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SHIELD PROPERTIES OF A THIN PLATE UNDER HIGH-VELOCITY IMPACT

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In perforating a thin plate (shield) a high-velocity particle (meteoroid) is shattered as the result of the wave processes which are generated within it. During the course of its deformation a velocity field arises in the particle; this field has a nonzero component perpendicular to the impact direction, so that the trajectories of the debris particles are at various angles to the trajectory of the particle; these debris particles then impact a target plate, placed behind the shield, over a much larger area than the cross-sectional area of the particle. This, together with the loss in momentum of the particle as it perforates the shield, determines the protective effect of the shield.

The process involved in the deformation and shattering of the particle in its collision with the shield was considered in [1]. In this paper we justify, based on the experiments conducted in [1], a method of quantitatively estimating the damage inflicted on the obstacle (target) protected by the shield. The method employed for accelerating steel spheres was described in [2]. In all our experiments we permitted a pressure of up to 1 mm Hg in the space between the shield and the target.

It is difficult to give a general description of the problem involving perforation of a shielded target, since the mechanism involved in explaining the target damage changes when the distance S between the target and the shield is varied. When S is small the impact onto the target is due to a nondiffuse (compact) debris cloud from a still deforming particle; as S increases, however, the damage to the target results in increasing measure, from the impact of the coarsest particles present in the concentrated debris field. It is necessary, therefore, to estimate the applicable interval over which the quantity $S_1 = S/d_0$ (where d_0 is the diameter of the impacting particle) varies corresponding to a given one of these target damage mechanisms. When the target chosen is thick (semiinfinite), we can use, as a quantitative measure of target damage and, hence also, of shield effectiveness, the depth h of the largest of the craters formed in the target.

The experimental results obtained are shown in Fig. 1 in terms of a set of curves showing $h_1 = h/d_0$ plotted against S_1; curve 1 corresponds to an impact of aluminum on aluminum with $\delta/d_0 = 0.3$ (δ is the shield thickness); curves 2, 3, and 4, with $\delta/d_0 = 0.2$, 0.6, and 0.67, respectively, correspond to impacts of steel onto D16. Here and henceforth, the first-named material corresponds to that of the particle and the second-named

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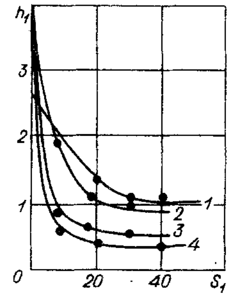

