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A CONTRIBUTION TO THE PROBLEM OF THE SUPERDEEP-PENETRATION MODEL

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Based on an analysis of the closing of a channel formed by a particle in its motion in a solid medium, the necessary and sufficient conditions of the process of superdeep penetration are formulated.

Creation of the superdeep-penetration model has received much attention [1–9]. S. P. and V. P. Kiselev [9], who used the results of previous investigations [1–5], almost attained the objective. They agreed with the conclusion of [1–5] that superdeep penetration is a specific effect the necessary condition of whose realization can be formulated as the obligatory total softening ("or melting," as is added in [1–3]) of the obstacle material near a penetrating particle. For this purpose the energy of interaction of the particle with the obstacle must be localized in the slip plane of the obstacle material nearest to the penetrating particle. If Δ and a are the distance between the neighboring slip planes and the thermal diffusivity, respectively, and U and d are the velocity and diameter of the particle, this means that

$$\frac{\Delta^2}{a} > \frac{d}{U} . \tag{1}$$

In [1–5, 9], the presence of a special nonseparating regime of flow of a softened obstacle material about a particle is considered to be a sufficient condition for the occurrence of superdeep penetration; this regime makes it possible to realize an unusual kind of analog of the D'Alembert effect for an ideal liquid in a metal [1, 2]. S. P. and V. P. Kiselev [9], analyzing flow of the obstacle material about a particle in this stage, assume the following: "Let, at the instant of time t, a spherical particle have velocity U and coordinate x. Over the period $\Delta t = d/U$, the particle will shift to the point $x' = x + d$; then a spherical cavity (pore) of radius $R = d/2$, which will be filled with the obstacle material under the action of pressure p, appears at the point x. If the pore manages to be filled over the period Δt, we have nonseparating flow about the particle ..." and hence superdeep penetration. However, drawing such a conclusion, S. P. and V. P. Kiselev [9] make a mistake. It lies in the fact that a spherical pore can never be formed even behind an ideally spherical particle in its motion in the material. An extended channel formation similar to a thin cylinder (Fig. 1) will always be formed behind it (just as behind any particle with axial symmetry moving in parallel to its axis). To determine the time of filling of the cylindrical channel formed we employ the system of equations of motion for the one-dimensional case with axial symmetry in cylindrical coordinates [10]

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial r} , \quad \frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial r} + \frac{\rho u}{r} = 0 , \quad p = p (\rho, T) , \tag{2}$$

where the last equality is the equation of state of the medium. Assuming that, in the first approximation, u depends on time insignificantly ($\partial u/\partial t = 0$) and disregarding compressibility, which can be estimated as very low at pressures of the order of 10 GPa [1–6], we obtain $\partial u/\partial r = -u/r$ and, having substituted this into the first equation of (2), we will have $-\frac{u^2}{r} = -\frac{1}{\rho}\frac{\partial p}{\partial r}$. Replacing the pressure gradient by its average value $2p/d$ in this equation, we obtain

$$u = -\sqrt{\frac{2pr}{d\rho}} . \tag{3}$$

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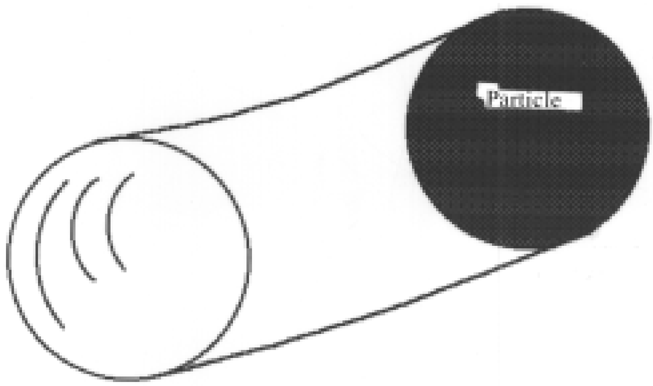

Fig. 1. Formation of a channel behind a penetrating particle.

