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Measurements of Cold Spray Deposition Efficiency

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An analytical model of the kinetics of coating formation during cold spray is presented. The model is used to correct experimental data on deposition efficiency. The experimentally observed values are shown to be affected by experimental conditions, such as the velocity of substrate motion, the number of passes, the mass of a single portion of powder, and the exposure time of a given surface section. It is noted that experimental conditions can exert a significant effect on the consequences of the high-speed interaction of particles with a substrate. Relations are suggested that allow one to correct the results of deposition efficiency determined experimentally and to avoid mistakes in interpreting the data obtained.

Keywords cold spray, deposition efficiency, kinetics

1. Introduction

One of the most important characteristics of cold gas-dynamic spray (CGDS), as well as of any other method of powder spray, is deposition efficiency. Investigation of its dependence on the governing parameters of the process (e.g., jet temperature, velocity, and size and concentration of particles) allows one to understand the nature of the cold spray phenomenon and, as a result, to reveal how the basic coating properties are influenced by spray parameters. It also helps in controlling these properties in accordance with necessary requirements. The deposition efficiency is usually determined as the ratio of the mass gain of the substrate during its exposure to the flow with a proper set of parameters and the decrease in powder mass in the feeder during the same time.

For many reasons, it is practically impossible to obtain a deposition efficiency that is equal to unity. First, polydisperse powders are usually used. As the jet during its impingement is spreading along the substrate surface, the finest particles either do not reach the surface at all or impact at acute angles, which deteriorates particle attachment. Although the largest particles are incident at a close-to-normal angle (i.e., the angle between the particle impact velocity and the substrate surface is close to 90°), their velocities may be insufficient for particle attachment. Such a behavior of particles can be explained by the gas-dynamic nature of their motion. The fact is that the gas-dynamic tract of the facility can be adjusted for spray only for a certain interval of particle sizes (e.g., Ref 1). Particles whose size significantly differs from the optimal value inevitably have less favorable conditions for attachment. Another reason for the decrease in powder deposition efficiency is that the particle velocity at the jet periphery can be lower than it must be for particle attachment. In addition, if the velocity is not sufficiently high, the surface should be self-activated by the impacted particles (e.g., Ref 2, 3). This means that the first particles impacting the natural surface always bounce. This can be avoided, however, by ensuring high-quality preparation of the surface and powder recirculation (reusing); a certain increase in deposition efficiency can be reached.

Due to the sufficiently complicated nature of CGDS, it is rather difficult to measure the deposition efficiency. Generally, three main stages of the spray process may be identified. At the initial stage, some time is required for surface preparation (i.e., the induction time), when only erosion occurs without any deposition. At the second stage, a thin layer of the particle material (hereinafter referred to as the first layer) is formed on the substrate surface. This stage is characterized by the interaction of particles with the substrate surface, and it depends on the preparation level and properties of the surface material. The third stage, which can be conventionally called the build-up stage, is characterized by the growing thickness of the coating layer. In this case, the particles interact with the surface formed by previously incident particles. Thus, it is clear why there is some uncertainty in measuring the powder deposition efficiency.

This article has the following structure. First, sections 2 and 3 describe, respectively, the experimental setup used and the experimental evidence of the existence of an induction time in cold spray. The idea that the transition to deposition occurs within a certain range of particle velocities is put forward. After that, an analytical model of coating-formation kinetics is constructed in sections 4, 5, and 6. With the help of this model, the behavior of the deposition efficiency is demonstrated in section 7. Procedures that are commonly used to measure the deposition efficiency are described in section 8, and the accuracy of determining the deposition efficiency is assessed. Experimental data on deposition efficiency obtained by one of the commonly used method are presented in section 9, and their correction is made using experimental data on the induction time. It is also shown that the use of the experimental method can lead to significant errors. Finally, a technique for obtaining more correct data on deposition efficiency and cold spray kinetics are proposed in section 10.

2. Experimental Setup

The data obtained from experiments described in Ref 2 are used in the present article. The experimental setup consists of

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typical cold spray equipment: a thin supersonic nozzle with a rectangular cross section; and the flow of air and helium mixtures allow accelerating particles up to an impact velocity sufficient for deposition. The stagnation temperature and pressure are 300 K and 2.0 MPa, respectively. The particle velocity was calculated by the method described in Ref 1 that was previously validated by experimental testing with the aid of a laser Doppler anemometry and track method (Ref 2). Only data obtained from experiments with aluminum particles (mean diameter 30 µm) deposited onto a copper substrate were used in the present article.

