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**RESISTANCE OF CERAMICS TO PENETRATION AT IMPACT VELOCITIES ABOVE
5 Km/S**

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Abstract - The resistance of ceramics to penetration at velocities exceeding crack propagation velocities has been studied. The strength resistance of ceramics is found to be as high as several tens GPa. At high penetration velocities, which exclude the weakening of a brittle target due to crack growth, the plastic flow of ceramics is to be occurred. Then, the ceramics strength resistance is to be identified as the dynamic hardness. The nature of realization of strength properties is the same both for metals and ceramics. As to resistance to penetration, ceramics differ from metals, as dynamic hardness of ceramics is about one order of magnitude higher as compared to metals. As a result, the inertial resistance of the ceramic targets to penetration becomes supplemented by the strength resistance of ceramics. It follows that high-velocity penetration of ceramic targets differ from the hydrodynamic model.

At collision velocities of a projectile and ceramic target, which raise the penetration velocities above the ultimate rate of brittle fracture propagation, loading conditions differ qualitatively from those under quasistatic loading and under moderate-velocity impact. Presumably, the high-velocity impact strength of a brittle matter is predetermined by fundamental strength properties rather than by crack nucleation and propagation⁽¹⁾. Therefore, the high strength of ceramics can be attained in the range of high-velocity impact^(1,2).

The high strength of ceramics should contribute the inertial resistance to penetration. In other words, the strength of ceramics becomes important compared to impact (hydrodynamic) pressure. Under such conditions, considerable deviations from hydrodynamic penetration model are to be occurred. According to this model, strength of the projectile and of the target is known to be neglected, and the penetration process is to be considered as the inviscid incompressible flow^(3,4).

The first step in the investigation of the resistance of ceramics

to high-velocity penetration should be a quantitative evaluation of the ceramic strength realized. This is of importance to represent the behaviour of brittle materials under high-velocity loading as well as to define limiting conditions for applicability of the hydrodynamic model to the targets of finite strength.

For collision of bodies of the finite strength, the pressure in the stagnation point on the axis at interface between the projectile and the target can be defined by Alekseevskii-Tate equation (⁵⁻⁷)

$$\rho_1 U^2/2 + R_1 = \rho_2 (V-U)^2 + Y_2 \quad (1)$$

Here, ρ_1 and ρ_2 are target and projectile densities respectively, U is the penetration velocity, and V is the "free flight" projectile velocity. R_1 and Y_2 are the strength terms for target and projectile respectively. On assumption that $R_1 \gg Y_2$, the target strength is to be defined as

$$R_1 = \rho_1 U^2/2 \left[1 - (\rho_2/\rho_1)^2 (V/U - 1)^2 \right]. \quad (2)$$

In this way, the experimental evaluation of R_1 requires measurements of the velocities V and U only.

In the present study, evaluations were performed under collision of an elongated copper rod with ceramic target. Collision velocities V from 5 to 8 km/s raise the penetration velocities above the ultimate rates of brittle fracture propagation. Boron carbide, alumina, silicon carbide ceramics and silica glass as target materials has been studied. Some properties of the targets and the values R_1 obtained are listed in the table 1.

TABLE 1

Target material	Density $\rho_1, \text{g/cm}^3$	Young modulus E, GPa	Microhardness H_m, GPa	Strength resistance R_1, GPa
Boron carbide	2,4	475	42-49	38,6 $\pm$ 7,2
Alumina	3,8	407	20-25	26,0 $\pm$ 5,5
Silicon carbide	3,0	330	25-30	22,0 $\pm$ 4,2
Silica glass	2,5	75,6	9-10	14,4 $\pm$ 2,5

The strength resistance of ceramic targets found to be by the order of magnitude 0,1 of longitudinal moduli.

To represent the general nature of realization of the effect of high strength in ceramics during high-velocity penetration, loading

conditions for target material under high-velocity impact are to be examined.

Under high-velocity impact, the stresses in the target are localized in a narrow zone immediately under projectile-target interface (7,8). In the stagnation point, the target material is in the state of hydrostatic compression due to large normal stress. These conditions are similar to the plane shock wave loading. It follows, the known relationships which were established for shock waves in solids, could be applied to the target material under high-velocity impact. If the shock wave amplitude exceeds the Hugoniot elastic limit (HEL), the plastic flow of solids is known to occur. Similar transitions were recorded experimentally in brittle media also (9).

Under high-velocity impact, the level of stresses is high enough to overcome the HEL and to give rise to plastic deformation of ceramics. At very high penetration velocities, which make target material weakening due to crack propagation inconceivable, ceramics penetration strength is considered to be defined by the σ_{HEL} . For reason given, the problem on mechanism for realization of the strength properties of ceramics under high-velocity impact can be solved in the same way as well as for metals, i.e. in terms of the plastic deformation.

