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Mechanism of heterogeneous flow—solid substrate interaction on the formation of coatings of different thicknesses using different types of spray accelerators

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Abstract. Physical processes of the inleakage of a supersonic heterogeneous flow of air-powder mixture to a solid substrate, tested on the experimental setup designed for applying protective coatings by a cold spray method, are considered. The interaction of a particle with a flat plane and cylindrical solid substrates, the multilayer coatings and the application of coatings using spray accelerators of different configurations are considered. A mathematical model is demonstrated based on the equation of energy balance in the impact area intended to estimate the interaction between a particle and a solid substrate during impact, as well as examples of results calculated using this model. Methods for calculation of the thickness of the coating applied to flat plane and cylindrical substrates are described. The features of one-step and multi-step coating applications with and without additional exposures are described. As an example, the results of testing the coating for porosity are given. A list of factors and additional exposures affecting the strength of the coating is given.

1 Introduction

The cold spray method of applying coatings is a process in which powder particles are introduced into a high-speed heated gas jet creating a heterogeneous flow, and then accelerating to a supersonic speed and collide with a substrate surface, which leads to the forming a coating on that surface [1, 2]. The coating is formed in the process of severe plastic deformation of particles during the impact on a surface.

Before the impact, particles have a temperature well below the melting point of the powder material. When a cold (not molten) particle hits the surface, either the erosion of a substrate material or the adhesion of a particle into the substrate occurs, i.e. the formation of a coating occurs, which depends on the concentration and flow rate of particles in the air-powder mixture, the particle velocity and the flow temperature. In one case, bonds are formed between a surface of the particle and the substrate, i.e. the adhesion occurs. In another case, elastic deformation energy accumulates in the particle volume, which is released in the form of the rebound kinetic energy. When the elastic deformation energy becomes greater than the total energy of adhesion, the particle bounces off the substrate. Otherwise, the particle is adhere to a substrate surface [3].

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After forming one layer of particles on a substrate surface, the materials of the inleakage particles and the formed coating come into the contact, i.e. a mutual adhesion of the powder particles occurs. Thus, a coating of the desired thickness is created. The surface profile of a single coating layer is determined by the material properties, the distance from the accelerator nozzle exit to a substrate, the angle between heterogeneous flow jet and a substrate surface, a substrate properties, a substrate deformation, a local heat transfer, etc. If to sum a large number of surfaces profiles of individual coating layers, providing a given thickness, the distribution of the total coating surface profile can be considered approximately as a continuous curve [4].

When a movable supersonic spray accelerator with a circular cross-section of small area is used for the cold spray coatings, the coating is created in one pass of accelerator along a substrate (scan step). Scan step of such accelerator is usually quite narrow compared to other types of accelerators, and the gap between two sequential scan steps on the same coating layer is usually small in order to ensure the uniform thickness of a coating on the layer. In some publications, for example, in [4], the angle between a heterogeneous flow jet and a substrate surface has been analyzed, and how it influences on the coating characteristics. It was determined that the relative efficiency of the coating formation is maximum at spraying angles from 80 to 90°. When the angle decreases approximately to 40°, almost no deposited particles adhere to a substrate, and the relative efficiency of the coating formation tends to zero.

In our experimental setup [5], designed for the application of protective coatings on pipes with a diameter of 150 and 300 mm, spray accelerators with the circular slotted nozzles are used. They apply the air-powder mixture over the entire circumference of the pipe cross-section at once. There is no need to optimize a path of accelerator in this case, and the uniformity and strength of the coating are influenced mainly by accelerator displacement velocity, mass flow rate of the powder, and thermal parameters of processes.

At present, the cold spray method of coatings is being intensively studied and developed in the world of science and technology and adopts a high profile among protective coatings technologies, hardening technologies, and additive technologies.

2 The equation of energy balance for the particle impact on a substrate

To simulate physical processes in the area of particle impact on a substrate, we can use the equation of energy balance, which is written in symbolic form [3]:

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

The equation (1) takes into account only the main stationary physical factors affecting the energy balance. In the equation (1), for example, there no terms for the heating energy of particles in the carrier-gas flow and the energy of substrate heating by the gas flow. These energies are implicitly taken into account by parameters characterizing the mechanical properties of the particle and substrate materials.

The kinetic energy of the particle during impact is defined by particle mass m_p and particle velocity V_p and is represented in the form:

$$E_{kin.\,p} = \frac{m_p \cdot V_p^2}{2}. \tag{2}$$

Upon impact, the particle penetrates the substrate to a small depth, and it is assumed that the deformation of the particle is a compression and free spreading over the surface [6].

