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## LITERATURE CITED

1. A. A. Deribas and A. M. Staver, "Shock compression of porous cylindrical bodies," Fiz. Goreniya Vzryva, No. 4, 568-578 (1974).
2. G. E. Kuz'min and A. M. Staver, "Determination of the flow parameters with the shock loading of powdered materials," Fiz. Goreniya Vzryva, No. 6, 898-905 (1973).
3. R. Courant and K. O. Friedrichs, Supersonic Flow and Shock Waves, Wiley (1948).
4. G. M. Artyunyan and L. V. Karchevskii, Reflected Shock Waves [in Russian], Izd. Mashinostroenie, Moscow (1973).
5. J. O. Erdman, "Explosively induced nonuniform oblique shocks," Phys. Fluids, 1, No. 6 (1958).
6. A. M. Staver, N. A. Kostyukov, and G. E. Kuz'min, "Investigation of flow behind an oblique shock wave with the explosion pressing of powders," in: Second International Symposium. Explosion Working of Metals, Marianske Lazne (1973), pp. 341-352.
7. N. A. Kostyukov, A. M. Staver, and G. I. Novozhonov, "Collision of shock waves in porous titanium," in: The Effect of High Pressures on a Substance [in Russian], Izd. Inst. Prikl. Mekh., Akad. Nauk SSSR (1976), pp. 120-125.
8. W. Herrmann, "Constitutive equation for the dynamic compaction of ductile porous materials," J. Appl. Phys., 40, No. 6, 2490-2499 (1969).
9. L. V. Al'tshuler, S. B. Kormer, et al., "The equation of state of aluminum, copper, and lead for the high-temperature region," Zh. Éksp. Teor Fiz., 38, 790-798 (1960).
10. L. V. Al'tshuler and A. P. Petrunin, "X-ray-graphic investigation of compressible volatile substances with the oblique collision of shock waves," Zh. Éksp. Teor. Fiz., 31, No. 6, 717-725 (1961).
11. L. V. Al'tshuler, L. B. Kormer, et al., "Irregular conditions of oblique collisions of shock waves in solid bodies," Zh. Éksp. Teor. Fiz., 41, No. 511, 1380-1393 (1961).
12. S. B. Kormer, A. I. Funtikov, et al., "Dynamic compression of porous metals and the equation of state with a variable heat capacity at high temperatures," Zh. Éksp. Teor. Fiz., 42, No. 3, 698-702 (1962).
13. G. A. Adadurov, A. N. Dremin, and G. I. Kanel', " Parameters of Mach reflection in Plexiglas cylinders," Zh. Prikl. Mekh. Tekh. Fiz., No. 2, 126-128 (1969).

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# PIERCING OF A BARRIER UNDER THE IMPACT OF GLASS PARTICLES SIMULATING STONY METEORITES

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Articles [1-3] discuss a number of the problems of high-speed impact, solved on the basis of experimental data obtained for the impact of steel particles on different barriers. In the present work, this information is analyzed with application to the conditions of a collision, more exactly modelling a meteoritic impact (the impact of glass particles simulating stony meteorites).

For the acceleration of spherical glass particles, a method was developed on the basis of the well-known principle of a cumulative explosion [4]. A decrease in the density of the gas cumulative jet in comparison with the schemes ordinarily used [4] has made it possible to conserve the integrity of glass particles with acceleration up to 8 km/sec or more. The parameters of the particles used in the work are given in Table 1 (d is the diameter of a particle; $\rho_0$ is its density; and $v_0$ is the impact velocity). The accuracy in measurement of the

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TABLE 1

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $d$, mm | 5,2 | 5,2 | 3,5 | 3,5 | 2,47 | 2,47 | 2,4 | 2,35 | 1,56 | 1,45 | 1,3 |
| $\rho_0$, g/cm$^3$ | 3,08 | 3,08 | 2,47 | 2,47 | 2,47 | 2,47 | 2,47 | 2,47 | 2,61 | 2,61 | 2,61 |
| $v_0$, km/sec | 0,8 | 2,4 | 1,35 | 3,2 | 1,0 | 3,1 | 3,8 | 4,4 | 2,8 | 5,4 | 7,8 |

