POWDER BOMBARDMENT OF A METAL PLATE: SUPERDEEP PENETRATION

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Superdeep penetration data (mass transfer) have been used in a model based on the assumption that particle—obstacle interaction is plastic.

It has been found [1-3] that when a dense flow ($\rho_f \simeq 10^3$ kg/m³) of particles moving at $U_f \simeq 1$ km/sec and having $d \leq 10^{-4}$ m interacts with a metal obstacle, a small proportion of the flow (~0.1%) penetrates to a depth $h \geq 10^3\ d_0$, although the kinetic energy of each separate particle ($E_0 \simeq U_f^2/2 \simeq 5 \cdot 10^5$ J/kg) is sufficient only for penetration to a depth $h \leq 10\ d_0$ [4, 5]. The phenomenon has been called superdeep penetration.

There is a model for this for elastic interaction [6, 7], but experiments [1-3, 8, 9] suggest that usually it occurs with plastic interaction, where it has been found that:

1) the effect occurs only with a dense flow, and simulation by the large-particle method [10, 11] showed that the variations in density and flow rate at the surface can be evaluated in an integral fashion from exponential formulas:

$$U_f(t) = U_{\ell f} \exp(-\alpha_1 t/\tau_0),\ \rho_v(t) = \rho_{\ell f} \exp(\alpha_2 t/\tau_0), \quad (1)$$

where $U_{\ell f} \simeq 2295$ m/sec, $\rho_{\ell f} \simeq 1107$ kg/m³, $\alpha_1 \simeq 1.61$, $\alpha_2 \simeq 0.92$, and $\tau_0 \simeq 7 \cdot 10^{-5}$ sec is the total loading time, although in fact the actual $U_f(t)$ and $\rho_f(t)$ are much more complicated;

2) near a channel formed by a particle in the plate there is a region of extensive plastic strain, at the center of which there is a zone in the material had been rendered amorphous [12], which indicates considerable heating there; and

3) there is a critical size ($d_c \simeq 10^{-4}$ m), and for particles having $d_0 \geq d_c$, superdeep penetration does not occur.

We have constructed a consistent model based on plastic interaction, which is presented in much more detail than in [13].

The particle flow produces a variable pressure pattern, in which compression pulses alternate with unloading ones. The length of a pulse is of the order of the characteristic interaction time ($\tau_i \simeq \tau_d \simeq d/U_p \simeq \varepsilon^{-1} \simeq 10^{-8}$ sec), while the intensity is

$$p(t) \simeq 0.3\ c\ \rho_f(t) U_f(t).$$

With c = 5 km/sec, p is 1-10 GPa. The specific energy provided by an individual compression pulse is $\varepsilon_i \simeq 10^4$ J/kg, which corresponds to heating by $\Delta T \simeq \varepsilon_i/c_p \simeq 10$-$20°$. The number of such pulses is $n \simeq \tau_0/\tau_i \simeq 7 \cdot 10^3$. With allowance for heat transfer, we find that the specific lattice energy is increased by 10^6 J/kg, which is comparable with the latent heat of fusion $E_m \simeq c_p T_m + L_m \simeq 10^6$ J/kg, in which c_p is the specific heat of the plate. Consequently, the plate is heated to $T \simeq T_m$ in a region whose dimensions are comparable with the characteristic flow dimension (~0.1 m) and is in a state of unstable equilibrium, where even a slight increase in any factor can break the bonds. That minor factor may be a penetrating particle, for which the specific interaction energy is $E_p \simeq U_p^2/2 \simeq 10^6$ J/kg. The interaction time is

$$\tau_d \simeq \tau_m = \frac{2}{3} \lambda c_p \rho_t (T_m - T_0)^2/q^2,$$

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in which τ_m is the characteristic melting time, $q = StH_0U_p$ is the heat flux through unit contact surface, St the Stanton number, and H_0 the interaction enthalpy. With $\tau_d \lesssim \tau_R = \bar{\lambda}^2/a^2$, in which τ_R is the thermal relaxation time, the energy released in the interaction is localized in the interaction zone ($\simeq\bar{\lambda}$), which results in melting and zone softening. The vicosity and strength are comparable with μ_m and H_m, the viscosity and strength of the liquid correspondingly ($\mu_m \simeq 10^{-5}$ m²/sec, $H_m = 0$).