3. Induction Time (Delay) of Deposition

To explain what the induction time is, it is necessary to see the experimental procedure. Let the gas jet have particles with a proper velocity, temperature, and concentration. At the time $t = 0$, the examined section of the substrate surface is placed into the jet. First, the particles are not attached, they are bounced, thus cleaning and deforming the surface. At the time $t = t_i$, the particles begin to attach in an avalanche-like manner, rapidly forming a coating. This time t_i is called the induction time (or the time of deposition delay). It characterizes the process of preparing the surface for deposition (i.e., the conditions under which the next particles will be attached). Experimental evidence is shown in Fig. 1: a few particles are attached to the surface after activation by the impact of particles. The photograph in Fig. 1 shows the instant just before the coating starts to grow. The induction time is related to the particle concentration in the flow. To find this relation, it is assumed that the particle size does not significantly differ from the average size (i.e., the case of a monodisperse powder is considered). Note that, in the case of polydisperse powder motion, which is the most typical one in practice,

Nomenclature

Latin Notations

D	diameter of the cone nozzle outlet section
D_p	diameter of the contact between a particle and the substrate
d_p	diameter of a particle
H	cross size of an outlet nozzle section directed perpendicular to a nozzle motion with respect to the substrate
H	size of the outlet nozzle section directed parallel to the nozzle motion with respect to the substrate
h_c	coating thickness
h_p	a typical particle thickness after deformation
k_d	deposition efficiency $k_d = m_c/m_p$
k_{d0}	stationary value of the deposition efficiency $k_{d0} = dm_c/dm_p$
k_p	coefficient of a powder packing
L	spraying strip length equal to the product of the substrate motion velocity with respect to the nozzle, and run-time of the powder feeder
m_c	mass of coating (i.e., mass of all attached particles)
m_{c0}	mass of a coating first layer
m_p	mass of a powder spent from the feeder.
m_{p0}	mass of a powder spent during formation of the coating first layer
m_{pi}	mass of a powder spent during the induction time
$\dot{m}_p$	powder-mass flow rate from the feeder
N_c	number of the attached particles
$\dot{N}_p$	a particle flow rate of the powder spent from the feeder (number of particles spent from the powder feeder per a unit of time)
N_p	number of particles falling onto the whole exposed surface during exposition
N_{pre}	average number of preliminary impacts into a definite surface point
n_c	number of particles attaching to a unit of a surface
n_{pi}	number of particles falling per a unit of a surface during the induction time
$\dot{n}_p$	number of particles falling onto a unit of a surface per a unit of time
p_1	probability of a particle attachment on a free substrate surface
P_2	probability of particles attaching to the surface formed by the particles themselves
S_{ex}	area of the surface exposed (i.e. a surface whereon the particles have fallen)
S_c	contact area between a particle and the substrate
s_c	contact area divided by the area exposed $s_c = S_c/S_{ex}$
S_{fr}	free (i.e. without particles attached) surface area
s_{fr}	free area divided by the exposed area $s_{fr} = S_{fr}/S_{ex}$
t	time
t_0	typical time of a coating first layer formation
t_I	induction time (delay) of spraying
t_{ex}	time of the surface exposition
$\dot{V}_p$	volume of the powder spent from the feeder per a unit of time
v_{cr}	first critical velocity
v_{cr}^*	second critical velocity
v_p	velocity of a particle impact
v_w	speed of a substrate motion with respect to the nozzle
x	coordinate along a nozzle motion with respect to the surface
y	coordinate across a nozzle motion with respect to the surface
y_m	half-width of a strip sprayed

Greek Notations

α	average number of impacts into a definite point of the surface per a unit of time
ε_p	final degree of a particle deformation (a final particle strain)
β_I	dimensionless parameter $\beta_i = (m_{pi}v_w)/(\dot{m}_p R)$
ρ_p	density of a particle material
ω	exponent with value 1 for the nozzles with rectangular sections and 1.35 for the round-section nozzles

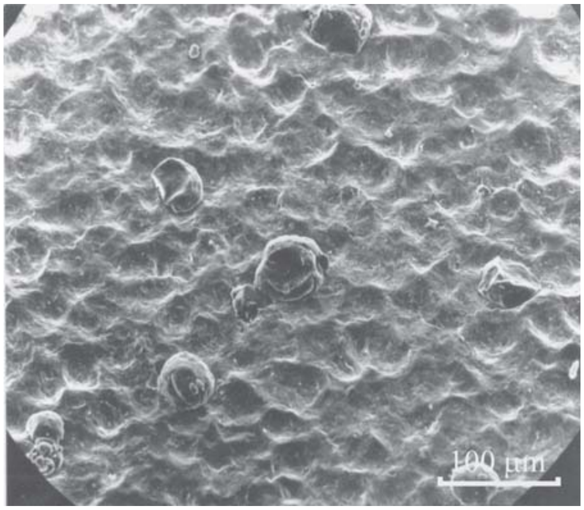

Fig. 1 Copper substrate surface after a 25 s delay in a two-phase jet. The impact velocity of aluminum particles is 600 m/s.

