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SPECIFIC FEATURES OF MICROPARTICLE DEFORMATION UPON IMPACT ON A RIGID BARRIER

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Based on experimental data and numerical modeling, it is shown that a lamina of melted metal of thickness of order 0.01d, *in which the temperature is close to the melting point of the particle material, can be formed upon high-speed impact* ($v_0 \approx$ 500–1200 m/sec) *of a fine metal particle* (d = 1–50 μm) *on a rigid undeformable barrier near the contact surface.*

The formation of a coating in a flow of a "cold" high-speed jet toward the barrier finds increasing application to gas-dynamic spraying technologies [1, 2]. However, the nature of interaction between a barrier and metal particles having the velocity $v_0 \approx$ 500–1200 m/sec and a temperature much less than the melting point of the particle material is not clear. It is difficult to study this phenomenon because of, in particular, the small particle sizes ($d \approx 10^{-6}$ m), the short period of interaction ($\tau \approx 10^{-8}$ sec), the uncertain phase state of interacting objects in microvolumes near the contact boundaries, etc.

In the present study, based on experimental data and numerical modeling, we consider the possibility of forming a thin melted layer in the neighborhood of contact upon impact of a separate particle on a rigid barrier.

In [1, 2], the following specific feature was established: the formation of a coating is possible when the kinetic energy of a particle is a factor of 1/3 greater than the magnitude of the thermal energy, which corresponds to the melting point, irrespective of the particle material.

In addition, an analysis of the particles attached to a polished substrate after the impact, which was performed by the methods of electronic and optical microscopy, has allowed us to reveal the characteristic features of their deformation. Figure 1 shows microphotographs of aluminum particles on the copper surface. One can see that corona-shaped ejections of metal are formed at the final stage of plastic deformation at the periphery of contact. They most probably appear as a result of the formation of a high-speed radial jet of metal, which is similar to a cumulative jet, at the wall. The main role here is played by the processes which occur near the contact, where deformation is intense and the mechanical energy converts to thermal energy. In these conditions, a thin melted layer of metal can be formed in the neighborhood of the wall. The formation of this layer depends on the ratio of heat generation to heat removal.

The impact of an aluminum particle of diameter $d = 2R = 50$ μm on a rigid barrier at the initial velocity $v_0 = 800$ m/sec and temperature $T_0 = 300$ K was modeled numerically. The program complex KRUG24, whose algorithm is based on the Lagrangian approach and the Prandtl–Reuss mathematical model of an elastoplastic material in flow, was used. The main differences of the algorithm used for calculating the dynamic problems of continuum mechanics from known approaches are given in [3, 4].

The problem posed was solved as follows. The computational domain was covered by a difference grid

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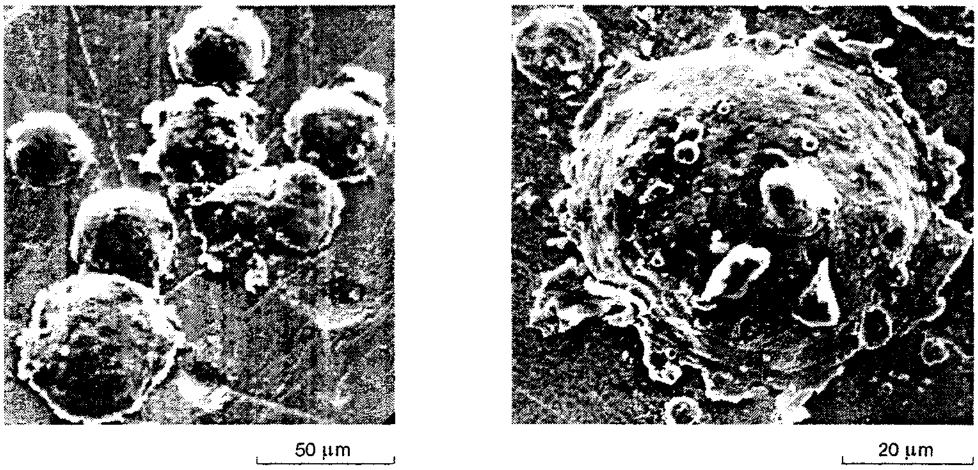

Fig. 1

consisting of triangular cells whose mass was set at the initial moment and was kept during the calculation. The equations of conservation and the governing relations of the mathematical model of a medium were integrated numerically by steps in time; the latter were chosen from the Courant stability condition. The velocities and coordinates were determined in the grid nodes, and the current flow density and pressure, the specific internal energy, and the components of the deviatoric stress tensor were determined at the geometric centers of the cells. Thus, the stress-strain state in the entire domain was completely calculated at each time step. The heat redistribution owing to the thermal conduction was not taken into account.