The pressure on the leading end determines the resistance to a cylindrical particle with length ℓ moving along its axis in the material:

$$p_F = p + H_t + \rho_t U^2/2 + \mu_t \dot{\varepsilon}.$$

In our case we have $H_t \simeq H_m = 0$, $\mu_t \simeq \mu_m$, and Reynolds number Re $\simeq 10^3$. The penetration can be examined in the approximation of a nonviscous incompressible liquid ($U < c$), when $p_F \simeq p + \rho_t U_p^2/2$ and the equation of motion for a particle is

$$M_p(dU_p/dt) = -p_F S_p + F. \tag{3}$$

The penetration depth for a single particle ($p = 0$, $F = 0$) can be determined by integrating (3) with the initial condition $U_p(t = 0) = U_0$ and the final condition $U_p(t = t_D) = 0$. With U_0 = 1-2 km/sec, the penetration of W particles into Fe is $h \lesssim 20\ d_0$, and the total interaction time is $t_D \lesssim 10^{-7}$ sec. The kinetic energy is dissipated in overcoming the resistance. Penetration to $h \simeq 10^3\text{-}10^4\ d_0$ requires the particle to have at least $10^2\text{-}10^3$ times more energy.

The only source of energy here is in the explosive used in the acceleration; that energy is stored in the plate material as the potential energy of the pressure pattern generated by the particle flux.

Part of that energy may be communicated to a projectile when the channel collapses. The pressure in the channel is $p_z \ll p$, and at the walls of the channel, there is a force difference proportional to $\Delta p = p - p_z$ directed toward the axis. That difference causes the channel to begin to collapse at a speed $W = W(\Delta p)$, and the collapse angle is

$$\alpha = \arccos\left[U_p/(U_p^2 + W^2)^{1/2}\right]. \tag{4}$$

The collapse velocity can be determined from the conservation of the Bernoulli integral when the collapse time is $\tau_x \simeq d/W \ll \tau_h$, in which τ_h is the particle movement time in the plate. Then

$$p_z + \rho_t u^2/2 = p + \rho_t U_p^2/2,\ u = U_p\sqrt{1 + \frac{2\Delta p}{\rho_t U_p^2}}, \tag{5}$$

$$u^2 = U^2 + W^2,\ W(p) = \sqrt{2\Delta p/\rho_t}. \tag{6}$$

If the (4) α exceeds α_c, the critical value of 15-25° [15], a jet flow arises from point 0 (Fig. 1), which is an accelerating jet that moves in the particle's direction. The velocity is $V_{s1} = u$ in the coordinate system linked to the point 0 [16]. The speed of point 0 in the laboratory coordinate system is

$$V_{s2} = u/\cos\alpha = U_p\left[1 + 2\Delta p/(\rho_t U_p^2)\right].$$

so the total velocity of the jet in the laboratory system is

$$V_s = V_{s1} + V_{s2} = U_p\left[(1 + 2\Delta p/(\rho_t U_p^2))^{1/2} + 1 + 2\Delta p/(\rho_t U_p^2)\right].$$

The jet rapidly ($t \simeq \tau_x$) reaches the particle ($V_s > U_p$), and is retarded at the rear surface and transfers part of its energy to it. The force on the rear surface is

$$F = S_s(\rho_t/2)(V_s - U_p)^2 + pS_s + p(S - S_s),$$

in which S_s is the jet–particle contact area. The speed of the contact point 0 is $V_{s2} > u > U_p$, so over a certain time ($\tau_d \lesssim d/2u \simeq 10^{-9}$ sec), the point of contact emerges from the rear surface. The cavity collapses and $S_s \to S$, $p_z \to p$, $\Delta p \to 0$, $V_s \to 2U_p$, so

$$F = S_p\rho_t U_p^2/2 + S_p p. \tag{7}$$

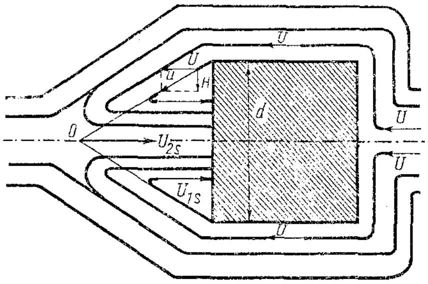

Fig. 1

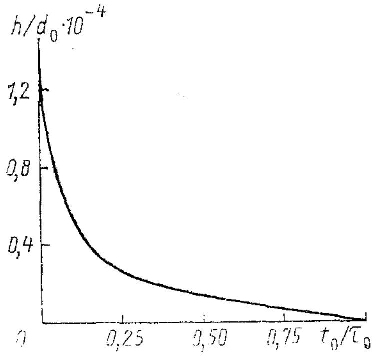

Fig. 2

Fig. 1. Flow of softened material around a cylindrical particle for a pressure pattern in the plate set up in the coordinate system related to the center of mass of the particle.

Fig. 2. Penetration depth for W particles in metallic Fe as a function of initial interaction time t_0/τ_0.

