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EXPERIMENTAL STUDY OF DEFORMATION AND ATTACHMENT OF MICROPARTICLES TO AN OBSTACLE UPON HIGH-RATE IMPACT

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Results of an experimental study of the high-rate (400–1200 m/sec) *interaction of spherical aluminum particles with a surface are given. Particle deformation was studied by means of a microscope. The mean values of the degree of particle strain were determined by statistical processing for specimens with different hardness (hardened and unhardened steel and copper) and produced in different spraying regimes (the pressure and temperature of a gas in a plenum chamber and a working gas). A relation between the degree of particle strain and the impact velocity was obtained by using the design particle velocities for the corresponding parameters.*

Determination of the conditions of particle attachment to a surface is an important problem, the solution of which gives insight into the mechanism of coating formation. In the "cold" gas-dynamic spraying, rigid metal microparticles are attached to the obstacle surface at the collision velocities $v_{\rm p} = 400$–1200 m/sec; therefore, investigation of the interaction between the particles and the obstacle in this interval is of practical importance.

Using the dimensional theory to analyze the problem of particle deformation upon a normal impact shows that the possible parameters of the problem are $\rho_{\rm p} v_{\rm p}^2/H_{\rm p}$, $\rho_{\rm p}/\rho_{\rm obs}$, and $H_{\rm p}/H_{\rm obs}$ [1–3], where $\rho_{\rm p}$, $\rho_{\rm obs}$, $H_{\rm p}$, and $H_{\rm obs}$ are the density and dynamic hardness of the particle and the obstacle, respectively. The strain of spherical particles is independent of their size, which makes it possible to model the impact phenomenon by choosing an appropriate particle size. Clearly, the main requirement in this case is to ensure the same hardness for the particles of different size, which is often not an easy task.

The aim of this paper is to study the deformation of the particles made of a material whose hardness is smaller than that of the obstacle. The material hardness was varied by the method of thermal treatment and the choice of materials. Thus, the role of the above-mentioned parameters was studied in the experiments.

1. Experimental Setup and Measurement Methods. The setup was composed of a gas heater, a dosimeter, and a nozzle unit. In the cases where helium was used as an accelerating gas, a standard vessel with helium (40 liters in volume and pressure $p = 15$ MPa) was connected to the setup. The pressure in the plenum chamber and the dosimeter and the temperature in the nozzle plenum chamber were controlled by manometers and a thermocouple temperature gauge. A more detailed description of the setup is given in [4]. In all the experiments, a supersonic nozzle of rectangular cross section (the dimensions of the critical and exit sections were 3×3 and 3×10 mm, respectively) with a supersonic part 100 mm long was used. This nozzle was designed for Mach number $\mathrm{M} = 2.75$, but owing to the considerable thickness of the boundary layer on the nozzle walls, the real Mach number was $\mathrm{M} = 2.5$ on the jet axis in the nozzle exit section. Thus, a pressure of 1.5 MPa in the plenum chamber ensured outflow of the jet.

In leaving the nozzle, the two-phase jet was directed at an angle of 90° toward a ring magazine (obstacle) in which cylindrical specimens with one of their faces polished were fixed. The magazine was

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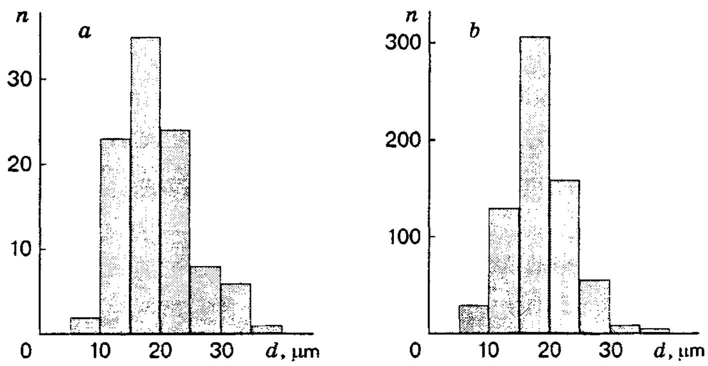

Fig. 1. The aluminum-particle distribution function: (a) initial sizes (d_{mean} = 19.4 μm, $sd(d)$ = 6.1 μm, and $s(d)$ = 0.6 μm); (b) restored sizes of the attached particles (the total function over all the specimens) (d_{mean} = 18.35 μm, $sd(d)$ = 5.15 μm, and $s(d)$ = 0.195 μm).

