05.1;05.3;06.1;06.4;06.5

Structural transition of ceramic material initiated by high-velocity impact

© V.Ya. Shevchenko[1], A.I. Kozachuk[2], A.I. Mikhaylin[3], S.N. Perevislov[4], B.V. Rumyantsev[2]

[1] Grebenshchikov Institute of Silicate Chemistry, Russian Academy of Sciences, St. Petersburg, Russia
[2] Ioffe Institute, St. Petersburg, Russia
[3] AO „NPO Spetsmaterialov", St. Petersburg, Russia
[4] NRC „Kurchatov Institute" — CRISM „Prometey", St. Petersburg, Russia
E-mail: brum@mail.ioffe.ru

Received December 5, 2022
Revised December 20, 2022
Accepted December 25, 2022

The use of high-modulus ceramic materials under conditions simulating the screen protection of space objects from damage by fragments of space man-made debris is considered. The introduction of an aluminum jet at a speed of $\sim$ 10 km/s into an aluminum barrier located behind brittle material screens was experimentally studied. A comparative analysis of the parameters of the residual cavity in the barrier made it possible to reveal the effect of the structural rearrangement of the ceramic material on the effectiveness of screen protection.

Keywords: screen protection, space man-made debris, ceramic materials.

DOI: 10.21883/TPL.2023.03.55676.19449

The examination of high-velocity interaction of solid bodies is one of the methods for study of materials in extreme conditions. These studies are made relevant, e.g., by the issue of safety of space flight, which arose after a catastrophic increase in the concentration of man-made debris in the near-Earth space.

Screens [1] are used most often to solve the problem of protection of space objects from a compact high-velocity impactor. These screens are efficient at compact impactor velocities below 7–8 km/s [2]. The efficiency of screen protection (SP) in more dangerous scenarios of exposure to man-made debris was examined in [3].

The aim of the present study is to estimate the efficiency of application of high-modulus ceramic materials in screen protection (with account for spallation [4] and other effects shaping the dynamic response of a screen to an impact) in conditions [3] simulating a collision between a fragment of space man-made debris and the duralumin structure of spacecraft.

The physical and mechanical properties of the studied brittle materials are listed in Table 1. Composite material „Ideal,"which has better mechanical characteristics than reaction-sintered materials based on silicon carbide and boron carbide [5–8] and glass (for reference), was among the new ceramic materials studied. Its fine mechanical performance (sound velocity, hardness, and strength) is attributable to diamond crystals, which are its main constituent.

The studies of kinetics of penetration of an elongated impactor into ceramic materials [9] reveal that the end result correlates with the ultimate bending strength. The results of numerical simulations (see the figure, panel *a*) confirmed the mechanism of manifestation of material strength [10] wherein unloading of the region of penetration of an elongated metallic impactor into a ceramic material is accompanied by the destruction of cavity walls and the formation of spallation fragments. Following a certain time delay, these fragments collapse inward onto the impactor, damaging it and destabilizing its further penetration. The amount of damage and the disruption of penetration depend on the relation between physical and mechanical properties and geometric parameters of the impactor and the ceramic barrier.

As the impact velocity increases, other factors characterizing updated conditions of conversion of the kinetic energy of the impactor in interaction with the barrier material (e.g., phase and structural transformations under high pressures) may come into play. For example, the efficiency of application of screens made of materials with a capacity for rapid radial response to high-velocity penetration of an elongated impactor by means of partial melting and evaporation in interaction with the SP was demonstrated in [3].

Preliminary results of numerical simulations of the influence of a high-velocity aluminum impactor on ceramic boron carbide screens (I.V. Guk, 2019, unpublished) revealed the formation of spallation fragments in the interaction region, but did not reproduce the effects of destabilization of an elongated impactor in the course of its subsequent penetration (see the figure, panel *b*). This is evident in panel *a* that characterizes the penetration into a ceramic block.