sufficiently narrow fractions characterized by their average size can be conventionally distinguished. Considering each fraction separately, information can be obtained about the powder as a whole. In the experiment, usually a volumetric or mass flow rate of the powder is measured. The relationship between the volumetric $\dot{V}_p$ and the countable $\dot{N}_p$ flow rate of the powder is determined by the formula:

$$\dot{V}_p = \frac{1}{k_p} \frac{\pi d_p^3}{6} \dot{N}_p \qquad \text{(Eq 1)}$$

where a typical value of the powder packing coefficient k_p is of the order of 0.5. The relationship between the mass and countable flow rate is determined as:

$$\dot{m}_p = \rho_p \frac{\pi d_p^3}{6} \dot{N}_p \qquad \text{(Eq 2)}$$

Knowing the total particle flow loss from the powder feeder, the particle flow per unit surface area can be easily found. For this, let the particles be uniformly distributed along the substrate area of the exposed surface (i.e., the average number of impacts onto each point of the exposed surface is the same). Note that this can be achieved rather seldom in the experiment, because the particle concentration at the jet edges is usually lower; if the shock-wave picture generated under off-design (nonisobaric) conditions of jet exhaustion is highly developed, it is very difficult to predict the level of nonuniformity of the particle distribution over the surface. In the general case, one should use some additional methods or assumptions for determining the particle flow density in the vicinity of a particular surface point. Thus, assuming that the surface area exposed S_{ex} coincides with the jet cross-sectional area, and, moreover, with the nozzle-exit section, the particle flow per unit of surface area can be easily estimated as $\dot{n}_p = \dot{N}_p/S_{ex}$. Obviously, a particular point on the surface is subjected to impact only by those particles whose centers are within the area with a diameter D_p around this point. Here D_p is the diameter of the contact zone between the particle and the surface, which is determined by the particle diameter and its deformation while impacting the surface obtained, for example, by the following formula (from Ref 4, 5):

$$D_p = \frac{2d_p}{\sqrt{3 \cdot (1 - \varepsilon_p)}} \qquad \text{(Eq 3)}$$

Assuming that the number of impacts is subjected to Poisson's distribution, one can determine the probability that exactly m particles will impact into a given point during the time t by using the formulas taken from Ref 6:

$$p_m = \frac{(\alpha t)^m}{m!} e^{-\alpha t} \quad \alpha = \dot{N}_p \frac{\pi D_p^2}{4 S_{ex}} = \dot{N}_p \frac{S_c}{S_{ex}} = \dot{N}_p s_c \qquad \text{(Eq 4)}$$

Here α is the average number of impacts into a given point of the surface per unit time (i.e., the average impact frequency), $S_c = (\pi D_p^2)/4$ is the area of the "particle-substrate" contact, and $s_c = (S_c/S_{ex})$ is the area of the "particle-substrate" contact divided by the area exposed.

Poisson's distribution can be approximated (if the number of expected impacts into the point during exposure αt_{ex} is sufficiently large) by the normal distribution. Thereby, the dispersion (i.e., standard deviation squared) shall be equal to an average value. Knowing the average frequency of impacts onto the point, the average number of impacts during the induction time can be determined by the formula:

$$N_{pre} = \alpha t_i \qquad \text{(Eq 5)}$$

Because the number of impacts onto a given point of the surface must be approximately equal, and it characterizes the activation processes, an assumption that the delay time of deposition is inversely proportional to the powder flow rate follows from Eq 4 and 5.

The delay of time makes conducting the experiment more difficult. Thus, pulse (short work time) regimes and regimes with a moving substrate are most often used in the experiment. Obviously, if the particle concentration in the flow is insufficient or the exposition time is short, it can be mistakenly concluded that the powder tested is suitable for CGDS. Thus, the induction time of the process must be measured to choose a correct operating time for the device and a correct particle concentration for the powder in the flow. In the second case, a correct velocity of substrate motion should be chosen. In this case, the exposure time of the unit (or point) of the surface is calculated by the formula:

$$t_{ex} = \frac{h}{v_w} \qquad \text{(Eq 6)}$$

where h is the size of the nozzle outlet directed toward the substrate motion with a velocity v_w. Note that this value is a variable for round-cut nozzles and coincides with the diameter only at the axis.

