Selection of Preform in Glass Molding Press of Aspherical Chalcogenide Lens

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Abstract. Glass molding press (GMP) is an effective method of mass production of glass lens, especially for chalcogenide glass lens. During the process of GMP, the preform is another key factor to achieve a good yield rate except the molding parameters. Three kinds of preforms are provided to conduct the molding experiment, which are made from the same material of chalcogenide glass. The first one is of the rough double-spherical surfaces, and the second one is turned by diamond cutting tools, and the last one is polished as smooth as possible. At the same conditions of 315°C heating temperature and maximum pressing force of 0.7MPa for 45s, only the polished preform can be pressed into a qualified aspherical lens, which has a shape accuracy of 0.875um and of 0.625um in peak-valley (PV) for concave and convex surface, respectively.

1. Introduction
Thermal imaging in the 8 to 12\textmu m wavelength range was once the sole domain of the military because of the high cost of the hardware (mainly the detector) [1]. With the increasing advancement of uncooled infrared (IR) detector, thermal cameras have been applied to a wide variety of commercial applications. But most of thermal imaging optics are made of expensive single-crystal materials, e.g, Ge and ZnSe, which limit its high-volume commercial application because single-crystal material could be formed into IR lens only by the single-point diamond turning (SPDT) technology until now, which does cost a lot and has low efficiency. Accordingly, chalcogenide glass was introduced several decades ago and has been used for infrared applications. Chalcogenide glass is a kind of amorphous material, which has a good performance of low thermally-induced refractive index difference in the wavelength of 2 to 20um. At the same time, chalcogenide glass has some advantages such as high-volume moldable characteristics and low fabrication cost [2].

The moldable characteristics of chalcogenide glass has been used for the glass molding press (GMP) technology, which has recently become an attractive approach alternative to the traditional glass lens manufacturing process—polishing [3]. GMP is a simpler process than polishing and lenses can be compressed into aspherical shape without requiring the usual subsequent finishing operations.

However, the physical properties of chalcogenide glasses are very different from the optical glasses commonly used in GMP. In addition, it is difficult to control the many parameters of the GMP process (e.g., heating temperature, heating time, the pressing force, cooling rate, and cooling range, etc.). Thus, to decrease the number of case studies, an effective strategy for GMP process design is required, and the related results should be analyzed systematically [4]. More important, the initial preform and lens
mould should be processed seriously in advance and lens mould should be coated with materials to improve the de-moulding performance. Here chalcogenide glass NBU-IR1 [5] from Ningbo University is chosen for experimental analysis of double aspherical lens, and after the key parameters including heating temperature, pressing time, pressure range and cooling temperature are optimized, the preforms have been processed by turning and polishing tools in order to get the best formed aspherical lens. The molding results of aspherical lenses are evaluated by peak-valley (PV) in shape and Ra in roughness of surfaces through profilometer Taylor Surf 1240.

2. Selection of chalcogenide glass materials
The chalcogenide glass material NBU-IR1 (Ge$_{20}$Sb$_{15}$Se$_{65}$) is from Ningbo University, and its key properties are 4.72g$\cdot$cm$^{-3}$ in density, 14.1×10$^{-6}$K$^{-1}$ during 293-373K in expansion coefficient, 19.11GPa in Young modulus, 0.27 in Poisson's ratio, 0.23W$\cdot$mK$^{-1}$ in thermal conductivity, 0.34J$\cdot$g$^{-1}$K$^{-1}$ in specific heat, and 538K in transfer temperature.

