STUDY CONCERNING THE PENETRATION OF HIGH-VELOCITY FINE PARTICLES INTO VARIOUS MATERIALS

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Results are shown of a study concerning the penetration of fine particles (size range from a few microns to a few tens of microns) moving at a velocity up to 16 km/sec into barriers made of plastic materials (thickness up to a few microns), brittle materials, or soft materials.

Many studies have been made concerning the penetration of fast moving bodies into various barriers (e.g., [1-6]).

For targets made of plastic materials, assuming that the energy expended on forming a crater is proportional to the kinetic energy of the particle and that the crater is almost spherical in shape, we have

$$\frac{h}{D_0} \sim \varepsilon^{\frac{1}{3}} \sim v_0^{\frac{2}{3}}, \quad \frac{D}{D_0} \sim \varepsilon^{\frac{1}{3}} \sim v_0^{\frac{2}{3}}$$

(it will be assumed here and subsequently that the velocity vector of a particle is normal to the target surface).

In most experimental studies the test data have been evaluated in terms of a power law, which for the general case can be written as

$$\frac{h}{D_0} = \text{const}\left(\frac{\rho_0}{\rho}\right)^n \left(\frac{\varepsilon}{\omega}\right)^m. \tag{1}$$

Here $\varepsilon = \rho_0 v_0^2/2$ and ω is some mechanical strength parameter of the target material (E, G, B); according to the data in [3-5], n = 1/3 and m = 1/3.

TABLE 1. Compilation of Results Pertaining to the Penetration of Particles into Plastic Targets, according to Various Semiempirical Relations (α (h/D$_0$) = $\alpha\, v_0^{2/3}$, v_0, km/sec)

Particle material	Chromium		Corundum	
Target material	AMG-6	D-16-T	AMG-6	D-16-T
Formulas				
(4), (6)	0,93		0,16	
[3]	0,76		0,55	
]4]	1,1		0,77	
[5]	1,1	0,83	0,55	0,43

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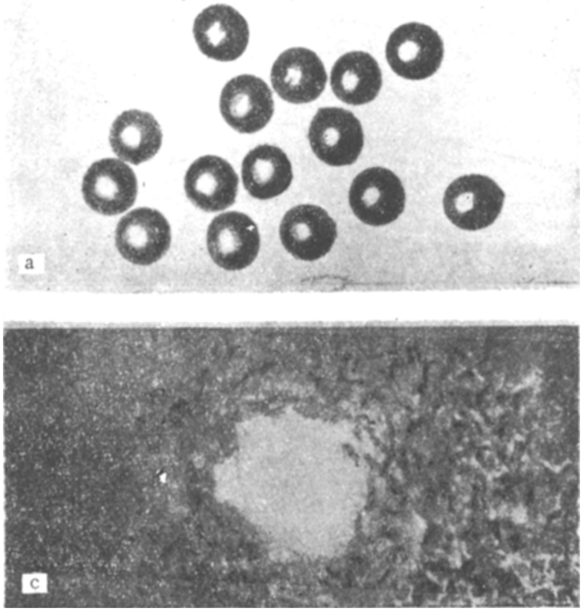

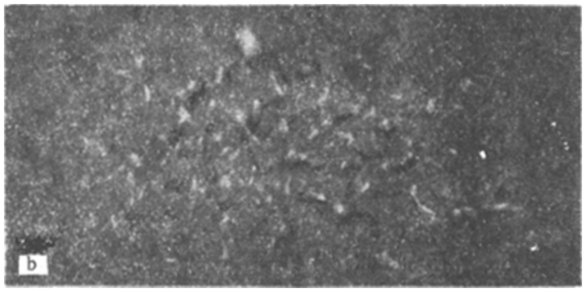

Fig. 1. Photographs: (a) of spherical glass particles, (b) of anodized surface of a D-16-T target before impact, (c) of crater in a target (corundum particles, D_0 = 60 μm, v_0 = 4.7 km/sec, D = 132 μm, h = 22 μm).

