Title:
Compensation of Shape Change of Amorphous Carbon Mold for Glass Molded Fresnel Lens

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Keywords:
Shrinkage compensation, amorphous carbon mold, pyrolysis, glass Fresnel lens, concentrator photovoltaic

DOI: 10.14733/cadconfP.2014.54-56

Introduction:
Fresnel lens is commonly used as a primary optics for concentrator photovoltaic (CPV) system to concentrate the sunlight onto solar cells due to its thin and lightweight characteristics. Although an injection molded polymethylmethacrylate (PMMA) Fresnel lens and silicone on glass (SOG) Fresnel lens have been commercially available in the CPV industry, these Fresnel lens fabrication methods have long-term durability problems [1]. A glass molded Fresnel lens can be a suitable solution for primary optics of CPV system, however, conventional glass molded Fresnel lens using precision ground tungsten-carbide (WC) mold could show lower optical efficiency due to the relatively large groove tip radius of precision ground WC mold. A method to fabricate amorphous carbon (AC) mold for glass molded Fresnel lens which have sharp tip radius was developed by the our recently developed AC mold fabrication process using replication and carbonization process of furan precursor [2]. Fig. 1 shows the schematics of proposed fabrication method of AC mold for glass molded Fresnel lens. A nickel master pattern which had the negative shape of Fresnel lens was machined by precision diamond turning process. To fabricate AC mold, a Polydimethylsiloxane(PDMS) template was replicated from the nickel master and a mixture of furan resin was poured on the PDMS template. After curing process of furan mixture, a carbonization process was carried out in an N_2-pured furnace with a maximum carbonization temperature of 1000°C to obtain AC mold.

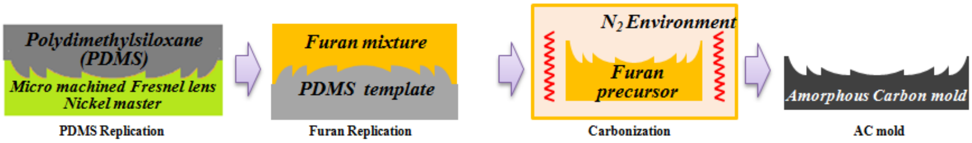
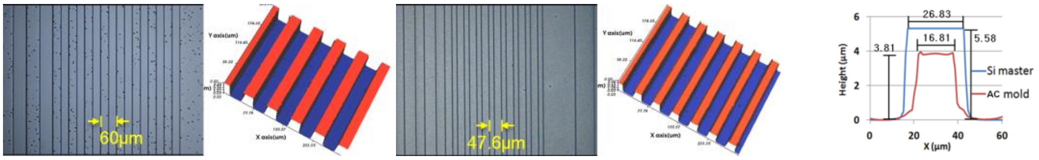


Fig. 1: Schematics of fabrication process of AC mold having negative shape of Fresnel lens.

In the fabrication process of AC mold for Fresnel lens, a significant shape change was occurred during the carbonization process due to the thermal decomposition of furan replica and it should be compensated to obtain the designed Fresnel lens profile. In this study, a material shrinkage model which can expect the shape change during the carbonization process was developed, and applied to the shape change compensation using a computer added design.

Development of shrinkage model to expect shape change in carbonization process:
To examine the trend of shape change in the carbonized AC mold, a AC mold having micro grating pattern was fabricated using the silicon master with pattern widths of 30 ~ 150 μm, pitches of 60 ~ 300 μm and hegith of 5.54 μm. The surface profile of fabricated AC molds were measured by white light

scanning interferometer microscope and compared with the original master pattern for quantitative analysis of the shape change during the carbonization process as show in Fig. 2.