Figure 2 shows the induction time as a function of the impact velocity obtained from experiments on spray aluminum particles

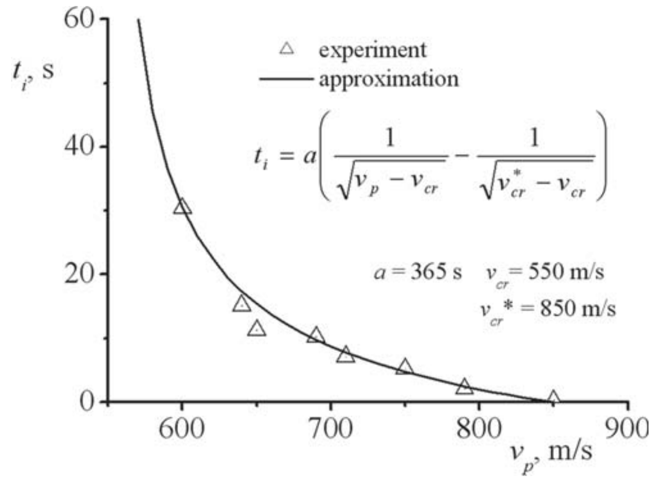

Fig. 2 Induction time versus the impact velocity for aluminum particles. The mass flow rate of the powder per unit area is 0.06 kg/m^2/s.

on a copper substrate. An approximating curve of the $t_i = a[(1/\sqrt{v_p - v_{cr}}) - (1/\sqrt{v^*_{cr} - v_{cr}})]$ type with the values $a \approx 365$ s, v_{cr} = 550 m/s, and v^*_{cr} = 850 m/s is used.

The picture demonstrates a significant growth for the induction time with decreasing impact velocity. In practice, particle attachment is observed in this case during some arbitrarily large period of exposure time. A certain conventional critical velocity may be identified, such that the surface is eroded if the particle impact velocity is lower than the critical value. If the velocity is higher than the critical value, the particles can attach to the surface if a sufficient level of the surface activation is reached. The following fact can be also noted: with increasing impact velocity, the delay time decreases to zero. From the physical point of view, this means that the particles can attach to a nonactivated surface. Thus, the second critical velocity can be identified, such that the particles attach to the natural (i.e., nonactivated) surface if the impact velocity is higher than the second critical velocity.

4. Determination of the Coating First Layer Mass

The following assumptions can be applied for determining the first layer mass (i.e., the mass of the layer formed on the surface when the substrate is completely coated at least by one layer of particles). Assume that, at a certain time, some part of the exposed surface with the area S_{ex}, area S_{fr}, is free (i.e., it is not occupied by particles). Then, introduce the free area divided by the exposed area $s_{fr} = S_{fr}/S_{ex}$. During the next moment of time, only a few particles, dN_p, occur on the exposed surface. Among them, $s_{fr}dN_p$ particles are on the free area. Among that number of particles, $p_1 s_{fr} dN_p$ particles are fixed on the free surface (p_1 is the probability of attachment on the free surface). Thereby, the free area occupation is determined by the expression:

$$ds_{fr} = -p_1 s_c s_{fr} dN_p \qquad \text{(Eq 7)}$$

On the other hand, during the same time, $p_2(1-s_{fr})dN_p$ particles will be attached onto the occupied surface (p_2 is the probability of particle attachment to the occupied surface). This implies that the total number of particles attached is determined by the expression:

$$dN_c = [p_1 s_{fr} + p_2(1 - s_{fr})]dN_p \qquad \text{(Eq 8)}$$

To evaluate the first layer mass, some additional simplifications are made. Consider that the probability of attachment to the free surface p_1 at $t \le t_i$ is equal to zero. As the coating thickness increases, let the probability of attachment to the free surface p_1 not vary during the time that the first layer is formed. This allows the authors to obtain analytical solutions (Eq 9 and 10) for the free surface and mass of the particles deposited m_c, respectively:

$$s_{fr} = \begin{cases} 1 & t < t_i \\ \exp[-p_1\alpha(t - t_i)] & t \ge t_i \end{cases} \qquad \text{(Eq 9)}$$

$$m_c = \begin{cases} 0 & t < t_i \\ p_2\dot{m}_p(t - t_i) + \dfrac{p_1 - p_2}{p_1}\dfrac{\dot{m}_p}{\alpha}[1 - \exp(-p_1\alpha(t - t_i))] & t \ge t_i \end{cases} \qquad \text{(Eq 10)}$$

