The efficiency of ceramic-faced metal targets at high-velocity impact

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Abstract. The paper represents experimental results and engineering evaluation concerning the efficiency of composite materials to be used as an additional protection during the high-velocity interaction of a tungsten rod with a target in the velocity range of 1...5 km/s. The main parameter that characterizes the high-velocity interaction of a projectile with a layered target is the penetration depth. Experimental data, numerical simulation and engineering evaluation by modified models are used to determine the penetration depth. Boron carbide, aluminum oxide, and aluminum nickelide are applied as a front surface of targets. Based on experimental data and numerical simulation, the main characteristics of ceramics are determined, which allows composite materials to be effectively used as additional elements of protection.

1. Introduction

Different types of ceramics and composite materials (cermets, nanostructured materials) with high dynamic strength characteristics are used as additional elements of protective constructions [1]. To select the most effective ceramics for layered constructions from available and newly developed materials, there is a need in the comparison of shock resistance by varying the initial conditions for the high-velocity impact of compact and rod projectiles. Experimental data for the penetration depth of high-density rods into semi-infinite targets are given for aluminum oxide Al2O3, boron carbide B4C and aluminum nitride AlN in [2, 3]. Reliable methods for the evaluation of characteristics during high-velocity impact are experimental investigation, physical and numerical simulation for the penetration of projectiles into targets and constructions containing the layers of metals, ceramics, and composites [4-11].

The determination of the penetration deep and residual velocity of a projectile behind a target is a very effective test to detect the shock resistance of ceramic materials [2, 5, 7, 8]. In experiments, targets consist of semi-infinite ceramic blocks or configurations of layers, where ceramics is placed on the front surface of semi-infinite targets or between metal plates.

2. Formulation of the problem and investigation results

Based on the experimental and numerical results obtained [5-11], ceramic and composite materials such as aluminum oxide Al2O3 (corundum), boron carbide B4C, and a composite AlN were
investigated as additional elements of armor protection, considering strength and weight-dimension characteristics.

The main physical and mechanical characteristics of materials are given in Table 1, where: \( \rho_0 \) is the density; \( E \) is the Young’s modulus; \( H_m \) is the microhardness; \( H_d \) is the dynamic hardness; \( \sigma_T \) is the yield strength.

**Table 1. Physical and mechanical characteristics of materials**

| Material  | \( \rho_0 \times 10^3 \), kg/m³ | E, GPa | \( H_m \), GPa | \( H_d \), GPa | \( \sigma_T \), GPa |
|-----------|---------------------------------|--------|----------------|----------------|-----------------|
| B₃C       | 2.4                             | 475    | 38             | 42-49          | 64.5            |
| Al₂O₃     | 3.8                             | 407    | 28             | 20-25          | 59.3            |
| AlN       | 3.25                            | 18     | -              | -              | 16-22           |

An imitation model [5, 8] based on the hydro-dynamical model of armour-penetration was proposed to predict the penetration depth of rod projectiles into solid targets. The main advantage of this model is to take into account the dynamic compressibility of a projectile material in the area of contact with a target. The calculations conducted for the penetration depth of tungsten rod projectiles into steel targets at the impact velocities of 1000...5000 m/s are in good agreement with experimental data [2, 3, 5, 6, 8]. Figure 1 shows the relative penetration depth of TNI-90 projectiles (tungsten – 90%, nickel – 3%, iron – 7%) with a length of 6 cm and an elongation of 10 calibers into steel and ceramic semi-infinite targets. The calculation results are in good agreement with experimental data.

![Figure 1. Relative penetration depth of tungsten rods into semi-infinite targets](image)

During shock-wave loading, ceramic plates are broken into fragments and, in most cases, can not be reconstructed after experiments, which does not allow the penetration depth of projectiles to be determined. This fact is illustrated by the X-ray image of the projectile and fragments of the fractured ceramic plate Al₂O₃ at the impact velocity of 760 m/s (figure 2).

The experiments have shown that ceramics has a significant resistance to the penetration of a projectile at impact velocities below 1000 m/s due to high strength characteristics. At the first stage of penetration this fact is proved by the intensive plastic deformation of the head part of the projectile and fragmentation of ceramics in the contact zone. Then the deformed projectile penetrates into the
fractured ceramic sample.

