PARTICLE IMPINGEMENT ANGLE INFLUENCE ON NATURE OF INTERACTION WITH OBSTACLE

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Introduction

The interest in the processes of interaction of solid-phase particles with obstacles is due to the variety of their application in various branches, including the development of new technologies and, in particular, the CGS, which are based on using highly dispersed powders.

The method of cold gasdynamic spraying (CGS) [1, 2] belongs to the processes of the formation of powder coatings and possesses some features common with the gas-thermal methods of powder deposition (the plasma, gas-plasma, detonation deposition), etc. [3, 4, 5]. In particular, high-velocity heterogeneous flows are used in both cases, in which the energy is transferred to the dispersed phase, and the transfer to the obstacle is made. In the gas-thermal (high-temperature) methods, the deposited particles are heated up (completely or partially) to the melting point, but may be overheated. In this connection, the question of the adhesion and coating formation is considered within the framework of the liquid droplet interaction with a solid obstacle, at a typical impact velocity from several dozens up to several hundreds of meters per second, deformation (divergence) of the droplet, its cooling, crystallization, and physico-chemical interaction with the surface with the formation of connections.

In terms of the temperature and dynamic conditions, such processes of joining of macro-bodies are closer to the CGS as the magnetic-pulsed welding, cold, ultrasonic welding by explosion. These kinds of materials joining are realized at temperature below the melting point, but with a high level of the kinetic energy and, respectively, a high rate of plastic deformation. The difference of CGS from the above processes lies in that highly dispersed materials of the micron and nano-size range are subject to joining under the CGS conditions. It is this dimensionality effect, which introduces significant differences in the process of bodies interaction.

A number of determining processes are, however, realized both at the macro and micro scales. The following ones belong, in particular, to them. The loading of two interacting solids above the elasticity limit causes therein the violation of shear stability, plastic flow, and a possible rupture (in particular, of brittle materials). It is known that for ensuring a good adhesion joining (a strong joining) it is necessary to free the joint surfaces of the physical and chemical pollutants, To this end, the processes are used, which ensure shear displacements of interacting loaded bodies along the surfaces of their contact.

The physical and chemical (oxide films) components of the surface are removed and favorable conditions are reached for the formation of junctions in contact region. These processes are realized most completely at oblique collisions. Typical regimes and collision angles are presented for the welding by explosion in [6, 7]. For different materials to be joint the range of optimal collision angles amounts to $\gamma \approx 10 – 36 ^\circ$. The joint materials are steel 3, steel D16, stainless steel, Ti.

In our previous works [8, 9] related to the formation of coatings from micron particles in solid state, the interaction character was studied mainly at impact angles close to the normal impact. It was, however, noticed that the oxide films are removed from the particles surface more efficiently at an oblique impact in connection with the fact that even at a minor particle slip along the obstacle surface the fragments of the ruptured particle oxide layer are mainly carried away from the contact.
region. Unlike this, in the case of a normal impact of the particle, an axisymmetric radial plastic flow occurs, but in a region close to the impact direction, the oxide material remains and may become a barrier for the formation of adhesion connections.

Numerous experimental results of the creation of abrasive particles of micron size with obstacles were presented in the work \cite{10}. A strong dependence of the erosion interaction character of the impact angle (in the work \cite{10}, the angle between the obstacle surface and the particle trajectory prior to the impact) was shown. A qualitative dependence of the erosion wear of obstacles was presented versus the impact angle of particles. It is seen from the results that the maximum velocity of the brittle failure realizes at the impact angle of 90°, and it is negligibly small at 0°. For viscous failure, the erosion maximum takes place for the impact angle of about 20°.

A more complex pattern of the interaction of a flow of solid particles with the obstacle for impact angles close to the normal ones realizes at CGS \cite{8} in connection with the fact that the processes of particles consolidation (with the obstacle and with one another) and of the erosion rupture (and/or surface activation) occur concurrently. The preliminarily conducted experiments under the CGS conditions showed a strong dependence of the character of particles interaction on the angle of their impact onto the obstacle.

Besides, for solving a number of practical problems related to the formation of coatings on inclined obstacles, there arises a need of having a preliminary information about the laws of the two-phase flow interaction with the bodies of various profiles, about the plastic deformation character, the dependence of the adhesion-erosion transition on the particles impact angle, that is the knowledge of critical angles of such transitions.

