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Effect of water on wear of phosphate laser glass and BK7 glass

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ABSTRACT

Using a reciprocating ball-on-flat tribometer, the friction and wear behaviors of phosphate laser (PL) glass and BK7 borosilicate glass were investigated by rubbing against Al_2O_3 ball in dry air and liquid water to reveal the effect of water on the wear of the two glasses. In dry air, the wear of PL glass and BK7 glass shows a typical characteristic of mechanical wear. The damage of PL glass dominates by the formation and extension of Hertzian crack, and the damage of BK7 glass dominates by exfoliation-in-chips and three-body abrasive wear. Water affects both the subsurface fracture and material removal for the two glasses. On the one hand, the subsurface fracture is suppressed greatly for both the PL glass and BK7 glass when they are rubbed in water. The lower shear stress caused by water film at friction interface is considered as the main reason of weakened subsurface cracking for the two glasses. On the other hand, compared with dry air, water promotes the material removal of PL glass but reduces the material removal of BK7 glass. It suggests that the material removal of glass in water depends on the combined effect of the chemical stability of glass and the contribution of water lubrication.

1. Introduction

Nd-doped phosphate laser (PL) glass and BK7 borosilicate glass are two important optical material used in high-peak-power solid-state laser systems [1]. Nd-doped phosphate laser glass is an ideal gain medium which is used as the power amplifier because of its high storage capacity for optical energy [2], while BK7 glass usually serve as the relay lenses and the substrate for optical mirror coatings due to its excellent chemical stability [3]. Surface quality of optical components obtained by lapping and polishing process is closely related to the material removal mode which is influenced by the process parameters [4]. How to obtain a high material removal rate combined with a low subsurface damage is the key issue during the finishing processes of optical glass components [5]. Therefore, it is of great importance to understand the material removal and subsurface damage behaviors of glass substrate.

In previous researches, single pass scratch test usually has been used to evaluate the wear and damage behaviors of glass [6–9]. These investigations revealed that the surface and subsurface damage of glass depended on glass mechanical properties along with contact stress. For example, Houérou et al. [6] found that the scratch damage presented obvious differences in fused silica glass, soda lime silica glass, float glass, and BK7 glass, due to the different backbone structure. Payel et al. [8,9] investigated the effect of load on the scratch damage of soda lime silica glass. They found that, with increase in load, the subsurface damage of soda–lime–silica glass evolved from fully crushed damage to the formation of extensive micro-fracture and finally to the occurrences of lateral cracks and shear deformation bands. However during lapping process, the material removal is more expected to occur in reciprocating wear between the grains and glass, rather than less single pass scratch. In reciprocating wear, the deformation and damage of glass should be very different from that in single pass scratch, and it deserves to pay more attention.

The strength and wear resistance of glass materials depend on not only the mechanical properties of the material itself, but also the exposed environment, such as water environment (it contains gaseous water and liquid water) [10–16]. For example, it has been reported that reciprocating wear of soda lime silica glass in dry air caused a rough and deep wear track, while in humid air, the wear track was smooth and the wear volume was significantly decreased [14]. Thus, it was suggested that the wear of glass surface in humid air was a water-assisted tribochemical wear process. It has also been reported that wear resistance of fused silica, borosilicate, barium boroaluminosilicate and aluminosilicate glasses decreased as the RH increased [10,14,15]. These wear behaviors of glass materials could be explained by stress corrosion theory.

Stress corrosion [17] is a classical theory, which depicts that molecules possessing proton donors and lone-interface electrons such as H_2O can cause network bond-breaking by dissociative

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chemisorptions across the glass backbone, which facilitates crack propagation [18–20]. For silicate glasses, water molecules can accelerate the hydrolysis of Si-O-Si network to cause more severe fracture at glass surface. In contrast to silicate glasses, water can easily attack P-O-P network in phosphate glasses by stress corrosion due to their lower chemical stability [13,21]. Recently, we reported nanoscale wear behavior of phosphate laser glass and BK7 borosilicate glass against CeO_2 particle in humid air [22]. Wear depth of PL glass was found to be significantly deeper compared to BK7 glass in single-asperity elastic contact friction. Hence it can be concluded that the effect of stress corrosion on the wear of PL glass is greater than that of BK7 glass. This can be attributed to the lower energy threshold required to hydrolyze P-O-P network bonds. However, the effect of water on the wear in PL glass and BK7 glass has not been addressed in macroscopic scale, especially on the surface and subsurface damage.

In this work, the reciprocating friction and wear behaviors of PL glass and BK7 glass against alumina balls (Al_2O_3 balls) were investigated in dry air and liquid water, respectively. The friction coefficient and wear volumes of the two glasses were quantitatively collected in the two environments. The surface damage and subsurface fracture in the two glasses were observed, and the corresponding wear mechanisms were discussed. Research results provide further insights into the effect of water on the material removal and damage in glass processing.

