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A comparative study on the effect of loading speed and surface scratches on the flexural strength of aluminosilicate glass: Annealed vs. chemically strengthened

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ABSTRACT

Quasi-static and dynamic three-point-bending experiments were conducted on both annealed and chemically strengthened aluminosilicate glass scratched by different normal loads. Scratched areas were observed by optical microscope and atomic force microscope. Chemically strengthened glass shows better resistance to surface scratch. These dynamic experiments were carried out using a modified Split Hopkinson Pressure Bar (SHPB) device and a pulse-shaping technique was used to keep constant loading speed to the specimens. In tests, high-speed photography was also used to observe the failure process of the specimens. The test results showed that the flexural strength of aluminosilicate glass (AG) strongly depends on the applied loading speed. Compared with its annealed counterpart, the chemically strengthened glass (CSG) showed higher flexural strength to both static and dynamic loadings. Moreover, the three-point bending experiments were conducted on scratched AG and CSG specimens and decrease of 20–40% in flexural strength was observed. The fractography analysis showed that in dynamic loading conditions the fracture surface was not smooth and has more secondary cracks as compared to static loading.

1. Introduction

Aluminosilicate glasses are used as transparent armors or windshields of airplanes due to their unique properties such as high hardness, relatively lightweight, high compressive strength and outstanding optical transparency. In many applications, the glass undergoes high-rate deformation, such as bird strike on the aircraft windshield and bullet impact on vehicle windows. It is reported that the compressive strength of glass increases with the increase of strain rates [1]. Xu [2] showed that borosilicate glass can bear up to 1.5 GPa uniaxial compression stress before fragmentation. However, the brittleness of glass is the critical issue to their applications. Vlasov et al. [3] reported that under ballistic impact loading conditions, the most dominant and vital failure modes are spalling and bending-induced tension on the back side of the glass plate. Chemically strengthening is a promising process to improve the glass mechanical properties [4–6]. It is an ion-exchange process in which the glass substrates are dipped into the molten salt with the temperature below glass transition point. In most cases, smaller Na^+ ions in the glass are replaced by larger K^+ ions from the salt bath. This exchange process of K+ and Na+ ions develops a compressive stress layer in the glass and by controlling the amount of K + ions exchange within glass can result in different stress profiles. The thickness of compressive stress profile is critical and a thin compressive layer makes it more vulnerable to failure.

Many researchers have worked on the flexural strength of glass over the past several decades [7–9]. However, in most of these published works, experiments on glass specimens are only conducted in quasi-static loading conditions. Recently, there is a few literatures focusing on the dynamic flexural strength of glass and ceramics. Xu [10,11] conducted both four-point-bending tests and ring-on-ring biaxial flexural strength tests on borosilicate glass under both quasi-static and dynamic loading conditions. The experimental results showed that the flexural

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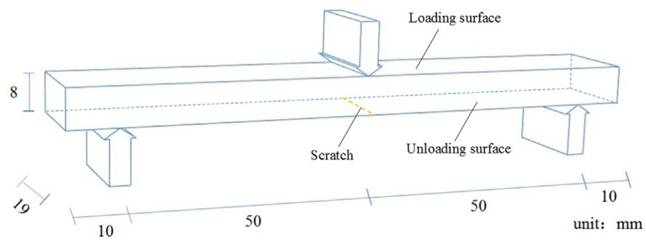

Fig. 1. Schematic of the three-point-bending experiment of glass specimen.

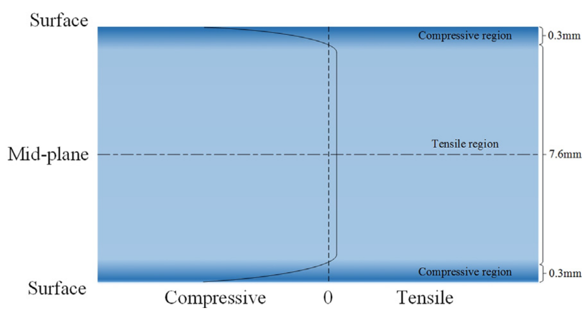

Fig. 2. Schematic of residual stress in CSG.

strength of the borosilicate glass strongly depends on the applied loading rates. Belenky [12] also reported that the flexural strength of alumina is distinctly rate-sensitive. However, there are less papers focus on the dynamic flexural strength of chemically strengthened aluminosilicate glass, and it is of significant interest to experimentally observe its failure process to static and dynamic loading.