We substitute (7) into (3) to get $M_p dU_p/dt = 0$. As $M_p \neq 0$, U_p = const and the particle moves uniformly. The duration of that motion is governed by the time for which the pressure pattern p(t) exists in the plate: $\tau_0 \simeq 7 \cdot 10^{-5}$ sec. The speed in the uniform (stationary) motion of the particle U_p^* can be determined by integrating (3) with F = 0 and $U_p^* = U_p(t = \tau_x + \tau_\ell)$, where τ_ℓ is the time needed for penetration to $x = \ell$:

$$U_p^* = (2p/\rho_t)^{1/2}\,\mathrm{tg}\left\{\mathrm{arctg}\left[(1+\rho_t U_p^2/2p)\gamma - 1\right]^{1/2} - \frac{\rho_t d}{4\rho_p l}\right\}, \quad \gamma = \exp(-\rho_t/\rho_p). \tag{8}$$

If p(t) can be taken as constant, the penetration depth is

$$h_p \simeq U_p^*(\tau_0 - t_0), \quad 0 \leq t_0 \leq \tau_0, \tag{9}$$

in which t_0 is the time reckoned from the start of the interaction between the particle flow and the baffle up to the time of arrival of the given particle. The mean value is $p(t) - \bar{p} \simeq 4.4$ GPa, and with $\rho_t = 7.83 \cdot 10^3$ kg/m³, $d \simeq \ell = 10^{-5}$ m, $\rho_p = 19{,}660$ kg/m³, and $U_0 = 1.6$ km/sec we get that the maximum penetration depth is $(t_0 = 0)\,h_p \simeq 6 \cdot 10^3\, d_0$, $U_p^* \simeq 900$ m/sec.

More generally, the pressure pattern varies over time, and there may be several parts with steady-state motion, and $U_p^* = U_p^*(t)$. In the limit, the individual particle penetration depth is

$$h_p(t_0) = \int_{t_0}^{\tau_0} U_p^*(t)\,dt. \tag{10}$$

The (10) integral was calculated numerically from the (1) approximation. The penetration depth as a function of t_0, which defines the position of the particle in the flow, is shown in Fig. 2, where we have incorporated the change in the initial interaction rate with t_0. The limiting penetration depth for W in Fe is $h_p \simeq 0.12$ m $\simeq 12{,}000\, d_0$.

This mechanism may be realized if there is a region of weakened material near the particle, which is necessary to the penetration. At any instant, one should have

$$\tau_x + \tau_d \leq \tau_R.$$

We substitute for τ_x, τ_d, and τ_R to get

$$d \leq d_c, \quad d_c = \frac{\bar{\lambda}^2}{a^2}\sqrt{\frac{2p}{\rho_t}}\left[1 + \frac{2p}{\rho_t U_p^{*2}}\right]^{-1}. \tag{11}$$

This d_c thus defines the maximum particle size for which superdeep penetration can occur.

On the other hand, such penetration is possible if a jet is formed as the channel collapses. The condition for the formation is $\alpha \geq \alpha_c$ (or $\cos\alpha < \cos\alpha_c$), and we substitute for α from (5) to get

$$p \geqslant p_c, \; p_c = \frac{1}{2}\rho_t U_p^{*2}\,\mathrm{tg}^2\alpha_c \tag{12}$$

This inequality represents the sufficient penetration condition. For tungsten particles with an iron plate, $d_c \approx 88$ μm and $p_c \approx 0.3$-1 GPa.

Conclusions. Superdeep penetration can occur if two basic conditions are met: 1. Necessary: local softening near the penetrating particle due to the overall effects from the variable-pressure pattern generated by the powder flow and the energy deposition at the striker-plate contact surface, which is expressed mathematically as a constraint on the penetrating particle size. 2. Sufficient: when the channel collapses as formed by a particle in the presence of the pressure caused by the flow, conditions must be met that are necessary for a jet flow to occur, which catches up with the particle and is retarded at the rear surface to give it energy sufficient to balance out completely the energy lost in overcoming the resistance. The pressure generated in the plate by the particle flow should exceed the (12) critical pressure p_c, which is related to the minimal potential energy level produced by the flow.

The penetration depth is proportional to the powder flow loading time or flow length.

NOTATION

ρ) density; U, V, u) velocities; d) diameter; h) penetration depth; E, ε) energies; p) pressure; μ) viscosity; H) strength; $\dot{\varepsilon}$) strain rate; L_m) latent heat of fusion; ℓ) particle length; t) time; τ) time interval; Re) Reynolds number; St) Stanton number; M) mass; F) force acting on rear surface of particle; α) channel wall collapse angle; T) temperature; S) area; λ) plate thermal conductivity; λ') distance between slip planes; a^2) thermal diffusivity. The subscripts denote the following: f) particle flow; 0) initial state; t) plate; p) particle; c) critical state; s) channel wall and impelling jet; z) channel cavity; d) deformation; R) relaxation; F) at front end of particle.

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