(a) (b) (c)

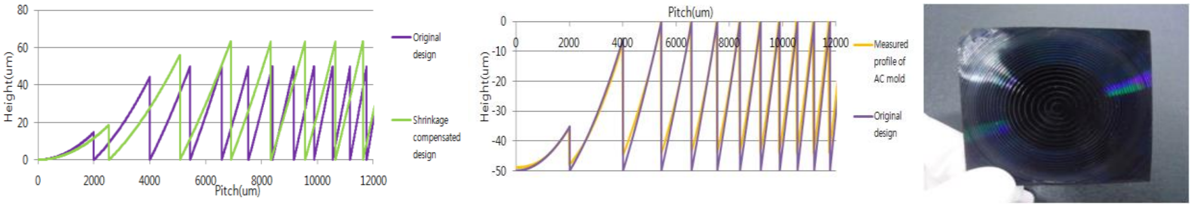
Fig. 2: Microscope images and measured 3D surface profile of (a) silicon master (Pitch : 60 μm) and (b) fabricated AC mold, and (c) comparison of cross sectional surface profile of silicon master and AC mold.

Fig. 2 shows a significant shape change was occurred during the carbonization process and the shape change was not isotropic. We also found the shape change was affected by the pattern size and shape from the measured results of the other gratin patterns. To predict the shape change in the carbonization process, a gradual shrinkage model was developed. In the carbonization process of furan resin, 45wt% of material is thermal decomposed in H_20, CO and CO_2 gases. At the surface region, the decomposed gases can easily escape from the material and large volumetric shrinkage is occurred. Since the gas escape ratio is inversely proportional to the distance between surface and the internal location, and the unescaped gases can be remained as a pore in the AC, a relatively small volumetric shrinkage is occurred in the internal region of material. Therefore, the volumetric shrinkage value at a specific point ($C_{@position}$) can be expressed as a function of gas escape distance (d, distance between specific location and surface area of material) as shown in eqn. (1). Since the pitch shrinkage of 22.7% is not affected by the pattern shape and size, we assumed the shrinkage ratio of specific location, where the gas escape distance was larger than specific value ($D_{critical}$), was saturated as the pitch shrinkage (C_0 =22.7%).

$$\begin{aligned} C_{@\,position} &= f(d) = \frac{C_0}{D_{critical} + C_{\max}} d + C_{\max} && d < D_{critical} \\ C_{@\,position} &= C_0 && d \geq D_{critical} \end{aligned} \qquad (1)$$

,where the C_{max} is the shrinkage ratio at the surface area. To apply the proposed gradual shrinkage model for expecting the shape change in the AC mold fabrication process, a shrinkage simulation algorithm was developed based on the finite element method, in which the shrinkage ratio of each element was assigned using the eqn. (1). To find the C_{max} and $D_{critical}$ values which minimize the errors between measured and simulated surface profiles, a simple optimization method was applied, and the C_{max} of 67% and $D_{critical}$ of 2.5μm were found. The developed shrinkage model can expect the shape chage of VC mold in carbonization process in maximum error range of 1.87%.

<u>Fabrication of AC mold for glass molded Fresenel lens:</u>
Based on the developed shrinkage model, an enlarged negative Fresnel lens shape which can compensate the shape change in the proposed AC mold fabrication process was applied to the Ni master machining process. Fig. 3 (a) shows the comparison of original design and compensated profile of negative Fresnel lens with a focal length of 300 mm, and (b) shows the comparison of Fresnel lens profiles between original design and measured data from AC mold. The y direction deviation between designed lens profile and measured AC mold profile was mainly due to the measurement error of mechanical stylus measurement method, and the x direction deviation was less than 50 μm which was less than design tolerance margin. It clearly shows the effectiveness of the developed shrinkage expectation model and compensation method.



(a) (b) (c)

Fig. 3: Comparisons of negative Fresnel lens profiles between (a) original design and shrinkage compensated design, and (b) original design and measured data from fabricated AC mold, and (c) image of fabricated AC mold for glass molded Fresnel lens

Conclusions:

A method to simulate the shape change in AC mold fabrication process was developed, and an AC mold having designed Fresnel lens surface profile was obtained using Ni master having shrinkage compensated surface profile. Since the measured tip radius of AC mold was ~ 5 μm, the proposed AC mold fabrication method can be used as a mold for glass molded Fresnel lens with high efficiency.

Acknowledgements:

This research was supported by the Human Resources Program in Energy Technology (No. 20134030200350) and the New & Renewable Energy Program (No. 20123010010110) of the the Korea Institute of Energy Technology Evaluation and Planning(KETEP) granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea

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