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AN INVESTIGATION OF CERAMIC/ALUMINIUM COMPOSITES AS SHIELDS FOR HYPERVELOCITY IMPACTS

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Summary—The protection efficiency of single-shield bumpers made of composites based on the aluminum matrix containing the disperse ceramic inclusions of SiO_2 or Al_2O_3 is considered for a Whipple-type shield. The aim of the paper is to compare the protection efficiency of the first bumpers made of the metal composites with that for the duralumin shield by impact of spherical steel projectile with the velocity of 5.5 and 7.5 km/s. Mass fraction of the ceramic inclusions accounts for 15 and 30 percent of the total composite. A thick backwall plate was used, and the maximum depth of fragment craters on the witness plate is taken as a protection characteristic of shields made of different materials: reference aluminum alloy, composites under study, and loosely-packed metal powder bumpers. The bumpers made of the metal composites, Al-matrix plus embedded ceramic inclusions, are shown to have the poorer protection efficiency than those made of the duralumin alloy when used with steel impactors. It is shown that by impact of the hypervelocity steel projectile the shield material strength, if it is rather low but not zero, may essentially affect the damage pattern of the backwall in spite of the high level of realized impact pressures.

INTRODUCTION

The shielding system used against meteoroid/debris impacts now universally accepted involves the use of different multi-screen modifications of the Whipple shield. The principal part of the system is a thin outer bumper plate located a certain standoff distance from the protected wall. The function of the first screen is to rupture and to disperse a projectile with a view of decreasing the local action of its fragments on subsequent constructional elements. Considerable advances has been made in creating the effective shielding for practical spacecraft systems from meteoroid and orbital debris impacts [1–3].

However, a search for materials and the inner structure of the first bumper to shatter more effectively a projectile and to disperse more intensively a bumper material is in progress. Stilp and Weber have shown that the impedance mismatch and the order of the layers in two-layer bumpers strongly influences the debris cloud velocities and the fragment number and size [4]. Other shielding approach is the use of metal composites based on a plastic aluminum matrix containing dispersed ceramic inclusions [5]. Robinson and Nolen have studied an impact of an aluminum projectile with the velocity of 4–5 km/s on the composite bumpers consisting of the aluminum matrix with 20–25 v/o SiC inclusions. The authors have reasoned that, owing to collision of high-velocity projectiles against the shield made of a material containing the embedded inclusions and having a shock impedance different from that of the matrix material, the projectile will be more broken than for homogeneous aluminum bumpers. Also, they have concluded with care that similar material applications in the antimeteoroid protective systems are in sight.

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As described in Ref. [6], the crater depth in semi-infinite targets of aluminum matrix metal composites containing ceramic inclusions is considerably reduced as compared to plastic matrix materials. Hence, this paper deals with the use of metal composites based on aluminum matrix containing the disperse SiO_2 or Al_2O_3 inclusions as the first bumper in the single-shield system. The aim of the paper is to compare the protection efficiency of bumpers made of the disperse metal composites with that for the duralumin shield by impact of spherical steel projectile with the velocity of 5.5 and 7.5 km/s.

EXPERIMENTAL PROCEDURE

Two-component composite plates of thickness t_s = 1–1.3 mm are prepared by hot pressing of mechanical mixtures of a fine aluminum powder and SiO_2 or Al_2O_3 powders at 450°C followed by annealing. Mass fraction of the second component, ceramic, accounts for 15 and 30 % of the total composite. The mean sizes of powder grains are 10–20 μm for aluminum, 50–100 and 5–10 μm for SiO_2 and Al_2O_3, respectively. The porosity of composite materials, Π, is defined by measured values of density, ρ_s, and the theoretical maximum density, ρ_{th}, calculated by the mixture rule (Table 1). The areal density of the composite shields is nearly constant and equal to $t_s\rho_s$ = 0.27–0.33 g/cm^2.