![Figure 2](image1.png)

Figure 2. X-ray image of Al₂O₃ ceramics fracture during the impact of a 7.62 mm bullet (a) and the computation for the level distribution of the fractured material (b)

The efficiency of ceramic samples was determined using an indirect method, in particular, by the penetration depth of a projectile into a massive metal target placed behind ceramics according to the scheme, as showed in figure 3.

![Figure 3](image2.png)

Figure 3. Scheme for recording the penetration depth of a projectile into layered targets

The efficiency of the shock resistance of ceramics (ε) is determined from equation [12]:

$$\varepsilon = 1 - \frac{\rho_M r + \rho_K c}{\rho_M x}$$  \hspace{1cm} (1)

where \(x\) is the penetration depth into a semi-infinite metal plate; \(r\) is the penetration depth into a ceramic-faced metal plate; \(c\) is the thickness of a ceramic plate; \(\rho_M\) is the density of a plate; \(\rho_K\) is the density of ceramics. The efficiency of construction (ε) is less then or equal to zero, if the mass of a composite plate does not exceed the mass of a target per unit area.

The efficiency of ceramics and composites was evaluated using the experimental data, numerical simulation [8-10] and formula (1) in the impact velocity range of 1...6 km/s, as shown in Fig. 4. The notations are used as follows: an averaged experimental dependence for Al₂O₃ ceramics at impact velocities of less than 2 km/s (1); ZrO₂ (2); corundum (3); Al₂O₃ (4); (TiB₂ + B₂C) (5); (TiC + NiCr)
The experiments were carried out using the following projectiles: a 7.62 mm bullet (1); a ball (2-6); a rod (7). The results show that the maximum efficiency of ceramics corresponds to impact velocities up to 1.5 km/s. The efficiency of ceramics is decreased with increasing impact velocities. Some increase in the efficiency was observed for Al₂O₃ ceramics (corundum) and a (TiB₂ + B₄C) metal composite at impact velocities of 5-6 km/s. The main reason for the decrease in the efficiency of ceramics is the decrease in the strength of material due to the fracture of ceramics in shock wave.

![Figure 4. Efficiency of ceramics and composite materials at high-velocity impact](image)

The penetration depth of a tungsten rod into layered targets was calculated considering weight-dimension characteristics. A target is a combination of a semi-infinite steel plate and ceramic plate with a thickness of c placed on the front surface of the main target (figure 3). The mass efficiency was calculated by the relation [13] according to the standards of ARL (Army Research Laboratory, USA):

$$e_m = \frac{(x-r)\rho_M}{c\rho_M}$$  \hspace{1cm} (2)

The efficiency of ceramics $\delta$ with allowance for the weight-dimension characteristics of a layered structure was calculated by the imperial ratio:

$$\delta = e_m \frac{L_{cer}}{r}.$$  \hspace{1cm} (3)

where $L_{cer}$ is the penetration depth into homogeneous semi-infinite ceramics.

Figure 5 shows the calculation results demonstrating the efficiency of ceramics with allowance for the weight-dimension characteristics (δ) relative to steel. The efficiency values δ correspond to the ceramics as follows: AlN (1); Al₂O₃ (2); B₄C (3). Ceramics is considered to be effective if the value $\delta > 1$. These dependencies clearly illustrate the high efficiency of composite materials in combination with steel plates against high-velocity rod projectiles at impact velocities up to 1.5 km/s. The efficiency of ceramics depends on mechanical and strength properties of material under dynamic loading. For a example, boron carbide is most effective among other ceramics investigated and reaches maximum impact velocities of 2 km/s.
Figure 5. Weight-dimension characteristics of layered “steel-ceramics” targets at high-velocity impact

3. Conclusion

Thus, the authors of the paper developed the engineering methods evaluating the penetration of high-density rod projectiles into the elements of layered targets. The efficiency of ceramics such as boron carbide, aluminum oxide, and aluminum nickelide placed on the front surface of steel plates was evaluated in the wide range of high-velocity impact. The results have shown that the efficiency of ceramics depends on the mechanical properties of material under dynamic loading. The determining factors were revealed to explain the fracture and fragmentation of material in the contact area. Boron carbide was shown to be more effective ceramics compared to the other ceramics investigated and reached a maximum impact velocity of about 2.0 km/s.

The experimental results demonstrate the reasonable use of complex combined protection against high-velocity rod projectiles and the prospect for the strengthening of protection through the application of high-strength composite materials.

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