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HYDRODYNAMIC MODEL OF SUPERDEEP PENETRATION OF ABSOLUTELY SOLID AXISYMMETRIC PARTICLES INTO A SEMIINFINITE METAL TARGET

S. K. Andilevko

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The process of superdeep penetration of axisymmetric absolutely solid microparticles into a metal target under conditions of loading the latter by a flux of powder particles generated by a special accelerator is investigated. An exact solution of the problem of superdeep penetration is given for the case where the pressure produced in the target by the particle flux interacting with it can be considered to be constant.

Introduction. The superdeep-penetration (SDP) effect has being studied for more than 10 years [1-4]. Its essence lies in the fact [1-3] in upon loading of a metal target by a high-speed ($U_f \approx 1-3$ km/sec) dense ($\rho_f \approx 0.5-5$ g/cm^3) flux of powder particles (with an initial characteristic size of the particles $d < 10^{-4}$ m) a some portion of the flux (< 0.1%) penetrates to a depth exceeding $10^3-10^4 d$. Such a large depth of penetration cannot be explained in terms of traditional concepts [5, 6]. Therefore, it is not suprising that a correct SDP model has not been constructed so far.

The difference of SDP from other processes associated with penetration of particles into solids consists in intensive treatment of the target by a flux of powder particles and penetration of individual particles that occurs against the background of this treatment. The pulsed pressure ($p \approx 10$ GPa) generated in collision of the flux with the target [1-3] allows consideration of the processes occurring in the zone of its existence without taking into account the tensile strength of the target [7]. The velocity of the flow particles does not exceed, as a rule, the velocity of sound in the metal target, $U_f < c$, and the Reynolds number is Re > 10^2, which allows the target material in interaction of a particle with it to be described in the approximation of an incompressible nonviscous liquid.

The process of penetration of each individual particle of the flow into the target under SDP conditions can be separated into two stages:

1) a retardation period due to the hydrodynamic head (its duration is determined by the time required for a particle to penetrate one length and the characteristic time of channel collapse);

2) particle motion after channel collapse (experimentally determined [1-3] channel collapse subsequent to particle penetration is a result of the pressure field in the target material generated by the flux of powder particles when the pressure in the rarefaction region arising behind the moving particle is much lower than the pressure created by the flux in the target material).

1. Retardation Period. In this stage, particle motion is determined only by inertia forces and the hydrodynamic head. At Re > 100, when there is no need to take into account the viscous component of the resistance, the equation of motion can be written as

$$M \frac{dU}{dt} = - C \frac{\rho S U^2}{2} . \qquad (1)$$

A solution of (1) for the initial condition $U = U_0$ at $t = 0$ is known:

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$$U = U_0 \Big/ \left(1 + C \frac{\rho S U_0}{2M} t\right), \tag{2}$$

$$x = \frac{2M}{\rho S} \ln \left(1 + C \frac{\rho S U_0}{2M} t\right). \tag{3}$$

Equations (2) and (3) relating the rate and time of the process and the particle position and time, respectively, fully describe the first stage of particle penetration.

2. Second Stage of Particle Penetration. This stage sets in after particle penetration to the depth $x > L$, when the processes associated with forced closing (collapse) of channels formed by the particle during its movement in the target material begin to exert a considerable influence on the penetration owing to the pressure p generated in the target by the flux. Here, the streamlines of the substance around the particle (in a coordinate system attached to the particle, Fig. 1) turn toward the axis of its motion at the angle α. After a time

$$t_c = d/(2W) \tag{4}$$

the channel collapses at point O separated from the rear side of the particle by $l = 0.5d \cot \alpha$. At this point two streams develop (Fig. 1): a stream in the same direction as the flow around the particle V_1 (jet 1) and a stream in the opposite direction V_2 (jet 2). The velocity of the particle changes during its motion, and therefore the coordinate system attached to it cannot be considered inertial. However, a physically small time interval Δt can always be found during which the velocity almost does not change and, consequently, the particle and point O can be considered stationary in the coordinate system attached to the particle. At point O the streamlines of the target material turn, the velocity remains unchanged, and the motion changes to the opposite direction, $V_1 = -V_2 = V$. The two streams 1 and 2 appearing at point O have the velocity $V_1 = U - V$ and $V_2 = U + V$, respectively, in the laboratory coordinate system. The substance mass entrained by jets 1 and 2 can be determined from the conservation laws for mass and momentum. In the coordinate system attached to the particle

$$dm_0 = dm_1 + dm_2,$$

$$\cos \alpha \, V dm_0 = V dm_1 - V dm_2, \tag{5}$$

whence

$$dm_1/dm_0 = (1 + \cos \alpha)/2, \quad dm_2/dm_0 = (1 - \cos \alpha)/2. \tag{6}$$

The velocity V is determined from the Bernoulli equation

$$\frac{1}{2}\rho V^2 + \frac{1}{2}\rho U^2 + p. \tag{7}$$

In a time comparable to t_c, jet 2 catches up with the particle and, slowing its motion on the rear side of the particle, pushes the latter. From this moment, formulas (2) and (3) fail to be valid for describing the penetration process.