Table 1. The characteristics of test materials

	D16T	Pressed Al	15%SiO_2	30%SiO_2	15%Al_2O_3	30%Al_2O_3
ρ_{th}, g/cc	2.78	2.71	2.67	2.64	2.82	2.06
ρ_s, g/cc	2.78	2.62	2.66	2.62	2.55	2.57
Π, %	–	3	1	1	10	13
τ_s, MPa	185–260	100–120	50–60	50–60	25–30	25–30
	Shock pressure for two impact velocities (unidirectional calculations)					
$P_{5.5}$, GPa	105	99	100	98	95	95
$P_{7.5}$, GPa	165	159	162	160	153	153

The impact of steel projectiles normal to the bumper is investigated. The 1 mm diameter steel balls are accelerated by a tubular explosive accelerator at velocities up to V_p = 5.5 and 7.5 km/s [7]. The final projectile diameter, d_p, is 0.9 and 0.83 mm, respectively. The test setup is conventional as follows: the bumper target being tested is located 50 mm from a witness plate (D16 aluminum alloy, 5 mm in thickness). The bumper plates 60 mm in diameter is supported by a steel flange which protects the witness plate from action of explosion products. The flange is mounted on the duralumin tube 150 mm in inner diameter which is closed by the witness plate. The explosive gun is vertically positioned 60 cm uprange the bumper. The volume between bumper and backwall is not pumped out and is filled with air at atmospheric pressure. The decrease of gas pressure below 1 atm did not significantly increase the maximum depth of the largest craters on the thick backwall even for the aluminum projectile [8] but complicates the experiments. As a reference bumper to be compared, the 1 mm duralumin plate (made of the aluminum alloy D16T) is used.

After the impact of a projectile with a shield, a debris cloud involving fragments of the projectile and the shield materials forms behind the bumper. The protection efficiency of the bumper can be judged by the fracture pattern of the backwall, such as the bending deflection, the wall perforation, the size of the damage zone and the depth of secondary fragment craters [5, 9]. In this work a thick backwall plate was used, and the maximum depth of fragment craters, P_c, on the witness plate did not exceed 1 mm. Thus the backwall could be considered semi-infinite, and the and maximum value of P_c is taken as a protection characteristic of shields made of different materials. The measurement accuracy of P_c is ±0.02 mm. The crater depths given in Fig. 1 are normalized to the projectile diameter which is known with an accuracy of 5 % [10].

RESULTS AND DISCUSSION

Figure 1 gives the data on the relative penetration, P_c/d_p, on the backwall plate for the eight bumper materials under study at V_p = 5.5 and 7.5 km/s. For each bumper material a number of data are presented for three to five of the deepest craters. With incorporation of the disperse ceramic inclusions into the shield material the crater depth increases by 10–30 % relative to the values for the duralumin shield. The influence of inclusions SiO_2 or Al_2O_3 and their concentration and dispersity was not evident within the accuracy of P_c/d_p defining. Notice that the pressed aluminum powder shield results are essentially coincident with the data for the homogeneous duralumin bumpers.