The first layer formation is practically completed when condition 11 is fulfilled. Further, as it follows from Eq 10, the coating increases linearly (i.e., $dm_c/dt = Const$):

$$t_0 - t_i \approx 3\frac{1}{p_1\alpha} \qquad \text{(Eq 11)}$$

Substituting t_0 from Eq 11 into Eq 10 instead of t, Eq 12 is obtained for the particle mass in the first layer of the coating m_{c0}. Here α is also replaced using Eq 3 and 4, where $\varepsilon_p = 1 - h_p/d_p$:

$$m_{c0} = \frac{\dot{m}_p}{\alpha}\left(1 + 2\frac{p_2}{p_1}\right) = S_{ex}\frac{\rho_p d_p}{2}(1 - \varepsilon_p)\left(1 + 2\frac{p_2}{p_1}\right) \qquad \text{(Eq 12)}$$

Note that the number of particles in the first layer (and, consequently, the first layer mass) depends on probabilities, and, consequently, on the properties of the substrate and particle materials.

When the probabilities are commensurate in value (if the materials of the substrate and particles are identical, the probabilities must be identically equal), the particle mass in the first layer can be evaluated as:

$$\frac{m_{c0}}{S_{ex}} \approx 3\frac{\rho_p d_d}{2}(1 - \varepsilon_p) \qquad \text{(Eq 13)}$$

The value of the final strain of a particle can be taken as approximately 0.5 (Ref 7).

Owing to the more sophisticated nature of cold spray, the probabilities introduced are effective average values; the experimental kinetics curve corresponding to these probabilities can be approximated by Eq 10.

5. Buildup Stage of Spray

Obviously, after the formation of the first layer of the coating, the curve of the further increase in the coating mass should have a constant slope, because the particles interact with the surface that they themselves have formed. A decrease or increase in the growth rate should be considered as evidence of changes in interaction conditions with the surface. Assume that the first layer of mass m_{c0} is formed on the substrate surface at the time $t = t_0$. Then, a further increase in the coating mass (or the number of particles attached) is described by the linear dependence:

$$m_c = m_{c0} + k_{d0}\dot{m}_p(t - t_0) = m_{c0} + k_{d0}(m_p - m_{p0}), \quad t > t_0 \qquad \text{(Eq 14)}$$

On the other hand, assuming that the exponent in Eq 10 is negligibly small compared with unity, the following expression is derived:

$$m_c = p_2\dot{m}_p(t - t_i) + \frac{p_1 - p_2}{p_1}\frac{\dot{m}_p}{\alpha} \text{ at } t > t_0 \qquad \text{(Eq 15)}$$

Under the following assumptions, Eq 15 acquires the form of Eq 14:

$$p_2 = k_{d0} \qquad \text{(Eq 16)}$$

$$p_1 = \frac{3m_{c0}}{m_{p0} - m_{pi}} - 2k_{d0} \qquad \text{(Eq 17)}$$

6. Kinetics of Growth of the Coating Mass

Figure 3 demonstrates the variation in the mass of the deposited layer versus the powder mass spent (or the time at constant powder consumption from the feeder). The mass of the powder spent is plotted on the *x* axis, and the coating mass is plotted on the *y* axis. In Fig. 3(a) and (b), the probability of particle attachment to the occupied surface (i.e., at the build-up stage of the spray) is assumed to be equal to 0.5. Particle attachment to the free surface is somewhat better (case 1), somewhat worse (case 2), and equal (case 3) compared with particle attachment to the occupied surface. A straight line from the coordinate origin corresponds to the case where the induction time is equal to zero $t_i = 0$ (or $m_{pi} = 0$), and the probabilities are $p_1 = p_2 = 0.5$ (i.e., the surface and particle materials are identical). Curves 1 and 2 refer to case 1 ($p_1 > p_2$) and case 2 ($p_1 < p_2$). The induction times shown in Fig. 3(a) are identical. Figure 3(b) presents the case where the induction times are different $t_{i1} < t_{i2}$ (or $m_{pi1} < m_{pi2}$). The solid curves are built by Eq 10 for cases 1 and 2, respectively. As m_p increases from zero to m_{pi}, the coating mass is equal to zero, it further increases according to Eq 10, and, at $m_p > m_{p0}$, it approaches the approximating curve determined by Eq 15. The dashed curve 3 refers to case 3 ($p_1 = p_2 = 0.5$). Obviously, the coating grows more rapidly in case 1 where the particle attachment to the free surface is somewhat better than attachment to the occupied surface. When attachment to the free surface is somewhat worse, it is logically expected that the induction time is larger. This variant is shown in Fig. 3(b). Obviously, in this case the coating growth is additionally delayed.

