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MOTION OF PARTICLES THROUGH THE INTERFACE OF DIFFERENT-DENSITY METAL SPECIMENS UNDER THE CONDITIONS OF SUPERDEEP PENETRATION

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The parameters of motion of particles in a thin layer of material adjacent to the plane boundary of two semi-infinite specimens of different densities under the conditions of superdeep penetration are calculated on the basis of the hydrodynamic model. Results of the calculations are checked experimentally. The efficiency of superdeep penetration for different-density materials (aluminum, steel, copper) and their combinations is determined.

The study of superdeep penetration (SDP) of powder particles into mono- and bimetal targets [1, 2] showed the presence of certain special features in the behavior of penetrating particles in the region of junction of different-density materials. The hydrodynamic model of SDP [3, 4] allows an analysis of the parameters of a penetrating particle (striker) in its passage through the contact surface under the conditions where the pressure generated in a combined bimetal specimen by a powder flux is constant on both sides of the boundary.

Problem Formulation. A two-layer bimetal specimen composed of different-density metals A and B ($\rho_A \neq \rho_B$) is treated with a dense high-speed flux of particles according to the SDP scheme [1-4] on the source side of the free surface of layer A. The interface between metal layers A and B (AB) is taken to be ideally plane; the possible presence of microasperities is disregarded. It is assumed that the thicknesses of A and B greatly exceed the size of the penetrating particles, and the pressure generated by the particle flux in the combined specimen near the AB is constant (at least in the zone with a thickness of several lengths of the striker on both sides of the AB).

Let a single particle move in layer A in the direction normal to the AB. Since the thickness of any part of the combined specimen multiply exceeds the sizes of the penetrating particles, only those of them that penetrate by the SDP mechanism can reach interface AB. According to [3, 4], the particles move in the specimen at a stationary velocity $u_A = 0.5\sqrt{p/\rho_A}$. Shortly after the passage of the AB, when changes in the character of the motion of the striker caused by a density drop virtually disappear [3, 4], a new value of a stationary velocity of motion $u_B = 0.5\sqrt{p/\rho_B}$ must be set. The ratio $u_A/u_B = \sqrt{\rho_B/\rho_A} \neq 1$; consequently, the changes in the mode of particle motion which must be determined in the present work occur in the zone of the material adjacent to the AB from the right (a transient layer).

A Particle in the Transient Layer. The equations of motion of a particle in metal monospecimens at a constant [3] and variable [4] pressure were obtained proceeding from the laws of conservation of momentum and mass under the conditions of streamlining of a particle by the softened material of the obstacle (in the coordinate system tied to the particle) with an overtaking high-speed jet which originates at the point of convergence of the channel formed by the striker in penetration (Fig. 1). In the combined specimen, from the instant of contact of the striker with the AB, the corresponding system of equations [3, 4] is modified due to the difference in the density of the material of the obstacle in front of the frontal surface and behind the rear one. In contrast to [3, 4], the law of conservation of mass and momentum of the particle has the form

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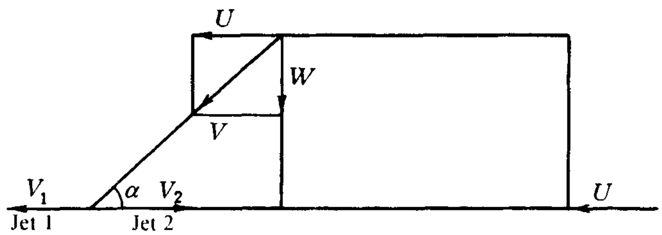

Fig. 1. Scheme of streamlining of a particle in superdeep penetration.

$$MdU = Vdm_2 - Udm_3\,, \quad dm_0 = \rho_A\, SUdt\,, \quad dm_3 = \rho_B\, SUdt\,, \tag{1}$$

where, as in [3, 4],

$$\frac{dm_2}{dm_0} = \frac{1-\cos\alpha}{2}\,, \quad \cos\alpha = \frac{U}{V} = \frac{1}{\sqrt{\left(1+\dfrac{2p}{\rho_A U^2}\right)}}\,. \tag{2}$$

Substituting (2) into (1), we write

$$M\frac{dU}{dm_0} = \frac{1}{2}(1-\cos\alpha)\,V - \frac{\rho_B}{\rho_A}\,U\,. \tag{3}$$