Under flexural loading, glass strength is typically limited by surface defects rather than bulk defects [13]. Therefore, surface scratches on the surface of the glasses would affect the flexural strength obviously. Li et al. [14] conducted a series of single point scratch tests on soda-lime glass slides using spherical and conical indenters to study the deformation and brittle fracture behavior of scratched glass. Varner et al. [15] studied the scratch behavior of ion-exchanged alkali aluminosilicate glass using sliding indentation by pyramidal tips. Their experimental results showed that the scratch behavior for highly ion-exchanged glasses differs from non-strengthened glasses by the preferential formation of lateral cracks prior to the formation of the median crack. Furthermore, in reference [16] the authors experimentally showed that the flexural strength after Vickers diamond scratching of ion-exchanged glass decreases sharply. Swab et al. [17] studied the influence of surface scratches on the flexure strength of soda-lime silicate and borosilicate glass. A diamond scribe with a spherical tip containing embedded diamond chips was used to generate all the scratches. It was found that in all instances the flexure strength decreases significantly when a 1 N scratch is introduced on the tin surface but when the scratch load increases any additional strength loss is minimal.

In this paper, we experimentally studied the surface scratch and loading speed effects on the three-point-bending strength of both annealed aluminosilicate glass (AG) and chemically strengthened aluminosilicate glass (CSG). A blunt indenter was used to scratch the specimens by different normal loads and the dynamic tests were conducted utilizing a modified SHPB. The failure process in the glass specimens under three-point-bending test was analyzed using high-speed cameras which captured the entire crack initiation and propagation processes. Additionally, the 3-point-bending experiments were also conducted on scratched annealed and CSG specimens to understand the influence of surface scratch on the flexural strength of both materials.

2. Experimental procedure

2.1. Preparation of glass specimens

The annealed and chemically strengthened aluminosilicate glass tested in this work was provided by Tie Mao Glass Company of China, in the form flat plates of thickness 8.0 mm. The specimens were first cut from the as received plates with dimensions of 19 mm × 8 mm × 120 mm. In the three-point-bending tests, the specimens were loaded in the thickness direction, as shown in Fig. 1. It should be pointed out that two thin surface layers which were controlled by compressive residual

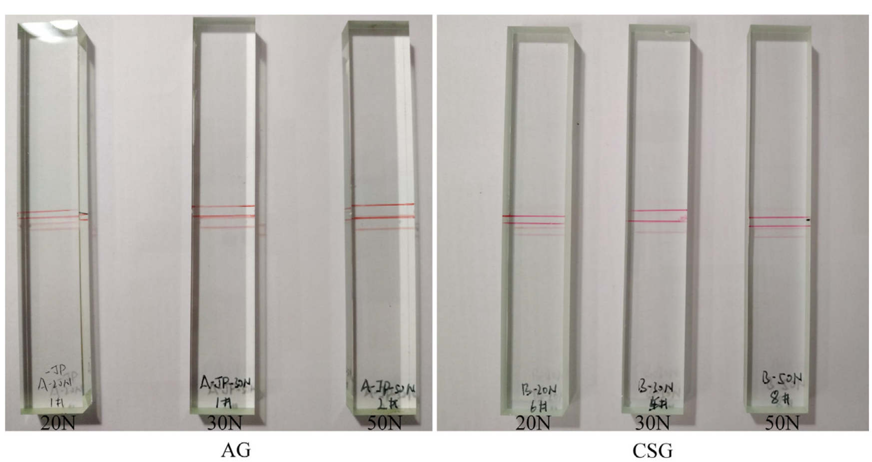

Fig. 3. Scratched specimens during experiments.