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# Behavior of Strengthened Glass under High-Velocity Impact

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# Поведение упрочненного стекла при высокоскоростном ударном нагружении

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*Проведено сравнение поведения необработанного стекла и стекла, подвергнутого обработке плавиковой кислотой. Установлены факторы, определяющие высокие баллистические характеристики упрочненного стекла.*

***Ключевые слова***: необработанное стекло, плавиковая кислота, упрочненное стекло, ударное нагружение.

Treatment of silicate glass by hydrofluoric acid results in removing surface defects which are responsible for quite low strength of the glass. In this way, strength of the treated glass can be increased by two orders of magnitude [1]. The strengthened (treated) glass was found to exhibit quite high ballistic performance: a 10–15 mm thick strengthened glass plate is capable of stopping a deformable steel projectile at impact velocities as high as 720 m/s.

The present work was aimed at finding out principal differences in impact behavior of untreated and treated glasses and revealing factors determining the high ballistic performance of the strengthened glass.

The impact behavior of the untreated and treated glass plates was studied experimentally by means of high-frequency photographic recording ($2 \cdot 10^5$ frames per second) and multi-frame x-ray recording (operating voltage of 400 kV, exposure time of 0.1 $\mu$s) under the same loading conditions (impact by 60° cone nose steel projectiles at a velocity of 700 m/s). Test specimens were 15 mm thick and $150 \times 150$ mm wide.

Examples of the high-frequency photographs are presented in Fig. 1. In both treated and untreated glass, propagation of a disturbed zone ahead of the projectile was recorded. The propagation velocities were found from data of the time-resolved photographic recording as shown in Fig. 2 representing position versus time plots for radii of the disturbed zones and the projectile rear end.

The disturbed zone in the untreated plates propagates with a velocity of 1500 m/s. It is equal to the crack velocity in silicate glass [2], and the disturbed zone can be unambiguously identified as a fractured zone. It is seen in the photographs that the stress wave is being reflected from the rear surface of the plate by 4 $\mu$s after the striking instant. The reflection is followed by the opposing fracture propagating toward the projectile. By 7 $\mu$s, joining of the direct and opposing fractures occurs, and the plate is completely disintegrated. These data are in line with the known concepts of impact behavior of brittle bodies [3, 4].