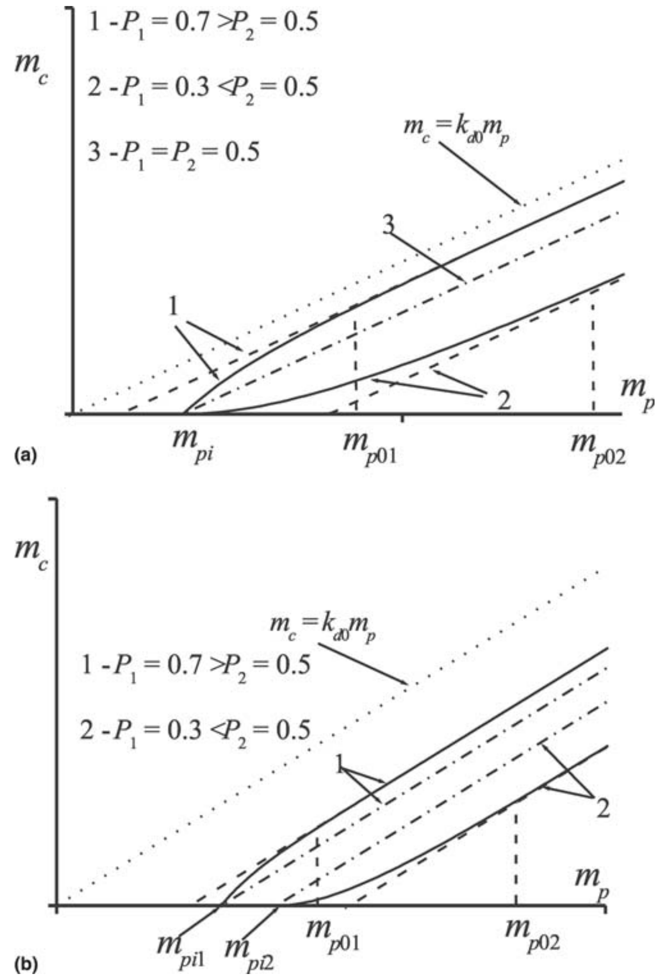

Fig. 3 Coating mass versus the mass of the powder spent for (a) identical and (b) different induction times. See the description in the text.

7. Deposition Efficiency

The next step is to determine the experimental deposition efficiency k_d as a ratio of the coating mass to the mass of the powder spent. At the build-up stage of spray, the derivative dm_c/dm_p is assumed to be k_{d0}, and it is called the theoretical deposition efficiency.

Figure 4 shows the dependence of the modeled deposition efficiency on the mass of the powder consumed. Curves 1 and 2 that were calculated by Eq 18, derived from Eq 10, correspond to cases 1 and 2 considered above at different induction times:

$$k_d = k_{d0}\left(1 - \frac{m_{pi}}{m_p}\right) + \frac{m_{c0} - k_{d0}(m_{p0} - m_{pi})}{m_p}\left\{1 - \exp\left[-\frac{3(m_p - m_{pi})}{m_{p0} - m_{pi}}\right]\right\} \qquad \text{(Eq 18)}$$

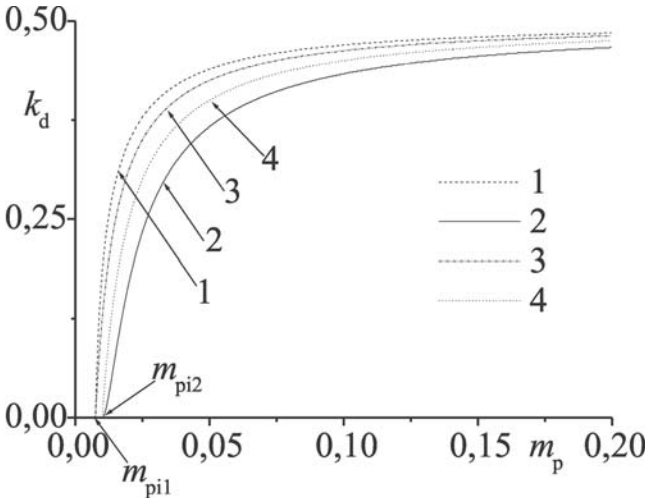

Fig. 4 Deposition efficiency versus the mass of the powder spent. See the description in the text.

