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Damage visualization and deformation measurement in glass laminates during projectile penetration

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Abstract

Transparent armor consists of glass-polymer laminates in most cases. The formation and propagation of damage in the different glass layers has a strong influence on the ballistic resistance of such laminates. In order to clarify the course of events during projectile penetration, an experimental technique was developed, which allows visualizing the onset and propagation of damage in each single layer of the laminate. A telecentric objective lens was used together with a microsecond video camera that allows recording 100 frames at a maximum rate of 1 MHz in a backlit photography set-up. With this technique, the damage evolution could be visualized in glass laminates consisting of four glass layers with lateral dimensions 500 mm × 500 mm. Damage evolution was recorded during penetration of 7.62 mm AP projectiles with tungsten carbide core and a total mass of 11.1 g in the impact velocity range from 800 to 880 m/s. In order to measure the deformation of single glass plates within the laminates, a piece of reflecting tape was attached to the corresponding glass plate, and photonic Doppler velocimetry (PDV) was applied. With the photonic Doppler velocimeter, an infrared laser is used to illuminate an object to be measured and the Doppler-shifted light is superimposed to a reference light beam at the detector. The simultaneous visualization and PDV measurement of the glass deformation allow determining the deformation at the time of the onset of fracture. The analysis of the experimental data was supported by numerical simulations, using the AUTODYN commercial hydro-code.

Keywords: Glass laminate; Transparent armor; Impact damage; High-speed photography; Photonic Doppler velocimetry

1. Introduction

Transparent armor is one of the most critical components in the protection of light armored vehicles. Typical transparent armor consists of several layers of glass with polymer interlayers and backing. The design of transparent laminates for ballistic protection is still mainly an empirical process. Considering the high number of parameters influencing the performance, such as number, thickness and type of the glass layers, and thickness and type of the bonding layers and the polymer backing, the necessity to have tools for a systematic optimization becomes obvious. A detailed understanding of the dominant mechanisms during projectile penetration is required in order to improve the performance of multi-layer ceramic faced transparent armor.

The damage mechanisms in single glass plates have been studied by several researchers. The fracture propagation initiated by projectile impact and explosive loading was visualized by means of Schlieren photographs and shadowgraphs by Schardin [1], Christie [2], Rader [3] and Glenn [4]. Crack propagation velocities in the range from 1500 to 2000 m/s were determined in these investigations. Already in the late 1930s, Schardin [5] had conducted tests, where a projectile impacted the edge of a glass plate, and observed the

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fracture propagation by means of a Cranz-Schardin camera using the shadowgraph technique. He described The formation and propagation of stress waves in this so-called edge-on loading situation [6]. In the 1980s, Hornemann et al. rediscovered the usefulness of the edge-on impact (EOI) technique for the investigation of fracture phenomena [7]. Senf et al. [8] and Strassburger et al. [9] conducted the comprehensive studies using the edge-on impact technique in order to determine he propagation velocities of crack and damage in several types of glass and glass ceramics [10] targets impacted with steel projectiles in the velocity range from 50 to 1000 m/s. Senf et al. also demonstrated the nucleation of cracks by the compressive (longitudinal) wave in the interior of K5-glass blocks with dimensions 150 mm × 100 mm × 100 mm in a high-speed photographic study [11]. Bourne et al. [12] also found the evidence of compressive failures in soda-lime and borosilicate glasses by means of high-speed photography during plate impact tests. A failure front was formed through nucleation of cracks at local inhomogeneities in the glass, and a failure front velocity of about 2 km/s was measured. Behner et al. [13] conducted the reverse ballistic experiments with rod shaped projectiles and cylindrical borosilicate glass targets. Failure front velocities in the range from 1390 m/s to 2200 m/s were observed for impact velocities between 948 m/s and 2328 m/s. The work of Behner was extended by Anderson et al. [14], and the simulations of the experiments were conducted by Anderson and Holmquist [15].