Fig. 1

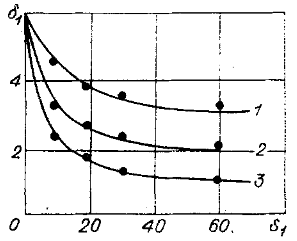

Fig. 2

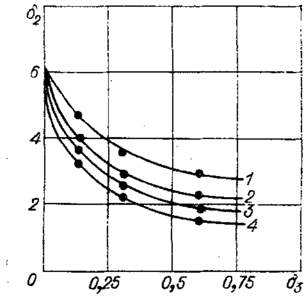

Fig. 3

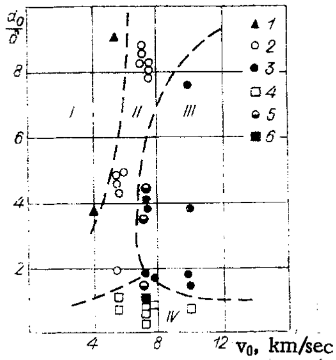

Fig. 4

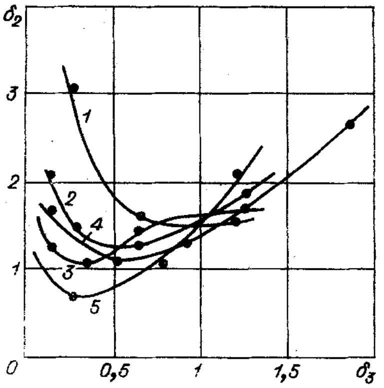

Fig. 5

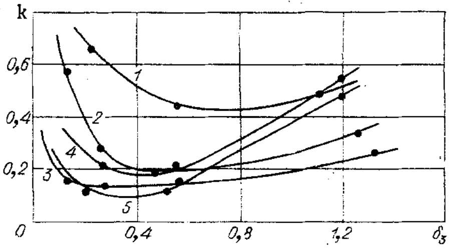

Fig. 6

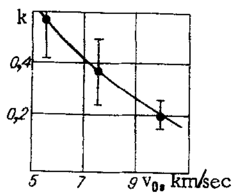

Fig. 7

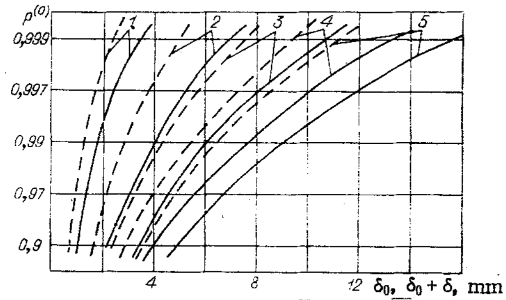

Fig. 8

to that of the shield; the target (protected by the shield) is assumed to be of Duralumin. The data shown are in good agreement with the data obtained in [3]; moreover, it indicates that, for S_1 greater than some value in the interval from 25 to 30, the crater depth h_1 is practically constant. A similar result was also obtained when the shield thickness was taken equal to the limiting thickness δ_0 of the target [4] (see Fig. 2, where $\delta_1 = \delta_0/d_0$ and the curves 1, 2, and 3 correspond to impacts of steel onto D16 with $\delta/d_0 = 0.125$, 0.3, and 0.6, respectively). The fact that the target damage when S_1 is to the left of the interval (25, 30) differs noticeably from that when S_1 is to the right of this interval testifies to the fact that when S_1 has a value in this interval a change occurs in the target damage mechanism. As S_1 increases from a small value to a large value, it passes through a critical value in the interval (25, 30) (strictly speaking, this statement applies to a given pair of materials).

The following relationship holds for a given target material when impacted by individual debris particles in the range of velocities considered:

$$\delta_0 \simeq (1.4 \pm 0.5)h; \qquad (1)$$

hence, when S_1 is large, the characteristic values δ_0 and h are equivalent. When S_1 is small, the relation (1) is invalid owing to the indicated nature of the effect of the debris particles on the target. If we regard perforation of the target as inadmissable target damage, then the quantity δ_0 serves as a criterion of shield effectiveness. The dependence of the total ballistic limit thickness $\delta_2 = (\delta + \delta_0)/d_0$ on δ for various values of $S_1 < 30$ is shown in Fig. 3, where the curves 1, 2, 3, and 4 correspond to impacts of steel onto D16 with $S_1=8.8$, 17.6, 29.4, and 58.8, respectively.

Very detailed experimental data were obtained for large separations between the shield and the target. In this case, for a given set of materials, the damage inflicted on the target is determined by the shield thickness δ and the impact speed v_0. It is convenient to analyze characteristic features of the debris fields by introducing the notion of target damage structure. The simplest case is that of incomplete shattering, the central portion of the impacted body remaining intact. This occurs when the impact speed is relatively low or when the shield is very thin and is associated with a weak shock wave propagating through the impacting particle; an increase in the shield thickness is analogous to an increase in the impact speed v_0 (contributes to the damage). When δ and v_0 are sufficiently large, complete failure of the body occurs. Dimensions of cavities arising from individual debris particle impacts are, in this case, similar; we shall henceforth refer to this as the uniform target damage structure. A further increase in the impact speed leads to the phenomenon of clearly defined boundary cavities, indicating a transition to an annular target damage structure. At high impact speeds (10-12 km/sec) the cavities inside the annular region are substantially less than the boundary cavities. The high impact pressures lead to a dispersion of the body into finely divided debris particles, including melting and vaporization of a portion of them. These impact speeds give rise to a spray of metallic dust in the target damage zone. Much deeper annular cavities are formed by the debris particles; their appearance is associated with peripheral effects during the shattering of the shield and the impacting body.