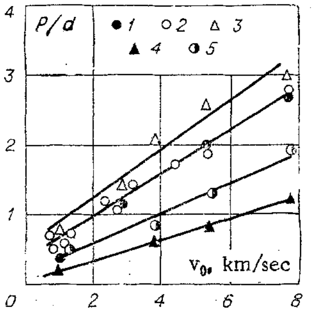

Fig. 1

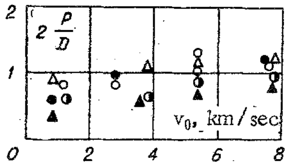

Fig. 2

velocity in all the experiments was not worse than 5%; the error in measurement of the particle size (after ablation with acceleration) was not more than 3-5%. The materials used for the barrier were aluminum alloys, copper, and stainless steel. We note that individual data on through penetration with the impact of glass particles are given in [1]; there are no systematic data in the literature, which is obviously connected with the lack of a method of acceleration.

The first series of experiments was made using massive targets, in which edge effects exert no appreciable influence on the final result of the collision. Such targets have received the name of semiinfinite. Crater formation in a semiinfinite target has been the most studied in the region of high-speed impact, both experimentally and theoretically. A description of the physical scheme of the process and a correlation of the principal results of various methods can be found, for example, in [5, 6].

With the impact of a high-speed particle on a semiinfinite target, a characteristic crater is formed, whose volume, as a result of plastic flow of the material, can considerably exceed the volume of the particle itself. A search for the laws connecting the parameters of the particle and the barrier with the characteristics of the crater is important both for study of the phenomenon of high-speed collision and for evaluating the surface damage (erosion) of a construction. The applicability of the data obtained for such evaluations is promoted also by the fact that, with the variations of various investigators with respect to the dimensions of the striking particles, over a wide range (from hundreths to tens of millimeters) no appreciable scale effect was observed (at least for impact velocities $v_0 > 3$ km/sec).

The results of the experiments are given in Fig. 1 in the form of dependences of the ratio of the crater P to the diameter of the particle d on the impact velocity; 1 corresponds to an impact on a target made of D-16AT; 2, of AMG-6; 3, of AD-1M; 4, of steel Kh18N1OT; and 5, of copper M1 (the designations are used in all subsequent figures). The final parameters of the crater are strongly affected by the strength characteristics of the material of the target, which, in the later stages of the process, are comparable to inertial forces, which is confirmed by the data obtained. While the depths of the craters in targets made of D-16AT and AMG-6, which are very close in their strength characteristics, are described by practically the same dependence; with these same impact velocities, the values of P in the less strong AD-1M are considerably lower.

In engineering practice, a number of empirical and semiempirical relationships connecting the depth of the crater with the parameters of the particle [5-9] are used. This is due to the complexity of making calculations within the framework of sufficiently exact theoretical models. A comparison of the data obtained with these dependences showed that the results of the impact of glass particles on targets made of aluminum alloys are described satisfactorily by the Herman–Jones formula [8]; there is no agreement between the remaining experimental data and these dependences.

It is usually assumed that craters forming with high-speed impact in isotropic plastic barriers have a form close to hemispherical. Under the conditions of the experiments set up, where the impact velocity is still relatively small, this law can break down. The characteristics of the form of a crater is the ratio of the