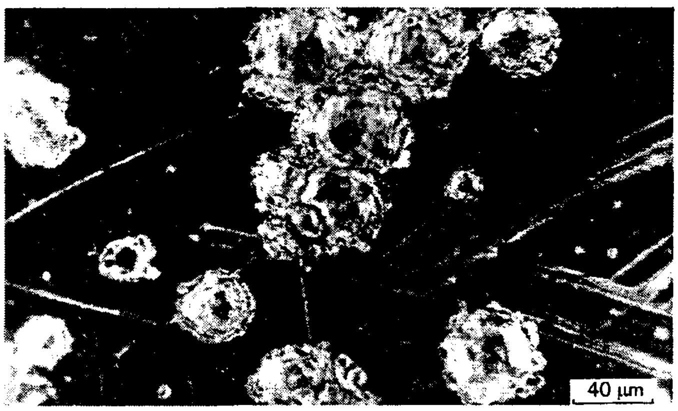

Fig. 2. Photograph of the aluminum particle attached to the copper substrate.

rotated at the velocity ν = 5–10 rpm, which forced the specimens to pass by the nozzle at the linear velocity $v = 2\pi\nu R \ll v_p$. By varying the specimen velocity, it was possible to vary the number of particles attached to the surface. The distance from the nozzle exit section to the obstacle surface was chosen within 15–20 mm. The specimens were made of copper and St. 45 unhardened and hardened steel.

In the experiments, powdered aluminum particles were used. Figure 1a shows the distribution of the particles n in sizes d. The particles were almost spherical. This allowed us to calculate their acceleration more accurately on one hand and reduced the number of similarity criteria on the other hand; hence, this facilitated the modeling of particle impact on the substrate and an analysis of their deformation. One can see from Fig. 1a that the average particle size was approximately 19.4 μm.

In the experiments, the pressure and temperature in the nozzle plenum chamber and the gas (helium and air) were varied, which made it possible to vary the impact velocity of the particles on the substrate.

2. Measurement Method. To observe the particles and determine their sizes, we used an MBI optical microscope with magnification 1800. Figure 2 shows a photograph of the particles attached to the substrate.

For measurements, we chose separate particles whose in-plane shape was close to a circle. The circle diameter D was estimated by the scale combined with an ocular, which was precalibrated by comparison with the standard located in the object plane. To measure the height of the particles above the surface, the effect of small focus depth for short-distance objectives of a microscope was used (about 1 μm for the objective used). Using the difference between the positions of the objective where the specimen surface and the upper part of the particle are seen sharply, we determined the height h of the particle fixed at the surface. Assuming that the fixed particle is a paraboloid of revolution, we used the two quantities to restore the particle volume and its initial diameter:

$$d = \left(3hD^2/4\right)^{1/3}.$$

A comparison of the fixed-particle distribution function that corresponds to the diameters restored (see Fig. 1b) with the initial distribution function (see Fig. 1a) shows that we have the same function with a probability of 95%. Consequently, the representation of the fixed particles in the form of a paraboloid of revolution is correct.

Having calculated the initial particle diameter, we determined its degree of strain caused by the impact by the formula

$$\varepsilon = 1 - h/d,$$

where h is the height of the fixed particle and d its initial diameter.

