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Experimental and numerical evaluation of transparent bulletproof material for enhanced impact-energy absorption using strengthened-glass/polymer composite

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ABSTRACT

The ballistic impact resistance of glass/polymer composites was evaluated in relation to application in high-performance and lightweight bulletproof materials by using a strengthened soda-lime silicate glass. An effective strengthened-glass fabrication method was developed, which involves combined reinforcement incorporating ion exchange using dispersed concentrated potassium nitrate powder, followed by quenching at 15 K/s. The static compression test of the strengthened glass was approximately 3.7 times greater than that of the parent glass. The elastic modulus of the strengthened glass through the dynamic compression tests increased from 58.7 to 72.9 GPa as compared to the parent glass at a strain rate of 1042/s. As a result, we confirmed that the strengthened glass exhibits anisotropic behavior and high impact resistance. In addition, the fracture behavior of tested specimens from the finite element simulation appeared in good agreement with the experimental results. By laminating the two strengthened-glass samples with two continuous polycarbonate sheets at the back, we achieved a ballistic limit velocity of 892.9 m/s and reduced the thickness of the bulletproof materials from 28.83 to 18.15 mm.

1. Introduction

Glass or glass/polymer composites are widely used in transparent bulletproof windows for automobile, military-vehicle, warship, and aircraft windscreens, because of their lightweight, high impact resistance, transparency, high resistance to chemical attack, and low manufacturing costs [1–3]. Currently, in order to obtain glass/polymer composites with a high impact limit velocity for projectiles along with minimal areal density, a number of studies on the ballistic performance of these materials are being conducted using ballistic impact tests [4,5] and finite element calculations [6,7].

There are many important factors that influence ballistic performance, such as the mechanical properties of the laminated glass [8], the impact velocity of the projectile [9], the fracture behavior of the glass under impact [10], and the lamination sequence [11]. In particular, if the flexural strength (σ_f) of the glass is increased, this can increase the resistance to the kinetic energy applied by an incident bullet; further, increased σ_f leads to multiple resistance types, due to a reduction in the impact energy transmitted to the back layer of the bulletproof material [9,12]. Moreover, the ballistic performance is also increased when the Vickers hardness (H_V) and fracture toughness (K_C) values of the glass are increased, because the resultant glass has high damage and crack propagation resistance on the glass surface once the impact of a high-velocity bullet is suppressed [13]. Therefore, in order to produce a glass/polymer composite with high ballistic impact resistance, it is necessary to determine a means of strengthening glass so that an optimal compressive-stress depth on the glass surface is obtained. This can be achieved via the suppression of surface-flaw or crack propagation. In addition, most of the glass/polymer composites have anisotropic properties on the shock loading [14,15]. Therefore, the dynamic properties such as the elastic properties as a function of the strain rates can predict the impact resistance and shock wave

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propagation in anisotropic specimens [15,16]. As such, in order to confirm the protection effect of the strengthened-glass/polymer composites, it is important to have a full analysis of the static and dynamic mechanical tests.

There are many methods of strengthening glass, such as the use of composite material laminates [17], surface crystallization [18], ion exchange [19,20], and thermal strengthening [21]. Above all, ion-exchange or heat-strengthened glass has excellent impact resistance, because these glass surfaces have high strain energy as a function of the compressive stress. Accordingly, as regards strengthening of laminated glass for use in bulletproof material while considering the compressive stress, the light transmittance, cost, and thickness (over 3 mm) of the glass, the methods involving ion-exchange or heat strengthening by quenching are most suitable. These techniques can yield uniform and high compressive stress on the fabricated glass surface. However, the traditional ion-exchange method is generally conducted in a molten salt bath using a diluted potassium nitrate (KNO_3) solution with low KNO_3 concentration, and the long process time of this method is problematic. In addition, when ion-exchange glass is destroyed under application of the critical load by an incident bullet, many new slip bands are created in the fracture direction and small fragmentations occur [16]. The resultant small glass fragments damage the rear polymer film and accelerate the destruction of the bulletproof material; this can cause serious injury. Therefore, to solve the ion-exchange-method problems, further studies are required to ensure optimal strengthened-glass fabrication conditions and to develop a new process with reduced ion-exchange time.