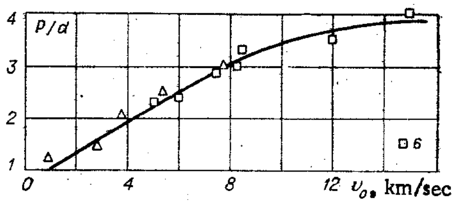

Fig. 3

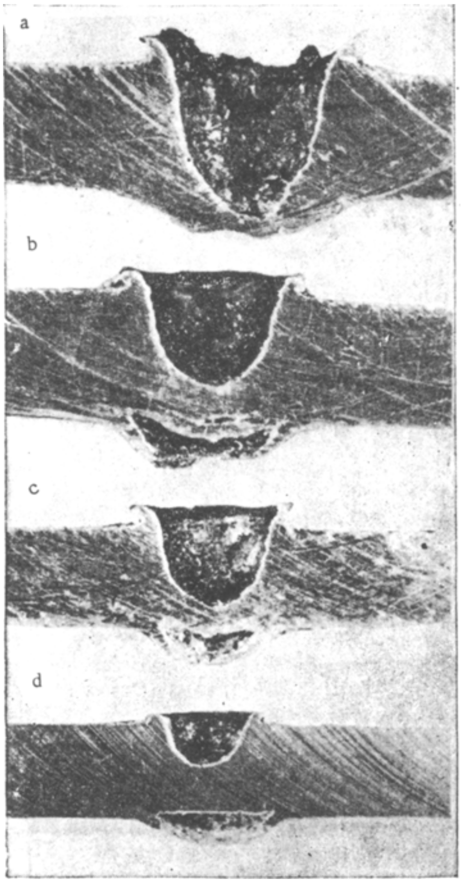

Fig. 4

depth of the crater to its diameter D, measured at the initial level of the surface of the barrier. Values of this ratio as a function of the impact velocity are shown in Fig. 2. In targets made of aluminum alloys, whose yield points are considerably lower than the corresponding characteristics of steel or copper, the craters become hemispherical, even for impact velocities of $\sim$1 km/sec. In copper and steel barriers, over practically the whole investigated range of velocities, $P < D/2$. The results differ from the data of [5], where, in aluminum barriers, there is an anomalous deviation of the form of the crater from hemispherical. In [5] this is interpreted as a consequence of a definite orientation of the grains in the rolled plates used as a barrier. A comparison of all the data shows that, in the first approximation, in the range of impact velocities under consideration, the form of the crater is determined by the ratio of the densities of the plate and the barrier. A deviation of this ratio from unity leads to corresponding deviations of the form of the crater from hemispherical.

The crater in the target is formed as a result of the development of shock-wave and inertial processes, accompanying the interaction between the striking particle and the barrier. The parameters of these processes are determined above all by the velocity of the particle and the ratio $\rho_0/\rho_1$ ($\rho_1$ is the density of the material of the barrier). Figure 3 gives a comparison of the depth of craters formed by the impact of glass and Pyrex (6 indicates data of [10]) particles on barriers made of an aluminum alloy and of pure aluminum. The results practically coincide in an overlapping range of velocities. Thus, the results obtained can, with sufficient justification, be extrapolated to impact velocities of $v_0 \simeq 15$ km/sec. The dimensions of the Pyrex particles were tenths of a millimeter, which is more than an order of magnitude less than the dimensions of the glass particles, i.e., the weak effect of the scale factor is confirmed also in these experiments.

The second series of experiments was made using barriers whose thickness was comparable with the dimensions of the craters formed in them. As a result of the interaction between a high-speed particle and such barriers (called barriers of finite thickness), wave processes, accompanying the arrival of the shock wave at the rear free surface, exert a great effect. Under these circumstances, the surface is deformed; the outer layer of the barrier frequently splits off [Fig. 4, a) barrier with a thickness of $\delta = 7$ mm, $v_0 = 4.4$ km/sec, d = 2.35 mm; b) d = 7 mm, $v_0 = 7.8$ km/sec, d = 1.3 mm; c) $\delta = 5.5$ mm, $v_0 = 5.4$ km/sec, d = 1.45, all barriers of AD-1M; d) $\delta = 5.3$ mm, $v_0 = 7.8$ km/sec, d = 1.3 mm, barrier of M1]. By the limiting thickness, penetrated by a high-speed particle $\delta_0$, there is understood the maximal thickness of the barrier for which there is a through breakdown, even if expressed by a system of unsealing cracks [1]. The limiting thickness is not such an exactly fixed quantity as the depth of the crater P and in experiments is determined by the choice of the thickness of the barrier. The principal factors leading to a limiting breakdown are analyzed in [1]. These are either joining of the crater to the splitting cavity and the fracture of the layer splitting off or fractures of the bridge between the bottom of the crater and the rear surface of the target with its plastic deformation.

The variety of the observed types of limiting penetration is due to different combinations of the above factors. With the penetration of barriers made of aluminum alloys by steel particles, splitting phenomena are only weakly expressed. On the contrary, with the impact of glass particles, the limiting thickness is mainly determined precisely by splitting effects. This difference is easily explained, assuming that the amplitude of the shock wave, arriving at the rear free surface of the barrier limiting penetration by a glass particle, is greater than with the impact of a steel particle. The maximal intensity of the shock wave formed at the initial moment of the collision can be evaluated, assuming the collision to be plane and the shock adiabats of the materials to have the form

$$u_s = a + bu_p,$$

where $u_s$ is the velocity of the shock wave; $u_p$ is the mass velocity; and a and b are constant quantities. For the investigated materials, with a good degree of exactness, we can set

$$u_p \simeq \lambda v_0,$$

where $\lambda < 1$ is a constant quantity for a fixed pair of materials. Then the ratio of the initial pressures at the front of a shock wave, propagating in a barrier with the impact of particles of different density ($\rho_{01}$ and $\rho_{02}$) with an identical velocity, has the form

$$\frac{p_{01}}{p_{02}} \simeq \frac{\lambda_1 (a_1 + \lambda_1 b_1 v_0)}{\lambda_2 (a_2 + \lambda_2 b_2 v_0)} \tag{1}$$

