) could be designed either on the planer surface (first surface in Figure 1) or aspherical surface (second surface). However, DOEs on the second surface are good for sine condition [3], which reduces the design error. This is also a preferred design for mold fabrication, which can minimize the tool alignment issue during diamond turning because the DOEs and aspherical profile are on the same surface. Figure 1 is the layout of the refractive and diffractive hybrid lens.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{diffractive and refractive hybrid lens design}
\end{figure}
Figure 2 illustrates the details of the diffractive element shape. In this design, aspherical surface is described by Equation 1,

$$z = \frac{cr^2}{1 + \sqrt{1 + (1 + k)c^2r^2}} + a_2r^2 + a_4r^4$$  \hspace{1cm} (1)

where the curvature of the optical surface $c = -1/69.312$ and the conical constant $k = -18.3594$, $a_2 = -3.936369 \times 10^{-3}$, $a_4 = -3.179234 \times 10^{-6}$. The diffractive profile is described by the following equation:

$$\Phi = -417.418 \rho^2 + 2.0909 \rho^4 + 3.0827 \rho^6$$  \hspace{1cm} (2)

where, $\rho$ (0<\rho<1) is the normalized radial aperture coordinate and the height $d$ is given by

$$d = \frac{\lambda \Phi}{2\pi(n_d - 1)}$$  \hspace{1cm} (3)

where 0<\phi<2\pi.

Figure 3: OPD of the diffractive and refractive hybrid lens

EXPERIMENTS

Optical Mold Preparation

To create the diffractive pattern on the mold surface, diamond turnable 715 copper nickel alloy was selected for this experiment. The aspherical substrate was first diamond turned on the Moore 350 FG ultraprecision machine. A special single point diamond cutter with 2 µm half radius (Edge Technology, Indianapolis, Indiana) was used to machine the diffractive features. Prior to experiments, mold surfaces were coated with a 5 nm Titanium and 100 nm Platinum.

Molding Process

The mold assembly was heated to 715 °C (thermocouple reading) in vacuum on a laboratory scale molding system (Figure 4). The description of the system can be found elsewhere [1]. Connecting rods, electrical cables were removed for clarity. In this system, a Transducer Techniques THC-500V load cell was used to measure applied load and control molding process. Based on the sensitivity of the loadcell and the signal conditioning software, a resolution of 0.09 N can be achieved [1].

Figure 4: Schematic of the close up view of the compression forming stage: (a) mold heating pedestals (b) Nickel mold (c) heating cartridges (d) thermocouple position (e) substrate holder

A typical molding process consists of heating, molding and releasing stages. Figure 5 shows the temperature and load conditions for this process. To start, glass gob is first heated to 715 °C and kept for 2 hours and 45 mins to make sure the glass has a uniformed temperature distribution above $T_g$ (glass transmission temperature). Then during the molding (forming) stage, the bottom mold gradually moved up to apply load on the glass gob. The softened glass gob is deformed into the desired shape between the two molds. The maximum molding load was about 510 N before it started decreasing due to the viscoelastic nature of glass. The molded glass was kept between two molds for 45 s then cooled down in 160 s to allow the optic to reach the desired geometry. The last step was to
remove the molded glass by lowering the bottom mold. To avoid oxidization, N\textsubscript{2} was introduced to purge the chamber and then pumped out to create the vacuum in the chamber. The pressure was kept at about 30 millitorr during the entire experiment.

RESULTS AND DISCUSSION

Replication Accuracy

The molded DOEs were measured for geometric accuracy and surface finish. Wyko (Veeco NT9100 optical profiler) scans of the coated mold and molded glass were performed on the same surface. A close up view of the diffractive features is plotted in Figure 6. It can be seen that the DOE features were successfully transferred to the glass substrate. The difference between the molded glass optics and the mold may have resulted from the glass thermal shrinkage and is currently under investigation.

Surface Evaluation

The surfaces of the molded lens were also measured by using Wyko optical profilometer (as shown in Figure 7). The diffractive profile and molded surface finish are illustrated in the 2D color scan. As compared to a previous study [2], it appears that current mold glass combination does not produce the surfaces for imaging optics. Efforts to improve surface roughness and de-molding are currently underway.

CONCLUSION

To compensate the chromatic aberrations, an all glass refractive-diffractive lens provides an alternative to a lens assembly with the same function, which is usually bigger and heavier than the hybrid lens. By use of single point diamond turning, aspherical and DOE features were created on the same mold surface and the need for alignment was eliminated.

The molding experiments demonstrated that the non-planer profile with micro features could be fabricated on glass surfaces by compression molding, leading to a promising way to produce high-quality, low-cost hybrid lenses.

ACKNOWLEDGEMENTS

This work was supported in part by the German Research Foundation (DFG) within the SFB/TR4 “Process Chains for the Replication of Complex Optical Elements.” AY acknowledges SFB/DFG for providing financial support for travel to Aachen. The research was also supported by the National Science Foundation (USA) under Grant No. 0547311. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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