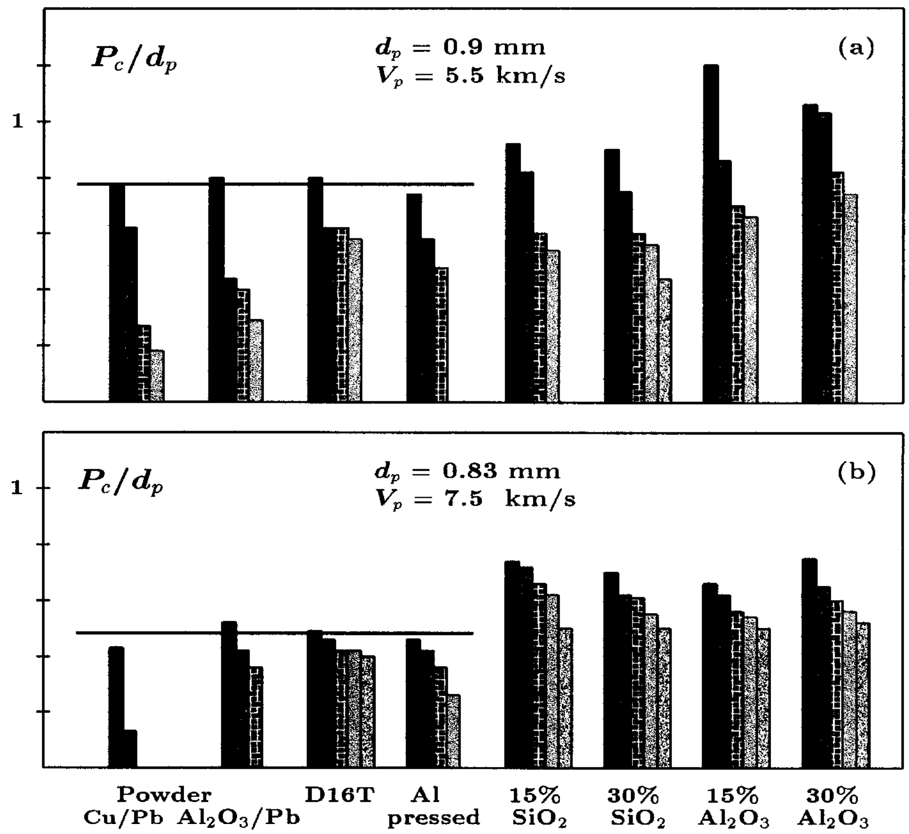

Fig. 1. Relative depth of craters on the back wall for the different bumper materials by the impact of the steel projectile with velocity of 5.5 (a) and 7.5 km/s (b).

Figure 2 shows the impact crater pattern on the witness plate of debris cloud for several bumpers at two impact velocities. In the case of the composite bumpers the debris cloud fragments are mainly spread over the narrower area than damaged one for duralumin bumper. The diameter of effective damaged area, D_d, involving 90 % of total area of all fragment craters is reduced about 1.5 times for tests with composite bumpers. This statement is demonstrated in Fig. 3 which shows the radial distribution of the sum of areas for all craters lying outside the circle with the radius R (the centre of circle placed in the centre of damaged area; the areas' sum is normalized to the total area of all craters on the witness plate). For instance, at the steel/Al im-

