Mechanism of the powder material particle in different phase states—solid substrate interaction

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Abstract. The paper discusses impact of solid and molten particles of a powder material in heterogeneous flow acting on solid surface and its effect on characteristics of coating applied by a gas-dynamic (cold spray) method. An equation of energy balance in impact zone of the particle on the substrate is given. Obtained equation accounts the particle size, mass average temperatures in heated portions of the particle and the substrate, before impact temperatures of the particle and the substrate, fraction of the heated mass of the particle and the substrate during impact, specific heat capacities of the particle and the substrate material, the Brinell characteristic, and deformation of a solid particle. Results of the bibliographic study of the molten metal droplet formation, their kicks in the substrate depending on its velocity, substrate temperature and surrounding gas pressure are presented. The differences in the impact mechanism of solid and molten particles on the substrate and their influence on the coating formation and its properties are determined. Recommendations for operating parameters of high-quality coating are given.

1 Introduction

The protective coating application by a cold spray method is widely used in many industries (aerospace, chemical, fuel, military, mining, medicine, electronics and mechanical engineering) [1, 2].

The quality of applied coating is generally determined by conditions of interaction of the powder material particles with the substrate. These conditions include the speed of the particles as well as their size, temperature and phase state. In addition, pretreatment of the contact surface is of great importance [3–10]. Therefore, the study of fundamental physical processes occurring during the interaction of the particle with the substrate is of great practical importance.

Each particle attached to the substrate surface is a part of the coating. Theoretical and experimental studies of recent years are devoted to the study of the characteristics of such parts and their interaction with each other and the substrate.

Interaction of the particle with the substrate surface upon impact can be considered as several simultaneously occurring processes due to separate or joint influence of the components of particles flux and properties of the surface.

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Experimental study of such processes are carried out on gas-dynamic installations generating high-speed heterogeneous flows [1–4].

The kinetic energy changes depending on the type of impact (elastic or plastic), and limiting values correspond to absolutely elastic and absolutely plastic impact. The type of impact is determined by the particle velocity, which directly depends on the velocity of the carrier gas.

According to the physics laws, there is no energy transformation from one type to another during the elastic impact of the particle on the substrate. The particle rebounds from the substrate with a velocity equal to the rebound velocity. In this case, the coating is not applied.

Let's call the particle velocity at which the elastic impact occurs, the first critical one. Then we can assume the existence of a second critical velocity, which is the particle velocity at which the solid surface begins to collapse (due to erosion) when particles bombard the surface.

Indicated critical velocities can be calculated using continuum mechanics laws, which make it possible to determine the motion parameters of the high-speed (supersonic) heterogeneous flow [2].

When applying coatings by a cold spray method, it is of practical interest to establish the range of particle velocities at which the coatings are formed. This range should be the gap between the first and second critical velocities, i.e. between the velocity at which the elastic impact of the particle against the surface occurs, and the speed at which the material of the bombarded surface begins to collapse (undergo erosion) [2–5].

Limiting values of these velocities depend on properties of the particles and the surface. The particle velocity at the moment of impact depends on characteristics of the heterogeneous flow at the exit from the gas-dynamic accelerator. It also depends on the flow nature on the final interval of the particle flight when it overcomes the shock wave and compressed layer, as well as on the mechanical properties of the particle and substrate materials.

Factors influencing the interaction of the particle with the surface are the particle shape, the particle orientation at the contact with the surface, the particle velocity, the particle incidence angle, and properties of the particle and surface materials [3–7].

In context of a cold spray technology application for the coating deposition, we consider the impingement of a supersonic heterogeneous jet of finite dimensions onto an obstacle (figure 1).

Depending on properties of the particle material and characteristics and temperature of heterogeneous flow, the particle can have several phase states. We will consider a cold (not molten) and partially molten state.