With the transition to fairly thick shields, the target damage is due, for the most part, to debris from the shield material. Moreover, a portion of these debris particles has speeds substantially less than the speed of the impacting particle and are of irregular shape, giving rise to a significant variation in the cavity parameters. Figure 4 is a structural diagram for the impact of steel onto D16, obtained for $S_1 \simeq 60$ and d_0 varying from 0.8 to 2.3 mm (impacts labelled 1 are for the case of incomplete shattering and are placed in zone I; impacts labelled 2 define the zone II of uniform target damage; impacts labelled 3 define the zone III of annular target damage structure; impacts labelled 4 involve thick shields and define zone IV; impacts labelled 5 and 6 define the transition zones II-III and III-IV, respectively). The zone boundaries are drawn approximately. Diagrams of this kind establish the debris field boundaries and make it possible to determine the nature of the target damage without carrying out the experiment. Our experiments with spheres of diameter $d_0=8$ mm validate such diagrams and confirm their applicability when the scale of the phenomena changes.

In accordance with the problem as formulated above, the basic measurable parameter in our experiments is the depth of the largest of the cavities formed in a thick target. Our results, expressed in terms of the coordinates δ_2 and $\delta_3=\delta/d_0$ [wherein we used the relation (1)], are shown in Fig. 5 along with the data from [3] (curves 1 to 3 correspond to impacts of steel onto D16 at impact speeds $v_0=5.5$, 7.5, and 10 km/sec, respectively; curves 4 and 5 correspond to impacts of steel onto titanium and steel onto steel, respectively, at an impact speed $v_0=7.5$ km/sec). Qualitatively, these curves are of an identical nature. For very thin shields, δ_2 tends to a value equal to the ballistic limit thickness for an unshielded target. As δ_3 increases, δ_2 decreases and reaches a minimum at some value of δ_3 which depends on the impact conditions. With a further increase in the shield thickness, the quantity δ_2 increases and it continues to do so until it becomes comparable with the ballistic limit thickness for the given material and the impact speed v_0. For shields of such thickness, the quantity h rapidly falls to zero. An explanation of the behavior described by these relationships, from the point of view of the wave processes considered above, is fairly obvious.

In analyzing how best to defend against meteoroid impacts, it is extremely important to see how the target damage changes with an increase in the impact speed, since at the present time it is possible to obtain experimental data only in the lower range of meteoroid velocities. Experimental results show that the depth of target damage decreases as the impact speed increases. In the velocity range 5 km/sec $\leq v_0 \leq 12$ km/sec, this same result was reported by others (see, for example, [5]). In the majority of papers it was assumed that, with a substantial increase in the impact speed, the target damage, with S_1 large, tends to zero as the result of complete vaporization of the material of the body. Establishing the presence of an annular target damage structure, determined by peripheral effects, confirms the finiteness of the target damage for arbitrary impact speeds.

When thin shields ($\delta_0 < 1$) of various materials are employed, the parameter that determines the shielding properties is the density of the shield material; it is on this parameter that the level of pressures in the shock wave traversing the impacting particle depends (see Fig. 5). As the shield material density decreases, the minimum point on the δ_2 versus δ_3 curve moves to the right along the δ_3 axis, i.e., to secure the most complete breakup of the impacting particle a decrease in the initial pressure level in the shock wave must be compensated by an increase in the duration of the pressure impulse. Available experimental data confirm the fact that strength characteristics have only a weak influence on the shielding effectiveness of thin shields.

The use of shields leads, first of all, to a decrease in the weight of the wall of the structure being protected, or, if the shield and wall are of like materials, to a decrease in the structure wall thickness. Based on these results, we propose the following approximate method for protection from meteoroid impacts. To calculate the total ballistic limit thickness of shield and target, we employ the relationship

$$\delta_2 = k\delta_1,$$

where δ_1 is the relative ballistic limit thickness of a single-walled target, calculated in accordance with the formulas given in [4, 6]; $k < 1$ is an empirical coefficient which depends on the same parameters as δ_2.