Strassburger et al. [16] investigated the propagation of wave and fracture in glass laminates by means of the EOI technique, and observed a strong attenuation of the stress waves in the bonding layers. From the second layer on fracture was initiated mainly close to the rear side of the glass layers after the reflection of the compressive wave as a rarefaction wave. Bourne and Millet [17] studied the influence of boundaries in glass targets using plate impact tests. They observed a strong influence of the surface finish, i.e. the flaw distribution at the surfaces, on the formation of cracks in a soda-lime glass laminate. Only very few reports are available in the open literature on impact damage in glass-laminates of the type that could be employed as transparent armor in military vehicles. Bless and Chen [18] provided a detailed description of damage due to high velocity impact of fragment simulating projectiles on thick laminates, comprising seven layers of soda-lime glass. However, the focus was on the damage assessment after the impact test was completed. Grujicic et al. [19] developed a material model for soda-lime glass, which treats glass as a stochastic brittle material which damage dominated deformation and ultimate failure are controlled by the pre-existing flaws. The model was applied to predict the multi-hit performance of laminates consisting of five glass and five polycarbonate layers, respectively [20]. Each of the glass laminates was tested with 4 shots and the computational results were compared to the final state of damage after each hit. In the study presented here, damage evolution was observed during projectile penetration and dynamic fracture propagation, and the deformation of single glass layers were measured.

2. Experimental configuration and measuring techniques

Eight impact tests were conducted with caliber 7.62 mm armor piercing (AP) projectiles with tungsten carbide core, which total mass was 11.1 g. The impact velocities were in the range from 800 m/s to 880 m/s. The glass-laminates consisted of four layers of commercial soda-lime glass and a 3 mm thick polycarbonate layer at the rear side. The thickness of the glass-layers was 10 mm + 3 × 12 mm, resulting in a total thickness of glass being 46 mm. Four of the laminates were bonded with PVB (polyvinylbutyral), PU (polyurethane) bonding layers were employed with four of the laminates. Each of the bonding layers had a thickness of 0.8 mm. The lateral dimensions of the laminates were 500 mm × 500 mm. The edges of the single glass plates were ground and polished in order to enable a clear view into the interior. Damage evolution in the glass-laminates was visualized by means of Shimadzu HPV microsecond video camera, which was positioned at the side of the specimens, perpendicular to the shot axis. Due to the large dimensions of the glass plates, a telecentric objective lens had to be used with the high-speed camera in order to achieve a sufficiently high parallelism of the optical path. Pre-tests with a regular zoom lens had demonstrated that the superposition of reflections from the surfaces of the glass plates simulated an unrealistic damage evolution. The glass-laminates were illuminated with a flashbulb from the opposite side such that the intact glass layers appeared bright in the high-speed photographs. The damaged parts of the glass appeared dark, due to the deflection of the light by the fracture surfaces. The glass-laminates were clamped between two steel frames and the steel frames were held by fixed counter bearings so that the target as a whole could not move in the direction of the shot. In order to measure the residual projectile velocity in case of target perforation a high-speed video camera was placed at the side behind the target.

For the measurement of the deformation of single glass plates within the laminates, a piece of reflecting tape was attached to the corresponding glass plates, and photonic Doppler velocimetry (PDV) was applied. The PDV measuring technique was developed and described by Strand et al. [21] and utilizes the optical Doppler effect for velocity measurement. With a photonic Doppler velocimeter an infrared laser is used to illuminate the moving object to be measured. “Optical fibers are used to transport light from the laser to a probe containing a lens that focuses the light onto the moving surface. This same probe then collects a fraction of the light that is scattered or reflected from the moving surface and sends the Doppler-shifted light to the detector” [21]. The Doppler-shifted light is then superimposed on a reference, non-Doppler-shifted light beam at the detector. The resulting beat signal is then recorded on a digitizer. The beat frequency is directly proportional to the velocity of the moving object and can be extracted from the raw data by means of short-time Fourier transformation. Fig. 1 shows a schematic of the experimental set-up. The layout of the laminated glass targets is illustrated in Fig. 2.