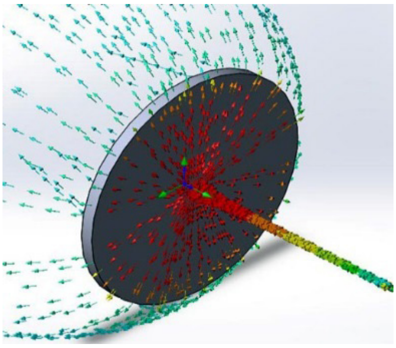

Figure 1. Leakage of a supersonic heterogeneous jet of finite dimensions onto an obstacle

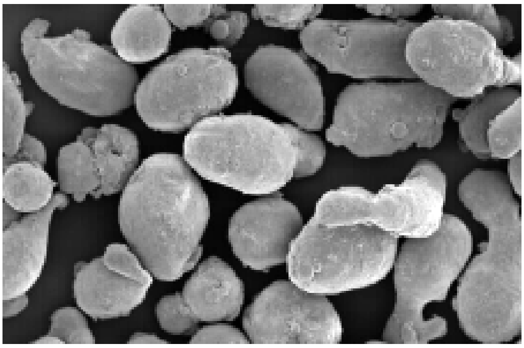

Figure 2. Shape of deformed particles

The particle shape at the moment of impact on the substrate is close to ellipsoidal, which was established by visual examination of metal coatings at multiple magnifications. And only at particle velocities of ~ 1000 m/s their deformed shape is close to the disk shape (figure 2).

2 Deformation of solid particles

Upon impact, the solid particle penetrates the substrate to a shallow depth, and deformation of the particle is compression and spreading over the surface. The defining process is spreading. It means that the particle deformation energy is spent on overcoming the forces of resistance to yield strength during deformation of its surface from the initial spherical shape to an ellipsoid. The metal particle deformation upon impact on the substrate is shown in figure 3.

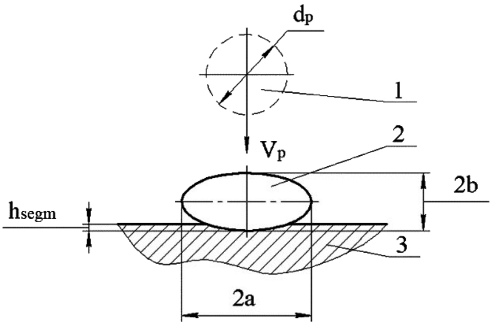

Figure 3. Deformation of a solid metal particle upon impact with a substrate: 1—particle shape before impact; d_p—particle diameter; V_p—particle velocity at the moment of impact on the substrate; 2—particle segmental shape after impact, 2b—diameter of the segment; h_{segm}—penetration depth of the particle 1 into the substrate 3

In symbols, the energy balance equation in the impact zone of the particle on the substrate can be written as follows:

$$E_{kin.\,p} = E_{def.\,p} + E_{def.\,wall} + E_{heat.\,p} + E_{heat.\,wall}, \tag{1}$$

where $E_{kin.\,p}$—the particle kinetic energy; $E_{def.\,p}$—the particle deformation energy; $E_{def.\,wall}$—the substrate deformation energy; $E_{heat.\,p}$—the particle heating energy; $E_{heat.\,wall}$—the substrate heating energy.

The particle kinetic energy at the moment of impact is determined by the particle mass m_p and velocity V_p.

Particles strain energy is spent for the change of particle shape from spherical to close to ellipsoid (spheroid) at the moment of impact on the substrate, where d_p—the particle diameter; σ_T—the tensile yield strength of the particle material; a and b—the large and small semi-axes of the of the spheroid, respectively, and $\alpha = \sqrt{1 - \left(\frac{b}{a}\right)^2}$.

Degree of solid particles deformation upon impact on the substrate is calculated by the formula:

$$\varepsilon = \frac{2b}{d_p}. \tag{2}$$

The substrate deformation energy is spent to a plastic compression of the substrate material, the value of which is determined by penetration depth of the particle into the substrate body h_{segm} and the substrate compression resistance strength (H_β—the substrate Brinell hardness index).

The energy spent on heating the particle $E_{heat.\,p}$ depends on $m_{\tau,\,p}$—the mass of the particle heated during the time of the impact τ; $\bar{T}_{\tau,\,p}$—the average mass temperature of the heated portion of the particle; c_p—the specific heat capacity of the particle material at temperature $\bar{T}_{\tau,\,p}$; $T_{st.\,p}$—the average temperature of the particle before the impact.

The energy spent on heating the substrate $E_{heat.\,wall}$ depends on $m_{\tau,\,wall}$—the mass of the substrate heated during the time of the impact τ; $\bar{T}_{\tau,\,wall}$—the average mass temperature of the heated portion of the substrate; c_{wall}—the specific heat capacity of the substrate material at temperature $\bar{T}_{\tau,\,wall}$; $T_{st.\,wall}$—the substrate temperature before the impact.