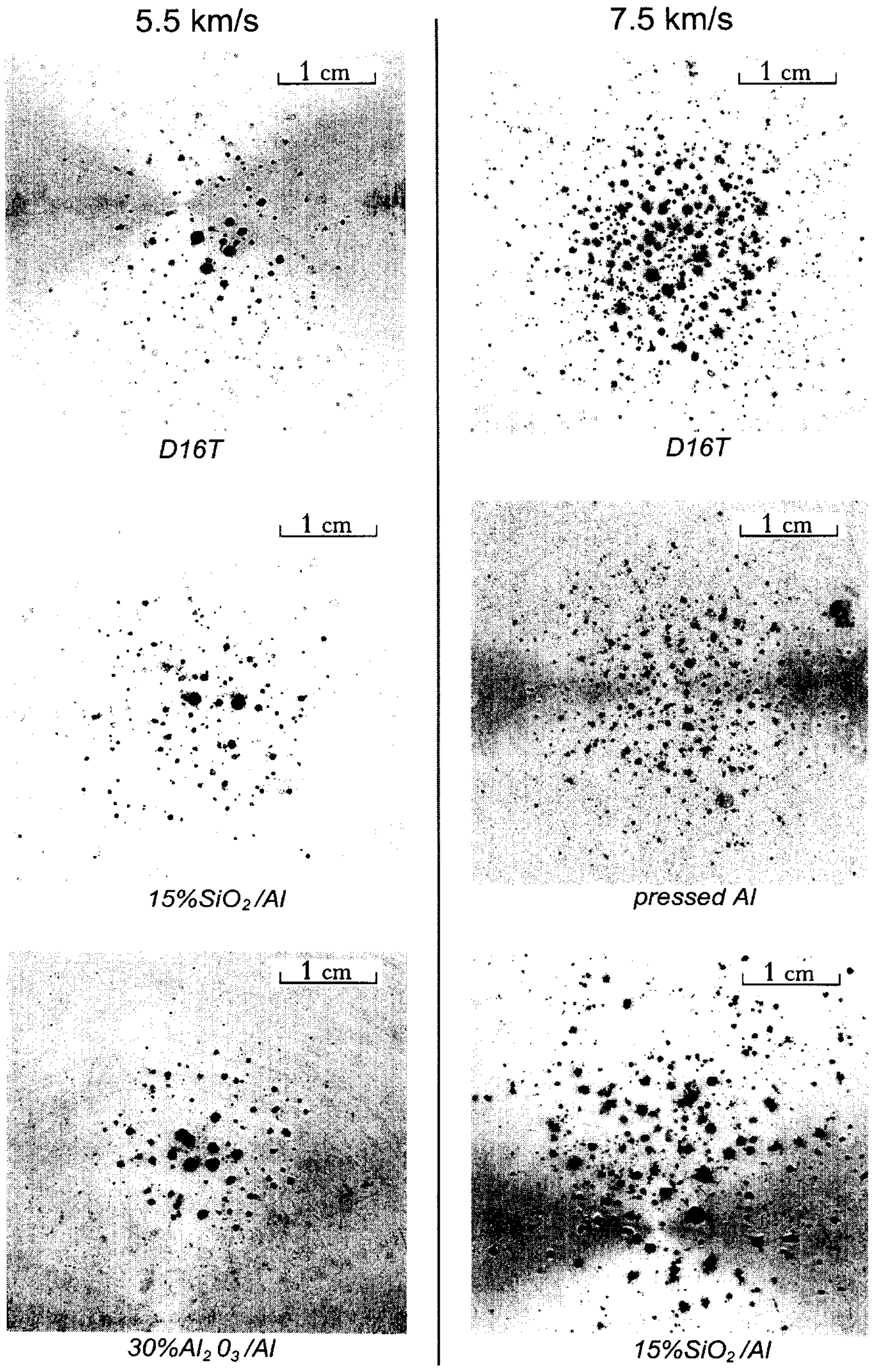

Fig. 2. A back wall viewed from the impact side at velocities 5.5 and 7.5 km/s.

pacts the values of D_d are 35 and 60 mm at V_p = 5.5 and 7.5 km/s, respectively; at the steel/composite impacts the corresponding values of D_d decrease to 23 mm and 43 mm.

Let us consider some possible reasons of decreasing the protection efficiency of bumpers made of metal composites with the embedded ceramic inclusions:

1. *Shield Thickness Variability.* The relative thickness of shields, t_s/d_p, in experiments ranges from 1.1 to 1.3, i.e. shields are rather thick. According to [9], a minimum of P_c/d_p is attained for

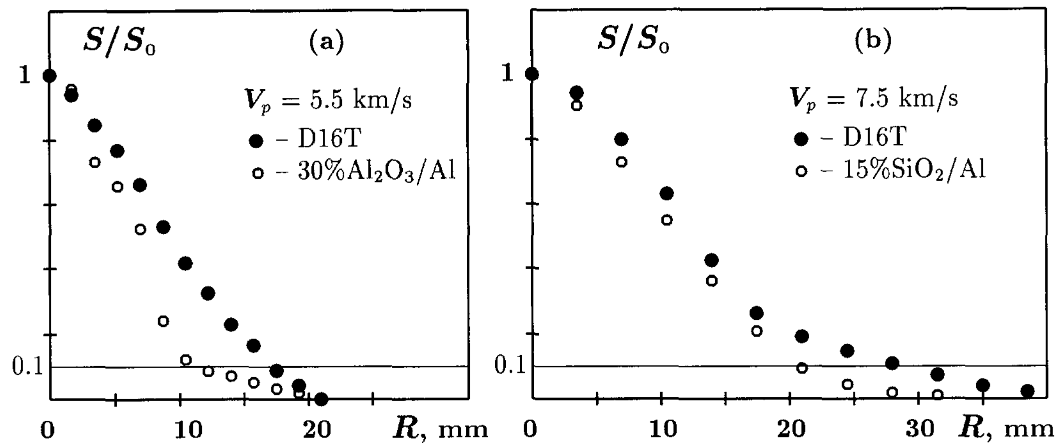

Fig. 3. Radial distribution of areas' sum for all craters lying outside the circle with the radius R for duralumin and composite bumpers.

steel/aluminum impacts with the velocity of 5.5 km/s and t_s/d_p values of 0.6–1.3. Within these t_s/d_p limits the P_c/d_p is essentially invariant. With the impact velocity of 7.5 km/s, the minimum of P_c/d_p is attained at t_s/d_p = 0.4–0.8. For the thicker shields the crater depth increases as $\Delta(P_c/d_p) \cong 0.6\Delta(t_s/d_p)$. For actual $\Delta(t_s/d_p)$ = 0.2, the estimate of P_c/d_p increasing is about 0.12 and can not properly explain the observed increase in the fragment crater depths for the composite shields containing ceramic inclusions.