Expression 18 is simplified to Eq 19 if the second component in Eq 18 is not taken into account (i.e., the materials of particles and the substrate are identical). Curves 3 and 4 are constructed by Eq 19, and correspond to cases 1 and 2.

$$k_d = \frac{m_c}{m_p} = \begin{cases} 0 & m_p < m_{pi} \\ k_{d0}\left(1 - \dfrac{m_{pi}}{m_p}\right) & m_p \geq m_{pi} \end{cases} \qquad \text{(Eq 19)}$$

Note that the influence of the substrate material on deposition kinetics is described with the help of the induction time and attachment probability on the free surface. Comparing curves 1 and 3, as well as curves 2 and 4, in Fig. 3 and 4, one can conclude that deviation of the probability of attachment on the free surface from that on the occupied surface affects the deposition kinetics at the initial part of coating growth. In the first approximation, only the induction time can be taken into account to explain the deposition kinetics, and the difference between the attachment probabilities on the free and occupied surfaces can be neglected. In Fig. 3, it corresponds to the replacement of the kinetics curve by a curve whose slope equals the theoretical deposition efficiency. However, as seen in Fig. 3, the "effective" induction time appears to be unequal to the "true" induction time. Because the experimental difference between the "effective" and "true" induction times can be expected to be insufficient, a further analysis will be performed using Eq 19.

For any number of particles spent from the feeder, there is always a certain error in determining the theoretical deposition efficiency. The larger the mass of the powder spent (spray time), the closer the deposition efficiency experimentally measured to the theoretical one:

$$\frac{|k_d - k_{d0}|}{k_{d0}} = \frac{m_{pi}}{m_p} \qquad \text{(Eq 20)}$$

It is seen from Eq 19 that the experimental value tends to zero because the number of particles spent tends to the number of particles that is necessary for surface activation, but not because the theoretical deposition efficiency is equal to zero. Thus, to explain the phenomenon correctly, it is important to know the induction time of deposition.

8. Measurement Procedures

Three methods of the experimental setup are commonly used to measure the deposition efficiency. Each method will be considered in detail.

8.1 Method A

The substrate is inserted into the two-phase jet fast enough, and then it stands still during a certain exposure time. After a proper exposure time, the mass of the powder spent from the feeder and the mass growth of the substrate are measured. In this case, the powder flow rate from the feeder is constant in time, as a rule (i.e., $\dot{m}_p = Const$). Thus, a relationship between the experimental and theoretical deposition efficiencies is determined according to the formula:

$$k_d = k_{d0}\left(1 - \frac{t_i}{t_{\exp}}\right) \qquad \text{(Eq 21)}$$

Note that the applicability of this method is restricted by time, because the coating increases nonuniformly. As a rule, it has a conical shape, which leads to variation in the conditions of particle attachment at the jet edges. This degrades the measurement accuracy of the experimental and theoretical deposition efficiencies. It can be expected that this method is less accurate compared with two others considered below.

8.2 Method B

A certain dose of the powder is placed into a cartridge. At the zero time ($t = 0$), the cartridge is pushed into the gas-dynamic path, so that a portion of the powder goes out as a dense cloud. Thus, a pulsed spray regimen with a rather high particle concentration near the substrate surface takes place. The substrate mass is determined before and after the exposure. In this case, Eq 19 can be applied. As with method A, and for the same reason, this method is restricted by the powder dose placed into the cartridge. However, it should be expected that a preliminary weighing of the powder portion would provide better accuracy than that in method A.

8.3 Method C

The substrate moves under the jet with a constant velocity. Therewith, it can cross the same place on the surface more than one time. In practice, the substrate velocity and the number of passes are adjusted to produce a sufficient coating mass for the measurement accuracy. Here, the flow rate of the powder spent from the feeder is also constant in time.

To derive an expression for deposition efficiency, the elementary area is considered as $dxdy$. Obviously, moving under the jet toward x, it is subjected to the impacts of particles during the time $h(y)/v_w$. Thus, the number of particles incident on the elementary area is $\dot{n}_p h(y)/v_w)dxdy$. If the number of incident particles is greater than the number necessary for surface activation, which is $n_{pi}dxdy$, then the number of particles attached to the elementary area $dxdy$ is $n_c dxdy = p_2(\dot{n}_p h(y)/v_w - n_{pi})dxdy$. Thus, the total number of particles spent is determined by the integral:

$$N_p = \int_0^L dx \int_{-H/2}^{+H/2} \frac{\dot{n}_p h(y)}{v_w} dy \quad \text{(Eq 22)}$$

Expression 22 shows that the number of particles spent during the feeder operation time L/v_w is $N_p = \dot{N}_p L/v_w$, where L is the length of the spray strip, taking into account the number of passes. By virtue of the simplicity of the physical interpretation, integration is not necessary.

The total number of particles attached is determined by the expression:

$$N_c = \int_0^L dx \int_{-y_m}^{+y_m} p_2(\dot{n}_p h(y)/v_w - n_i)dy \quad \text{(Eq 23)}$$

Here, the half-width of the deposited strip y_m is determined from the condition $n_{pi} = \dot{n}_p h(y_m)/v_w$ or $t_i = h(y_m)/v_w$.