The heating scheme of the particle and the substrate during their interaction is shown in figure 4.

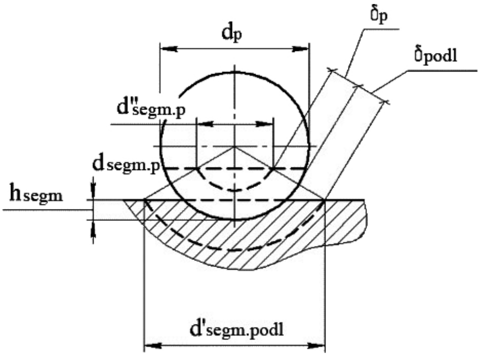

Figure 4. Heating scheme of the particle and the substrate on interaction: d_p—diameter of non-deformed particle; h_{segm}—particle penetration depth into the substrate; $d'_{segm.\,podl}$—diameter of the heated segment deformation of the substrate; $d_{segm.\,p}$—diameter of the heated segment of the particle; $d''_{segm.\,p}$—diameter of the cold segment of the particle; δ_p—particle heating depth; δ_{podl}—substrate heating depth

Substituting the corresponding expressions in (1), we obtain the final form of the energy balance in the impact zone of the particle on the substrate [3–5]:

$$\frac{m_p \cdot V_p^2}{2} = \pi d_p \sigma_T \left[2a^2 + \frac{b^2}{\alpha} \ln \frac{1+\alpha}{1-\alpha} - d_p^2\right](1-\varepsilon) + 2\pi h_{segm}^2 d_p H_\beta + \\ + m_{\tau,\,p} c_p \left(\bar{T}_{\tau,\,p} - T_{st.\,p}\right) + m_{\tau,\,wall}\, c_{wall} \left(\bar{T}_{\tau,wall} - T_{st.wall}\right). \quad (3)$$

The equation accounts the particle size, mass average temperatures in heated portions of the particle and the substrate, before impact temperatures of the particle and the substrate, fraction of the heated mass of the particle and the substrate during impact, specific heat capacities of the particle and the substrate material, the Brinell characteristic, and deformation of a solid particle, etc.

3 Deformation of melted particles

During application, the molten particles kick the colder surface of the substrate with subsequent spreading and simultaneous deformation and solidification.

At the initial moment of impact, a spherical particle, flattening under the action of inertial forces, spreads over the surface from the place of primary contact. These processes take place simultaneously. Under the action of inertial forces, the particle spreading velocity over the surface will differ from the particle velocity. Simultaneously with the particle spreading, the boundary of its solidification will also move, and the movement direction is perpendicular to the substrate surface. The final solidification and spreading of the particle occurs simultaneously, thus its shape is retained in the coating [6]. When the particle kicks the substrate at the angle of 90 degrees, the particle shape is close to a disk (see figure 2) with a thickness of 1/10–1/20 of the initial diameter of a spherical particle. However, in a real coating, the shape resulting from spreading can be completely different, since particles fall on the substrate at different angles [7–10].

Together with the circular surface spreading, heat transfer from the particle material occurs in the direction perpendicular to the substrate surface, and the solidification front propagates in the same direction.

We assume that the solidified particle, when kicks at the right angle on the flat substrate surface, acquires the disk shape from the initial spherical one.

Deformation of the molten particle upon impact on the substrate is calculated by the formula:

$$\varepsilon = 1 - \frac{h}{d_p}, \tag{4}$$

where h—the height of the fixed particle; d_p—the initial diameter of the particle.

Deformation of the molten metal particle upon impact with the substrate is shown in figure 5 [10–17].