Having performed the replacement $u = dr/dt$ in (3), we have the differential equation

$$\frac{dr}{dt} = -\sqrt{r}\sqrt{\frac{2p}{\rho d}}\,, \tag{4}$$

which can be integrated with the initial $r(t{=}0) = d$ and final $r(t = \tau) = 0$ conditions. For the total time of filling of the channel we have

$$\tau = d\sqrt{\frac{2\rho}{p}}\,. \tag{5}$$

The channel or the pore must be filled in a time shorter than d/U so as to ensure nonseparating flow about the particle, i.e.,

$$\tau < \frac{d}{U} \quad \text{or} \quad U < \sqrt{\frac{p}{2\rho}}\,. \tag{6}$$

Thus, the necessary (1) and sufficient (6) conditions create an unusual kind of velocity corridor for superdeep penetration:

$$U_{\min} = \frac{ad}{\Delta^2} < U < \sqrt{\frac{p}{2\rho}} = U_{\max}\,. \tag{7}$$

From (7) it is clear that the threshold pressure of superdeep penetration exists, since the condition $U_{\max} \geq U_{\min}$ must rigorously be obeyed:

$$p \geq p_{\text{cr}} = \frac{2\rho a^2 d^2}{\Delta^4}\,. \tag{8}$$

For $\Delta = 1.5{\cdot}10^{-6}$ m, $d \sim 10^{-5}$ m, $\rho \approx 7830$ kg/m^3, and $a = 2{\cdot}10^{-5}$ m^2/sec [9] we obtain $p_{\text{cr}} \approx 0.4$ MPa and $U_{\min} \approx 440$ m/sec. The resistance force acting on the particle from the obstacle is as follows:

$$F = -\left(\sigma + p + \rho\frac{U^2}{2}\right)\frac{\pi d^2}{6}\,. \tag{9}$$

The first term on the right-hand side of (9) is a strength one and it is vanishingly small in the case of softening of the material (the necessary condition of superdeep penetration (1) is fulfilled); the second and third terms owe their

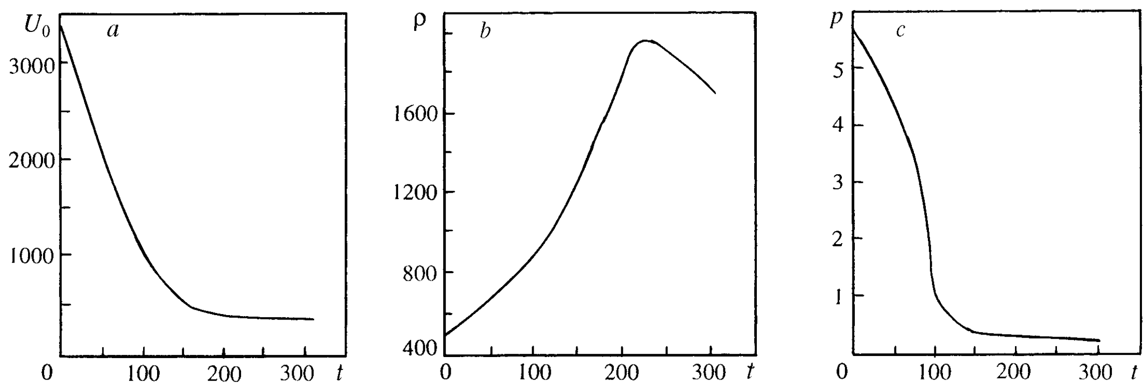

Fig. 2. Parameters of the particle flux at the level of the obstacle surface vs. loading time.

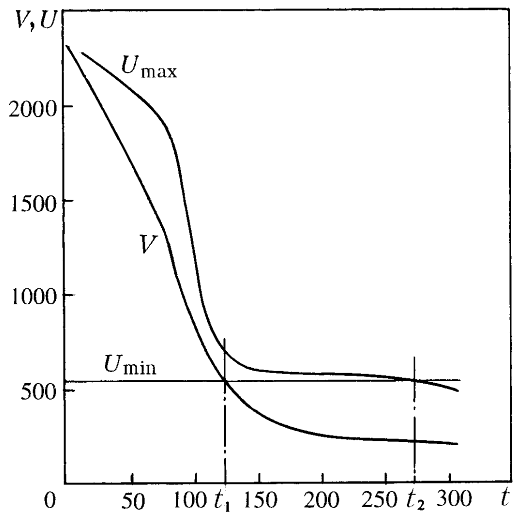

Fig. 3. Corridor of superdeep penetration and particle velocity (with allowance for starting deceleration in superdeep penetration).