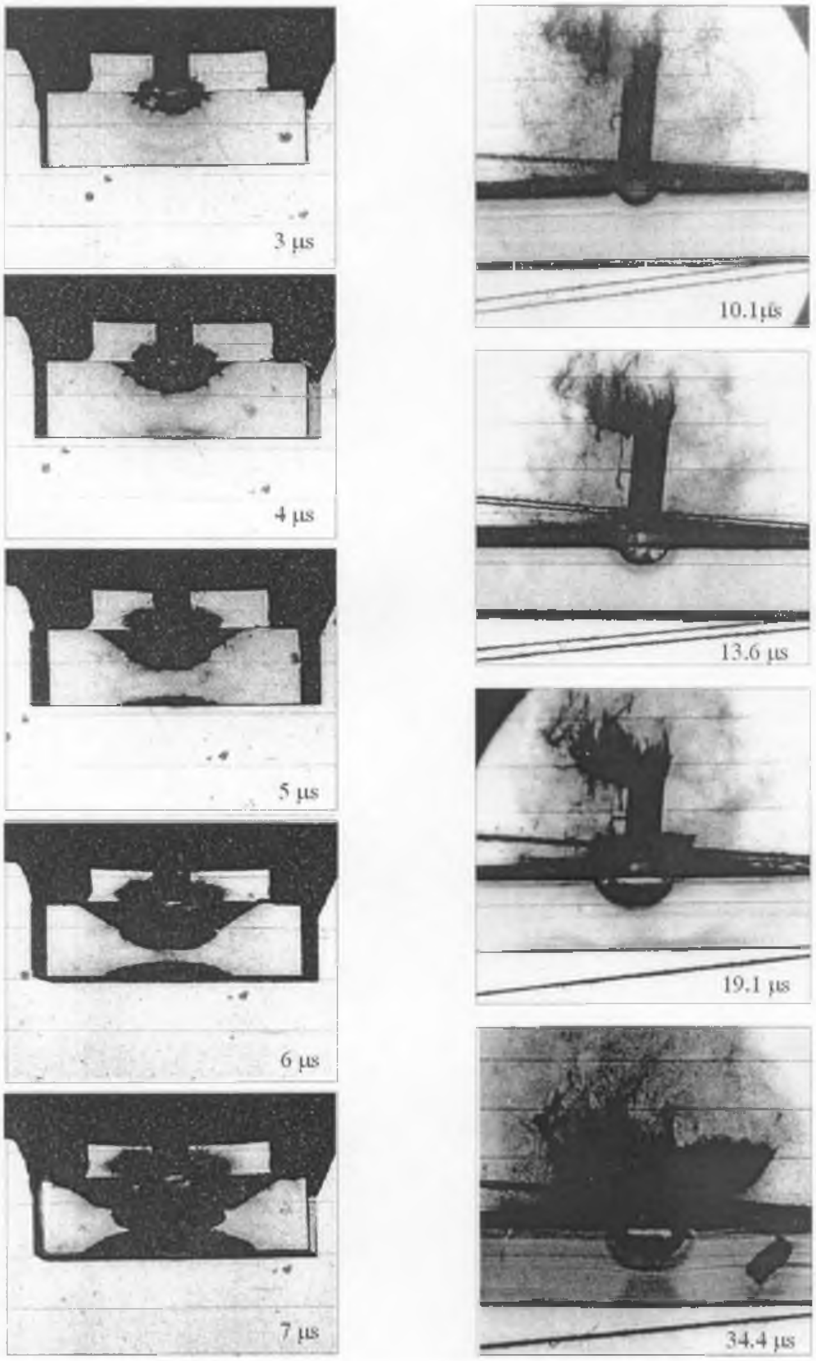

Fig. 1. High-frequency photographic sequences of untreated (left) and strengthened (right) glass plates impacted by a steel projectile at $V = 700$ m/s.

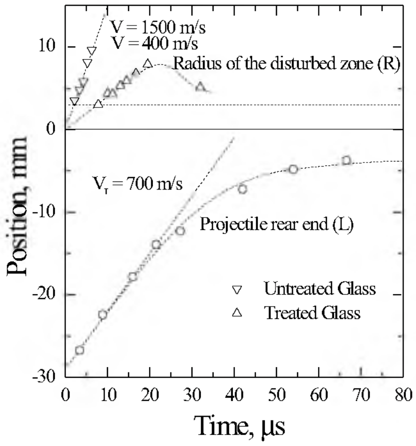

Fig. 2. "Position vs time" curves for the disturbed zones in glass (top) and projectile rear end (bottom).

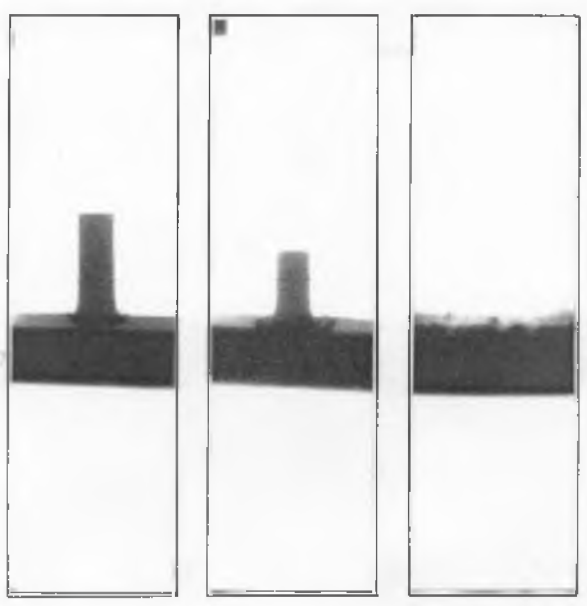

Fig. 3. Flash x-ray photographs of the projectile erosion on the front surface of a 10 mm thick glass plate. (Impact velocity $V = 700$ m/s.)

A quite different pattern is observed in the treated glass plate. The projectile is eroded on the glass plate front surface without penetrating it (see flash x-ray photographs in Fig. 3). The disturbed zone propagates with a velocity of 400 m/s. This velocity corresponds to the projectile flow velocity, $U = V_i \tan(\alpha/2)$, on a rigid surface (here $V_i$ is impact velocity, and $\alpha$ is the projectile cone nose angle). After 20 $\mu$s, propagation of the zone terminates, and its reverse motion (contraction) is observed. Noteworthy is the fact that the reverse motion starts at a point in time where a deceleration of the projectile occurs and, consequently, the impact pressure on the projectile/target interface is reduced. Thus, the disturbed zone in the treated glass can be interpreted as a region of quasi-static stresses induced by the pressure on the projectile/target interface. Important is the fact that no fracture is nucleated in this region.

The next significant difference in the impact behavior of treated and untreated glass plates is that no opposing fracture is observed in the treated plates.

Fracture of the treated plate originates at its side edges about 40 $\mu$s after the striking instant.

The data of high-frequency photography and flash x-ray recording lead to the following conclusions concerning the behavior of the strengthened silicate glass under high-velocity impact loading conditions.

- The projectile is eroded on the front surface of the strengthened glass plate without penetrating it, i.e., the glass plate acts as an “absolutely rigid wall.” This kind of behavior is accounted for the fact that the stresses induced by the projectile impact do not exceed contact tensile strength of the treated plate.
- No opposing fracture takes place in the strengthened glass plate as the tensile stresses on the rear plate surface induced by the reflection of the stress wave do not exceed the tensile strength of the treated glass.
- Fracture of the strengthened plate nucleates at its side edges as there are rough defects on the edges, which can not be completely removed by the treatment. The fracture occurs much later after decelerating the projectile down to zero velocity (full stop of the projectile on the plate front surface).

Quite apparently, the above mechanism for the strengthened glass can be realized provided that velocity – dependent stresses do not exceed the strength of the glass, i.e., within a definite impact velocity range. Otherwise, the impact behavior of the treated glass does not differ from that of the untreated glass.

## Резюме

Проведено порівняння поведінки необробленого скла і скла, що було оброблене плавиковою кислотою. Установлено фактори, що визначають високі балістичні характеристики зміцненого скла.

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