Table 2 presents experimental data on the SP efficiency determined for a fixed distance between screens and a barrier (see the figure, panel *b*) in the case of a collision between a fragment of man-made debris and the aluminum barrier. The design of the experiment involving an aluminum impactor 3 cm in length and 0.07 cm in diameter with its velocity ranging from 10.2 to 3.7 km/s was detailed in [3]. The use of a barrier of an excess thickness made of AMG6 aluminum alloy provided an opportunity to preserve the cavity and reduce the influence of the back surface to zero.

Table 1. Characteristics of brittle materials

Material	Density $\rho\cdot 10^{-3}$, kg/m^3	Sound velocity, km/s		Hardness H_V, GPa	Ultimate bending strength, GPa
		C_l	C_t		
„Ideal" [5,6]	3.3	14.6	–	63–68	0.43–0.48
Boron carbide [7]	2.52	14	8.8	30	0.44
Silicon carbide [8]	3.1	12	7.7	25–30	0.40–0.42
Silicate glass	2.5	5.9	3.6	5.5	0.15

Table 2. Results of experimental determination of the efficiency of a screen made of different materials protecting an AMG6 barrier from an elongated aluminum impactor with an initial velocity of 10 km/s

Number	Screen material	Material density $\rho\cdot 10^{-3}$, kg/m^3	Number of screens	Overall thickness, cm	m^*, g/cm^2	Cavity depth L, cm	Cavity volume V, cm^3	S_L	S_V
1	–	–	–	–	–	11.3 ± 0.4	10.8 ± 0.5	0	0
2	„Ideal"	3.33	2	0.64	2.1	8.8	3.6	0.23	0.67
3	AMG6	2.7	2	0.66	1.8	8.5	4.4	0.25	0.59
4	Glass	2.5	2	0.70	1.8	9.2	6.9	0.19	0.42
5	Boron carbide	2.52	2	0.8	2.0	9.1	4.2	0.20	0.61
6	Boron carbide	2.52	1	0.82	2.1	8.9	4.2	0.22	0.61
7	„Ideal"	3.33	1	1.0	3.3	5.5	3.6	0.52	0.69

*Mass of a unit screen area.

The SP efficiency was estimated by measuring the relative change in barrier damage parameters in the presence of screens in terms of depth S_L and volume S_V:

$$S_L = 1 - L_i/L_0, \quad S_V = 1 - V_i/V_0,$$

where L_i and V_i are the depth and the volume of the cavity in the barrier protected by screens (i.e., with SP) and L_0 and V_0 are the corresponding values determined without screens.

It follows from Table 2 (rows 2–5) that screens made of different materials reduce the cavity depth by 20–25%, which is indicative of equal levels of local effect of the head end of an elongated impactor on SP under a constant length mass. The influence of the screen material strength does not manifest itself in experiments with a high-velocity collision.

The reduction in volume of the cavity in the barrier protected by screens is proportional to the attenuation of absorbed energy of the impactor due to its dispersion between the screens and the barrier. An additional (compared, e.g., to AMG6 screens in the third row in Table 2) reduction of the cavity volume in the case of installation of screens made of brittle materials is attributable to a secondary radial destabilizing effect of spallation masses of ceramic screens on the elongated impactor (see the figure, panel *b*). The following condition needs to be satisfied in this case: the time of flight of the impactor should exceed the time of radial response (collapse) of spallation fragments of the screen. Since the thickness of the screen is relatively small, the radial effect on the propagating impactor is rather weak and grows stronger with an increase in screen thickness (see the figure, panels *a* and *b*).

The „Ideal"ceramic screen has a clear advantage in impactor dispersion parameter S_V, which assumes the highest values (0.67 and 0.69, rows 2 and 7 in Table 2), This may be attributed to:

— the structural phase transformation of diamond into graphite (accompanied by an increase in specific volume) upon unloading of the region of impactor penetration into the screen under a pressure of 25 GPa [11];

— high sound velocity and, consequently, high acoustic impedance and fine strength characteristics (including spallation strength, which specifies the rate of collapse of fragments upon destruction of the cavity surface).

