Investigation on Fog Defects of Molded Glass Lenses

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Precision glass molding (PGM) is the dominant mass-production technology of aspheric glass lenses. The development of high-precision optical systems puts forward strict requirements for the surface quality of lenses, and a homogeneous surface without defect is in demand. However, PGM tends to leave fog defects on the molded glass lenses owing to the complex forming conditions, which affected the optical performance of lenses and reduced the yield rate of industrial production. Few existing studies have focused on this issue, and the characteristics and generation mechanism of the fog defects have not been thoroughly revealed. In this paper, systematical studies on the fog characteristics and its generation mechanism were carried out. The morphology and composition of fog defects were analyzed in detail. The mechanism of the fog defects was successfully revealed considering the interference properties between glass and mold under the PGM conditions. The experimental and analysis results are helpful to understand the essence of fog defects deeply and provide an effective guidance for molding glass lenses with high surface quality in the future.

NOMENCLATURE

PGM = Precision glass molding
WC = Tungsten carbide
ChG = Chalcogenide glass
DLC = Diamond-like-carbon

1. Introduction

Aspheric glass lenses are increasingly applied in various optical products, such as mobile phones, automotive lenses, endoscopes, and projectors [1]. Precision glass molding (PGM), a high-efficiency and low-cost manufacturing process, has been employed for the high-precision mass production of aspheric glass lenses [2, 3]. However, a surface defect that resembles fog tends to appear on the molded lenses after PGM as shown in Fig. 1, which affects the optical performance of lenses and reduces the yield rate of industrial production. Being a critical quality defect, this issue should be thoroughly investigated.

Surface defects of the molded lenses are closely related to the interface contact characteristics between the glass and mold under the PGM conditions [4]. The interface adhesion between the glass and the mold, which leads to lens scratches, has been a focal point of previous research [5]. Zhao et al. [6] studied the adhesion mechanism between glass and tungsten carbide (WC) molds with three different coatings and reported that the adhesion depended on the factors include the chemical compositions of the glass, coefficient of thermal expansion, mold surface quality, and process parameters of PGM. While related studies have primarily focused on coating in terms of atomic diffusion [7], degradation [8], and wear [9], less attention has been given to the changes in the glass surface. Furthermore, Zhou et al. [10] observed that microdimples tend to form on the molded Chalcogenide glass (ChG) surfaces at high temperatures due to gas generation and release from the glass. However, there are limited existing studies specifically addressing fog defects or thoroughly elucidating their characteristics and formation mechanisms.

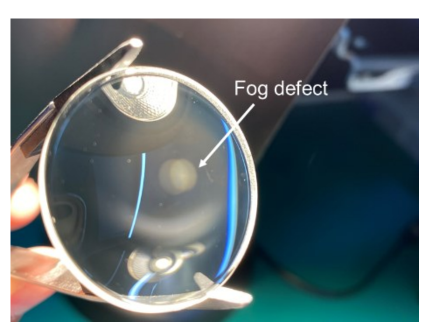


Fig. 1 Fog defect on the surface of molded glass lens

The fog defect was investigated through experimental analysis in this study, wherein the micro-morphology and composition of the fog were presented. Based on the obtained experimental results, a comprehensive analysis of the fog was conducted. Furthermore, by considering the interference properties between glass and mold, the underlying mechanism responsible for fog generation was revealed successfully.

2. Experimental setup

In order to understand the characteristics of fog defect, the morphology and composition of fog were observed and analyzed. Glass cylinder compressing experiments were conducted on a glass molding press machine (Toshiba, Model: GMP-311V) to obtain the surfaces with fog defects. Since the S-FSL5 glass was prone to generate fog defects during the molding process, it was selected to fabricate cylindrical samples measured 5 mm in height and 12 mm in diameter. As shown in Fig.2, these cylinders were placed between the mold inserts and compressed by the upper mold insert at a temperature of 580 °C, followed by cooling with nitrogen gas. The adopted mold was made of WC and covered with a diamond-like-carbon (DLC) coating. The end faces of glass cylinders were polished to be smooth before molding and the fog defects could be observed clearly on the molded cylinders.