2. *The Influence of Variations in Impact Pressure.* The composite densities in our experiments are lower than the theoretical value calculated by the mixture rule. The porosity of the materials used ranges from 1 to 3 percent for bumpers made of pressed aluminum powder or the mixture of aluminum and quartz sand. The mixture of aluminum with fine alumina powder has a material porosity of 10–13 percent. Hence, the impact pressure may be considerably changed for shields made of different materials. The shock compressibility of two-component mechanical mixtures is calculated as a sum of the components' compressibilities [11]. Hugoniots of individual components are taken from Ref. [12]. The effect of the composite porosity is considered by the formal simple Thouvenin approach [13]. The initial impact pressures calculated as an unidirectional approximation are presented in two last rows of Table 1.

The estimate of the impact pressure of a steel projectile against porous shields indicates that the pressure is reduced, at most, from 5 to 10 percent with respect to that realized during the impact of a projectile with a duralumin shield. The strength of the metal composites discussed in this study is low, however, their density and shock impedance are rather high and can produce high pressures at collision. Yet, the evident worsening of shielding properties of metal composite bumpers is noted.

At this stage in our research we have concluded that the metal composite bumpers rupture an impacting projectile worse than aluminum bumpers, and the largest craters on witness plate are formed by projectile fragments. At first glance this view is supported by the results described in the next subsection 3 of the paper. Yet, the results of the subsequent experiments with powder bumpers (subsections 4 and 5) has revised our viewpoint.

3. *The Influence of Shear Strength of Shield Materials.* The following two factors are assumed to cause the high-velocity projectile failure at impact: the projectile velocity defines the stress level in its body, and the relative thickness of the shield defines the time of the interaction the projectile with the bumper. The mechanical strength of a bumper material is not an unimportant factor. The last inference is based on the data obtained in experiments on metal shields: aluminum alloys, steel, copper, brass, etc., having different but high values of strength of the order of 100 MPa and above.

Suppose that the deterioration of shielding properties of the pressed composite bumpers is due to a decrease in shear strength of a shield material. During perforation of a thin shield by a high-velocity projectile, the impact pressure value is quickly reduced by rarefaction waves. When a projectile passes through a shield, the level of mechanical stresses at the lateral periphery of the projectile can be reasonably determined by the force interaction at the contact surface dividing the materials of the projectile and the shield. Shear stresses operate principally over the contact surface. The shear strength of the least strength material will define a mechanical stress level at the projectile periphery.

To check this assumption, the measurements of the shear strength, τ_s, of materials used have been performed using the split Hopkinson pressure bar as a punching test device [14]. The method consists of dynamically punching a plate from the test material using a cylindrical indentor. Disk-shaped specimens with 20 mm diameter and 2 mm thickness were tested. Diameters of the indentor and the hardened steel backup ring were equal to 8 and 9 mm, respectively, in the tests. In Table 1, measured values of τ_s are presented for tests done using a strain rate of 40–100 s^{-1}.

Figure 4 gives the results of measuring the maximum crater depth on the backwall plate and the shear strength of materials for the outer bumper. As indicated in the figure, the shielding action of bumpers made of different materials correlates with the shear strength of the material, i.e. the lower the shield material strength, the poorer its shielding action. This inference is true for relatively low values of τ_s < 100 MPa. The conclusion concerning the influence of bumper strength on the degree of dispersion of the projectile striking at the velocity above 5 km/s is inconsistent with present concepts. Conceivably the observed correlation is due to a number of test factors disregarded or not properly considered.

4. *Impact against Shields Made of Powders.* To understand the above correlation of the protective action of shield materials possessing shear strength, we have performed some experiments with a bumper material having zero strength. By keeping the impact velocities such as for the tests with the no-shear strength bumpers, two parameters that determinate, in our view, the fracture of a impacting projectile — the impact pressure P_s and the shield relative

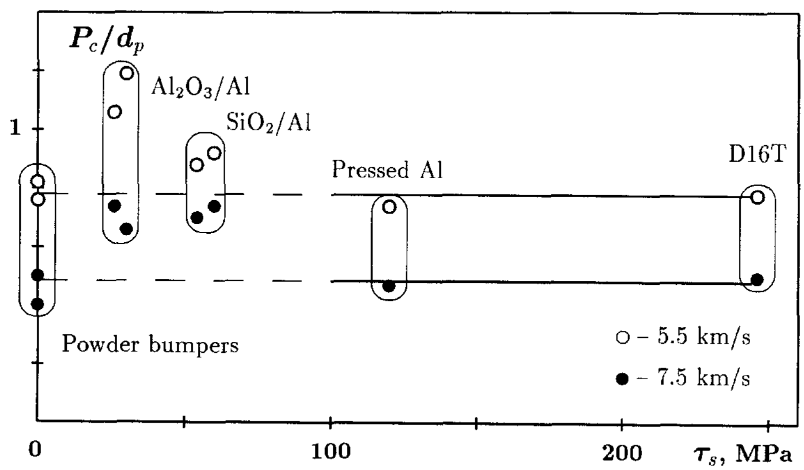

Fig. 4. Maximum crater depth versus the shear strength of bumper materials.