Figure 6 shows how k varies with δ_3 for shields made of aluminum alloy, titanium, and steel for the case $S_1 > 30$ (the impact parameters for the curves 1 to 5 are the same as those for the curves of Fig. 5). As was to be expected, there is a qualitative correspondence between the quantities k and δ_2, which is maintained even for functions of the impact speed (Fig. 7, impact of steel onto D16). In specific calculations it would be convenient to have a constant value of the quantity k, which would hold over a wide range of impact conditions. It follows from the data given above that, for a wide range of δ_3 values (approximately $0.3 \leq \delta_3 \leq 0.8$), the quantity $k_1 \leq 0.3$. It is clear that the quantity $k_1 = 0.35$, with a corresponding choice of δ_3, guarantees that the target will not be perforated. Moreover, with an increase in the shield material density, the actual value of k diminishes, and the k_1 value selected then guarantees a definite margin of "nonperforatability" of the target wall. The tendency for k to decrease as the impact speed increases makes it possible to extend the present scheme to the meteoroid range (at least to the lower range) of velocities. We propose to select the shield thickness from the condition $\delta_3 \simeq 0.5$–0.6, although the minima of the curves in Fig. 6 for the heavy shields are located to the left along the δ_3 axis; a value of the shield thickness selected in this way provides a valid choice for k_1 over a wide range of shield material densities. Similar reasoning for the case of small distances between the shield and the target ($5 \leq S_1 \leq 20$–25) yields the value $k_1 = 0.7$.

The collision of a meteoroid with a spacecraft is, to a considerable degree, a random phenomenon (in actuality, this assumption amounts to a probabilistic model for actual statistical data). For the physical event in question, there are two possible outcomes: perforation of the target wall or nonperforation of the target wall; the most probable number of perforations τ is substantially less than the general number of meteoroids in space, i.e., the sample size is much greater than the probability P of a positive outcome of trials. Consequently, the probability of obtaining n perforations of a space vehicle, P(n), follows the Poisson law

$$P(n) = (\tau^n/n!)e^{-\tau}, \tag{2}$$

if τ is a constant quantity. This latter assumption is also approximate, since it is known that the number of meteoroids (even if we ignore meteor streams) varies with time. From a practical point of view, an interesting case is that in which the probability P(0) of no perforations is close to one. From Eq. (2) it follows that

$$\tau = -\ln P(0). \tag{3}$$

Relation (3) determines, for a specified reliability level P(0), the most probable number of spacecraft wall perforations during its time of flight. On the other hand, for a known frequency of impacts N(m) (where m is the meteoroid mass), the number of such impacts during the vehicle time of flight T amounts to NTQ, where Q is the area of the vulnerable surface of the spacecraft. Equating this quantity to the value τ obtained from (3), we can obtain the "critical" meteoroid mass m_1 against which shielding must be provided in order to guarantee the required reliability level. The functions N(m) are of the form

$$N(m) = Am^{-r}, \ r > 0;$$

therefore, $m_1^r = AQT/\tau$.

Assuming that the meteoroid has the shape of a sphere and that its density is equal to some mean value ρ_0, we can calculate the diameter d_1 of the meteoroid of corresponding mass m_1.

Thus, corresponding to a specified reliability level and a known meteoroid model with its attendant function N(m), a mean meteoroid density ρ_0 and a mean meteoroid velocity v_0, we can determine the parameters of the protective shield and of the vehicle wall structure. This procedure is illustrated, by way of example, in Fig. 8, where, for various "exposures" QT, the solid curves show how the single wall thickness depends on the specified reliability level; the dashed curves show the corresponding dependence for the sum of the shield and target wall thicknesses (curves 1 to 5 correspond to exposure values (in units of $m^2 \cdot h$) of $4.5 \cdot 10^3$; $1.1 \cdot 10^5$; $6.75 \cdot 10^5$; $1.7 \cdot 10^6$; and $3.4 \cdot 10^6$, respectively). In our calculations we used Whipple's meteoroid model (see [7]):

$$N(m) = 10^{-14.48}(0.44/\rho_0)^{1.34} m^{-1.34}, \ \rho_0 = 2.7 \ \text{g/cm}^3, \ v_0 = 30 \ \text{km/sec}.$$

In our calculations of the shielded wall, we used a value of $S_1 > 30$.

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