DIMENSIONS OF THE CRATER FORMED BY THE PENETRATION OF FAST PARTICLES INTO SOLID BARRIERS

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Semiempirical relations are presented for determining the depth and diameter of the crater formed by 16 km/sec spherical particles penetrating into a solid semiinfinite barrier.

In a previous paper [1] the authors reported the results of an experimental study of the penetration of 16 km/sec particles into semiinfinite barriers of plastic, brittle, and soft materials, and gave empirical relations for the relative depth of penetration h/D_0 and the relative diameter of the crater D/D_0 as functions of the projectile and target characteristics. Similar data for velocities up to 10 km/sec appear in [2-5]. The existing experimental data can be generalized by a certain semiempirical relation.

The following model of the penetration process is assumed.

The motion of a particle (projectile) in a solid barrier is similar to its motion in a liquid or gaseous medium, and is described by the equation

$$C_x \frac{\rho v^2}{2} S_0 = -m_0 \frac{dv}{dt}. \tag{1}$$

Setting $v = dh/dt$ and $\Omega = V_0/S_0$ we obtain

$$\frac{dh}{\Omega} = -2\frac{\rho_0}{\rho}\cdot\frac{1}{C_x}\cdot\frac{dv}{v},$$

from which the relative depth of penetration is found to be

$$\frac{h}{\Omega} = -2\frac{\rho_0}{\rho}\int\limits_{v_0}^{v_*}\frac{1}{C_x}\cdot\frac{dv}{v}. \tag{2}$$

Here v_*, the minimum velocity for which motion in the given medium is possible, is determined from the condition

$$\frac{\rho v_*^2}{2} = \sigma$$

and is equal to

$$v_* = \left(\frac{2\sigma}{\rho}\right)^{\frac{1}{2}}. \tag{3}$$

A particle moving in a solid with a velocity greater than a certain value v_{**} forms a cavitation recess whose maximum cross section can be found from the condition

$$C_{x_0}\frac{\rho v_0^2}{2} S_0 = \sigma S_{**} \tag{4}$$

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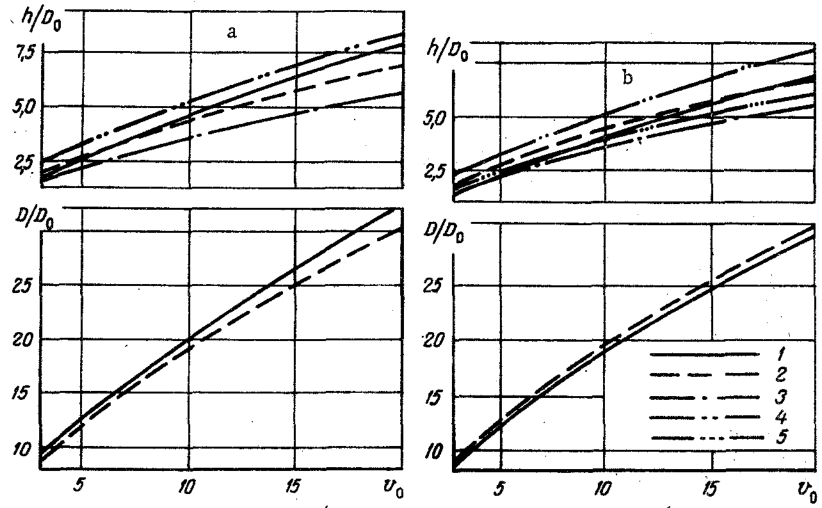

Fig. 1. Relative depth h/D_0 and relative diameter D/D_0 of a crater as functions of impact speed v_0 for a) AMG-6 aluminum targets and chromium particles. 1) by Eqs. (14), (15); 2) data from [1]; 3) data from [2]; 4) data from [3, 4]. b) D16-T duralumin targets and chromium particles. 1) by Eqs. (14), (15); 2) data from [1]; 3) data from [2]; 4) data from [3]; 5) data from [4]. v_0, km/sec.

to be

$$\frac{S_{**}}{S_0} = C_{x_0} \frac{\rho v_0^2}{2\sigma}.$$

If the ratio of the depth of penetration to the distance from the forward tip of the projectile to its midsection is more than two, the cross section of the crater S is approximately equal to the maximum cross section of the cavitation recess S_{**}. Then

$$\frac{S}{S_0} = C_{x_0} \frac{\rho v_0^2}{2\sigma}. \qquad (5)$$

The minimum velocity of the projectile (particle) v_{**} at which a cavitation recess is formed is found from Eq. (4) and the condition $S_0 = S_{**}$ to be

$$v_{**} = \left(\frac{2\sigma}{C_x \rho}\right)^{\frac{1}{2}}. \qquad (6)$$

Equation (5) is obviously not applicable to soft materials such as rubber or felt or to loose porous media such as sand or poroton where the cavitation recess is not preserved and the penetration of the particle often does not even produce a crater. Penetration into brittle barriers is generally accompanied by the appearance of cracks and spallation [1, 5] leading to a significant increase in the size of the crater at the surface as compared with the maximum size of the cavitation recess formed.