3. Design of aspherical lens and lens mould
The infrared lens is made of two sides of aspherical surfaces. The aspherical shape is expressed by

$$Z = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} + Ar^2 + Br^4 + Cr^6 + Dr^8 + Er^{10} + Fr^{12} \quad (1)$$

where $Z$ is asphericity, $r$ aperture radius, $k$ conic coefficient and $c$ reciprocal of radius of curvature, $A$, $B$, $C$, $D$, $E$, $F$ are the coefficients of each order of $r$, $r^2 = x^2 + y^2$, the coefficients of convex aspherical surface are $k=0$, $A=0$, $B= -6.171\times10^{-5}$, $C= -2.95\times10^{-7}$, $D= 2.88\times10^{-9}$, $E= -9.554\times10^{-11}$, $F= 6.478\times10^{-13}$, its radius of aspherical surface is $R= -17.098$mm; the coefficients of concave aspherical surface are $k=0$, $A=0$, $B= -1.687\times10^{-4}$, $C= -2.305\times10^{-6}$, $D= 1.091\times10^{-7}$, $E= -3.959\times10^{-9}$, $F= 4.853\times10^{-11}$, its radius of aspherical surface is $R= -97.01$mm. The lens aperture is 19.6mm, and effective lens aperture is 14mm. The center thickness is 7.0±0.04mm and the overall thickness 7.75±0.04mm. The required processing accuracy is no more than 0.8um in peak-valley (PV) and no more than 0.08um in roughness Ra.

According to the design requirements, the whole assembly configure including lens and moulds is achieved. The initial surfaces on moulds have the same aspherical parameters as lens. Assuming that the volume cannot be compressed, the lens preform can be calculated based on the condition under which the lens volume is unchanged before and after pressing. To facilitate the forming process, the preform should hold two sides of spherical shapes. Accordingly, the chalcogenide glass preform is shown in Fig.1 (a) and (b). In Fig.1 (b), a small flat area on the top of convex surface is due to the disadvantage of machining process.

![Figure 1. The real preform and mold pictures, (a) concave spherical surface, (b) convex spherical surface of preform (c) upper mold, (d) lower mold, (e) inner sleeve and (f) outer sleeve](image-url)
4. Selection of mold material and mold fabrication

4.1. Selection of mold material
Because the chalcogenide glass has high viscosity after heating, it needs a special mold material used for GMP. The material should have a high density, high adhesion temperature, high chemical and thermal stability and small thermal expansion coefficient. So cemented carbide CW500 is selected for lens mold, which is produced by DIJET Co. Its properties are 26.2GPa in HV hardness, 15.5 in specific gravity, 680GPa in Young’s Modulus, 4.4×10^-6/K in thermal expansion coefficient, 53W/m-K in thermal conductivity, 0.2 in Poisson’s ratio and 5.8GPa in compressive strength.

4.2. Fabrication of mold
The aspherical molds are ground by diamond grinding wheel on ultra-precision machine Nano form 250. Fig.1(c)-(f) show all aspherical molds and sleeves. Fig.1(c) is the real upper mold with convex aspherical shape, and (d) the lower mold with concave aspherical shape, (e) is the inner sleeve with eight vent holes, and (f) the outer sleeve. The aspherical shapes are measured by profilometer UA3P-300 and the final shape accuracy is 0.1015 \( \mu \text{m} \) of PV for upper mold and 0.096 \( \mu \text{m} \) for lower mold, respectively.

Although the surface of mold is smooth enough, it’s easy to cause adhesion between mold and lens preform. Hence the mold should be coated by Ni-P alloy or diamond-like-carbon (DLC) or noble metal to improve the demold performance. Through our experiments, it’s found that the Ni-P alloy is not effective enough in demold behavior. Therefore, Ni-P film is excluded in our study.

5. Selection of Preform and GMP parameters
The spherical lens preform is expected to be compressed into aspherical lens by lens-molding experiment. Through optimizing analysis and trial-and-error method, an optimal molding parameters could be achieved as follows in Table 1 and Table 2. The whole GMP process is divided into six stages including three heating stages, one pressing stage and two cooling stages, whose temperatures are set to be shown in Table 1. The best pressing temperature is 315°C.