3. Statistical Data Processing. Because of measurement errors, the spread of the particle shapes, sizes, velocities, etc., it is necessary to perform many measurements and use the methods of statistical processing to obtain reliable information on the degree of particle strain. In our experiments, the number of measurements varied from 50 to 120 for different specimens, which ensured an error of the mean not greater than 3%. The usual procedure consists of determining the mean value $\varepsilon_{\text{mean}}$, the standard deviation $sd(\varepsilon)$, and the error of the mean $s(\varepsilon)$:

$$\varepsilon_{\text{mean}} = \frac{1}{N}\sum_i^N \varepsilon_i, \qquad sd(\varepsilon) = \left(\frac{1}{N-1}\sum_i^N (\varepsilon_{\text{mean}} - \varepsilon_i)^2\right)^{0.5}, \qquad s(\varepsilon) = \frac{sd(\varepsilon)}{\sqrt{N}}.$$

The ideal value of the degree of strain lies in the interval $\varepsilon = \varepsilon_{\text{mean}} \pm s(\varepsilon)$ with a probability of 68.3% and in the interval $\varepsilon = \varepsilon_{\text{mean}} \pm 2s(\varepsilon)$ with a probability of 95.5%.

Moreover, it is important to know whether the two mean values determined in the data processing for different specimens differ significantly or their difference can be ignored. To this end, the following procedure is used. Let the close values of the degree of strain $\varepsilon_{\text{mean1}} \pm s_1(\varepsilon)$ and $\varepsilon_{\text{mean2}} \pm s_2(\varepsilon)$ be obtained after the data processing for two specimens of, say, different hardness. It is required to determine whether the hardness affects the degree of strain. To this end, we find $s_{12}(\varepsilon) = (s_1^2(\varepsilon) + s_2^2(\varepsilon))^{0.5}$ and $\Delta\varepsilon_{\text{mean}} = |\varepsilon_{\text{mean1}} - \varepsilon_{\text{mean2}}|$. If $\Delta\varepsilon_{\text{mean}} > 2.576 s_{12}(\varepsilon)$, the probability that these values of the two specimens are different is 99%, i.e., one can study the effect of the specimen hardness on the degree of particle strain. If $\Delta\varepsilon_{\text{mean}} > 1.96 s_{12}(\varepsilon)$, the probability that the difference is negligible and the hardness effect can be ignored is 95%. The case where $1.96 s_{12}(\varepsilon) < \Delta\varepsilon_{\text{mean}} < 2.576 s_{12}(\varepsilon)$ requires additional investigation.

It should be noted that, accelerated by a gas jet, particles of different size acquire different velocities and, as a result, the degrees of their strain can be different. In this case, determination of the mean value of the degree of strain from a set of experimental data is incorrect, since the dependence of the degree of strain on the particle velocity shows up in addition to a random spread. However, as the investigations [5, Fig. 7] have shown, the impact velocity of the particle depends weakly on its size in the range of sizes (d = 10–30 μm) investigated. Therefore, the experimental data can be processed by finding the mean and by comparing each mean particle size with certain mean values of the degree of strain and velocity of the particle.

To determine the dependence of the degree of strain on the particle size from experimental data, one can use linear regression by the least-square procedure, which, evidently, works in a narrow range of particle sizes.

4. Results of Microscopic Investigations. Processing of measurement data for a large number of particles attached to one specimen included determination of the initial diameters of all the chosen particles and the degree of their strain. The mean values of the particle size, the degree of strain of a given specimen, and the standard deviation were determined. These data for different specimens are listed in Table 1 (columns 1–7). Figure 3 shows the measured degree of strain of the particles attached to specimen No. 4 (see Table 1); the