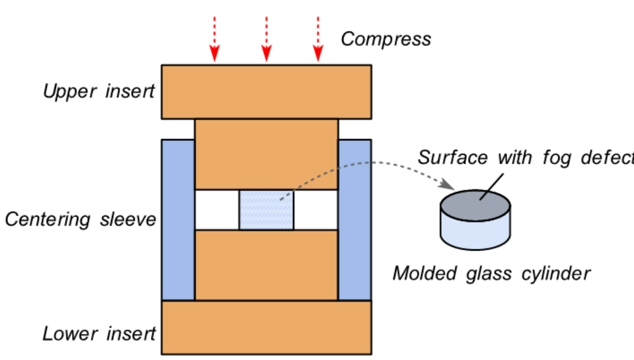


Fig. 2 Schematic of glass cylinder molding

Scanning electron microscope (SEM) was used to observe the micro-morphology of glass surfaces. The SEM images of the fog and fogless zones of glass were analyzed and compared. X-ray photoelectron spectroscopy (XPS) analysis was further conducted to obtain the composition of the fog. To assess potential crystallization in the fog defect area, glancing incidence X-ray diffraction (GIXRD) was employed to detect the glass surface at minimal depth. The experimental details are listed in Table 1.

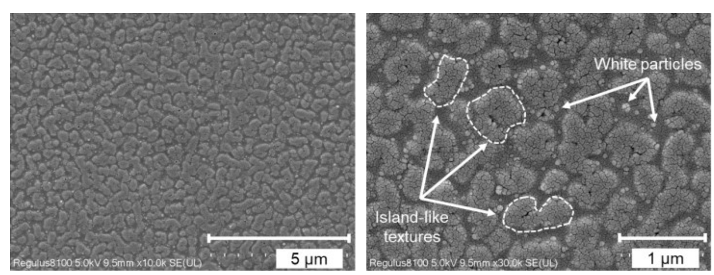
Table 1 Experimental details

Categories	Conditions
Glass material	S-FSL5, transition temperature: 500 °C
Molding parameters	Temperature: 580 °C, load: 6500 N, N_2 atmosphere
SEM	Gold spray treatment on glass surfaces before observation, time: 90 s
XPS	Depth profiling: 50 nm, 70 nm Elements analysis: K, C, F
GIXRD	Glancing incidence angle: 0.1° Scanning angle range: 5°-90°

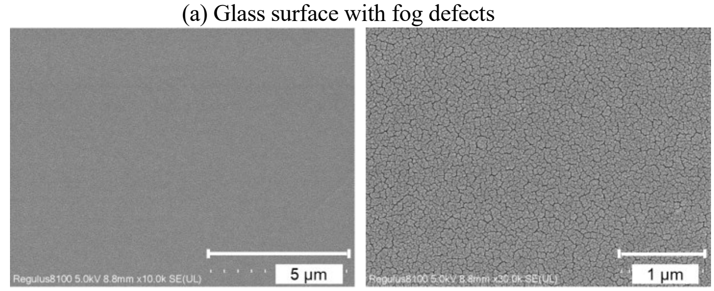
3. Results and discussion

3.1 The morphology of fog

The surface zone with fog defect exhibits poor transmittance under light compared to the rest of the surface, as depicted in Fig. 1. The fog manifests as a white barrier. Therefore, the micro-morphology of glass surfaces was observed to study typical characteristics of fog. Fig.3 (a) shows the micro-morphology of the fog defects on the glass surface, wherein island-like textures pervade and are accompanied by dispersed white particles. The size of island-like textures is approximately 300 nm, and the size of white particles is less than 100 nm. However, the glass surface without fog defects looks very smooth without any obvious features as shown in Fig. 3 (b). It can be inferred that the formation of macroscopic fog defects is due to the generation of microscopic island-like textures and white particles. In addition, there are micro-cracks in Fig. 3 (a), which is attributed to the spray-gold treatment of the glass surface for enhancing the conductivity during SEM observation.