Particle deformation energy is spent on transforming the particle shape from spherical to approximately ellipsoidal (spheroidal) during impact on the substrate:

$$E_{def.\,p} = \pi d_p \sigma_T \left[2a^2 + \frac{b^2}{\alpha} \ln \frac{1+\alpha}{1-\alpha} - d_p^2 \right] (1 - \varepsilon), \tag{3}$$

where d_p is the particle diameter, σ_T is the limit of the particle material yield, $\varepsilon = 2b/d_p$ is the degree of particle deformation during the impact, a and b are the large and small semi-axes of the deformed particle spheroid (figure 1), and $\alpha = \sqrt{1 - (b/a)^2}$.

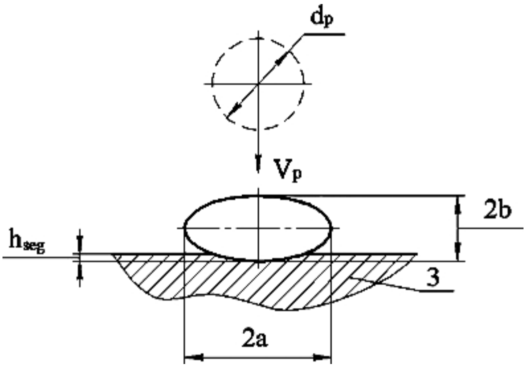

Figure 1. Deformation of the metal particle upon impact with the substrate

Substrate deformation energy is spent on the plastic compression of a substrate material. This energy is determined by the depth of particle penetration into the substrate bulk and by the compression resistance force of the substrate material. To estimate the depth of spherical particle penetration into the substrate material, a geometric model of the particle interaction with a substrate is used (figure 1), and the final expression has the following form:

$$E_{def.\,wall} = 2\pi h_{seg}^2 d_p H_\beta, \tag{4}$$

where H_β is the Brinell hardness of the substrate material.

The expression for the energy spent on particle heating has the form:

$$E_{heat.\,p} = m_{\tau,\,p} c_p (\bar{T}_{\tau,\,p} - T_{st.\,p}), \tag{5}$$

where $m_{\tau,\,p}$ is the fraction of the particle mass heated during the impact time period τ; $\bar{T}_{\tau,\,p}$ is the weight-averaged temperature of the heated particle segment; c_p is the specific heat of the particle material at a temperature of $\bar{T}_{\tau,\,p}$; $T_{st.p}$ is the average particle temperature before the impact.

The expression for the energy spent on substrate heating has the form:

$$E_{heat.\,wall} = m_{\tau,\,wall} c_{wall} (\bar{T}_{\tau,\,wall} - T_{st.\,wall}), \tag{6}$$

where $m_{\tau,\,wall}$ is the segment of the substrate mass heated during the impact time period τ; $\bar{T}_{\tau,wall}$ is the weight-averaged temperature of the heated substrate segment; c_{wall} is the specific heat of the substrate material at the temperature $\bar{T}_{\tau,\,wall}$; $T_{st.\,wall}$ is the substrate temperature before the impact.

Table 1. Results for the interaction of an Al particles and a Cu substrate

Particle diameter d_p, [m]	Particle velocity V_p, [m/sec]	Degree of deformation ε	Particle mechanical properties σ_T, [Pa]	Impact time τ, [sec]	Particle specific heat c_p, [J/kg K]	Substrate specific heat c_{wall}, [J/kg K]	Brinell hardness of the substrate H_β, [MPa]	Change in the temperature in the impact area $\bar{T}_\tau - T_{st}$, [°C]
$5 \cdot 10^{-5}$	410	0.701	$6.37 \cdot 10^{-7}$	$1.49 \cdot 10^{-7}$	929	400	400	230
$5 \cdot 10^{-5}$	508	0.598	$6.37 \cdot 10^{-7}$	$1.27 \cdot 10^{-7}$	929	400	400	323
$5 \cdot 10^{-5}$	615	0.503	$6.37 \cdot 10^{-7}$	$1.10 \cdot 10^{-7}$	929	400	400	470
$5 \cdot 10^{-5}$	1000	0.600	$6.37 \cdot 10^{-7}$	$1.00 \cdot 10^{-7}$	929	400	400	1770

By substituting the dependences (2)–(6) into equation (1), we obtain the final form of the energy equation:

$$\frac{m_p \cdot V_p^2}{2} = \pi d_p \sigma_T \left[2a^2 + \frac{b^2}{\alpha} \ln \frac{1+\alpha}{1-\alpha} - d_p^2 \right] (1-\varepsilon) + 2\pi h_{seg}^2 d_p H_\beta + \\ + m_{\tau,p} c_p (\bar{T}_{\tau,p} - T_{st.\,p}) m_{\tau,wall} c_{wall} (\bar{T}_{\tau,wall} - T_{st.\,wall}). \quad (7)$$

Equation (7) lets calculate weight-averaged temperatures of the heated particle segment and also the average temperature of the heated substrate segment in the contact area during impact. In this case, the following must be known: the particle diameter, the physical and mechanical properties of powder and substrate materials, the velocities of particles at the instant of impact with the substrate, and the degree of their deformation on impact. For example, table 1 shows results for the interaction of an Al particles and a Cu substrate [3].