occurrence to the formation of a cavity behind the particle. In the case of its total filling (the sufficient condition (6) is fulfilled) they vanish, just as the entire F. The D'Alembert effect (motion without resistance) is realized, which is usually responsible for the superdeep-penetration effect. In what follows, conditions (7), expressing both the necessary and sufficient conditions of superdeep penetration, will be named the corridor of superdeep penetration. Particles belonging to this corridor in parameters can move further actually without meeting resistance from the obstacle, i.e., uniformly, although a certain loss due to the softening and plastic deformation of the material behind the softening zone is inevitable. However it will not be taken into account in this step of investigations. We note that in determining the velocity of the particles in superdeep penetration, one must take into account their obligatory deceleration in the initial stage of the process of penetration until they reach the depth $h \sim d$, after which the superdeep-penetration mechanism comes into play. We determine the value of the velocity at this depth, having integrated the equation of motion of the particle:

$$M \frac{d}{dx} \frac{U^2}{2} = -\left(p + \rho \frac{U^2}{2}\right) S . \qquad (10)$$

As a result we obtain

$$V = \sqrt{U_0^2 \exp(-z) - \frac{p}{\rho} (1 - \exp(-z))} , \qquad (11)$$

where $z = \frac{\rho_p S d}{M}$. It is precisely this velocity that will be employed in subsequent calculations. Condition (8) makes it possible to establish the dependence of the limiting size of penetrating particles on the pressure:

$$d \le d_{cr} = \frac{\Delta^2}{a} \sqrt{\frac{p}{2\rho}} \, , \tag{12}$$

which will yield $d_{cr} \approx 57$ μm at a pressure of ~1 GPa and $d_{cr} \approx 95$ μm at p = 3 GPa.

It should also be noted that, contrary to the assumption of [9], superdeep penetration does not reveal any substantial dependence on the strength properties of particles. Thus, superdeep penetration was observed for TiB_2 and Al_2O_3 powders [11], copper [12] and bronze [13], and for a number of other materials [14] with highly diverse strength properties. Unlike [9], the subsequent calculations of superdeep penetration are based on the gas-power-jet model [13, 15, 16] formulated directly for the acceleration scheme on whose basis the experiment was carried out [13, 16]. Figure 2 shows the dependences of the velocity (a), density (b), and pressure (c) of the particle flux on the loading time obtained according to the results of the calculations [13, 16]. Figure 3 illustrates the notion of a penetration corridor. For the part of the flux that approaches the obstacle after $t_1 \approx 125.00$ μsec superdeep penetration is no longer possible, but this part of the flux, by its action on the obstacle, prolongs the motion of the highest-velocity particles, which penetrate with velocity $U = U_{max}$ from the instant of time t_1 up to the instant t_2 (~277 μsec) and attain a depth of ~0.157 m ($H/d \approx 2.5 \cdot 10^3$). Beginning with t_2 the pressure in the obstacle becomes lower than the threshold value (8), which is critical for superdeep penetration.

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NOTATION

U_0, velocity of the particle flux at the level of the obstacle surface, m/sec; p, pressure generated in the obstacle by the particle flux, Pa; U, instantaneous velocity of a particle in its deceleration in the flux, m/sec; V, velocity of a particle upon penetration to the depth $H = d$, m/sec; H, penetration depth, m; M and d, mass and diameter of a particle, kg and m; S, midsection of a particle, m^2; ρ and ρ_p, densities of the obstacle and the particle respectively, kg/m^3; τ, total time of filling of the channel formed by a particle, sec; r and u, radial coordinate and component of the velocity of the obstacle material, m and m/sec; t, running time, μsec; t_1 and t_2, calculated time intervals, μsec; z, dimensionless parameter characterizing the penetration depth; a and T, thermal diffusivity and temperature of the obstacle, m^2/sec and K; Δ, thickness of the slide planes of the obstacle, m; d_{cr}, limiting diameter of penetrating particles before attaining which one can have superdeep penetration, m; p_{cr}, minimum threshold pressure of superdeep penetration, Pa; x, running penetration depth of a particle; σ, static strength of the obstacle, Pa; F, force of resistance from the obstacle to a penetrating particle, N. Subscripts: min, minimum value of the quantity; max, maximum; p, particle; cr, critical.

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