The laws of mass and momentum conservation for the softened substance passing around the particle have the following form in the physically small time interval Δt:

$$M dU = V dm_2 - U dm_3, \quad dm_0 = dm_3 = \rho S U dt. \tag{8}$$

Substituting (6) into (8), we obtain

$$M dU/dm_0 = \frac{1}{2}(1 - \cos \alpha) V - U. \tag{9}$$

Determining (Fig. 1)

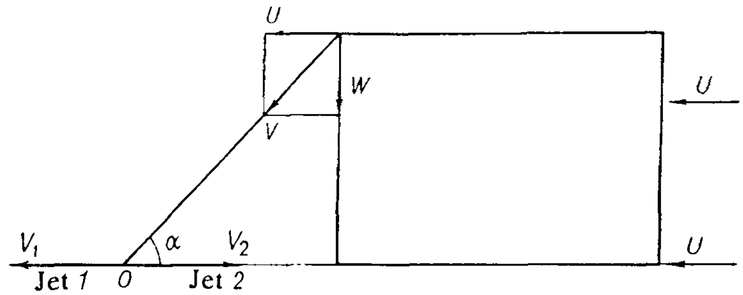

Fig. 1. Schematic of the flow of the softened target substance around a particle in a coordinate system attached to the particle.

$$\cos\alpha = U/V = 1 \Big/ \left(1 + \frac{2p}{\rho U^2}\right) \tag{10}$$

and denoting

$$y = \sqrt{2p/\rho U^2}\,, \tag{11}$$

we can write the equation of motion in the form

$$-(2M/\rho S)\sqrt{0.5\rho/p}\,\frac{dy}{\sqrt{1+y^2}-3} = dt \tag{12}$$

or, with reference to the displacement $dx = Udt$,

$$-(2M/\rho S)\,\frac{dy}{y(\sqrt{1+y^2}-3)} = dx\,. \tag{13}$$

Integration of (12) and (13) is accomplished for the initial condition $y = y_q$ when $t = t_q = t_s + t_c + T$. The time interval t_s is found from (3) for $x = L$, and the interval T determines the time from the moment of convergence of the channel "walls" at point O to the moment when jet 2 catches up with the particle and can be determined from the equation

$$l = \int_{\tau}^{t_q} V dt\,, \tag{14}$$

where $\tau = t_q - T$. Substituting the values of V from (7) and l into (14) and integrating it, we arrive at a transcendental equation for determination of y and, consequently, T:

$$\sqrt{1+y^2} - \sqrt{1+y_s^2} = \rho S d y_s/4M - \ln(y/y_s)\,, \tag{15}$$

where

$$y_s = \sqrt{2p/\rho U_s^2}\,,\quad U_s = U_0 \Big/ \left(1 + C\frac{\rho S U_0}{2M}\tau\right). \tag{16}$$

The quantity y_q determined from (15) is related to T via

$$y_q = \sqrt{2p/\rho U_q^2}\,,\quad U_q = U_0 \Big/ \left(1 + C\frac{\rho S U_0}{2M}(\tau + T)\right) \tag{17}$$

and

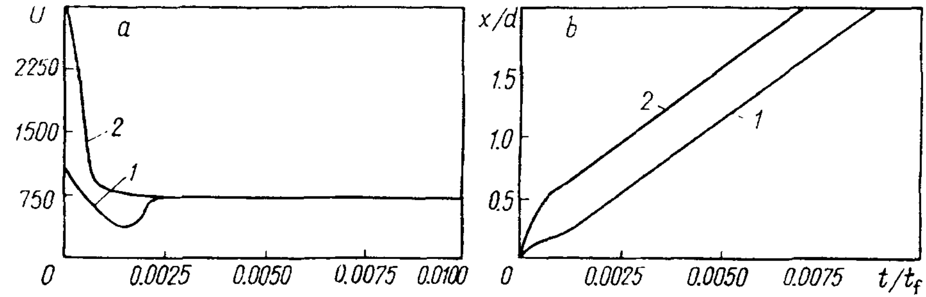

Fig. 2. Plots of the time variation of the velocity (a) and penetration depth (b) of a particle in penetration of tungsten powder particles of initial size $d = 10^{-4}$ m into steel for two initial-velocity values: 1) $u_0 = 1000$ m/sec; 2) 3000. U, m/sec.