In the literature, there are no data on the characteristics of a microparticle material that determine its strength properties. For example, Kudinov et al. [5] proposed to choose a dynamic particle hardness a factor of 1.5 greater than their static hardness. In our method of solution, the dynamic yield point, which was considered constant during deformation, was used as a major strength characteristic of the material. Previous studies of a high-speed impact of various macrobodies on barriers have shown that this mathematical model allows one to solve a broad range of dynamic problems; we note that the results are in satisfactory agreement with known experimental data [4].

The above-mentioned experiments on the interaction of aluminum particles with a polished substrate at their small concentration have allowed one to determine the characteristic particle strain, in particular, the ratio of the finite height of a particle to its initial diameter. At velocities of approximately 800 m/sec, this ratio is equal to about 0.25. In this case, the substrate does not undergo noticeable deformation. With account of this fact, in numerical calculations the barrier was assumed to be a rigid wall. The condition of nonpenetration and slip with friction taken into account and ignored was used as a boundary condition.

The calculation results were compared with the experimental finite particle strain data; this has allowed us to choose a dynamic yield point equal to $Y = 450$ MPa, which gives results that are the closest to the experimental ones. This dynamic yield point was used in all subsequent calculations.

Figures 2 and 3 show calculation results obtained under frictionless boundary condition. Figure 2 shows the distribution of the radial velocity component u over the particle height at the moment $t = 20 \cdot 10^{-9}$ in three sections relative to the radial coordinate (a) and the particle contour for $t = 0$ and 20 nsec (b). It is natural that the greatest velocity is observed at the most distant point on the radius. In addition, in approaching the barrier, the velocity increases in each section and reaches the maximum values in the layer adjacent to the barrier (the layer thickness is approximately $0.05\,d$). Figure 3 shows the distributions of the radial velocity component over the radius at various moments in the near-wall cells. At the early stage of impact, the radius of the contact surface is smaller than R (for $t = 10 \cdot 10^{-9}$ sec, it becomes equal to R), and

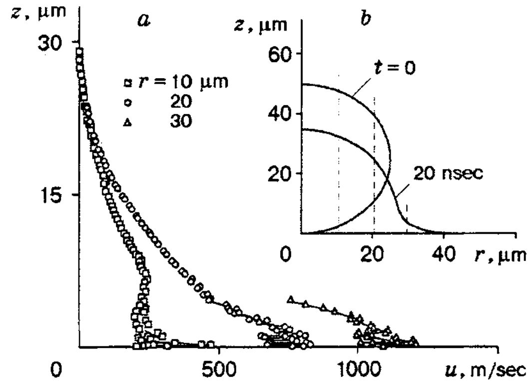

Fig. 2

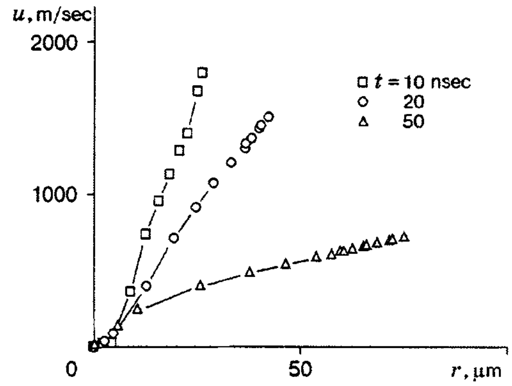

Fig. 3

the maximum velocity is approximately twice as large as the impact velocity v_0. After that, the radius of the contact surface is increased as a result of particle-material spread over the barrier and, as a consequence, the end point of this surface is decelerated because of the radial expansion and resistance of the material to shear strains.

We also calculated the distribution of the specific internal energy e in the cells of the difference grid in a layer of thickness 1 μm at the barrier. The internal-energy increment is equal to the shear-stress work upon corresponding plastic deformations. The temperature of the particle material was estimated under the assumption that the formula $e = c_v T$ is applicable (c_v = const). Near the wall, the temperature rise in comparison with the initial temperature is $\Delta T \approx 600$ K.