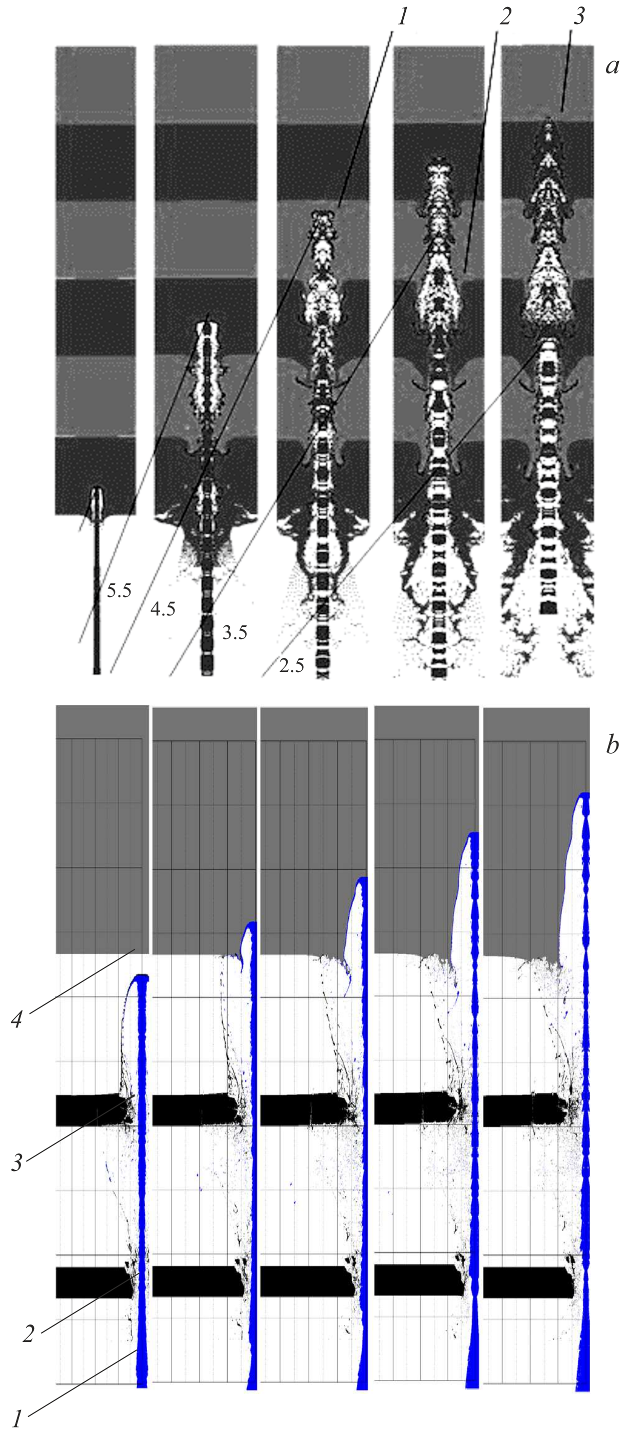
A significant reduction in cavity depth S_L (0.52, row 7 in Table 2) is due to the severe damage sustained by the impactor in a sufficiently „thick" screen (see the figure, panel *a*) [9].

As in the case of copper evaporation [3], the emergence of a lower-density phase in unloading of the penetration region exerts a perturbing influence on the impactor, destabilizes its directional effect, and enhances the dispersion of impactor fragments between screens and in the barrier.

While boron carbide is comparable in strength, it lacks modifications with a significant variation of density in the solid state [12] under pressures up to 50 GPa; therefore, protective screens made of this material are less efficient (rows 5 and 6 in Table 2).

It should be noted that the observed effect is manifested only for an elongated impactor (when the time of fight of the impactor through the penetration region exceeds the time delay of formation and collapse of products of the impactor–screen interaction).