Accordingly, we examine the characteristics of the resistance of the target material to deformation. For plastic materials, such a characteristic is the dynamic hardness H_d , which is related to the dynamic yield strength Y_d by the known correlatin relation (6)

$$H_d = (3 + 3.5) Y_d \quad (3)$$

The quantity Y_d is related to the Hugoniot elastic limit σ_{HEL} through the use of relation

$$Y_d = \sigma_{HEL} (1 - 2\mu) / (1 - \mu) , \quad (4)$$

where μ is the Poisson ratio.

Having in mind the relations given, it would be useful to compare experimental values R_1 with H_d calculated according to eqns (3) and (4) using σ_{HEL} values derived from shock wave experiments (10,11).

This comparison is presented in fig.1. Here, the straight lines confine the range where the relation (3) is valid.

The experimental values of R_1 lie within this range. Taking into account the scatter in measured values of σ_{HEL} , the values of R_1 are

Fig.1. Target strength resistance R_1 vs dynamic yield strength Y_d . Experimental data correspond to: silica glass (1), silicon carbide (2), alumina (3), boron carbide (4).

to be considered to correspond to H_d with enough accuracy.

This fact enables us to identify the ceramic strength resistance to high-velocity penetration as a resistance to plastic deformation, i.e. as the dynamic hardness H_d .

Experimental values of R_1 correlate to the elastic moduli E and are close to the microhardness of ceramics H_m . That is not to be regarded as a simple coincidence. Generally, hardness is governed by the critical shear strength, and correlate with the interatomic bonds strength, i.e. with the elastic modulus. For ceramics, the yield strength is close to the theoretical shear strength. Under penetration velocities, which exclude the target weakening by fracture, strength properties of ceramics manifest themselves at a HEL level that is rather high for materials in question. Then, the dynamic hardness of ceramics should be as high as the microhardness H_m . It is to be noted that at penetration velocities below crack propagation velocity, the penetration resistance strength of ceramics does not exceed $0.3H_m$ (12).

In summary, a key performance parameter for ceramics strength resistance to high-velocity penetration is the dynamic hardness. Experimental data and their analysis allow to consider that under high-velo-

city impact, the nature of realization of strength properties is the same both for plastic (metals) and brittle (ceramics) materials. In respect to resistance to penetration, ceramics differ from metals only quantitatively, as dynamic hardness of ceramics is about one order of magnitude higher as compared to metals.

It follows that characteristic of ceramics is much greater specific plastic deformation work $W = H_d / \rho_1$ as compared to metals. This is known to be a key parameter for limits of applicability of the hydrodynamic model to targets of the finite strength. The penetration velocities range, where this model works, is limited by the velocities $U_H \propto W^{1/2}$ (13). In other words, the target strength becomes important compared to the impact pressure at penetration velocities below U_H .

It would be of interest to compare the limiting velocities U_H for ceramics and for hard titanium alloy. It is this alloy that has maximal specific deformation work for metallic targets. In table 2, the values of W and U_H for ceramics and for Ti-alloy are listed.

TABLE 2

Target material	Boron carbide	Alumina	Silicon carbide	Silica glass	Ti-alloy
$W, \text{MJ/kg}$	16,1	6,8	7,3	5,8	0,8
$U_H, \text{km/s}$	7,5	4,9	5,1	4,5	1,7

It is seen that the penetration into ceramics could be described in terms of the hydrodynamic model at velocities several times greater as compared to the most hard metals.

For metal targets, the hydrodynamic limit for penetration is being approached asymptotically at striking velocities $V = 2 \dots 3 \text{ km/s}$, whereas it are velocities V at least of 10 km/s required to reach the point where the strength of ceramics could be neglected. At striking velocities below this threshold, penetration depth in ceramic targets is found to be 50% smaller as compared to hydrodynamic model estimation.

Conclusions— The plastic deformation of ceramics occurs when penetration velocity is high enough to exceed the crack propagation velocity and, thereby, to exclude the target weakening by fracture. The ceramic strength resistance to high-velocity penetration is to be identified as a resistance to plastic deformation, i.e. as dynamic

hardness. Under high-velocity impact, the nature of manifestation of strength properties is the same both for metals and ceramics. As to resistance to penetration, ceramics differ from metals, as dynamic hardness of ceramics is about one order of magnitude higher compared to metals. The strength of ceramics is comparable to the impact pressure in the target, whereas the strength of metals can be neglected compared to impact pressure under high-velocity impact. Therefore, the ceramic strength resistance contribute to a great extent the inertial resistance of the target to penetration.

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