thickness t_s/d_p — have been kept the same. The central idea of these experiments is to remove craters on the backwall due to an impact by bumper fragments and to answer the question: Are the deepest craters in the above tests formed by the impact of debris from the steel projectile or a bumper? When nullifying the shield material strength, a projectile is shattering into the less number of the larger fragments, then a maximum depth of craters is to increase. If the rupture of a projectile is determined by the impact pressure which has to be retained the same as in the considered experiments, the maximum depth of craters will not vary as against the results of the experiments with duralumin bumpers.

To do this, a thin layer of loosely-packed metal powder was placed on a paper sheet 10 μm thick and used as a bumper. In order to obtain the same necessary values of P_s the following high-porosity mixtures were used: (1) a mixture of lead and copper powders having a density ρ = 3.8 g/cc with the size of particles ranges from 10 to 20 μm, the copper mass fraction μ = 40 %, the porosity Π = 63 %, and (2) the mixture of lead and alumina powders (ρ = 3.5 g/cc, μ = 43 %, Π = 43 %). Although the layer thickness is 1 mm, the areal density of the shield exceeds that of previous experiments by about 1.2–1.4 times. The same calculated estimate of the impact pressure provides 100–104 and 168–172 GPa at impact velocities of 5.5 and 7.5 km/s, respectively, which is close to the impact pressure of a projectile against the duralumin shield. The shear strength of these materials appears to be equal to zero.

Figure 5 shows the distribution of craters on the backwall plates for the similar impacts against two different bumpers made of powder mixtures. A powder bumper significantly reduced the number of fragment craters to 50–60 as compared to 500–1000 for impacts against the duralumin shield. A drastic change in the backwall failure is due to the absence of large fragments of shield material. The occurrence of rather deep craters with $P_c \approx 0.5$–0.8 mm cannot be attributed to the small size of individual grains making up a bumper. All the craters observed appear to be formed by debris from the steel projectile. The depth of the largest craters on a witness plate is close to the data for pressed aluminum and duralumin shields (Figs. 1, 4). It is noted, that the area distribution of craters has the random nature for powder bumpers, and it has not the axisymmetric pattern which is typical for solid bumpers (Figs. 2, 5).

For all tests with solid, composite and powder bumpers the impact pressure, the bumper areal density and the bumper thickness are nearly constant. But the maximal crater depth formed by debris fragments is greater in the case of composite bumpers. If not assuming that in this case a projectile is broken up into the less number of fragments for a variety of uncertain reasons, the observed increase of the crater depth on the witness plate in the tests with composite bumpers is caused by appearing the larger fragments of the composite shield material in a debris cloud.

The results of these qualitative experiments provide a support for the view that the impact pressure play a basic role in damage an impacting projectile. However, the shield material strength (unless it is zero or more than 100 MPa) affects the degree of dispersing a shield material. A low strength is favorable to the formation of rather large fragments of bumper material in