3 Calculation of the coating thickness in case of movable spray accelerator with a circular cross-section of small area

For such a case, the kinematic scheme of the coating process is shown in figure 2. When applying the coating (3), its quality essentially depends on the following kinematic parameters of the accelerator displacement (2) relative to the substrate (1): spray distance L, spray angle α, accelerator velocity V relative to the substrate, scan step S, and the number of passes. The influence of these parameters is studied in detail in a number of publications, for example, in [7, 8].

For that kinematic scheme, a coating band in one scan step is quite narrow, and the gap between two sequential scan steps is small in order to ensure the uniform thickness of the coating.

It was shown in [4] that the Gaussian distribution curve can be used to calculate the height of a coating surface profile on a flat plane substrate (figure 3).

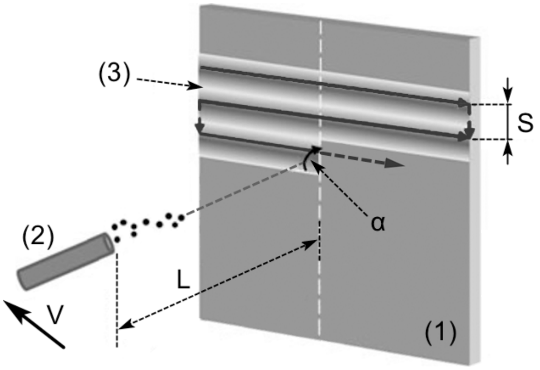

Figure 2. Kinematic scheme of the coating process

When spray parameters such as accelerator displacement velocity and spray distance are changed, the Gaussian curve will also change, but this does not affect the estimation of the coating thickness using the following equation:

$$y = \frac{K}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{x^2}{2\sigma^2}}, \tag{8}$$

where coefficient K and standard deviation σ can be fit based on experimental results to determine desired shape of the Gaussian curve. Coefficient K is a crest factor that affects the thickness of individual coating profile.

To calculate the coating height on the cylindrical substrate, a polar coordinate system is used due to a specific shape of the coating surface profile, and the Gaussian curve only cannot be used in this case [9].

The coating surface profile (2) on the cylindrical substrate (1) with a radius R is shown in figure 4.

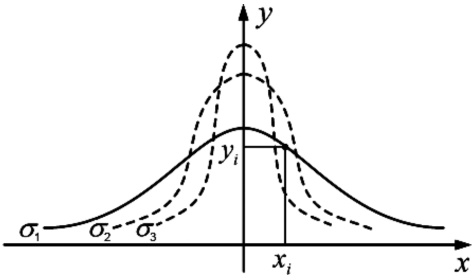

Figure 3. Coating surface profiles on the flat plane substrate

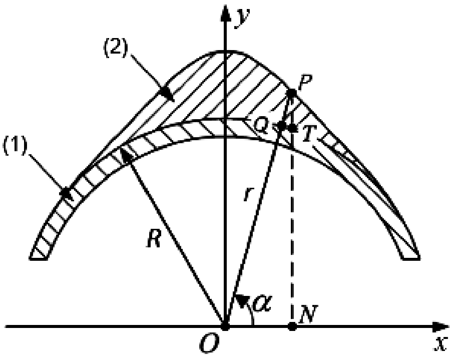

Figure 4. Coating surface profile on the cylindrical substrate

Polar coordinates r and α of the point P laying on the coating profile can be transformed to rectangular coordinates: $x_p = r \cdot \cos\alpha$, $y_p = r \cdot \sin\alpha$. Next, we need to determine the coating thickness $|PQ|$ at point P. In accordance with figure 5 and the equation (8), the following can be written:

$$r \cdot \sin\alpha = |PT| + |TN|, \tag{9}$$

$$|PT| = \frac{K}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{(r\cdot\cos\alpha)^2}{2\sigma^2}}, \tag{10}$$

$$|TN| = \sqrt{R^2 - (r\cdot\cos\alpha)^2}. \tag{11}$$

Substituting (10) and (11) in (9) gives the following:

$$r \cdot \sin\alpha = \frac{K}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{(r\cdot\cos\alpha)^2}{2\sigma^2}} + \sqrt{R^2 - (r\cdot\cos\alpha)^2}. \tag{12}$$

Having solved equation (12) for r, we can determine the coating thickness on the substrate surface at point Q:

$$|PQ| = r - R.$$

Finally, summing the number of coatings profiles for all scan steps S, we can consider the resulting profile with the averaged height H as a continuous curve for definition of the resulting coating surface (figure 5).

