MACRO-SUPER-PENETRATION

G. P. Cherepanov*

The present paper is focused on a discussion of the physical possibility of the superdeep penetration of hypervelocity macro projectiles into a solid material. An overview of some papers on superdeep penetration is provided in Section 1. Some experimental evidence of the superdeep penetration of microparticles is treated in Section 2. The theoretical analysis of the phenomenon is summarized in Section 3. In Section 4, it is concluded that superdeep penetration of an individual projectile represents a resonance-type phenomenon, which can exist only in a narrow band of high subsonic velocities near the Rayleigh speed, when an inertial self-sustained, self-propagating cavity is formed by the projectile.

INTRODUCTION

Superdeep penetration is referred to as the fast motion of a projectile in a solid material at distances hundreds and thousands of times greater than the characteristic initial diameter of the projectile. The first paper on superdeep penetration was published in 1960 by G.I. Barenblatt and G.P. Cherepanov (1). In this paper, the dynamic plain-strain cleavage regime was studied for the sub-Rayleigh steady-state motion of a thin rigid wedge in an elastic-brittle material.

In the middle of the 1970's, S.M. Usherenko, while studying the hypervelocity impact of dust clusters of microparticles impinging into metal targets, discovered the remains of some particles very deep beneath the surface. The depth of the penetration achieved was 100 to 10,000 times the diameter of the particle. Later, this discovery was studied and reported in a series of publications by Usherenko with coworkers (2,3).

*Department of Mechanical Engineering, Florida International University, Miami, Florida

Some attempts at a theoretical explanation of this phenomenon was undertaken by Cherepanov in the papers (4,5) and approximately 40 papers on superdeep penetration were reviewed. The authoritative American editions (6,7) included superdeep penetration in a list of number-one priorities of former Soviet technologies recommended for transfer to American soil. In the numerical experiments, R.D. Young et al (8) confirmed some features of the initial stage of superdeep penetration using a numerical code.

J.E. Backofen (9) told the author that he was close to the discovery of superdeep penetration back in the 1960's. (See also paper (10), where his idea of a kernel in shaped charge jets bears the germ of superdeep penetration.)

From a pragmatic point of view, superdeep penetration is quite unusual. However, the basic principles of dynamic deformation and fracture (Gilman (11), Cherepanov (12-14)) do not involve any special prohibitions to superdeep penetration in microscale and macroscale.

Recently, it was discovered (12,13) that the drag of a projectile moving in an elastic medium vanishes at the Rayleigh speed if one neglects the friction. The present paper shows that this result is also valid for arbitrary dry friction law (for more detail, see Chapter 9 in book (14) by this author).

TESTS

Superdeep penetration has been observed in the experiments whose details follow. Packages containing 10^6 to 10^9 microparticles with diameters of 0.1 to 100 micrometers were accelerated using two-stage helium guns or high explosive solid propellants or Titov's pipes up to the hypervelocity range, 1 to 7 km/s, which is close to the lower bound of the speed of slow meteorites. The penetration of the particles into various metal targets was investigated using optical and scanning electron microscope techniques, radiometallography, chemical analysis, and X-ray diffraction analysis.

The target materials were armco iron, steel, copper, lead, aluminum, and a variety of alloys, which are commonly ductile materials. The material of the particles was alumina, tungsten, iron, titanium, molybdenum, boron, cobalt, diamond, and others.

After impact, the cluster particles appeared to be uniformly distributed in the surface layer of a target material. The thickness of the layer, that is, the greatest depth of penetration, was investigated. The table below shows the typical results of tests conducted in the Laboratory of Materials at Dzerzinsky Military Academy in Moscow. The data were kindly rendered to the author by

Professor A.S. Balankin from the Mexican Institute of Technology (ITESM), who was formerly the General-Director of the Laboratory of Materials. These data were obtained by E.N. Yanevich and V.P. Osnovin from the same laboratory. Only molybdenum particles and aluminum targets are presented in the table.