($\lambda_1$, $\lambda_2$, $a_1$, $a_2$, $b_1$, $b_2$ are the corresponding values of $\lambda$, $a$, b). To describe the damping of the amplitude of the shock wave we use the known law for strong shock waves [11]. In the given case, it can be written in the form

$$p = p_0/(r/d)^\nu,$$

where p is the pressure at the front of the shock wave; $p_0$ is the initial value of p; r is the distance traversed by the wave; and $\nu = \text{const}$. The ratio of the pressures with the arrival of the shock waves at the surface in the case of a limiting penetration, taking account of (1), is equal to

$$\frac{p_1}{p_2} \simeq \frac{\lambda_1 (a_1 + \lambda_1 b_1 v_0)}{\lambda_2 (a_2 + \lambda_2 b_2 v_0)} \left(\frac{\delta_{02}}{\delta_{01}}\right)^\nu,$$

where $\delta_{01}$ and $\delta_{02}$ are the corresponding values of the limiting thicknesses. Using the formula for the dependence of the limiting thickness of the barrier on the parameters of the collision from [1], we obtain

$$\delta_{02}/\delta_{01} \simeq (\rho_{02}/\rho_{01})^{1/3},$$

whence

$$\frac{p_1}{p_2} \simeq \frac{\lambda_1 (a_1 + \lambda_1 b_1 v_0)}{\lambda_2 (a_2 + \lambda_2 b_2 v_0)} \left(\frac{\rho_{02}}{\rho_{01}}\right)^{\nu/3}.$$

Let us now compare the values of the pressures for the case of the impact of glass (subscript 1) and steel (subscript 2) spheres on barriers made of aluminum alloys. In this case, $\lambda_1 \simeq 0.47$, $\lambda_2 \simeq 0.63$, $a_1 = 5$ km/sec, $b_1 = 1.35$, $a_2 = 3.8$ km/sec, and $b_2 = 1.58$; for the spherical case, $\nu = 3$. In the range of velocities 1-10 km/sec, $p_1/p_2$

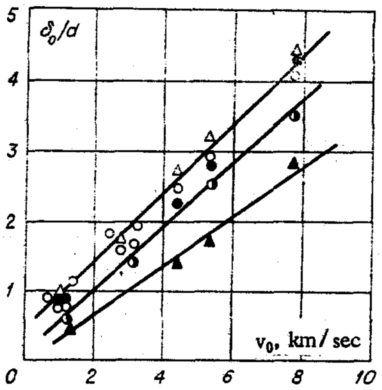

Fig. 5

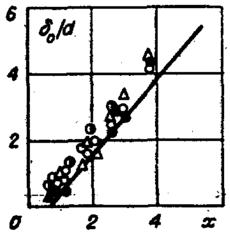

Fig. 6

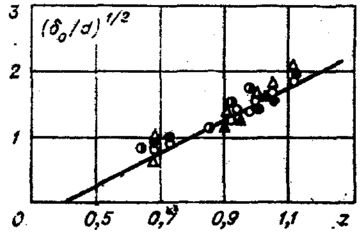

Fig. 7

$\simeq 2.25$-$2$. Of course, the value $\nu = 3$ in the case under discussion is too high; however, even in the case $\nu = 2$, in the indicated range of velocities, $p_1/p_2 \simeq 1.55$-$1.35$, i.e., even such an evidently low evaluation shows that $p_1$ exceeds $p_2$.

Data on the dependence of the limiting thickness on the impact velocity are given in Fig. 5. Using the example of barriers made of aluminum alloys, the weak dependence of the value of $\delta_0$ on the strength of the barrier is demonstrated once again.