Thus, the numerical modeling confirmed the assumption that there is a high-speed near-wall flow of metal in the radial direction (see Fig. 2). At some moments of time (under the ideal-slip condition at the wall), the velocity in the near-wall flow is a factor of 2 greater than the impact velocity at certain points. This flow occurs because of pulse-pressure unloading after the shock wave leaves the contact site and can lead to ejections of thin films of the particle material over the periphery of contact (see Fig. 1).

The calculations performed with allowance for the Coulomb friction law (the friction coefficient was specified) have shown that friction at the wall leads to an insignificant decrease in the finite strain. From the viewpoint of the physics of this process, the no-slip conditions, which result in the formation of a thin boundary layer, can be used as boundary conditions; to describe this layer, it is necessary to change greatly the physicomathematical model: to take into account the heat transfer and the possibility of metal melting and to determine friction in the melted layer by the Stokes law; in addition, the computational cells in the near-wall region should be refined.

With allowance for the aforesaid, we chose an approximate scheme of formation of a layer of melted metal on the basis of the classical friction and heat-transfer laws and integral methods for a boundary layer. It is shown below that melting can occur; this justifies the use of the ideal-slip condition adopted above. We now consider the balance of heat generation and heat removal at the wall with allowance for the results obtained for particle deformation as a whole.

It is noteworthy that for a flow of melted metal along the wall, the thickness of the temperature layer δ_T generally exceeds the thickness of the viscous boundary layer, because the Prandtl number Pr is small. In our case, the thickness of the melted layer δ_H can be greater than or equal to the viscous-layer thickness δ_μ. We determine the conditions under which each of these cases is possible.

If $\delta_H > \delta_\mu$ for arbitrary r, as in an incompressible viscous liquid, a viscous boundary layer develops in the neighborhood of the critical point in an axisymmetric flow of the layer toward the wall, because, in our problem, the flow rate for $z = 0$ is a linear function of the radius (see Fig. 3): $u_r = ar$, where u_r is a velocity at the layer boundary equal to the velocity at the wall obtained upon numerical strain modeling of the entire particle and r is the distance from the axis of symmetry of the spherical particle. As one can see from Fig. 3, the constant a is time-dependent; however, one can ignore the nonstationary character by considering the quasistationary boundary conditions for approximate estimates to use the exact solution of the Navier–Stokes equations for a similar problem [6]. The exact solution gives

$$\delta_\mu = 2\sqrt{\mu/(\rho a)}, \tag{1}$$

where μ is the dynamic viscosity and ρ is the density.

Hereinafter, the parameter a is estimated as follows:

$$a = u_R/R. \tag{2}$$

Here u_R is the velocity at the layer boundary for $r = R = d/2$.

The viscosity of liquid metals near the melting point is approximated by the formula $\mu = (T_{\text{melt}}/T) \times 2.75 \cdot 10^{-3}$ Pa · sec. We now show that T_{melt}/T is a little less than unity; therefore, we assume that $\mu \approx 2.5 \cdot 10^{-3}$ Pa · sec.

According to the strain calculations for a particle of $d = 50$ μm, the characteristic value of the velocity u_R for $v_0 = 800$ m/sec is $u_R \approx 1500$ m/sec. From (1) and (2), we find

$$\delta_\mu/R = 2/\sqrt{\text{Re}},$$

where $\text{Re} = Ru_R\rho/\mu$ is the Reynolds number. Substituting the parameters for an aluminum particle into this formula, we obtain $\text{Re} = 0.405 \cdot 10^5$ and, hence, $\delta_\mu/R = 0.86 \cdot 10^{-2} \approx 0.01$.

Thus, the assumption of the small thickness δ_μ and the correctness of the separation of the problems for an external flow and a boundary layer are supported.

To estimate the thickness of the melted layer δ_H in the case where $\delta_H > \delta_\mu$, we now consider the heat balance in the near-boundary zone in the integral approximation:

$$d\int_0^{\delta_H} 2\pi r u\rho H\,dz \approx 2\pi r\,dr\int_0^{\delta_\mu} \mu\Big(\frac{\partial u}{\partial z}\Big)^2 dz. \tag{3}$$

Here H is the specific heat of melting ($H \approx 400 \cdot 10^3$ J/kg for aluminum) and $\mu(\partial u/\partial z)^2$ is the volume source of heat generated by viscous friction. The left side of (3) is the increment of the heat flux over r through a cylindrical surface of radius r which is taken away by the melted metal in the form of the latent heat of melting.

It is necessary to note that Eq. (3) does not make allowance for additional heating after melting and the heat transfer beyond the upper and lower boundaries of the layer δ_H.