(a) Glass surface with fog defects

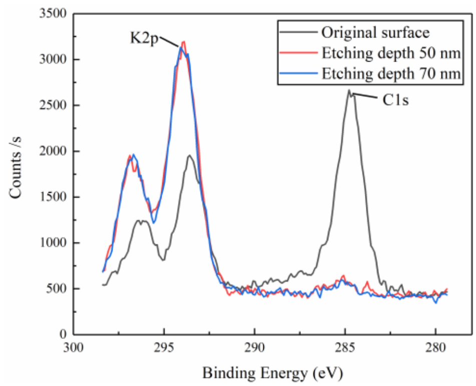


(b) Glass surface without fog defects

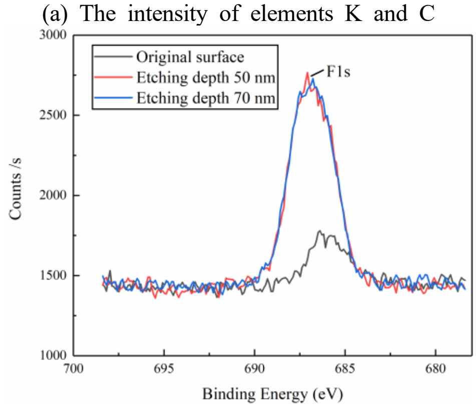
Fig. 3 SEM images of glass surfaces

3.2 The composition of fog

The distinctive micro-morphology of the fog defect has been identified in section 3.1, and another crucial aspect to consider is whether the composition of the fog differs from that of the glass material. In order to investigate this compositional disparity, XPS depth profiling was conducted to penetrate beyond the glass surface using an Ar^+ ion beam. The X-ray spot was greater than 50 μm, which was sufficient to cover the entire fog defect, including the island-like textures and white particles. Spectra were collected at depths of 50 nm and 70 nm below the surface and compared with those obtained from the original surface featuring a fog defect.



(a) The intensity of elements K and C



(b) The intensity of element F

Fig. 4 XPS analysis of fog defect

The intensity changes of elements K and C at different etching depths are presented in Fig. 4 (a). As the etching depth increased, the peak intensity of element K became stronger, while the trend of element C was opposite. This result indicates a higher concentration of carbon and lower concentration of potassium on the fog surface. The intensity curves were consistent at the depths of 50 nm and 70 nm, which indicated that the thickness of fog defect layer was less than 50 nm. In general, the potassium oxides K_xO_y are the key components for forming glass, the lack of K_xO_y tended to lead to the changes of glass physical properties. Moreover, K_2O exhibits instability when exposed to temperatures exceeding 350 °C. As for the enriched element C on the fog surface, it may be attributed to physical adsorption from organic carbon in the air or carbon on the DLC coating of mold. Fig. 4 (b) illustrates a comparison of fluorine levels below the fog surface, similar to Fig. 4 (a), an increase in peak intensity is observed but with a shift in peak position. This result indicates that the molecular structure of the fluoride has changed, and a large amount of fluoride has been lost on the fog surface.

The structural integrity of the glass was compromised as a result of the depletion of elements K and F, accompanied by alterations in partial molecular configurations. Consequently, the metastable glass ceased to exhibit its initial characteristics and exhibited a transition towards a fog surface adorned with numerous island-like textures and white particles.

3.3 The microstructure of fog

Considering the alterations in morphology and composition occurring on the fog surface, it was imperative to analyze whether the glass underwent a crystalline transformation. Given that the thickness of the fog defect layer was less than 50 nm, GIXRD analysis was employed to detect the crystal peak signals on the thin surface layer and while minimizing interference from the glass substrate.

