AN INVESTIGATION OF SOME PHYSICOMECHANICAL CHARACTERISTICS ASSOCIATED WITH THE PERFORATION OF A BARRIER

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ABSTRACT: The results of experiments to determine some of the parameters characterizing the perforation of a barrier made of a series of materials are set forth. These include the momentum imparted to the barrier when it is perforated, the diameters of the holes, the angles of front and rear dispersion, and a number of others.

1. Let us consider the case of delibrate perforation of a barrier of thickness t by a particle. We shall introduce the coefficients

$$k = \frac{m_2}{m_0 + \Delta P}, \qquad \beta = \frac{J_1}{J_0}, \qquad \nu = \frac{\varepsilon_1}{E_0}. \tag{1.1}$$

Here m_2 is the mass penetrating behind the barrier at velocity v_2, m_0 is the mass of the particle, ΔP is the mass lost by the barrier when it is perforated, J_1 is the momentum imparted to the barrier due to perforation, J_0 and E_0 are the initial momentum and the energy of the particle, ε_1 is that part of the energy converted to heat and irreversible volume strains behind the plastic wave. Thus, the coefficient k determines that part of the mass having the velocity v_2 behind the barrier, the coefficient β that part of the momentum received by the barrier. The equations for momentum and mass are written in the form

$$J_0(1-\beta) = m_2 v_2 - m_3 v_3,$$
$$J_0 = m_0 v_0, \qquad m_0 + \Delta P = m_2 + m_3. \tag{1.2}$$

Here v_0 is the velocity of the particle, m_3 is the mass detached in the direction opposite to the direction of impact with velocity v_3. If the process of perforation is determined by the mechanism set forth previously in [1,2], then the equation of conservation of mass up to commencement of forcing out of the "plug" [1] is written in the form

$$m_0 v_0^2 = (m_1 + m_0) v_1^2 + 2\varepsilon_1, \qquad m_0 v_0 = (m_1 + m_0) v_1. \tag{1.3}$$

Here m_1 is the mass of the barrier participating in the inelastic impact ($m_1 > \Delta P$) and moving at velocity v_1 behind the plastic wave in the barrier up to the time it leaves the rear surface of the barrier. From this

$$\nu = 1 - \frac{m_0}{m_0 + m_1}. \tag{1.4}$$

2. The powder system and the light-gas ballistic apparatus employed in [3] were used to accelerate compact spherical particles. The impact velocity did not exceed 3.5 kg/sec. The barriers were made of Mark D-16T duralumin, Mark ST-3 steel, brass, cadium, tin, zinc, lead, Mark P-500 polyethylene, poroion, sponge rubber, RK-9 rubber, polyethylene terephthalate (PETF), Mark ST glass-reinforced textolite, polyisobutylene rubber, butyl rubber, and Mark SKB synthetic rubber.

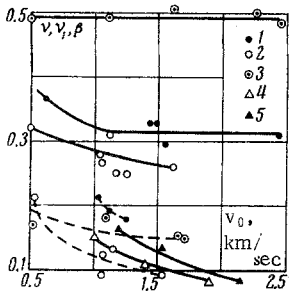

Fig. 1

The accelerated particles were made of the same metals. Steel particles were used for impact against barriers made of polymer materials. In all cases, the spheres had a diameter d_0 of 10 mm.

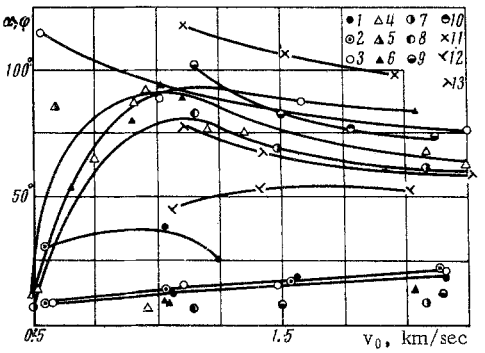

Fig. 2

Electronic chronometers of the "Neptun" type were used to measure the velocities v_0 and v_2; they received electric signals from wire sensors, and the velocities were determined on two bases for measurement [3]. The quantity ΔP increased with growth in l with v_0 = const and ρ_1 = const (ρ_1 is the density of the barrier), and with growth in ρ_1 with v_0 = const and l = const. The coefficients of the linear relationship $v_2 = a(v_0 - b)$ are given in the table. It can be seen that the velocity v_2 dropped for a given v_0 with increasing l and ρ_1.

As can be seen in the table, in a number of cases $d_0 \approx l$, thus one can consider with sufficient accuracy that the mass m_2 flies out distributed with distance, but with a velocity v_2 close to constant. This is also substantiated by the experiments described in reference [2]. It was noted in the experiments that there was a punched-out part of the barrier were distributed in the rear dispersion cone.

