STUDY OF HIGH-VELOCITY BODY IMPACT IN A LIGHT POROUS MATERIAL

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Impact at high velocity (5-10 km/sec) in the case in which the density of the medium ("target") is much less than that of the impacting body has not been examined in the literature [1]. In the following we present results of an experimental investigation of the characteristics of this process.

In the experiments we used steel spheres of dimensions of the order of a few millimeters, accelerated to a speed v_0 = 5-10 km/sec by expolsive charges [2]. The targets were blocks of styrofoam, polyurethane foam (poroplast), porous rubber, and fibrous materials. The density of these materials lies in the range from 0.06 to 0.35 g/cm^3. As a rule, the pore dimension and distance between pores is much less than the sphere diameter d_0.

For all the impact velocities in the experiments the initial embedding stage is a hypersonic process, since the sound wave propagation velocity in porous media is low [3].

The experiments dislcosed several basic regimes of the body embedding process.

1. The stresses which arise in the body are less than the body material strength. This is obviously possible for sufficiently small values of $\rho_1 v_0^2$ (here ρ_1 is the density of the target material). The following experiment can serve as an example: for ρ_1 = 0.11 g/cm^3 (styrofoam), v_0 = 5.1 km/sec, the sphere d_0 = 3.35 mm does not fracture, covering the distance p = 780 mm ≈ 230 d_0 before stopping. The final body mass amounts to 0.85 times the initial mass, which permits considering the dimensions at the beginning of penetration unchanged. We compare the embedding process with supersonic gas flow over a sphere. In this case the force acting on the sphere is

$$F = -k(v)\rho_1 r_0^2 v^2 \tag{1}$$

where ρ_1 and v are the flow density and velocity, and r_0 is the sphere radius. We note that k(v) = const = 1.44 for values of the Mach number M ≥ 4 [4]. From (1) for v = v_0 and s = 0 (s is the body travel distance) we obtain the deceleration law

$$v = v_0 \exp\left(\frac{-k\rho_1 r_0^2 s}{m}\right), \quad \text{or} \quad v = v_0 e^{-kx} \left(s' = \frac{s}{dI_0}, \quad x = \frac{3}{2\pi}\frac{\rho_1}{\rho_0} s'\right) \tag{2}$$

Here m is the sphere mass, and ρ_0 is the body material density.

Recording of the body motion in the target material was performed with the SFR photorecorder. Gaps of 1-1.5 mm were left between the 20-30 mm thick material layers. Scanning of the embedding process makes it possible to establish body passage through the gap and determine the average velocity of the body in a given segment. The measurements were made up to s = 50-60 d_0, results are shown in Fig. 1. Comparison with the curve $f(x) = e^{-2x}$ shows that k ≈ 2 for the materials studied. In order of magnitude this is close to the data of [4] for a gas (the difference of up to a factor of 1.5 is obviously related with the change of the nature of the flow).

In the study we did not investigate the deceleration near the stopping point. There are indications [5] of an abrupt change of the deceleration law and drag coefficient for small motion velocities in the case of impact in sand (v_0 = 0.7 km/sec).

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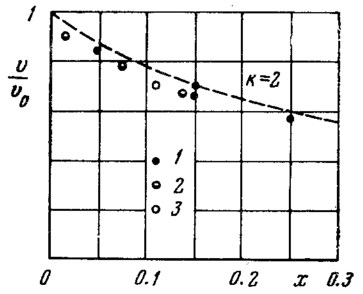

Fig. 1

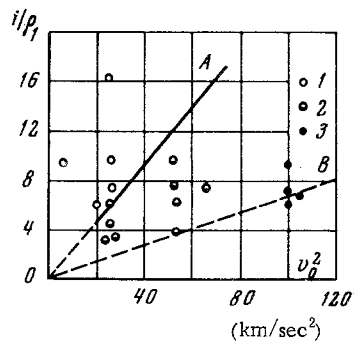

Fig. 2

Fig. 1. Deceleration of steel sphere in material: d_0 = 3.35 mm, v_0 = (5.1 ± 0.15) km/sec. 1) Styrofoam with ρ_1 = 0.06 g/cm^3; 2) styrofoam with ρ_1 = 0.11 g/cm^3; 3) porous rubber with ρ_1 = 0.15 g/cm^3.

Fig. 2. Breakup of steel sphere: 1) region of retention of integrity; 2) region of body breakup; 3) region of body material flow.

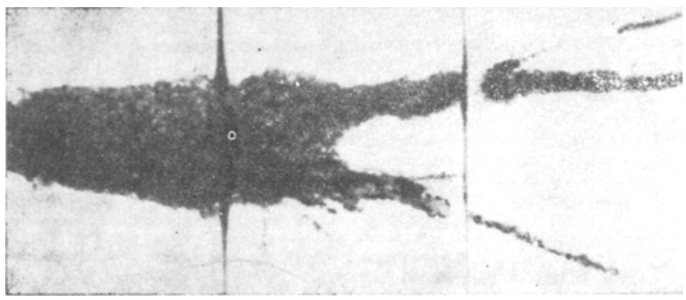

Fig. 3. Impact in poroplast (polyurethane foam): d_0 = 1.7 mm; v_0 = 7.35 km/sec, ρ_1 = 0.28 g/cm^3.