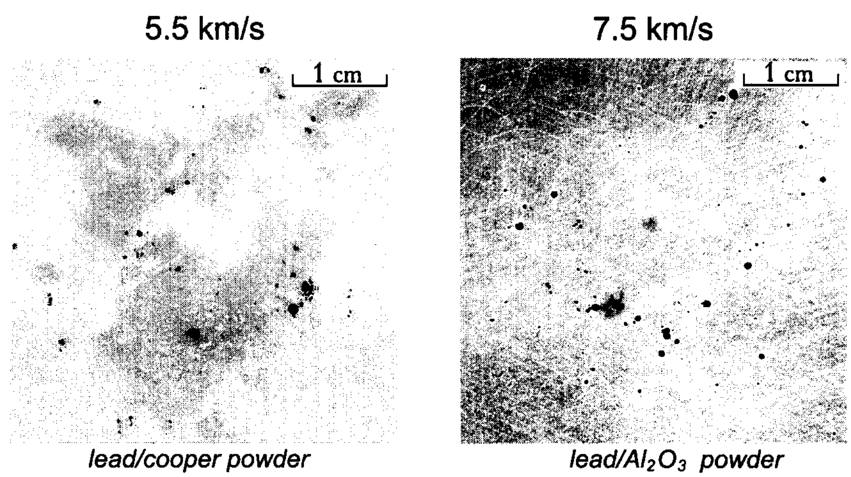

Fig. 5. A back wall viewed from the impact side in case of powder bumpers. Bumper materials are as follow: at left – a lead/copper powder screen, V_p = 5.5 km/s; at right – a lead/Al_2O_3 powder screen, V_p = 7.5 km/s.

the debris cloud and results in a decrease of the efficiency of shields made of pressed dispersed metal composites.

5. *Effect of The Bumper Areal Density.* It is qualitatively clear that not only the shield thickness effects on the time of interaction a projectile with the bumper but its areal density as well. The larger density is favourable for increasing the interaction time, and the energy sharing lost by the projectile during the perforation of a bumper (as in numerical simulations by Riney at the impact velocity of 15 km/s with aluminum projectiles against laminated bumpers with changing their areal density five-six times [15]). In our experiments the $t_s\rho_s$ has changed no more than 1.3 times. Most likely, this being so, we have not observed the effect of $t_s\rho_s$ on the results. This view is qualitatively supported by the results of the next two tests, wherein on keeping the impact pressure the areal mass of shields made of powders has been changed twofold with increasing or decreasing a bumper volume density. With a low impact velocity, this has enabled us to simulate an impact at the higher velocity by increasing the impact pressure caused by rising the shock impedance of the bumper material, and conversely.

In the first test a 1 mm thick layer of lead powder having a bulk density of $\rho_s = 6.67$ g/cc and $t_s\rho_s = 0.67$ g/cm^2 is used as a bumper. For the steel/bumper impact at $V_p = 5.5$ km/s the calculated impact pressure equals to 172 GPa, which corresponds in pressure to the projectile impact at $V_p = 7.5$ km/s with the above shields. The depth of the deepest crater on the backwall $P_c/d_p \leq 0.4$ is not over the value of 0.5 typical for impacts at the velocity of 7.5 km/s (Figs. 1, 3).

In the second test the projectile impacts upon the 1 mm layer of copper powder having $\rho_s = 1.61$ g/cc and $t_s\rho_s = 0.16$ g/cm^2 at $V_p = 7.5$ km/s. The impact pressure of 105 GPa is compatible with the pressure which relized by projectile impact at the velocity of 5.5 km/s against aluminum shields with $t_s\rho_s \cong 0.3$ g/cm^2. The depth of penetration rises sharply to $P_c/d_p \approx 1$, which is higher by 25 percent than the value of 0.8 characteristic for impacts with the velocity of 5.5 km/s. The diameter of the damage area in the back wall is reduced to 20 mm as against 40–60 mm in the case of the denser shields. The results uniquely show that in parallel with the impact pressure not only does the shield thickness plays the important role in rupturing the impacting projectile, but the bumper areal density also plays. The effect of areal density appears to be reflected by changes in the effective time of interacting the projectile with the shield and in the remaining kinetic energy of projectile fragments.

So, the results of tests with porous powder bumpers allow (1) to understand the reason of formation of the deeper craters on the backwall for tests with metal composite bumpers, and (2) to favour once more the view that the impact pressure and the shield thickness, and more precisely, it's areal density play a crucial role to shatter the impacting projectile.

CONCLUSION

The protection efficiency of thin shields made of metal composites based on the aluminum matrix containing the disperse ceramic inclusions of SiO_2 or Al_2O_3 (at a mass fraction of 15 and 30 percent) by impact of a spherical steel projectile at the velocity of 5.5 and 7.5 km/s is considered for a Whipple-type shield. The bumpers made of these materials are shown to have the poorer protection efficiency than those made of the duralumin alloy when used with steel impactors. There is a need to perform further researches with the resulting justified advisability of using the metal composites, Al-matrix plus embedded ceramic inclusions, as the first bumpers for constructing the meteoroid protection schemes in case of hypervelocity aluminum projectiles.

It is shown that by impact of the hypervelocity steel projectile the shield material strength, if it is rather low but not zero, may essentially affect the damage pattern of the backwall in spite of the high level of realized impact pressures.

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