In order to determine the coefficient k from (1.1), experiments were conducted in the following manner: a semi-infinite barrier made of material with a known relationship of the reactive momentum coefficient $\xi(v_0)$ was installed behind the thin barrier of the material under study [3]. The distance between barriers was chosen so that the entire mass m_2 was intercepted by a semi-infinite barrier installed on a ballistic pendulum. Then, m_2 was determined from the equation

$$\xi(v_2) = J_R\,[(m_1' + m_2)(m_2 v_2^2 - 2Q)]^{-1/2}, \qquad J_R = J_n - m_2 v_2. \tag{2.1}$$

Here, J_R is the reactive momentum, m_1' is the mass ejected from the crater in the semi-infinite barrier, J_n is the experimentally measured total momentum transmitted to the barrier, and Q are the losses of energy to latent heats of phase transformation [1,3]. The value of m_2 was determined in check measurements by weighing the sheets of rubber (traps) placed behind the barrier to be studied. It follows from calculations of k by the experimentally obtained mass m_2 that with through perforation, there is no back scattering up to $v_0 \sim 1$ km/sec ($k = 1$). Then, k decreases, and for velocities $v_0 \sim 3$ to 4 km/sec, it tends toward 0.5 ($m_3 \approx m_2$). It should be noted that no back scattering was ever noted for polyethylene, poroion, or rubbers, including RK-9 rubber.

In the case of through perforation, a part of the momentum of the particle J_1 was received by the remaining barrier. In order to determine J_1, it was attached to a ballistic pendulum so that the particle would fly on through without hindrance after penetrating it, and the pendulum fixed the momentum J_1. If there were no back scattering, then, according to (1.2),

$$J_0 = m_2 v_2 + J_1. \tag{2.2}$$

Experimentally, $v_3 \sim 0.05\, v_0$ [4], which substantiates (2.2). Then, both β and m_2 can be determined from these experiments. The values

of k obtained in this manner agreed satisfactorily with previously determined values. The relationship $\beta(v_0)$ also decreasing with growth in v_0 tended toward values much less than one. Thus, henceforth we can neglect the value of β for high velocities v_0.

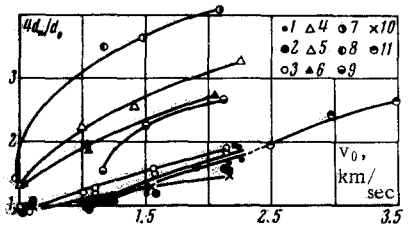

Fig. 3

In order to determine the coefficient ν by (1.4), sections of the holes in the barriers were made and the mass involved in irreversible strains was found by weighing. The sum of this mass and ΔP yielded the value of m_1. It is interesting to compute the coefficient ν_1 defining the part of the energy E_0 dissociated into heat in the front of the shock wave. The value of ν_1 is calculated by the known equation of state of the materials in the particle and the barrier, taking the cubic attenuation of pressure at the front of the shock wave into a consideration [1]. Sections of the holes and craters were constructed on a large scale for the conducted experiments for graphical representation of the pressure drop at the front of the shock wave in the particle and the barrier. The drops T(x) (where T is the temperature at the front of the shock wave) corresponding to the pressure drop at the front p(x) (x is the coordinate) made it possible to compute the share of the thermal component of internal energy and, consequently, ν_1.

The data on ν, ν_1, and β for Fe and D16T are plotted in Fig. 1. The following notation is used there $\nu(\nu_0)$: 1) Fe → D16T, l = 1.0 cm; 2) Fe → D16T, l = 0.5 cm; 3) Fe → Fe, l = 0.5 cm, $\beta(\nu_0)$; 4) Fe → → D16T, l = 0.5 cm; 5) Fe → D16T, l = 1.0 cm. In this case, the dashed lines show the relationship $\nu_1(v_0)$. It can be seen that ν_1 increases with growth of the density and the thickness of the barrier, β with growth of the thickness of the barrier with v_0 = const. The increase in ν and ν_1 with the thickness of the barrier can be explained qualitatively by the greater amount of heated mass. Averaging the values of ν due to scatter of the data is explained by inaccuracies the experimental determination of m_1. The share of the energy E_0 transmitted to the barrier was also determined experimentally by a calorimetric method for semi-infinite targets of Fe, Al, Cd, Sn, and Pb. Its ratio to E_0 drops with increased v_0, which can be explained qualitatively by the increase in energy carried off by the mass m_3 ejected from the crater. The problem of the diameter of the ejected part of the barrier ("plug") is important. Experiments involving through perforation showed that the hole in the barrier most often has the shape of a hyperboloid of revolution of one sheet, and a part of the material is sometimes carried off in face and rear fragments. One can assume that the "plug" has a cylindrical shape and is ejected before the total hole is formed. The shape of the hole (hyperboloid of revolution) is probably formed from the interaction of the sections of the hemispherical shock wave reflected from the rear surface and those still arriving. Thus, it is necessary to take the diameter of the "plug" as the minimum diameter of the hole d_*.

3. It is of interest to determine the dependence of the angles of rear (φ) and face (α) dispersion during perforation on various factors. For this purpose, sheets of Whatman paper were placed in front of and behind the target in order to fix the field of flight of small fragments. The results are presented in Fig. 2. The following notation is used: 1) Fe → D16T, l = 1.0 cm; 2) Fe → D16T, l = 0.5 cm; 3) Fe → Fe, l = = 0.5 cm; 4) Cd → Cd; 5) Fe → Cd; 6) Sn → Sn; 7) Fe → Pb; 8) Pb → → Pb; 9) Zn → Zn; 10) Fe → Zn; 11) Fe → sponge rubber; 12) Fe → → NETF; 13) Fe → ST.