In the considered embedding mechanism the maximal penetration depth corresponds to the maximal velocity for which breakup is still absent. The actual process is complicated by change of the body dimension as a result of mass erosion from the surface.

The breakup condition for a sphere traveling at hypersonic velocity v in a gas of density ρ_1 has the form [6]

$$\rho_1 v^2 \geqslant a\sigma \qquad (a \sim 3.5) \tag{3}$$

Here σ is the body material strength in tension or shear (depending on the material properties). Comparison of the deceleration processes makes it possible to suggest an analogous form of the breakup condition for motion in a light porous medium. Then for the same strength characteristics of the bodies used in the experiments the breakup (retention of integrity) boundary is represented in the plane of the variables v_0^2, $1/\rho_1$ by the ray $c_1 = \rho_1 v_0^2$.

2. The stresses which arise in the body are greater than the strength of the body material. Figure 2 shows results of experiments made in our study in the plane of the variables v_0^2, km^2/sec^2 and $1/\rho_1$ (g/cm^3)$^{-1}$. Region 1 corresponds to retention of body integrity (points 1), region 2 corresponds to breakup (points 2). We recall that here the bodies are steel spheres. The breakup boundary is obviously close to OA. The diagram (Fig. 2) is very approximate, but it does make possible a preliminary estimate of the nature of the interaction with a given body for a known body material. In cases of practical interest the choice of the body material is limited: meteorites are stony and iron-nickel; the bodies accelerated in labroatory conditions are made from steel, duraluminum, sometimes polymer materials.

The nature of the breakup depends strongly on the quantity $\rho_1 v_0^2$ and the body material. Spalling of the material at the surface and formation of short splinter tracks can be observed (glass at low impact velocity); breakup with plastic deformation of the body is possible (here deformation without breakup may

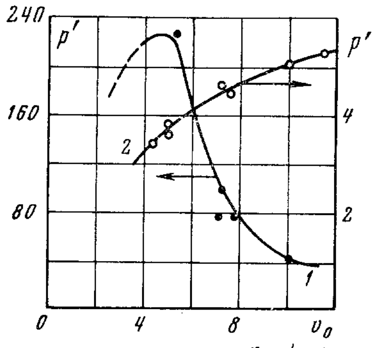

Fig. 4. Target penetration depth versus steel sphere impact velocity: 1) styrofoam with ρ_1 = 0.11 g/cm^3; 2) duraluminum.

also be observed in the transitional regime). Typical for spheres made from hardened steel at $v_0 \sim 6$-8 km/sec will be breakup into splinters (Fig. 3); their number increases with increase of the velocity. X-ray photographs taken prior to breakup record marked deformation in the transverse direction (into the disk); this leads to stronger deceleration than in the absence of breakup. A finite time is required for breakup and dispersion of the fragments; therefore the entrance segment is a broad cylindrical channel (Fig. 3).

3. The stresses which arise in the body are much greater than the body material strength. In this case flow of the material takes place. In the limiting case the material strength can be neglected and it becomes fluid-like. Such models have been thoroughly studied for high-velocity impact on metal [1] and in implosion theory [7]. The fragment traces disappear and the impact crater takes the form of a relatively broad hollow.

In a rough approximation we can asusme that the transition to this regime (zone 3 in Fig. 2) also takes place along some ray $c_2 = \rho_1 v_0^2$ in Fig. 2 (dashed curve OB); here definition of the exact boundary is not possible, which is also demonstrated experimentally. We note that OB fixes the beginning of the change of the nature of body breakup with regard to the residual effect – the crater and not the developed flow of the body material. The analogy with high-velocity impact on a dense material can ovbiously be carried out for considerably larger values of $\rho_1 v_0^2$. In this case the lower estimate of the penetration depth (in order of magnitude) can be made using the relations of shaped charge theory, as is frequently done in studies on impact on dense materials [1].

The process characteristics examined in sections 1-3 lead to reduction of the penetration depth into the light material with increase of impact velocity for $v_0 \sim 5$-10 km/sec. Figure 4 shows the relation $p' = p/d_0 = f(v_0)$ (curve 1) for styrofoam (ρ_1 = 0.11 g/cm^3). Data for impact on duraluminum (curve 2) are presented for comparison. With further increase of the velocity v_0 the penetration depth begins to increase because of increase of the residual deformation of the material as a result of inertial motion.

A physical analogy to the considered "anomalous" nature of the curve $p' = f(v_0)$ can be observed in the case of impact on metal with relatively low velocity of a body made from very strong material [8].

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