Introducing the notation $y = \sqrt{2p/\rho_A U^2}$ into (3), we obtain

$$-\frac{2M}{\rho_A S}\sqrt{\left(\frac{\rho_A}{2p}\right)}\frac{dy}{\sqrt{1+y^2}-a} = dt \tag{4}$$

or, since $dx = Udt$,

$$-\frac{2M}{\rho_A S}\,\frac{dy}{y\,(\sqrt{1+y^2}-a)} = dx\,, \tag{5}$$

where

$$a = 1 + 2\,\frac{\rho_B}{\rho_A}\,. \tag{6}$$

It is obvious from Eqs. (4)-(6) that at $\rho_A = \rho_B$ (the monospecimen) $a = 3$, and (4) and (5) fully coincide with the corresponding equations for a solid semi-infinite target [3, 4]. Equations (4) and (5) allow exact integration. With the initial condition of the stationary motion in layer A: $x = 0$, $V = u_A$ (i.e., $y = y_A = \left(\dfrac{2p}{\rho_A u_A^2}\right)^{1/2} = \sqrt{8}$) at $t = 0$ (the instant when a particle reaches the AB is taken to be the reference point of time) the motion through the boundary with the density jump is described by the equalities

$$t = \frac{2M}{\rho_A S}\sqrt{\left(\frac{\rho_A}{2p}\right)}\times$$

$$\times \ln\left(\frac{3+\sqrt{8}}{\sqrt{1+y^2}+y}\left|\frac{a\sqrt{1+y^2}+y\sqrt{a^2-1}-1}{3a+\sqrt{8\,(a^2-1)}-1}\;\frac{3-a}{\sqrt{1+y^2}-a}\right|^{a/\sqrt{a^2-1}}\right), \tag{7}$$

$$x=\frac{M}{(a^2-1)\,\rho_A S}\ln\left[2\left(\frac{y^2}{8}\right)^{a}\frac{\sqrt{1+y^2}-1}{\sqrt{1+y^2}+1}\left|\frac{3-a}{\sqrt{1+y^2}-a}\right|^{2a}\right].$$

However, the system of equations (7), which describes the motion of a particle in the transient layer, is open, since the quantity y that corresponds to the instant of complete passage of the striker through the layer is not determined. The depth of this layer x is reckoned from the instant when the particle touches the AB plane and consists of its length L, the distance traversed in a time that is necessary for compression of the channel in metal B (UR/W), and the distance required for the jet of material B to overtake the striker ($UR/V \tan\alpha$):

$$x=L+U\frac{R}{W}+U\frac{R}{V\tan\alpha}=L+\frac{R}{y}\left(1+\frac{1}{\sqrt{1+y^2}}\right). \tag{8}$$

Equation (8) and the second relation in (7) give the transcendental equality for the determination of the unknown y_b and, correspondingly, t_b and x_b, which will form the initial conditions of motion of the particle in layer B upon passage of the transition zone at $t = t_b$, $x = x_b$, and $y = y_b$. The motion of the striker during the period of time $0 \le t \le t_b$ is fully determined by (7).

Once the particle is overtaken by the jet of material B ($t > t_b$), the motion of the particle will again be determined by the solutions obtained in [3, 4]:

$$t=t_b+\frac{2M}{\rho_B S}\sqrt{\left(\frac{\rho_B}{2p}\right)}\times$$

$$\times \ln\left[\frac{\sqrt{1+y_b^2}+y_b}{\sqrt{1+y^2}+y}\left|\frac{(3\sqrt{1+y^2}+y\sqrt{8}-1)(\sqrt{1+y_b^2}-3)}{(3\sqrt{1+y_b^2}+y_b\sqrt{8}-1)(\sqrt{1+y^2}-3)}\right|^{3/\sqrt{8}}\right],$$

$$x=x_b+\frac{M}{8\rho_B S}\ln\left|\left(\frac{y}{y_b}\right)^{6}\frac{(\sqrt{1+y^2}-1)(\sqrt{1+y_b^2}+1)}{(\sqrt{1+y_b^2}-1)(\sqrt{1+y^2}+1)}\left|\frac{\sqrt{1+y_b^2}-3}{\sqrt{1+y^2}-3}\right|^{6}\right|. \tag{9}$$

As was proved in [3, 4], the motion determined by (9) occurs at a velocity that asymptotically tends to a constant quantity u_B, and the depth of penetration increases virtually linearly with time $x \sim u_B t$.