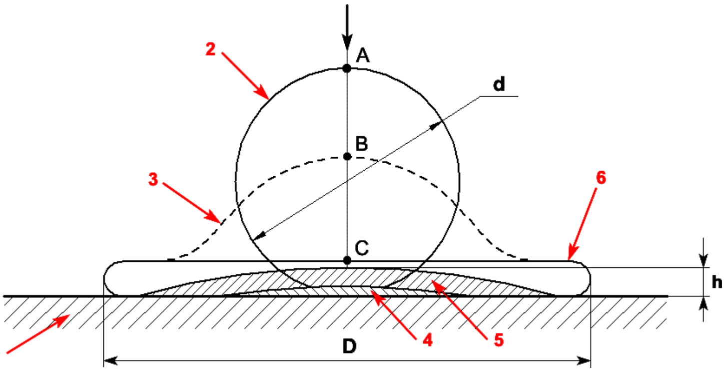

Figure 5. Deformation of the molten metal particle upon impact with the substrate: 1—substrate; 2—particle with the diameter *d*; 3—intermediate form of the particle; 4—solid phase of the particle; 5—crystallization phase of the particle; 6—final form of the crystallized particle (disk with the diameter *D* and the height *h*)

Substituting expressions (2) and (4) into the energy balance equation, we obtain the final form of the energy balance in the impact zone of solid (5) and molten (6) particles on the substrate [3–5]:

$$\begin{aligned}\frac{m_p \cdot V_p^2}{2} = \pi d_p \sigma_T \left[2a^2 + \frac{b^2}{\alpha}\ln\frac{1+\alpha}{1-\alpha} - d_p^2\right]\left(1 - \frac{2b}{d_p}\right) + 2\pi h_{segm}^2 d_p H_\beta + \\ + m_{\tau,p} c_p (\bar{T}_{\tau,p} - T_{st.p}) + m_{\tau,wall} c_{wall} (\bar{T}_{\tau,wall} - T_{st.wall}),\end{aligned} \tag{5}$$

$$\begin{aligned}\frac{m_p \cdot V_p^2}{2} = \pi d_p \sigma_T \left[2a^2 + \frac{b^2}{\alpha}\ln\frac{1+\alpha}{1-\alpha} - d_p^2\right]\frac{h}{d_p} + 2\pi h_{segm}^2 d_p H_\beta + \\ + m_{\tau,p} c_p (\bar{T}_{\tau,p} - T_{st.p}) + m_{\tau,wall} c_{wall} (\bar{T}_{\tau,wall} - T_{st.wall}).\end{aligned} \tag{6}$$

Characteristics of the coating microstructure—porosity and adhesion—depend on the solidified particle shape [15].

The solidified particle shape can have a different morphology: from splashes to a disc of regular shape. The disk shape is one of the main factors influencing the production of a high-quality coating with low porosity for most materials [13–17]. In [12], the dependence of the shape of the formed molten metal particle on the rate of its deposition on the substrate was investigated. With an increase in the rate of deposition of a molten tin particle of the same diameter on the steel substrate, a flattened drop is formed; then a donut, the central part of which is filled with a thin layer of metal; then a disc with weakly expressed edges; then a disk with star-shaped edges; and then the molten particle breaks up into small splashes.

As the particle diameter decreases, the shape change pattern shifts towards higher velocities, because there is an increase in the total force of the surface tension of the resulting drop in relation to its volume. An increase in the substrate temperature to a value sufficient for its penetration by a molten particle leads to an increase in the values of the velocity ranges.

Experimental studies have shown that the shape of a solidified drop depends on both the substrate temperature and the pressure of the surrounding gas [12–16]. It was also shown that there is a critical substrate temperature, exceeding which leads to the formation of disks in 50% of their total amount. Further increase in the substrate temperature increases the fraction of solidification of droplets in the form of disks [17].

Thus, in order to increase the adhesion and decrease the porosity of the applied coating, it is advisable to select such application modes in which the heated powder particles do not splatter upon contact with the substrate but form a coating consisting of molten particles having the disk shape upon solidification.

Operational application modes will depend on the particles and substrate material, carrier gas, etc. The selection of such modes is a separate scientific and practical task.

4 Conclusion

Improvement of characteristics of coatings obtained by a cold spray method, namely: an increase in the adhesion of the coating, a decrease in its porosity, an increase in the coefficient of use of the powder due to the greater proportion of the powder forming the coating, as well as an increase in the rate of formation of the coating—all of them depends on many factors that must be taken into account when setting the parameters heterogeneous flow. One of the important factors is the metal particles temperature and velocity in heterogeneous flow that forms the coating. The temperature range of particles for coating formation is from unheated to molten. The particle velocity range for coating formation is from the elastic impact of the particle on the substrate to the velocity at which the molten particle breaks up into small splashes. Certain combinations of these parameters make it possible to obtain coatings with specified and desired characteristics.

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