TABLE 1 - The Greatest Penetration Depth of Molybdenum Particles into Aluminum Targets

Velocity of a particles cluster (km/sec)	Diameter of particles, μm ↓					
	15 ± 12	30 ± 10	120 ± 30	200 ± 50	300 ± 50	400 ± 20
1 ± 0.2	3 mm	9 mm	13 mm	23 mm	*	*
1.4 ± 0.2	11 mm	18 mm	27 mm	29 mm	*	*
2 ± 0.5	*	*	31 mm	34 mm	x	x
2.5 ± 0.5	*	*	*	23 mm	x	x
3 ± 1	*	*	*	*	x	x
4 ± 1	*	*	x	x	x	x

*Superdeep penetration was not observed. x Experimental data are not available.

As can be seen, the maximum penetration achieved was 250 particle diameters in these tests. Notice that the Rayleigh speed in aluminum is equal to 2.9 km/s, that is, 0.92 c_2 , where c_2 is the velocity of the propagation of the transverse waves.

There are no published experimental observations of superdeep penetration of individual projectiles, either in micro or macro scale. Superdeep penetration has been used for alloying a metal surface layer with unusual components or making a porous surface layer, depending on the regime; for more details, see publications (2-7).

THEORY

Some investigators have considered a fluid medium as a target material and superdeep penetration as the propagation of a projectile in the fluid. They seek certain conditions under which the turbulent motion of the material allegedly turns to a laminar one (Andilevko et al (2), Altshuler et al (3).

Estimate the maximum depth of penetration in the extreme case when the target material is an ideal fluid with zero viscosity. The friction between the projectile and target material becomes automatically zero, from this viewpoint. The maximum depth of penetration can achieve the value following from the mathematical theory of jets of a perfect fluid:

$$d_p = (\rho_p / \rho_t)^{1/2} L \qquad (1)$$

Here, d_p is the maximum penetration depth, ρ_p and ρ_t are the density of the projectile and target materials, respectively, and L is the initial length of the thin jet of a projectile material entering into a target material. Equation (1) actually provides the maximum possible penetration subject to the hydrodynamic hypothesis. It is also necessary to suppose that the projectile mass is somehow distributed during the penetration in a thin jet similar to that arising by shaped charge shot. For example, a spherical particle of tungsten with an initial diameter of 200 μm should form a cylindrical jet with a radius of 10 μm without loss of initial velocity in order to achieve the greatest depth of 23 mm in an aluminum target. (Compare with the corresponding data of the table.)

Other investigators have considered the target as a solid, and superdeep penetration as the wedge-embedded regime propagation of a projectile in the solid. From a simple energy estimate, the effective surface energy of the target material necessary to support this viewpoint appeared less than that of glass according to Cherepanov (4). From this point of view the target materials must behave, by superdeep penetration, like ideally-brittle ones with no emitted dislocations and zero plastic deformations. Furthermore, the friction between a projectile and target material must be zero.

[Generally, the drag components caused by normal pressure and friction can be written as follows:

$$D_n = \eta_n \; ES_n \, , \; D_F = \eta_F \; \tau_s \; S_c \, . \qquad (2)$$

Here, E is Young's modulus, τ_s is the minimum yield limit of the target or projectile materials, S_n is the projection area of the projectile cross-section onto the plane perpendicular to the motion direction, S_c is the contact area, D_n and D_F are the drag components due to normal pressure and friction, respectively, and η_n and η_F are the corresponding drag coefficients depending on the velocity and shape of the projectile. From Equation (2), it follows that

$$D_F / D_n = \eta_F \tau_s / (\alpha E \eta_n) \, ,$$

where α is the angle of attack of the contact area.]

So, both points of view seem to be doubtful. Therefore, the model two-dimensional problem of cutting a material by a thin rigid knife moving under a small angle of attack was considered. The exact solution to the problem was found and analyzed for two opposite assumptions:

1) the material is an elastic solid, and
2) the material is an ideal compressible fluid.