The diamond–graphite phase transformation completes in less than 10^{-8} s [13,14], thus enhancing the process of collapse of transformation products inward onto the impactor penetrating through relatively thin screens.



a — Numerical simulation of penetration of a copper impactor with an initial velocity of 6.6 km/s into a silicon carbide block (in layers of 1 cm) at time points of 1, 8, 15, 22, and 29 μs (left to right) [10]. Inclined straight lines represent the trajectories of impactor elements with the propagation velocity (in km/s) indicated. *1* — End of hydrodynamic penetration, *2* — damage to the impactor, *3* — accumulation of impactor fragments at the bottom of the cavity. *b* — Penetration of an aluminum impactor (*1*) with an initial velocity of 10.2 km/s through screens (*2* and *3*) made of boron carbide into an aluminum barrier (*4*) in 1 μs intervals. The impactor moves from bottom to top. Time increases from left to right.

Thus, levels of attenuation of the damaging capacity of an elongated aluminum impactor with a velocity of ~ 10 km/s penetrating through protective screens made of brittle materials (glass, boron carbide, and ceramic diamond–silicon carbide composite material „Ideal“) were determined experimentally.

The benefits of application of „Ideal“in high-velocity interaction with an elongated aluminum impactor were demonstrated.

The higher efficiency of screen protection made of „Ideal“is attributable to a high value of sound velocity in this ceramic material (up to 15 km/s) and the presence of the diamond–graphite structural phase transformation that is accompanied by a change in specific volume.

Funding

Ceramic material „Ideal“ was designed at NRC „Kurchatov Institute“ — CRISM „Prometey“with financial support from the Russian Science Foundation (grant No. 21-73-30019).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] F. Whipple, Astron. J., **52** (1161), 131 (1947). DOI: 10.1086/106009
[2] IADC-04-03 v. 7, protection manual (2014).
[3] B.V. Rumyantsev, I.V. Guk, A.I. Kozachuk, A.I. Mikhailin, S.I. Pavlov, M.V. Sil'nikov, Tech. Phys. Lett., **47**, 409 (2021). DOI: 10.1134/S1063785021040271.
[4] A.S. Savinykh, G.V. Garkushin, S.V. Razorenov, V.I. Rumyantsev, Tech. Phys., **60**, 863 (2015). DOI: 10.1134/S1063784215060249.
[5] V.Y. Shevchenko, S.N. Perevislov, V.L. Ugolkov, Glass Phys. Chem., **47** (3), 197 (2021). DOI: 10.1134/S108765962103010X
[6] V.Ya. Shevchenko, S.N. Perevislov, Russ. J. Inorg. Chem., **66** (8), 1107 (2021). DOI: 10.1134/S003602362108026X.
[7] S.N. Perevislov, A.S. Lysenkov, D.D. Titov, M.V. Omkovich, D.D. Nesmelov, M.A. Markov, IOP Conf. Ser.: Mater. Sci. Eng., **525** (1), 012074 (2019). DOI: 10.1088/1757-899X/525/1/012074
[8] D.D. Nesmelov, O.A. Kozhevnikov, S.S. Ordan'yan, S.N. Perevislov, Glass Ceram., **74** (1), 43 (2017). DOI: 10.1007/s10717-017-9925-0
[9] B.V. Rumyantsev, Tech. Phys., **54** (6), 790 (2009). DOI: 10.1134/S106378420906005X.
[10] B.V. Rumyantsev, V.Yu. Klimenko, AIP Conf. Proc., **1426** (1), 56 (2012). DOI: 10.1063/1.3686220
[11] V.B. Rozanov, M.A. Rumyantseva, Kratk. Soobshch. Fiz. FIAN, Nos. 3–4, 9 (1997) (in Russian).
[12] A. Hushur, M.H. Manghnani, H. Werheit, P. Dera, Q. Williams, J. Phys.: Condens. Matter, **28** (4) 045403 (2016). DOI: 10.1088/0953-8984/28/4/045403
[13] https://nplus1.ru/news/2017/11/24/X-ray-transition
[14] G.I. Kanel', G.S. Bezruchko, A.S. Savinykh, S.V. Razorenov, V.V. Milyavskii, K.V. Khishchenko, High Temp., **48**, 806 (2010). DOI: 10.1134/S0018151X10060064.