TABLE 1

Specimen number	d_{mean}, μm	$sd(d)$, μm	$s(d)$, μm	$\varepsilon(d_{mean})$	$sd(\varepsilon)$	$s(\varepsilon)$	ε	
							$d = 10$ μm	$d = 30$ μm
1	19.8	4.4	0.62	0.37	0.083	0.012	0.29	0.44
2	18.6	3.2	0.46	0.35	0.152	0.022	0.25	0.42
3	18.3	5.2	0.48	0.43	0.085	0.008	0.39	0.45
4	16.3	5.7	0.53	0.44	0.096	0.009	0.41	0.46
5	21.1	4.4	0.70	0.48	0.082	0.013	0.44	0.53
6	20.5	5.0	0.85	0.47	0.078	0.013	0.45	0.48
7	19.6	4.7	0.73	0.52	0.103	0.016	0.44	0.60
8	18.7	5.4	0.62	0.63	0.065	0.008	0.63	0.64
9	17.8	4.6	0.58	0.63	0.077	0.010	0.64	0.63
10	19.6	4.6	0.44	0.72	0.069	0.006	0.66	0.77

Note. Specimens Nos. 1, 3, 5, and 8 refer to unhardened steel, specimen Nos. 4, 7, 9, and 10 refer to hardened steel, and specimens No. 2 and 6 refer to copper.

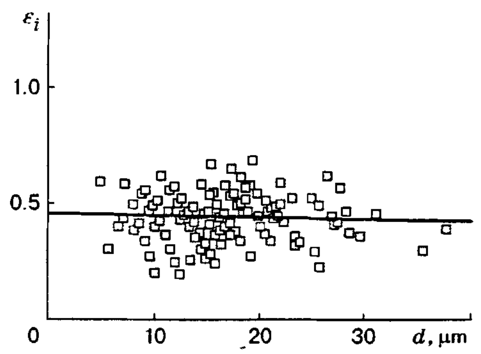

Fig. 3

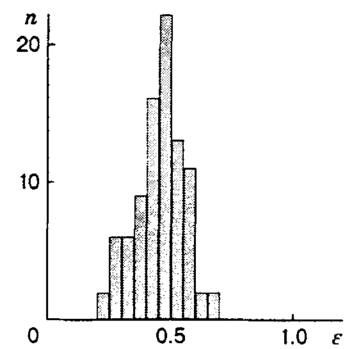

Fig. 4

Fig. 3. The degree of strain of the attached particles versus their restored diameters.

Fig. 4. Strain distribution function of the particles attached to specimen No. 4 ($\varepsilon_{mean} = 0.45$, $sd(\varepsilon) = 0.099$, and $s(\varepsilon) = 0.01$).

restored diameters are laid off as abscissa. Figure 4 shows the corresponding finite-strain particle distribution function.

In addition, linear regression by the least-square procedure was performed (Fig. 4). One can see that, for the same acceleration regime, there exists a weak but quite noticeable tendency for the degree of particle strain to decrease with increase in particle diameter. This may be caused by the lower velocity of large-diameter particles (see, e.g., [5, Fig. 7]). Using the linear approximation, we determined the expected value of the degree of strain of the particles of diameters 10 and 30 μm. These values are compared with the mean degrees of strain in Table 1 (columns 5, 8, and 9).

To increase the confidence of the results, microscopic measurements were performed twice on each specimen. The mean values and the mean-square errors were close. For example, the particle measurements on specimen No. 4 yield the degrees of strain $\varepsilon_1 = 0.454\,24 \pm 0.010\,45$ and $\varepsilon_2 = 0.442\,16 \pm 0.008\,78$, so that $\Delta\varepsilon_{mean} = 0.012 < 1.96 s_{12}(\varepsilon)$, i.e., the two samplings belong to the same general set. Thus, this measuring technique gives reliable results with high reproducibility.