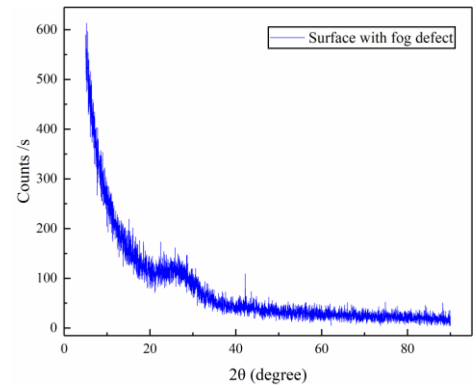


Fig. 5 GIXRD analysis of fog defect

The diffraction pattern Fig. 5 revealed the absence of any prominent crystal diffraction peak. The presence of a small diffraction peak between 20° and 30° indicated the existence of an amorphous microstructure, which was the typical pattern of amorphous glass. The result indicated that little or no crystal was formed in the surface layer during PGM. Although the compositions of the glass surface layer had changed, the fog defects still retained the properties of glass.

3.4 The mechanism of fog

Based on the results of the morphology, composition and microstructure of the fog defects, the mechanism behind fog formation can be further elucidated. During the PGM process, the glass was in close contact with the mold under elevated temperatures, which was easy to induce glass steering unstable state at the glass-DLC coating interface. The instability of glass was caused by changes in the content of partial compositions, such as the elements K and F in S-FSL5 glass, rather than crystallization. These changes leaded to generate island-like textures and white particles on the surface.

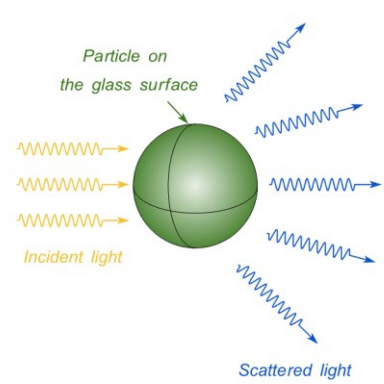


Fig. 6 Schematic of light scattering influenced by particles on the glass surface

The fog-like effect of the surface was attributed to the unique island-like textures and white particles. These surface microstructures were at the same scale or slightly smaller than the visible light wavelength (400 nm-780 nm). As shown in Fig. 6, when exposed to visible light, these features disrupted the direction of light propagation, resulting in light scattering. Consequently, the glass surface exhibited non-transparency and presented a foggy barrier known as fog defect.

4. Conclusions

This paper focuses on the fog defect that frequently occurs on the surface of molded glass lenses, and investigates its characteristics and generation mechanism in detail. The morphology, composition, and microstructure were analyzed based on experimental results to gain a profound understanding of the essence of the fog defect. The main conclusions can be summarized as follows:

(1) Compared to the smooth surface without fog defect, the fog defect that occurred on the surface of S-FSL5 glass consisted of numerous island-like textures and white particles. The size of island-like textures was approximately 300 nm, and the size of white particles was less than 100 nm; the white particles were randomly distributed within the island-like textures.

(2) The compositions of the surface layer with fog defect differed from those of original glass. Losses in elements K and F, along with changes in partial molecular structures, resulted in an unstable glass surface layer. The instability of the glass caused the generation of the unique surface morphology, and no crystallization occurred in this process.

(3) The fog-like glass surface was attributed to light scattering. The visible light wavelength level or smaller surface microstructures were generated on the glass surface during PGM. As a result, these microstructures interfered with the propagation of light, resulting in the occurrence of fog defect.

The investigation provides an effective guidance for improving the PGM process and molding glass lenses with high surface quality. Future research should explore reaction conditions and equations of ions and oxides in glass that contribute to fog generation. Additionally, efforts should be made towards developing methods for eliminating fog defects.

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