The relative depth of penetration into brittle materials of low strength is, according to [6], a linear function of the velocity

$$\frac{h}{D_0} \sim (v_0 - v_*).$$

Here v_* is the minumum velocity at which a crater will form. This relation can be derived from the equation of motion for a spherical particle in a medium

$$C_x \frac{\rho v^2}{2} S = -m \frac{dv}{dt},$$

if we let $C_x = a/v$; then,

$$\frac{h}{D_0} = \frac{4}{3a} \cdot \frac{\rho_0}{\rho} (v_0 - v_*). \tag{2}$$

When a particle moves at a high velocity in a soft material, or in a liquid or gas, then it may be assumed that C_x = const. In this case, from the equation of motion we obtained for a spherical particle (when no ablation or fracture occurs) the relative depth of penetration:

$$\frac{h}{D_0} = \frac{4}{3C_x} \cdot \frac{\rho_0}{\rho} \ln \frac{v_0}{v_*}, \tag{3}$$

with v_* defined according to the relation

$$\frac{\rho v_*^2}{2} = \sigma_p.$$

TABLE 2. Compilation of Results Pertaining to the Penetration of Particles into Soft Target Materials, according to Theoretical and Semiempirical Relations

Resin target and glass particles	β	v_*, km/sec	$\frac{h}{D_0} = \beta \ln \frac{v_0}{v_*}$, v_0 (km/sec) equal to 5	10	15
(8)	9,3	1,3	12,5	19	22,7
(3)	3,3	0,1	13	15,3	16,6

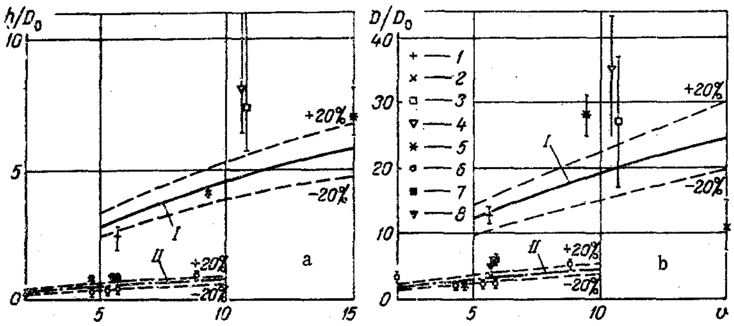

Fig. 2. Ratio of crater depth (a) and of crater diameter (b) to the initial particle diameter, as a function of the velocity, for plastic (coated) and brittle materials: chromium particles with D_0 = 5.3 μm and target material AMG-6 (1), D-16-T(2), quartz (3), chrome yellow (4); corundum particles with D_0 = 60 μm and target material AMG-6 (5), D-16-T (6), quartz (7), chrome yellow (8). In Fig. 2a: curve I according to formula (4), curve II according to formula (6). In Fig. 2b: curve I according to formula (5), curve II according to formula (7). Velocity v (km/sec).

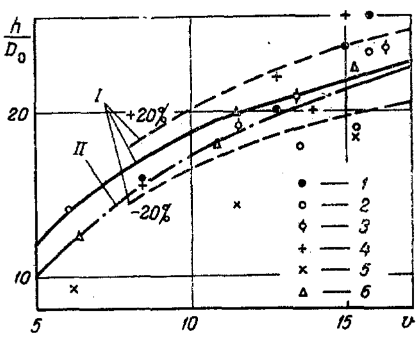

Fig. 3. Ratio of crater depth to initial particle diameter, as a function of the velocity, for soft targets materials: rubber target and glass particles with D_0 = 250 μm (1), 420 μm (2), 500 μm (3); felt target and glass particles with D_0 = 250 μm (4), 420 μm (5), 500 μm (6). Curve I according to formula (8); curve II according to formula (9). Velocity v (km/sec).

These expressions (1)-(3) have been used in the evaluation of our test data.

In order to impart high velocities to particles in this experiment, the authors accelerated them with a plasma jet from a coaxial pulse-type injector. The maximum error of a velocity measurement was 20%.

The experiment was performed with chromium particles (average diameter $D_0 \simeq 5.3$ μm) as well as with corundum and glass particles (average diameter $D_0 \simeq 60$ μm). The glass particles (Fig. 1), which had been produced and sorted out by a special method, were almost spherical and their dimensions did not deviate from the average by more than 10%; the chromium and the corundum particles had also been sorted out according to size, but were irregular in shape and yet nearly enough spherical.