As a result of these experiments, one can draw the following conclusions in regard to angles φ and α: 1) no dependence of angles φ and α on l could be found as the data for different l lay well on the relationship $\alpha(v_0)$ and $\varphi(v_0)$ for one pair; 2) φ and α did not depend on the density of the particle ρ_0 (agreement of the relationships φ_7 and φ_8, α_7 and α_8, α_4 and α_5, and others); 3) when l = const, the angles φ and α increased with increasing density of the barrier ρ_1; 4) φ increases slightly with increasing v_0; 5) the relationship $\alpha(v_0)$ has a clearly marked maximum at $v_0 \sim 1.0$ km/sec which is followed by a slight decrease; 6) the value $\varphi \sim 20^\circ$ to 25°, $\alpha \sim 60^\circ$ to 120°. The relationship 7 by (v_0) has a value of about 60° when $v_0 \sim 3.1$ km/sec is not shown in Fig. 2. The experiments showed that the face fragments (angle α) were distributed in a narrow zone at the side surface of the circular dispersion cone and the rear fragments covered the dispersion field almost evenly. It can be assumed that the annular dispersion of the face fragements is due to the introduced particle and the decrease in relationship $\alpha(v_0)$ following the maximum begins after the particle is broken into fragments.

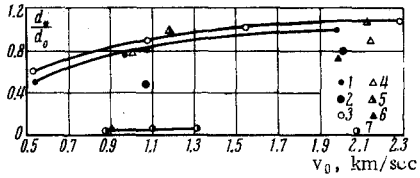

Fig. 4

Figure 3 shows the relationships $d_*(v_0)/d_0$ for metals. The notation corresponds to the notation of Fig. 2 with the following exceptions: 10) Fe → brass, l = 0.2 cm; 11) Fe → 6061-T6, l = 0475 cm. The relationship 11 is taken from [5] for a steel sphere d_0 = 0.63 cm and Mark 6061-T6 duralumin. It can be seen that the relationship 2 obtained in this work joins satisfactorily with relationship 11 at higher impact velocities v_0. Figure 4 shows the experimental data for $d_*(v_0)/d_0$ for polymer materials. The following notation is employed: 1) Fe → polyethylene, l = 1.0 cm; 2) Fe → PETF, l = 0.5 cm; 3) Fe → polyethylene, l = 0.1 cm; 4) Fe → PETF, l = 0.2 cm; 5) Fe → PETF, $l = 12 \cdot 10^{-4}$ cm; 6) Fe → sponge rubber, l = 5.0 cm; 7) Fe → Rk-9 rubber, l = = 2.5 cm. In some cases (for example, butyl rubber and polyisobutylene) the hole was observed to be completely filled in [9]. On the basis of the relationships of Figs. 3 and 4, one can conclude that the ratio d_*/d_0 with v_0 = const increases in the case of metals with increased density of the barrier ρ_1, thickness of the barrier l, and particle density ρ_0 (for the given range of velocities). At the same time, we observe an inverse pattern in the polymers: d_* decreases with increasing l even though the diameter of the perforation increases on the level of the initial and rear surfaces. One may assume that when l increases, the time for forming the hole increases and, consequently, the time for maintaining some temperature of local heating in the annular zone about the hole, which is essential to the process of filling in holes in polymers. As a consequence of this, the internal diameter

	l, cm	a	b, km/sec		l, cm	a	b, km/sec
Fe → D16T	0.5	1	0.14	Fe → polyethylene	0.1	1	0.03
Fe → D16T	1.0	0.89	0.18	Fe → porolon	3.85	1	0.03
Fe → Fe	0.5	0.666	0.18	Fe → sponge rubber	4.5	1	0.15
Fe → brass	0.2	0.9	0.14	Fe → RK-9 rubber	2.03	0.82	0.05
Cd → Cd	1.15	0.652	0.67	Fe → PETF	0.2	1	0.03
Sn → Sn	2.0	0.267	0.3	Fe → PETF	$12 \cdot 10^{-4}$	1	0.03
Zn → Zn	1.49	0.555	0.85	Fe → glass reinforced textolite	0.5	0.9	0.05
Fe(Fb) → Pb	0.97	0.55	0.2	Fe → polyisobutylene	3.6	1	0.2
Fe → polyethylene	0.99	1	0.05	Fe → butyl rubber	4.42	0.785	0

d_* decreases, even though the outer diameter of the perforation increases with growth in l. We also note that when l = const with increasing d_0, this $l = l_1$ (for the accepted v_0) and $d_* = \max d_*$ (l_1 is the maximum depth of penetration). For larger v_0 with the same d_0 = const, this is $l < l_1$ and $d_* < \max d_*$. Thus, the relationship $d_*(v_0)/d_0$ may be convex upwards, which is substantiated by experimental data (Fig. 3).

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