$$x_q = (2M/\rho S)\ln\left(1 + C\frac{\rho S U_0}{2M}t_q\right). \tag{18}$$

Equations (12) and (13) admit exact integration, after execution of which we obtain

$$t = (2M/\rho S)\sqrt{\rho/2p}\,\ln\left|\tan\left(\frac{\pi}{4} + \frac{1}{2}\arccos\left(\sqrt{1+y_q^2}\right)^{-1}\right) \times \left[\tan\left(\frac{\pi}{4} + \frac{1}{2}\arccos\left(\sqrt{1+y^2}\right)^{-1}\right)\right]^{-1}\left[\frac{(\sqrt{1+y_q^2}-3)(3\sqrt{1+y^2}+y\sqrt{8}-1)}{(\sqrt{1+y^2}-3)(3\sqrt{1+y_q^2}+y_q\sqrt{8}-1)}\right]^{3/\sqrt{8}}\right| + t_q \tag{19}$$

and

$$x = x_q + (M/8\rho S)\ln\left|\frac{y^6(\sqrt{1+y^2}-1)(\sqrt{1+y_q^2}+1)}{y_q^6(\sqrt{1+y_q^2}-1)(\sqrt{1+y_q^2}+1)}\left(\frac{\sqrt{1+y_q^2}-3}{\sqrt{1+y^2}-3}\right)^6\right|. \tag{20}$$

Equations (19) and (20) for $t \geq t_q$ together with Eqs. (2) and (3) for $t < t_q$ allow determination of the particle velocity and position at any time of the SDP process.

3. Discussion. Figure 2 presents time plots of the velocity and penetration depth of a particle for two cases:

$$1)\ \sqrt{1+y_q^2} - 3 \leq 0, \quad 2)\ \sqrt{1+y_q^2} - 3 \geq 0. \tag{21}$$

It is obvious that in both cases the particle velocity asymptotically tends to the value

$$U_{st} = \frac{1}{2}\sqrt{p/\rho}, \tag{22}$$

and the penetration depth grows practically according to the linear law $x = U_{st}t$. At $p = 10$ GPa, for steel $U_{st} \approx 565.053$ m/sec. It should be noted that the velocity U_{st} depends on the pressure, and the depth x is determined by the time of its application. In practice, the entire loading time is $t_f > 10^{-4}$ sec [1-5], and thus the limiting depth of penetration for steel is $H > 0.0561$ m, or $H/d > 5610$ for $d = 10^{-5}$ m.

Obviously, the model is efficaceous only in the case $t_c \ll t_f$, which is equivalent to the inequality

$$d \ll 2t_f\sqrt{p/\rho}, \tag{23}$$

and in the case of a steel target, the condition $d \ll 0.1$ m must be satisfied, which is achieved for $d < 10^{-4}$ m.

Finally, it should be noted that the present work concerns the ideal case where the pressure generated by the flux of particles in the target remains unchanged with time. In actual practice the pressure can vary strongly with time and this fact must be taken into consideration in performing integration of Eqs. (12)-(14).

Conclusions. The suggested hydrodynamic model of SDP makes it possible to obtain a self-similar solution to the problem of penetration of a solid axisymmetric particle into a target under conditions that actually correspond to the conditions of superdeep penetration for a constant pressure field generated in the target by a flux of powder particles.

It is established that the SDP is determined mainly by two basic factors:

1) considerable softening of the target material in the penetration region during its passage, which is provided by the comparatively prolonged ($t_f > 10^{-4}$ sec) pulsed action of the flux of powder particles on the target [1-3];

2) the intensity and time of existence of the pressure field in the target, whose energy allows particles to reach superhighest depths.

Precisely the fact that an overwhelming portion of the particles of the flux (considerably exceeding 99% of its total mass), being retarded on the target surface, imparts its energy to it, which then is accumulated in the form of a pressure field, determines the possibility of realization of the superdeep-penetration effect.

NOTATION

U, particle velocity (or in a coordinate system attached to the particle the velocity of the target substance flowing over the particle); W, velocity of displacement of the channel "walls" relative to the axis of motion; V, resultant of the two velocities U and W; V_1, velocity of jet 1 emerging from point O and directed opposite to the particle motion; V_2, velocity of jet 2 emerging from point O and aligned with the particle motion; U_f, velocity of the flux of particles; α, convergence angle of the channel walls; ρ, target density; ρ_f, flux density; d and L, particle diameter and length, respectively; l, distance from point O to the rear plane of the particle; O, point of convergence of the channel formed by the particle; t_c, time of convergence of the channel "walls"; t_s, time of particle penetration to the depth $x = L$; T, time interval between the moment of convergence of the channel "walls" at point O and the moment of contact of jet 2 with the rear surface of the particle; t_q, sum of the times t_c, t_s, and T, determining the duration of the first stage of penetration; t_f, total time of action of the flux of powder particles; p, pressure generated in the target by the flux of particles; dm, mass of the target substance; dm_3 and dm_0, mass of the target substance in a layer of thickness $U\Delta t$ in front of and behind the particle, respectively; M and S, mass and cross-sectional area of the particle, respectively; C, form-coefficient of the head part of the striker; U_q, particle velocity at the moment $t = t_q$; U_{st}, steady-state particle velocity; t, time; x, penetration depth at the current moment of time; H, limiting penetration depth; c, velocity of sound in the target. Subscripts: f, flux of particles; q, values reached by the moment of time $t = t_q = t_s + t_c + T$; 1 and 2, jets 1 and 2, respectively.

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