As target materials we used aluminum grades AMG-6 and D-16-T (anodized with sulphuric acid), grade KV quartz glass, grades 108 and 208 chrome yellow, grade OM-12 rubber, and felt.

A crater was photographed (Fig. 1) and its depth as well as mean diameter were measured under a model MIM-7 metallographic microscope. The crater diameters were measured at the level of the target surface, their depth were measured from that same level down (during the measurement of penetration depths into soft materials, the latter were distorted by stretching). There was a 20% measurement error.

Several craters were selected and measured on the target in each test, and the final result was based on their average depths and diameters respectively.

The test results for plastic and brittle targets and for chromium and corundum particles have been plotted in Fig. 2 in h/D_0, $D/D_0 = f(v_0)$ coordinates (the average values here are based on several tests at the same velocity, with the extreme deviations also shown).

The depths and the diameters of craters in AMG-6 and D-16-T targets were respectively equal, with all other conditions the same, and a combined evaluation of the results by the method of least squares yielded:

1) for chromium particles (D_0 = 5.3 μm, v_0 = 6-15 km/sec)

$$\frac{h}{D_0} = 0.93\, v_0^{\frac{2}{3}}, \tag{4}$$

$$\frac{D}{D_0} = 4.1\, v_0^{\frac{2}{3}}, \tag{5}$$

2) for corundum particles (D_0 = 60 μm, v_0 = 2-10 km/sec)

$$\frac{h}{D_0} = 0.16\, v_0^{\frac{2}{3}}, \tag{6}$$

$$\frac{D}{D_0} = 0.95\, v_0^{\frac{2}{3}} \tag{7}$$

(v_0 in km/sec).

A comparison of these results with certain known semiempirical formulas [3-6] (Table 1) shows an acceptable agreement for chromium particles but large discrepancies in the case of corundum particles. The latter are, evidently, related to the fracture of corundum particles during impact against a target, in which case these relations do not apply.

Unlike in the case of plastic target materials, the appearance of craters and the overall surface damage to targets of brittle materials (quartz, chromium) were characterized by chips and cracks; here a crater had most often an irregular shape. Some data on the penetration into brittle materials are also given in Fig. 2a, b.

Test data on the penetration depth of glass particles into soft materials (OM-12 rubber, felt) are shown in Fig. 3 in $h/D_0 = f(v_0)$ coordinates.

An evaluation of these test data according to Eq. (3) has yielded the following relations:

a) for a rubber target and glass particles (D_0 = 250-500 μm, v_0 = 6-16 km/sec)

$$\frac{h}{D_0} = 9.3 \ln\left(\frac{v_0}{1.3}\right), \tag{8}$$

b) for a felt target and glass particles (D_0 = 250-500 μm, v_0 = 6-16 km/sec)

$$\frac{h}{D_0} = 10 \ln\left(\frac{v_0}{1.8}\right) \tag{9}$$

(v_0 in km/sec).

The values of h/D_0 calculated according to formulas (8) and (3) for OM-12 rubber are shown in Table 2 (with $\rho_0 = 2.5 \cdot 10^3$ kg/m^3, $\rho = 10^3$ kg/m^3, $\sigma_p = 0.5 \cdot 10^7$ N/m^2 at Re > 10^3 and Ma > 3 C_x = 1 in Eq. (3) so that $\beta = 4/3C_x \cdot \rho_0/\rho = 3.3$ and $v_* = 0.1$ km/sec).

These results confirm the proposition that it is possible, at least, to evaluate the data on the piercing of soft targets in terms of relation (3) when $h/D_0 > 10$.

NOTATION

h is the path, depth, m (μm)
D is the diameter, m (μm)
S is the area, m^2;
m is the mass, kg
t is the time, sec (μsec)
ρ is the density, kg/m^3;
E is the modulus of elasticity, N/m^2;
G is the modulus of shear, N/m^2;
B is the Brinell hardness, N/m^2;
σ_p is the ultimate strength;

C_x is the resistance coefficient;
Re is the Reynolds number;
Ma is the Mach number.

Subscripts

0 refers to a particle;
no subscript for a target or for space coordinates.

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