**Experiment**

For the purpose of a more detailed study of these question, experimental investigations of the interaction of high-velocity solid-phase particles were conducted in the range of impact angles 0 – 90° on the CGS setup. Figure 1 shows the scheme of the variants of the mutual location and motion of the investigated samples and the deposition unit of the setup, which was described in detail in \cite{8}. To reduce the error in determining the impact angle, which is related to the scatter in particles trajectories over the angles, the masks-screens mounted ahead of the obstacle were applied. To the same end, the particles were used in experiment, whose relaxation length

\[
I_r = \frac{v_p \rho_p d_p}{C_D \rho (v - v_p)}
\]

was much larger than the distance between the obstacle and the screen, \(I_s\), that is

\[
I_r > I_s
\]

where \(v\) and \(v_p\) are, respectively, the velocity of gas and particles, \(\rho\) and \(\rho_p\) are the densities of the gas and particles, \(C_D\) is the coefficient of the particle aerodynamic drag.

Fig. 1. Scheme of the variants of the location and motion of the deposition unit and of investigated samples.

As a dispersed phase, the powders of domestic production with the known density were used. A standard drying and screening setup was used for particles preparation. The shape and size was controlled with the aid of optical microscopes.
A schematic picture of the oblique impact of a single particle is presented in Fig. 2. From geometric considerations for an arbitrary angle $\alpha$ of the particle impact onto the obstacle at speed $v_{p0}$ and at particle reflection under the angle $\beta$ at speed $v_{pr}$, the coefficient of the velocity recovery $k = \frac{v_{pr}}{v_{p0}}$ will be $k = \frac{\tan \alpha}{\tan \beta}$.

![Fig. 2. Schematic picture of an oblique impact of a single particle.](image)

To analyze the interaction mechanism one should expand the particle velocities into the normal $v_p^n$ and tangent $v_p^t$ components. It is obvious that at an oblique partially elastic impact without a slip, the tangent components are preserved – $v_{p0}^t = v_{pr}^t$, and the normal ones are not preserved because $v_{pr}^n = k v_{p0}^n$. With increasing impact angle $\alpha$, the value $v_p^n = v_{p0} \cos \alpha$ will drop, and $v_p^t = v_{p0} \sin \alpha$ will increase, which must lead to a change in the interaction character (from the predominance of compressing stresses to the shear ones) and the development of the process of deformations (the reduction of impact hardening and a trend to a more pronounced slip, with a passage of end dislocations to the surface).

Two realizations of the particles impact onto the obstacle are of interest. The first of them is a particle impact at which the adhesion junctions withholding the particle on the surface have the time to arise in the process of particle interaction with the obstacle that is the formation of coatings occurs at subsequent similar interactions. The second interaction type is an impact with the particles bounce, at which the adhesion forces do not ensure the particle retention on the obstacle.

**Experimental results**

According to the first type of collision and interaction, the experiments were conducted on the measurement of the alteration of the sample relative mass depending on the impact angle of particles $\alpha$. The results are shown in Fig. 3 for the obstacle materials St 30 (curve 1) and Al (curve 2). The aluminum particles of the mean size $d_{pm} = 20 – 30 \mu m$ were mainly used.
The (temperature-velocity) conditions are as follows: the stagnation temperature of the working gas (air) $T_0 = 470$ K, the Mach number at the nozzle exit $M = 2.5 – 3$. The previously obtained results of [9] are presented here for a lower stagnation temperature of air, $T_0 \approx 270$ K (curve 3) and the results on erosion wear taken from [10] (curve 4, for the obstacles with viscous rupture). As can be seen in Fig. 3, the quantity $\Delta m/M$ varies weakly in the range of impact angles $\alpha = 0 – 10$° ($\alpha$ is the angle between the normal to the obstacle and the particle motion trajectory prior to the collision), with the maximum at $\alpha = 5 – 8$°. With increasing $\alpha$ the trend of the dependence $\Delta m/M = f(\alpha)$ is similar for all investigated materials of obstacles and temperature-velocity regimes. The typical law (see curves 1, 2, and 3) is a considerable reduction of $\Delta m/M$ in the range $10 < \alpha < \alpha_{cr}$. The peculiarity lies in that the values of critical angles $\alpha_{cr}$ corresponding to the adhesion-erosion transition (that is the transition from the process of particles consolidation with obstacle to erosion) differ substantially depending on the temperature-velocity interaction regime and the kind of the obstacle material (that is the physico-mechanical properties). For an obstacle of a low-carbon steel (St 30), the critical transition angle $\alpha_{cr} \approx 70$°, for aluminum $\alpha_{cr} \approx 80$°. In the range of supercritical impact angles $\alpha > \alpha_{cr}$, the erosion process is determining.

Curve 3 shows the dependence $\Delta m/M$ of $\alpha$ at the impact velocity of particles $v_p$ being lower than the critical one $v_{cr}$, but at the particles density flux $G_p > G_{cr}$ [9]. It is seen that the trend of the behavior vs. $\alpha$ is similar to curves 1 and 2, but the adhesion-erosion transition occurs earlier, at $\alpha_{cr} \approx 35$°. Besides, the quantity $\Delta m/M$ is much smaller (by three orders of magnitude) than in the case of using the working gas with a higher temperature.