To evaluate the effect of the specimen hardness on the degree of particle strain, the mean degrees of

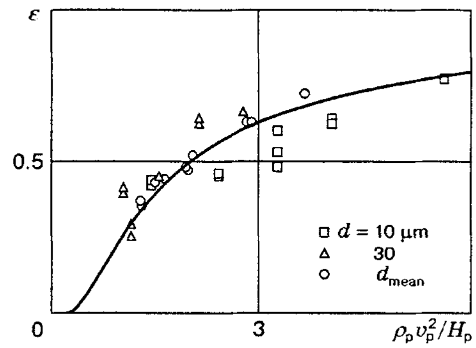

Fig. 5. Generalized relation between the degree of particle strain and the impact velocity.

strain obtained for the same acceleration regime by means of the above technique were compared. Comparison of hardened steel and copper specimen Nos. 7 and 6 (see Table 1) yields $\Delta\varepsilon_{\text{mean}} = 0.056$ and $s_{12}(\varepsilon) = 0.021$ and, hence, we have $\Delta\varepsilon_{\text{mean}} > 2.576 s_{12}(\varepsilon)$. With a probability of 99%, the mean degrees of strain for these specimens can be considered different, but the difference is small (about 10%). Comparison of specimen Nos. 1 and 2, 3 and 4, 5 and 6, 5 and 7, and 8 and 9 shows that the degrees of strain for these specimens coincide with a probability of 95%, i.e., the criteria $\rho_{\text{p}}/\rho_{\text{obs}}$ and $H_{\text{p}}/H_{\text{obs}}$ do not significantly affect the degree of strain of the attached particles, and the determining criterion is $\rho_{\text{p}} v_{\text{p}}^2/H_{\text{p}}$.

Microscopic studies of the surface with attached particles show that the clusters of particles are often attached (see Fig. 2), i.e., several particles between which a boundary cannot be drawn are attached. Probably, this is due to the higher activity of the surface parts adjacent to the attached particle. Thus, a single attached particle seems to be a nucleus that gives rise to the growth of a continuous coating over the specimen surface. Comparison of the steel and copper specimens shows that a greater number of particles are attached to the copper specimen in all the acceleration regimes.

5. Strain Versus the Impact Velocity. The degree of particle strain versus the particle velocity was found from the data given in Table 1 and the calculated particle velocities. According to the dimensional theory, the degree of strain must depend on the dimensionless parameter $\rho_{\text{p}} v_{\text{p}}^2/H_{\text{p}}$ and the ratios $\rho_{\text{p}}/\rho_{\text{obs}}$ and $H_{\text{p}}/H_{\text{obs}}$. The results given above imply that the effect of the last two parameters can be ignored.

Figure 5 shows the experimental dependence of ε on $\rho_{\text{p}} v_{\text{p}}^2/H_{\text{p}}$. The dependences obtained by linear regression correspond to particles with $d = 10$ and 30 mm and $d = d_{\text{mean}}$ (see Fig. 3). It is clear from Fig. 5 that, for the same velocity, the degree of strain of fine particles is smaller, i.e., the dynamic hardness of fine particles H_{p} is greater than that of coarse particles.

The experimental values for d_{mean} admit an approximation by one curve. Figure 5 shows the approximating curve plotted from the results obtained for particles of medium size. We note that the analytical expression of the approximating function

$$\varepsilon = \exp\Big(-k\,\frac{H_{\text{p}}}{\rho_{\text{p}} v_{\text{p}}^2}\Big),$$

in which $k = 1.4$ and $H_{\text{p}} = 56 \cdot 10^7$ Pa [3], possesses the necessary asymptotic behavior, since $\varepsilon \to 1$ as $v \to \infty$ and $\varepsilon \to 0$ as $v \to 0$.

In summary, the high-rate (400–1200 m/sec) interaction of spherical aluminum particles with a surface has been investigated experimentally. A microscopic study of the particle shapes has been performed. It has been shown that in the range considered, the parameters $\rho_{\text{p}}/\rho_{\text{obs}}$ and $H_{\text{p}}/H_{\text{obs}}$ do not significantly affect the degree of particle strain, and the determining parameter is $\rho_{\text{p}} v_{\text{p}}^2/H_{\text{p}}$.

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