In this study, we confirmed the optimum fabrication conditions for strengthened glass for use in bulletproof materials with polymer composites based on increased ballistic performance and decreased thickness and weight. Specifically, in order to solve the problematic long process time (4–12 h) of the traditional ion-exchange method, a novel technique based on combined reinforcement was developed that involves ion exchange for a short process time of 5–20 min using dispersed concentrated potassium nitrate powder, followed by quenching. Fabricated bulletproof material containing the strengthened glass was then evaluated based on the National Institute of Justice (NIJ) standard-0108.01 using a 5.56-mm M-16 bullet, and it was confirmed that the optimum lamination sequence yielded excellent ballistic performance in accordance with NIJ level III (V_{50}: 838 ± 15 m/s). V_{50} is defined as the ballistic velocity at which 50% of the projectile penetrates the material and V_{100} is defined as the ballistic velocity at which 100% of the projectile penetrates the material. In a pre-experimental study [18], we fabricated a bulletproof material with a thickness of 28.83 mm, 63.98-kg/m^2 area density, 5.76-kg weight, and 850-m/s V_{50} using parent soda-lime silicate (SLS) glass. Recently, bulletproof materials using SLS glass with a thickness of 23.85 mm have been reported [22]; therefore, we confirmed in this study that thin (18–20 mm), lightweight glass/polymer composites can be fabricated using strengthened glass. Further, the light transmittance of the fabricated bulletproof material was measured, and it was found that this glass/polymer composite satisfied the Military Specification (MIL-G-5485D) standard for transparent bulletproof materials. Lastly, we conducted finite element simulation, and the results were verified through a comparison of the simulation and experimental results.

2. Experimental procedures

2.1. Preparation of strengthened SLS glass

SLS glass specimens from Hankuk Glass Industries (Seoul, Republic of Korea) with a composition of 71.9SiO_2–13Na_2O–9.3CaO–5.6MgO–0.1Fe_2O_3–0.07Al_2O_3–0.02K_2O–0.01TiO_2 (mol%), dimensions of 310 × 310 mm^2, and thicknesses of 3 and 8 mm were prepared. To remove the cracks on the edges of the parent SLS glass samples, the edges were polished using silicon carbide sandpaper ranging from 400 to 2500 grit. In order to reduce the ion-exchange time, the parent glass was strengthened using the newly developed method. This is a combined-reinforcement technique involving quenching after ion exchange using dispersed concentrated KNO_3 powder (Ducsan Ltd., 99%, Republic of Korea). Specifically, the bottoms and surfaces of the SLS glass specimens were covered with KNO_3 powder in a stainless steel tray and then heated at a heating rate of 10 K/min in an electric furnace at 490 °C for 5–20 min. This was followed by rapid cooling at 15 K/s using an air compressor. We then confirmed the optimal fabrication conditions required to obtain strengthened glass with enhanced mechanical properties using various ion-exchange times.

2.2. Mechanical property testing

The H_V and K_C values of the parent and strengthened SLS glass specimens were measured using a Vickers microhardness tester (Matsuzawa Inc., MXD-CX3E, Japan). A maximum load of 4.9 N (500 gf) was applied to the specimen surfaces with a dwell time of 30 s. Ten indentations were measured for each glass, and the mean and standard deviations were calculated. H_V was calculated using the ASTM C 1327–08 standard test method and K_C was computed as a function of the propagated crack length from the corner of the indentation, following ASTM E 1820–11.

A universal testing machine (Hounsfield Co., H10K-C, UK) was used to measure the static three-point σ_f. Rectangular (4 mm wide and 45 mm long) glass specimens were prepared with various thicknesses (3 and 8 mm) using a 10-kN calibrated load cell and a cross-head speed of 2 mm/min, which led to a strain rate of 0.4×10^{-3}/s. Inner and outer spans of 20 and 40 mm were used, respectively. A minimum of 10 specimens were tested and the mean and standard deviations were calculated. The static compression test with maximum breaking load (P) and σ_f were confirmed using the ASTM C 1161–13 standard.

The dynamic compressive tests were conducted using the split Hopkinson pressure bar (SHPB) apparatus with 20 mm diameter input and output pressure bars. As shown in Fig. 1(a), the height and diameter of the tested specimens were 8 mm, respectively. The cylindrical specimen is sandwiched between the input–output pressure bars. The elastic waves were measured with pairs of strain gauges (Measurements Group CEA-06-250UW-350), and the signals from both gauges were amplified (Measurements Group 2210A bandwidth 100 kHz). Dynamic compressive tests were conducted at various strain rates in the range between 833/s and 1042/s. In order to avoid repeated loading of the dynamic test, a plate of aged steel was placed on the impact surface of the bars (2 mm thick and 20 mm in diameter). The theoretical details and the evaluation method can be found in Refs. [14,15]. To obtain reliable stress–-strain curves of the parent and strengthened-glass specimens, at least three specimens were evaluated for each case.

2.3. Testing of physical and optical properties

To confirm the compressive stress depth, a selected surface of the strengthened glass was polished to a depth of approximately 1.0 mm; the polished surface is labeled in Fig. 1(b). The penetration depths of the potassium ions in the strengthened-glass specimens with various thicknesses (3 and 8 mm) were measured using an electron probe microanalyzer (EPMA; JEOL Ltd., JXA-8900, Japan), from the polished surface to a depth of 0–600 μm. The compressive stress layer obtained by quenching after ion exchange was