As a result of complicated computations, the drag of the plate appeared to be equal to:

$$D = \frac{\pi\alpha^2 \rho V^2 l}{4\sqrt{1-M^2}} \qquad \text{(for an ideal compressible fluid)} \tag{3}$$

$$D = (\alpha + f)\frac{2R(m)\alpha E l}{\pi m^2 \beta_1 (1+\nu)}\left(\frac{\pi^2}{4} - \theta^2\right) \tag{4}$$

(for an elastic solid with account of dry friction between the projectile and target material) ,

where

$$R(m) \equiv \beta_1\beta_2 - \beta_4^2\,,\ \theta = \tan^{-1}\frac{fR(m)}{\beta_1(1-\beta_4)}$$
$$\beta_1^2 = 1 - \frac{1-2\nu}{2-2\nu}m^2\,,\ \beta_2^2 = 1 - m^2\,,\ \beta_4 = 1 - (m^2/2) \tag{5}$$
$$M = V/c\,,\ m = V/c_2\,,\ c_2^2 = E/[2\rho(1+\nu)] = \mu/\rho\ .$$

Here, α is the small angle of attack, f is the friction coefficient on the contact area between the knife and material, l is the width of the knife, ρ is the material density, E and ν are Young's modulus and Poisson's ratio, μ is the shear modulus, V is the speed of the knife, c is the sound speed in a fluid, c_2 is the velocity of shear waves in a solid, and M and m are Mach numbers. For small α, Equation (3) coincides with that earlier derived by Chaplygin and for $m \to 0$ by Rayleigh.

Compare both hypotheses, taking into account that the compressibility in both cases should be equal to that of a real material; that is, the compressibility should coincide in both models. Hence,

$$c_1 = c, \; i.e., \quad M^2 = \frac{c_2^2}{c_1^2} m^2 = \frac{1-2\nu}{2-2\nu} m^2 , \tag{6}$$

and

$$D = \eta_s \alpha^2 \mu l , \; \eta_s = \frac{R(m)}{m^2 \beta_1} \left(1 + \frac{f}{a}\right) \left(1 - \frac{4\theta^2}{\pi^2}\right) \quad \text{(for a solid)} \tag{7}$$

$$D = \eta_f \alpha^2 \mu l , \; \eta_f = \frac{\pi}{4} m^2 \beta_1^{-1} \quad \text{(for a fluid)} \; . \tag{8}$$

Here η_s and η_f are the corresponding drag coefficients.

The η_f increases while V grows, tending towards infinity at $V = c_1$; and the η_s decreases while V grows, vanishing at $V = c_R$, where c_R is the root of equation, $R(m) = 0$ (Rayleigh speed). The drag of the knife in an elastic solid becomes zero at Rayleigh speed. This result agrees with other computations of the drag of projectiles moving at the Rayleigh speed (12,13). The calculation further shows that the energy flux at the nose of the cutting knife and far from the knife vanishes at Rayleigh speed. This means that the effective surface energy of solids appears to be zero for cutting Rayleigh speed. For more detail, see book (14).

Generalize this consideration for the 3D case of an infinite number of thin identical wings moving in the same direction in a solid and forming a double-periodic square lattice of profiles in the cross-section, perpendicular to the motion direction. In this case, it can be proven that there exists a certain critical speed at which the drag of wings becomes minimum; this speed depends on the geometrical dimensions of a wing and square lattice, but is always less than the Rayleigh speed.

CONCLUSION

Superdeep penetration represents a resonance-type phenomenon that holds only in a narrow range of subsonic penetration speeds, close to Rayleigh speed. Probably at Rayleigh speed, an inertial self-sustained, self-propagating cavity is formed around the projectile. Implementation of superdeep penetration in macroscale would ope n the door for the wide exploration of fast-moving undergound crafts.

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