In spite of the fact that the mechanism of a limiting penetration varies considerably as a function of the ratio of the properties of the materials of the barrier and the particle, a common approximate description can be found for all the known experimental data [1, 2]. In the very simple form proposed in these articles, the dependence of the limiting thickness on the parameters of the particle and the barrier has the form

$$\delta_0/d \simeq 1.15\left[(\rho_0 v_0^2/\rho_1)^{1/3} - 0.7\right]\cos^{2/3}\alpha, \tag{2}$$

where $\alpha$ is the angle of deviation of the trajectory of the particle from a normal to the barrier. The relationship (2), as well as a number of analogous relationships, is constructed under the assumption of the existence of a functional connection between the value of the limiting thickness and the specific kinetic energy of the particle, which is a natural development of the hypothesis of the approximate proportionality of the volume of a crater in a semiinfinite target to the kinetic energy of the striking body. The formula does not contain any of the strength characteristics of the material of the plate; the weak effect of the strength on the value of $\delta_0$ has been noted repeatedly. The applicability of (2) in the case of the impact of glass particles is illustrated in Fig. 6, where the experimental data obtained are given in the coordinates $\delta_0/d$, $x = (\rho_0 v_0^2/\rho_1)^{1/3}$; the solid line corresponds to (2). The deviation of the experimental data from dependence (2) does not exceed the exactness of the formula with respect to the data using which it was constructed.

Article [2] gives the form of the dependence of the limiting thickness on the conditions of the collision, in which, as the parameter determining the phenomenon, there is taken the ratio of the specific kinetic energy of the particle to the initial level of the pressure in the barrier, $z = (\rho_0 v_0^2/\rho_1 u_s u_p)^{1/3}$. The dependence describes all the experimental results known to the authors, but its applicability is presently limited to impact velocities $v_0 \simeq 15$ km/sec. The question of the possibility of extrapolating this dependence remains open. Data obtained for the impact of glass particles are well described by this dependence. A comparison is given in Fig. 7 (the straight line corresponds to a dependence from [2]).

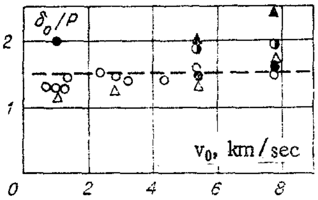

Fig. 8

For evaluations of the limiting thickness the following relationship is sometimes used:

$$\delta_0 \simeq kP, \tag{3}$$

where k = const. It has been shown that, in the case of the impact of steel particles on barriers made of aluminum and its alloys, such an approximate connection actually exists. For the impact of glass particles on aluminum alloys in the investigated range of velocities, (3) is satisfied even for $v_0 > 1$ km/sec (Fig. 8); here $k \simeq 1.5$. For barriers made of other materials, k is not a constant quantity, and evaluations made using (3) are inaccurate.

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## LITERATURE CITED

1. V. M. Titov and Yu. I. Fadeenko, "Through penetration under meteoritic impact," Kosmich. Issled., 10, No. 4, 589 (1972).
2. L. A. Merzhievskii and Yu. I. Fadeenko, "Breakdown of thin-walled pipelines filled with liquids under impact of meteorites," Kosmich. Issled., 11, No. 6, 944 (1973).
3. L. A. Merzhievskii and V. M. Titov, "Penetration of plates under high-speed impact," Zh. Prikl. Mekh. Tekh. Fiz., No. 5, 102 (1975).
4. V. M. Titov, Yu. I. Fadeenko, and N. S. Titova, "The acceleration of solid particles by a cumulative explosion," Dokl. Akad. Nauk SSSR, 180, No. 5, 1051 (1968).
5. Eichelberger and J. Kainike, "High-velocity impact," in: The Physics of Rapid Processes [Russian translation], Vol. 2, Izd. Mir, Moscow (1971).
6. High Velocity Impact Phenomena, Academic Press, New York–London (1970).
7. Fuchs, "Phenomena under impact," Raketn. Tekh. Kosmonavt., 1, No. 9 (1963).
8. F. L. Whipple, "On meteorites and penetration," J. Astronaut. Sci., 10, No. 3, 92 (1969).
9. P. V. Belyakov, F. F. Vitman, and N. A. Zlatin, "The process of the collision of deformable bodies and its modelling. II," Zh. Tekh. Fiz., 3, No. 8, 990 (1963).
10. D. R. Sawle, "Hypervelocity impact in thin sheets and semiinfinite targets at 15 km/sec," AIAA Paper No. 69-378.
11. L. I. Sedov, Similarity and Dimensional Methods in Mechanics, Academic Press (1959).