Thus the process of formation of a crater is thought of as consisting of two phases: 1) the penetration of the projectile (particle) into the barrier with the formation of a cavitation recess; 2) the displacement or ejection (at higher projectile energies it is explosive in character) of disintegrated, molten, or evaporated target and projectile materials; this increases the diameter of the crater at its bottom where the pressure is maximum without appreciably changing the size of the crater at the surface, of the depth of penetration.

As in a liquid or gas the coefficient of resistance C_x generally depends on the velocity of the projectile and the characteristics of the target and projectile materials such as density, strength properties etc. We write C_x as a power function of $\varkappa = \rho v^2/2\sigma$ and $\theta = \rho/\rho_0$:

$$C_x = \alpha (\theta\varkappa)^n. \qquad (7)$$

The parameter $(\theta\varkappa)$ can be regarded as the analog of the Reynolds number for the motion of bodies in a liquid or gas; the constant α depends on the shape of the body.

It is physically justified to take the strength characteristic σ in Eqs. (3)-(7) as the compression strength.

The relative depth of penetration h/Ω and the relative diameter of the crater D/Ω as functions of the impact speed v_0 and the target and projectile characteristics are obviously determined by the values of n and α.

From Eqs. (2) and (5) we obtain:

for $n \neq 0$

$$\frac{h}{\Omega} = -\frac{1}{n\alpha}\theta^{-(n+1)}[\varkappa_0^{-n} - 1], \tag{8}$$

for $n = 0$

$$\frac{h}{\Omega} = \frac{1}{\alpha}\theta^{-1}\ln\varkappa_0, \tag{9}$$

$$\frac{S}{S_0} = \alpha\theta^n\varkappa_0^{n+1}. \tag{10}$$

For spherical particles, used in most experiments on the interaction of fast particles with barriers, Eqs. (8)-(10) take the form:

for $n \neq 0$

$$\frac{h}{D_0} = -\frac{2}{3n\alpha}\theta^{-(n+1)}[\varkappa_0^{-n} - 1], \tag{11}$$

for $n = 0$

$$\frac{h}{D_0} = \frac{2}{3\alpha}\theta^{-1}\ln\varkappa_0, \tag{12}$$

$$\frac{D}{D_0} = \alpha^{\frac{1}{2}}\theta^{\frac{n}{2}}\varkappa_0^{\frac{n+1}{2}}. \tag{13}$$

The processing of the experimental data [1-5] on the penetration of fast spherical particles into semi-infinite barriers of plastic and brittle materials for $v_0 = 3$-16 km/sec and $h/D_0 > 1$ indicates that the most probable values of α and n are: $\alpha = 5.4$, $n = -1/3$.

Finally the working formulas for determining the relative depth of penetration h/D_0 of spherical particles for $h/D_0 > 1$ and the relative diameter of the crater D/D_0 take the form:

$$\frac{h}{D_0} = 0.37\left(\frac{\rho_0}{\rho}\right)^{\frac{2}{3}}\left[\left(\frac{\rho v_0^2}{2\sigma}\right)^{\frac{1}{3}} - 1\right], \tag{14}$$

$$\frac{D}{D_0} = 2.32\left(\frac{\rho_0}{\rho}\right)^{\frac{1}{6}}\left(\frac{\rho v_0^2}{2\sigma}\right)^{\frac{1}{3}}. \tag{15}$$

Figure 1 compares the values of h/D_0 and D/D_0 calculated by Eqs. (14) and (15) with data from [1-4].

For the motion of fast projectiles in soft materials, porous and loose media in appears that $C_x \simeq$ const ($n = 0$) and the relative depth of penetration is described by Eqs. (10) and (13).

NOTATION

h is the path length or depth of penetration, m;
D is the diameter, m;
S is the area, m^2;
V is the volume, m^3;
m is the mass, kg;
t is the time, sec;
v is the velocity, m/sec;

ρ is the density kg/m^3;

σ is the compression strength, N/m^2;

C_x is the resistance coefficient.

The subscript $_0$ denotes initial parameters and particle (projectile) characteristics. Quantities without subscripts are flow parameters or target characteristics.

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