We assume that the velocity profiles in the viscous boundary layer correspond to the distribution in a laminar flow. Then,

$$\int_0^{\delta_H} 2\pi r u\rho H\,dz \approx \delta_H \cdot 1.5\pi r u_r\rho H, \qquad 2\pi r\,dr\int_0^{\delta_\mu} \mu\Big(\frac{\partial u}{\partial z}\Big)^2 dz \approx \delta_\mu \cdot 1.5\mu\Big(\frac{u_r}{\delta_\mu}\Big)^2 2\pi r\,dr.$$

With allowance for the adopted approximations, after simple transformations we obtain $r(d\delta_H/dr) = \delta_\mu u_r^2/(4H) - 2\delta_H$.

Taking into account that, in the above case, the quantity δ_μ does not depend on r [see Eq. (1)], one can write the resulting equation in the form

$$r\,\frac{d(\delta_H/\delta_\mu)}{dr} = \frac{u_r^2}{4H} - 2\,\frac{\delta_H}{\delta_\mu}.$$

We now consider the sign of the derivative at the point where $\delta_H = \delta_\mu$. If the derivative is positive ($u_r^2 \geqslant 8H$), the thickness of the melted layer grows on r more rapidly than the thickness of the viscous layer. For aluminum, we have $H = 400 \cdot 10^3$ J/kg and $u_r \geqslant 1800$ m/sec; this corresponds to $v_0 \geqslant 1000$ m/sec.

We consider the case $v_0 \leqslant 1000$ m/sec where $\delta_H = \delta_\mu = \delta$. The velocity profile in the boundary layer is assumed to be linear. The integral balance of the heat generated and carried away has the following form:

$$d(0.5\delta \cdot 2\pi r u_r \rho H) \approx \delta\mu\Big(\frac{u_r}{\delta}\Big)^2 2\pi r\, dr.$$

After appropriate transformations, we obtain

$$\frac{1}{2}\frac{\delta}{r}\frac{d\delta}{dr} + \Big(\frac{\delta}{r}\Big)^2 = \frac{u_R^2}{\mathrm{Re}\, H}.$$

The expression $\delta/r = \sqrt{2/3}\, u_R/\sqrt{\mathrm{Re}\, H}$ satisfies this equation. It is clear that, for $\delta_T = \delta_\mu = \delta$, the thickness of the boundary layer δ increases proportionally to r. In our case, we have $(\delta/r)_{r=R} \approx 0.96 \cdot 10^{-2}$. For $r = R$, we obtain $\delta \approx 0.24$ μm.

Let us estimate the temperature of the boundary layer. The heat taken away by the melted metal from the control volume bounded by a cylindrical surface of radius r is calculated by the formula

$$Q = 0.5\delta u_\delta \cdot 2\pi r \rho H = \frac{u_R^2 \rho H}{\sqrt{\mathrm{Re}\, H}}\frac{\pi r^3}{R}. \qquad (4)$$

If the wall is heat-insulated, the heat flux toward the upper bound of the layer, where melting occurs, is determined as follows:

$$q = \frac{dQ}{dS} \approx \lambda \frac{\Delta T}{\delta/2}, \qquad (5)$$

where $S = \pi r^2$, $\lambda = \mu c_p/\mathrm{Pr}$ is the thermal conductivity, c_p is the specific heat, Pr is the Prandtl number, $\Delta T = T - T_{\mathrm{melt}}$, and T is the average temperature of the boundary layer. From (4) and (5), we obtain

$$\Delta T \approx \frac{1}{2}\frac{u_R^2}{c_p}\mathrm{Pr}\Big(\frac{r}{R}\Big)^2.$$

For $r = R$, the estimate for liquid aluminum [$c_p = 1084$ J/ (kg $\cdot$ K) and Pr = 0.037] gives $\Delta T = 38$ K. This result supports the validity of the use of the assumption that the metal in the boundary layer is superheated insignificantly.

Making allowance for heat removal from the boundary layer to the wall, metal superheating in the layer, and metal heating outside the layer to the melting point give even smaller values of the thickness δ; therefore, the resulting estimates cannot be regarded as upper estimates.

Our analysis shows that upon impact of a fine metal particle on a rigid undeformable barrier near the surface, a lamina of melted metal of thickness $\delta < 0.015d$, in which the temperature is close to the melting point of the particle metal, can form. The formation of this layer explains the phenomenon of high adhesion of particles with a substrate upon gas-dynamic spraying.

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