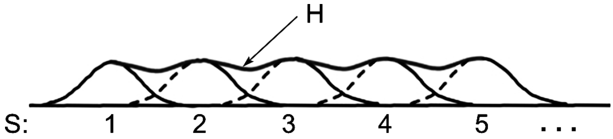

Figure 5. Resulting coating surface profile

4 Applying a coating layer to the entire cylindrical surface at once

To apply coatings on cylindrical surfaces, we have created the experimental setup with special prefabricated accelerators of heterogeneous flow, which make it possible to apply a continuous coating layer on the inner and outer sides of pipes of diameter of 150 and 300 mm [5]. The principle of operation of accelerators is shown in figures 6 and 7. Dashed lines with arrows on the figures indicate a heterogeneous flow. The flow enters the accelerator and evenly distributes within its cavities, and then leaves the circular slotted nozzle of accelerator. Thus, a continuous coating layer is applied to the entire cylindrical surface at once.

One of the key characteristics of a thick coating, including ones applied in a continuous layer, are its strength and porosity [10]. In order to increase the strength of a coating with a thickness of more than 2.5 mm, special techniques are used. For example, using step-by-step and layer-by-layer spray with additional exposure intended to recover residual stresses in the coating, it is possible to create coatings that are significantly thicker than obtained in a one-step process. After applying a coating layer with a thickness of 0.15–0.2 mm, the powder supply stops. Further, the created coating layer is blown with heated air until the recovery temperature of the coating material structure (0.2–0.3 of melting point) is reached, and then the powder begins to feed and the next coating layer is applied. The cycle is repeated until the specified coating thickness is obtained. For example, table 2 shows the porosity test results for a stainless steel coating applied to a flat plane substrate of a Steel 20.

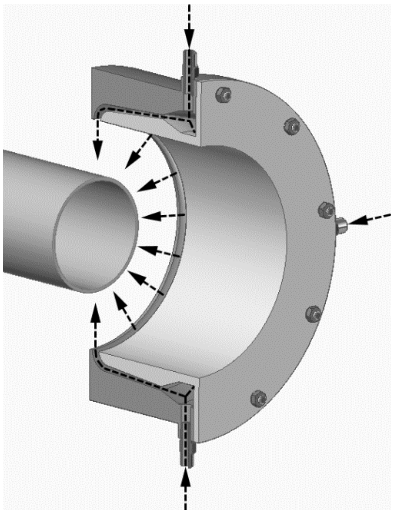

Figure 6. Circular slotted accelerator for outside coating (a cross section shown)

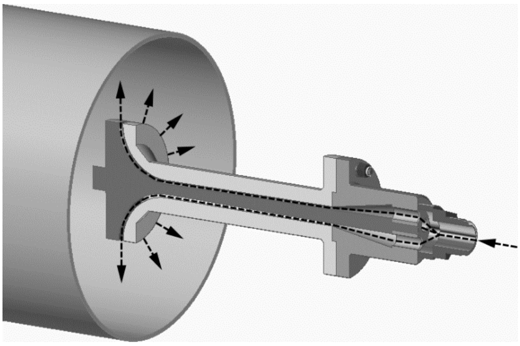

Figure 7. Circular slotted accelerator for inside coating (a cross section shown)

Table 2. Porosity test results for a stainless steel coating

Parameter	Measured values	
	Coating without additional exposure	Coating with additional exposure
Number of measurements	160	160
Total pore area	28,057 μm^2	27,839 μm^2
Pore size	172 μm^2	167 μm^2
Porosity percentage	3.21%	3.09%

5 Conclusion

Using considered calculation methods, it is possible to estimate the energy balance in the area of particle impact on a substrate and the coating thickness for the given process parameters and material properties. Regarding the strength of thick coatings, well-established engineering estimation methods have not been developed yet, despite the known basic physical processes that cause residual stresses in cold spray coatings. This can be explained not only by the complexity of processes, but also by the thermal, physical and chemical phenomena taken into account.

Experiments performed on the experimental setup let to highlight the following factors and additional exposures, which make it possible to increase the coating strength:

- matching the material properties of a coating and a substrate and, first of all, their thermal-expansion coefficients;
- regulation of the thermal effect of the gas-dynamic flow on the particles and substrate by changing the distribution of its thermal power over the heating spot as well as adjusting the distance from the edge of accelerator nozzle to a substrate or changing the accelerator displacement velocity;

- decreasing the elastic modulus of the coating material, for example, by introduction of additives of plastic material into the heterogeneous flow;
- using intermediate layers between a substrate and a coating, that provide a smooth transition of properties from a substrate material to a coating material;
- changing the coating thickness as well as applying multilayer coatings with alternate layers of different materials.

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