Discussion and Experiment. Figure 2a presents the dependence of the velocity on the motion in the transient layer (a vertical straight line $\Delta x/L = 0$ corresponds to the surface of contact of different-density metals) for the combined specimen where A is iron and B is aluminum, titanium, copper, and lead. In passage of the particle from a denser material (Fe) to a less dense one (Al and Ti), a nonlinear increase in the velocity of motion is observed; with an inverse ratio of densities (passage from Fe to Cu and Pb) it decreases. In both cases, after the contact plane at a distance of about $3L$, the velocity of the particle reaches rather quickly a stationary value of the velocity u_B which is typical of specimen B at the given level of pressure. The same is observed for other materials. The corresponding dependences for the cases where Al, Ti, Cu, and Pb were taken as specimen A are presented in Fig. 2b, c, d, and e, respectively. As the pressure in the obstacle decreases, the level of velocity decreases in proportion to the square root of pressure on all the portions of motion. Thus, for transitions of the Al $\rightarrow$ Pb or Ti $\rightarrow$ Pb type, the modes where the SDP in the Al $\rightarrow$ Pb and Ti $\rightarrow$ Pb specimens will stop in a narrow ($\sim 3L$) zone of the transient layer can be found. The size of the particle in the calculations presented was 10 μm; the time interval of the passage of the transient layer by the particle

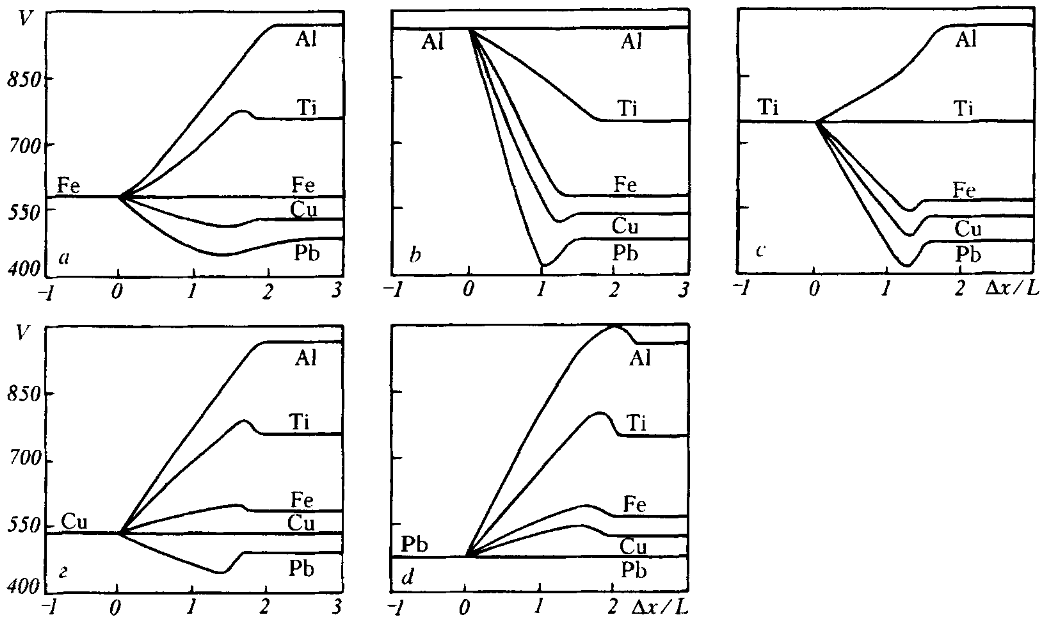

Fig. 2. Velocity change in the transient layer for specimens of: iron contiguous to Al, Ti, Cu, and Pb (a); aluminum contiguous to Ti, Fe, Cu, and Pb (b); titanium contiguous to Al, Fe, Cu, and Pb (c); copper contiguous to Al, Ti, Fe, and Pb (d), and lead contiguous to Al, Ti, Fe, and Cu (e). The imaginary vertical straight line $\Delta x/L = 0$ corresponds to interface AB. V, m/sec.

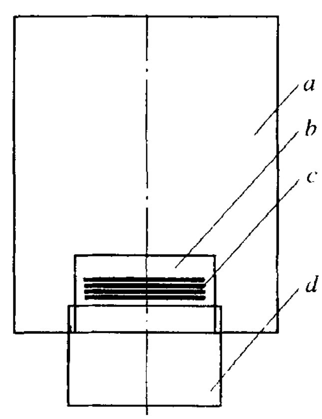

Fig. 3. Combined specimen: a) mono- or bimetal specimen; b) chamber for laying of foil; c) foil layers; d) shutting plug.

for all the materials was within the limits of 0.01–0.03 μsec. All the above holds true for a normal (or nearly normal) fall of the striker onto the AB. In the case where the striker meets the contact plane at an angle to the normal, the symmetry of the problem is certainly broken (in particular, the symmetry of the pushing jet) and a rotational moment appears, which, besides the total increase in energy expenditures, must inevitably cause the rotation of the particle. The possibility of this rotation is confirmed experimentally [1, 2].