2. Material and methods

2.1. Material

The polished N31 Nd-doped PL glass slide with a size of $20 \times 20 \times 2$ mm, provided by Shanghai Daheng Optics and Fine Mechanics Co., Ltd., China, is typically used in the high-peak-power solid-state laser system "Shenguang III" manufactured in China. The polished BK7 optical glass (named K9 glass in china) slide with a size of $20 \times 20 \times 2$ mm was purchased from Hefei Kejing Materials Technology Co., Ltd. Using micro-Vickers hardness tester (HXD-1000TMC, Taiming, China), the hardness and fracture toughness of the two glasses were measured. Using nanoindenter (TI750, Hysitron, USA), the Young's modulus of the two glasses was detected. Using electronic universal testing machine (WDW-100, Yuchen, China), the fracture strength of the two glasses was measured. All the measured mechanical properties and the chemical composition of N31 Nd-doped PL glass and BK7 glass were summarized in Table 1. The balls used in friction and wear test were Al_2O_3 balls with diameter of 1.6 mm, which were purchased from Haining KOVE Bearing Co., LTD., China. The hardness and Young's modulus is 18 GPa and 360 GPa, respectively.

2.2. Friction and wear test

Before the test, the glass substrate and ball surface were cleaned by rinsing with ethanol and ultrapure water, respectively, followed by blow-drying with dry nitrogen gas. All the friction and wear tests were performed on a universal ball-on-flat tribometer (MFT-3000, Rtec, USA) equipped with a home-made environment chamber and built-in microscope camera, as shown in Fig. 1. Tests were performed through reciprocating sliding, in dry air (relative humidity was less than 2%) and pure water (~0.3 mL water was dripped on the friction interface), respectively, at room temperature. A constant normal load of 0.9 N was applied by a servo loading system. Sliding speed was 5 mm/s, sliding time was 5 min and sliding distance was 5 mm. Each experiment was repeated at least 5 times to ensure the repeatability.

2.3. Wear and damage observation

First, wear tracks of PL glass and BK7 glass were analyzed using white light scanning profilometry (Rtec, USA), and the wear depth and wear volume were estimated by the cross-sectional profile lines of the wear tracks. Next, surface and subsurface damage of the two glasses were observed using scanning electron microscope (SEM, EVO18, Zeiss, Germany) after cleaning debris. In order to observe the subsurface damage, glass slide needs to be cut perpendicularly to the wear track using diamond wire saws. A built-in microscope camera was installed opposite the test surface to allow in situ observation and analysis of the dynamic damage process of glass, as shown in Fig. 1.

2.4. Chemical analysis

In order to reveal the possible tribochemical reaction, Raman spectra (InVia, Renishaw, England) was firstly employed to analyze the wear debris attached on the wear track in PL glass and BK7 glass, after rubbing in dry air and water. Furthermore, the concentration of some characteristic ions, such as P^{5+}, Si^{4+}, Ba^{2+}, K^{+} and Na^{+}, in the solutions after wear test of PL glass and BK7 glass in water was detected by an inductively coupled plasma optical emission spectroscopy (ICP-OES, 720 OES, Agilent, USA).

3. Experimental results

3.1. Friction of PL glass and BK7 glass against Al_2O_3 ball

Fig. 2 shows the friction coefficient of PL glass and BK7 glass against Al_2O_3 balls as a function of sliding time (μ-t curve) in dry air and water. For PL glass, an obvious increase in friction coefficient from 0.22 to 0.65, was observed under dry condition in the initial 40 s. After that, a stable friction coefficient ~0.75 was found in dry air. But in water, there was no obvious increase in friction coefficient, and the stable friction coefficient was 0.46, which was much smaller than that in dry air. The smaller friction coefficient indicated that water acted as a lubricant during the wear of PL glass. For BK7 glass, the friction coefficient increased sharply from 0.22 to ~0.7 in the initial 10 s and then kept relatively stable in the both dry and water environment. There was no significant

Table 1
Mechanical properties and chemical composition of PL glass and BK7 glass used in the experiments.

Material	Chemical composition (wt%)						Hardness (GPa)	Young's modulus (GPa)	Poisson ratio	Fracture strength (GPa)	Fracture toughness (MPa m$^{1/2}$)
PL glass	P_2O_5 50–60	Al_2O_3 8–12	K_2O 10–14	BaO 8–12	Li_2O 2–3	Nd_2O 1–3	3.9	67.6	0.27	0.33	0.53
BK7 glass	SiO_2 69.13	B_2O_3 10.75	BaO 3.07	Na_2O 10.40	K_2O 6.29	As_2O 0.36	5.7	88.5	0.20	0.63	0.72