| Table 1. Temperature for each GMP stage (°C) |
|---------------------------------------------|
| Temperature 2\text{nd} Cooling 1\text{st} Cooling pressing 3\text{rd} heating 2\text{nd} heating 1\text{st} heating |
| Upper mold 190 250 315 315 255 200 |
| Lower mold 190 250 315 315 255 200 |

| Table 2. Pressure parameters for pressing stage |
|-----------------------------------------------|
| Pressing stage Initial pressure (MPa) Pressing time (s) Time step (s) |
| Phase 0 0.05 5.0 0.1 |
| Increasing pressure (MPa) Pressing time (s) Pressure step (MPa) |
| Phase 1 0.15 10 0.01 |
| Phase 2 0.25 15 0.01 |
| Phase 3 0.40 15 0.02 |

Table 2 shows the pressure parameters of pressing stage including 4 phases, and the initial pressure is 0.05MPa, keeping this pressure for 5.0s by time step of 0.1s. Then the pressure is increased to 0.7MPa step by step. The pressing period is 45s. According to the conditions, a piece of preform is to be formed by GMP machine, Fig.2 (a) and (b) are the upper concave and lower convex surface of aspherical lens, respectively. Fig.2 (c) is a 7-station GMP machine HGLMOD-06 of Taiwan UCN Co.
From Fig.2 (a) and (b), the concave surface is not smooth and the center of convex surface is not completely pressed by mold and its surface is relatively rough. At the same time, the lens preform is a little bigger than design, which leads to the adhesion of lens to inner sleeve wall.

Considering the problems above, we turn the convex surface of preform by diamond cutting tools to eliminate its small flat center area and remove the outer diameter by 2mm. The heating and pressing parameters are kept unchanged. Fig. 2(d) shows the convex surface turned by diamond cutting tool, (e) is the preform with the outer diameter removed by 2mm, (f) and (g) are the convex and concave surfaces of molded lens of Fig. 2(e), respectively.

Because the chalcogenide glass is extremely fragile, the edge of preform is broken to some degree, however, it will not affect the hot-pressing process due to its melt status. The molded results show that the formed aspherical lens is much better than that of Fig.2 (a) and (b). The measured concave surface is 18.55um in PV and convex one 29.12um. The respective roughness is 4.94um and 6.81um.

The shape accuracy and roughness are very low that don’t meet the design requirement. The next step is to further machine the molds for compensation to enhance the shape accuracy and polish the surface to improve the roughness. Fig.3 (a) and (b) are the improved preform by polishing tool.

Using the same pressing parameters, the final aspherical lens is achieved as shown in Fig.3(c) and (d). The measured results show that the aspherical shape accuracy is 0.875um in PV (the design size is no more than 0.8um), 0.09um in roughness Ra (the design size is no more than 0.08um) for concave surface and 0.625um in PV (the design size is no more than 0.8um), 0.059um in roughness Ra (the design size is no more than 0.08um) for convex surface. In addition, we get the vertex radius $R_{cx}=17.022\text{mm}$ (the design size is $17.098\text{mm}$) of convex aspherical lens surface and the vertex radius $R_{cc}=96.51\text{mm}$ (the design size is $97.01\text{mm}$) of concave aspherical lens surface. The center thickness is $t=6.68\text{mm}$ (the design size is $7.0\pm0.04\text{mm}$) and the overall thickness is $T=7.80\text{mm}$ (the design size is $7.75\pm0.04\text{mm}$). According to the measured data, it proves that our molded results meet the design requirements.

6. Conclusion
In this paper, the preform is highlighted to achieve its effect on the finished aspherical products. The first preform is directly given from a melt-forming blank part of chalcogenide glass with rough double-
spherical surfaces. The second one is processed by diamond turning tools and the third one is polished as smooth as possible. Given the same molding conditions, only the polished preform can be pressed into a qualified double-aspherical lens, which has a high shape accuracy. They also have a high roughness in Ra for concave and convex surfaces. The overall thickness and center thickness meet the design requirements. As a result, to meet the high-accuracy requirement, we need to turn the preform by diamond turning tools and polish it as possible as smooth before taking GMP method to conduct the lens molding of infrared aspherical chalcogenide. Additionally, the lens molds should be made from cemented carbide such as WC or SiC, etc. and coated with hard metal films such as DLC or noble metals to enhance its demolding performance.

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