The theoretical results obtained were checked experimentally. For this purpose, the technique of determining the efficiency of the SDP scheme by the method of a combined specimen was used (Fig. 3); in this method, the layers of steel foil placed into the test chamber were used for recording the particles. After the treatment of the obstacle with the flux of cobalt powder (the mean size of the particles was ~9 μm), the foil was studied on an optical microscope where all inclusions on the foil surface were counted. Allowing for the

TABLE 1. Distribution of the Particles of Inclusions over the Foil Layers and the Total Concentration of Cobalt (figures in the subscripts correspond to the numbers of the layers)

No. of specimen	N_1	N_2	N_3	N_c	n_{Co}, %
1	177800	51300	2000	231100	0.0197
2	181100	61800	3800	246700	0.0195
3	189800	11200	1200	202200	0.0174
4	176500	50900	2500	229900	0.0191
5	168700	11900	600	181200	0.0165
6	188600	21200	1300	211100	0.0179
7	190200	27300	2200	219700	0.0183
8	82100	21800	300	104200	0.0151
9	2100	–	–	2100	0.0142

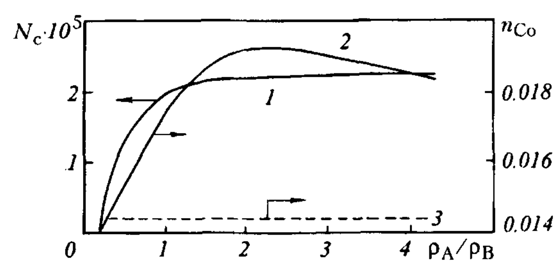

Fig. 4. Dependence of the efficiency of SDP with respect to the penetrated particles (curve 1) and concentration (curve 2) on the density drop on the AB surface (dashed line 3, initial level of the concentration of cobalt in the foil). n_{Co}, %.

statistical character of the SDP, the experiment was repeated three times and the data were averaged. Of course, this technique cannot seek a very high accuracy, because of the inevitable error in counting small inclusions, but a comparative analysis can be made with its aid. For higher assurance in the results obtained, we also made a chemical analysis of the first four layers of the foil for the presence of cobalt in them. The results of these measurements and counting of the number of particles are given in Table 1; the numbers of the specimens are as follows: 1, monospecimen of iron; 2, monospecimen of aluminum; 3, monospecimen of lead; 4, iron–aluminum combination; 5, iron–lead; 6, lead–iron; 7, lead–aluminum; 8, aluminum–iron, and 9, aluminum–lead. The initial level of the concentration of cobalt in the foil was 0.0143 wt.%; no inclusions were observed. It is very instructive that precisely for the aluminum–lead combination, extremely low amounts of inclusions (hundreds of times lower than for monospecimens) were revealed only on the first (the uppermost in the direction of penetration) foil, and the level of cobalt concentration turned out to be virtually at the level of the initial one. In this case, all the bimetal specimens with the interface between the less dense and more dense (in the direction of penetration) materials are characterized by a decrease in the number of penetrated particles (Fig. 4), which fully confirms the conclusions drawn on the basis of the above calculations. It should be noted that the data of the method of a combined specimen are in good agreement with the results of the chemical analysis (Fig. 4). A certain decrease in the number of penetrated particles that is typical of specimen Nos. 4, 6, and 7 (see Table 1), where penetration occurred from the side of the denser layer, can, probably, be explained by the total effect of the interface, which is obviously more complex than can be envisaged by any model.

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NOTATION

R, radius of the particle; L, length of the particle; u, stationary velocity of the striker; U, instantaneous velocity of the particle; W, velocity of motion of the channel walls to the axis of motion of the striker; V, total velocity of the channel walls, $V^2 = U^2 + W^2$; M, mass of the particle; S, area of the midship section of the striker; t, current time; x, current motion; N, number of inclusions in the foil; n_{Co}, concentration of Co in four upper layers of the foil; ρ, density; α, angle of convergence of the channel walls; a and y, notation adopted in the text. Subscripts: A, parameters of material A; B, parameters of material B; b, values reached at the instant of completion of the passage of the transient layer; c, total number.

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