Curve 4 showing the impact interaction with erosion wear qualitatively agrees with the above results confirming the general law consisting of the fact that with increasing $\alpha$, there is a more and more considerable growth of the erosion wear velocity reaching its maximum at $\alpha = 65 – 75$°. This range of impact angles on curves 1 and 2 is related to the region of the adhesion-erosion transition.

Presented experimental data show that along with the impact velocity $v_{p0}$ and the particle concentration, the impact angle $\alpha$ is an important parameter of the process of the interaction of particles and the obstacle, which affects not only the value of the obstacle mass variation but also the character of change (the consolidation or erosion).

A certain analogy with the CGS can be seen at the welding of macro bodies by explosion. In particular, the condition ensuring the junction at a given contact velocity $v_c$ is the necessity of choosing the impact angles $\gamma$ [7] within the range from $\gamma_{min}$ to $\gamma_{max}$.
\[
\gamma_{\text{min}} = 2 \arcsin \left( 0.57 \sqrt{\frac{H_v}{\rho c_v^2}} \right) \quad \gamma_{\text{max}} = 2 \arcsin \left( 14.7^{-1.25} \sqrt{\frac{T_m a/K}{\rho \delta_2 \sqrt{\delta_1 / (\delta_1 + \delta_2)}}} \right),
\]

where \( H_v \) is the material hardness after Vickers, \( T_m \) is the melting temperature, \( K \) is the material thermal conductivity, \( \rho \) is the density, \( \delta_1 \) is the thrown plate thickness.

For steel at \( v_c = 2400 \text{ m/s} \) \( \gamma_{\text{min}} = 13^\circ \), \( \gamma_{\text{max}} = 36^\circ \).

The consideration of previously obtained results at the interaction under angles \( \alpha \sim 0 \) and of newly obtained results for \( \alpha = 0 - 90^\circ \) enables us to arrive at generalized concepts of the deformation character, structure and properties of the formed materials of coatings.

At \( \alpha \sim 0 \), a single spherical particle experiences an elastic-plastic deformation [11]. The particle material diverges axisymmetrically with respect to the contact initial point, but there is no displacement near it, which cause the maximum unloading stresses, the hardening (cold-hardening), and, on the other hand, the absence of micro-shift leads to the capture of oxide film and other foreign films impeding the formation of junctions. Besides, the gases absorbed by the surface at an impact compression have a damping effect on the particle, oxidize intensively the contacting surfaces, which also contributes to the adhesion and obtaining the qualitative coatings.

To solve these problems and to ensure a good adhesion, one usually employs the techniques of activation of obstacles surface (including the removal of a thin surface layer, degreasing, etc.) and the surface roughness creation (the abrasive processing). The latter enables the arrangement of shear micro-deformations, an extra activation, and the obtaining of a strong junction. If, however, the obstacle material has the open pores with diameter \( d_{\text{por}} \) higher than the maximum diameter of particles and with the depth \( l_{\text{por}} \geq 2d_{\text{por}} \), then it is impossible to cover such nonuniformities of the obstacle at the impact angle \( \alpha \sim 0 \). This is related to an abrupt deceleration of deposited particles in the pore channel and the reduction of their velocity down to a value lower than the critical one \( v_p < v_{cr} \).

The development of conditions for shear flows on the obstacle surface, which arise at the impingement of a flow of particles under the oblique angle \( \alpha \geq 10^\circ \), enabled the solution of a question on the coverage of pores. Figure 4a shows the original sample of a porous obstacle of a cast aluminum alloy, the typical equivalent diameter of pores \( d_{\text{por}} = (0.5 - 2) \text{ mm} \).

![Fig. 4. Photographs of the aluminum alloy samples: a – the original one, with the open porosity, b – with a coating deposited under the angle \( \alpha = 0 \) and c – under the angle \( \alpha = 60^\circ \).](image-url)

Figure 4b, c shows the porous material samples with the aluminum coating at a flow of a gas-powder jet under the angle \( \alpha = 0 \) and 60°. It is seen that at \( \alpha = 0 \) the pores are not covered, even at the deposited layer thickness of more than 100 µm. At \( \alpha = 60^\circ \), the coverage of pores occurs.
Conclusion

The investigation of such samples with a coating under the microscope showed that at an oblique impact of particles, an intense shear plastic deformation of the particles material arises at a relaxed normal (compressing) component. Coating properties also change according to this. In particular, an elevated hardening of the aluminum coating realizes under small angles (HV = 600 MPa), at $\alpha = 60^\circ$ (HV = 300 – 350 MPa). The choice of the regimes of particles interaction depending on the impact angle enables the optimization of the process of coatings formation, and also ensures the covering of pores and cavities on the surface of products.

REFERENCES