The deposition efficiency measured in the experiment is determined by the ratio of Eq 23 and 22. In the case of a plane nozzle, the relations are easily integrated because the exposure time of the elementary area of the surface is independent of the coordinate y. The following expression is obtained for the deposition efficiency in this case:

$$k_d = k_{d0}\left(1 - \frac{m_{pi}v_w}{\dot{m}_p h}\right) = k_{d0}\left(1 - \frac{t_i v_w}{h}\right) \quad \text{(Eq 24)}$$

Note that, considering Eq 6, Eq 24 can be derived from Eq 19 and 21.

In the case of a conical nozzle, the expression is complicated because the size h is changed according to the formula:

$$h(y) = 2\sqrt{(D/2)^2 - y^2} \quad \text{(Eq 25)}$$

where D is the jet diameter and y is the coordinate perpendicular to the direction of substrate motion counted from the centerline of the coating strip.

In this case, the deposition efficiency is determined by the formula:

$$k_d = k_{d0}\frac{2}{\pi}(\arcsin\sqrt{1-\beta_i^2} - \beta_i\sqrt{1-\beta_i^2}), \quad \beta_i = \frac{t_i v_w}{D} \quad \text{(Eq 26)}$$

The function on the right side of Eq 26 can be replaced by a more simple approximate expression $(1-\beta_i)^{1.35}$. Therefore, an extended (more common) formula can be accepted for the deposition efficiency, where ω is equal to 1 or 1.35 for the rectangular or round nozzle cross sections, respectively:

$$k_d = k_{d0}\left(1 - \frac{m_{pi}v_w}{\dot{m}_p h}\right)^{\omega} \quad \text{(Eq 27)}$$

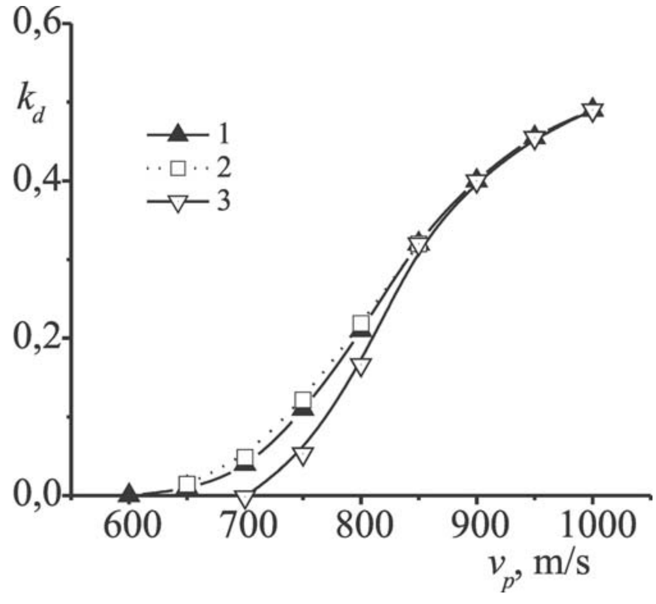

Fig. 5 Deposition efficiency measured in the experiment and the corrected value: experimental values (1), corrected values (2), and the values that would be obtained in an experiment with a weight dose of 17 mg (3).

In the case of a round nozzle, the diameter of the outlet section is used instead of h. Because the value in brackets is smaller than unity, the experimental deposition efficiency in the case of the nozzle with a rectangular outlet is closer to the theoretical value.

9. Correction of the Deposition Efficiency

Using the data presented in Fig. 2, one can estimate the powder mass that will be spent for surface activation and first layer formation. In the experiments on determining deposition efficiency, method B was used, where the powder weight dose was equal to 100 mg, which yielded a specific mass of about 3.3 kg/m^2. Substituting the values found into Eq 19, a correction can be found of the theoretical deposition efficiency for the data obtained in the experiment (Ref 2) (Fig. 5). It is seen that the dose with a weight of 100 mg is sufficient for obtaining reliable experimental data. Nevertheless, if the weight of the dose is much smaller than 100 mg (e.g., Fig. 5 shows the data that would be obtained with a dose of 17 mg), the differences would be fairly noticeable; for instance, the critical velocity would be 700 m/s rather than the real value of 600 m/s.

10. Discussion

Using the theory of deposition kinetics that was described above, another procedure can be proposed for the experimental determination of the deposition efficiency. Namely, it is necessary to measure the coating mass during deposition twice. First, the coating mass is measured as usual, but then the coating mass is measured with the increasing mass of the powder spent from the feeder. Then, the theoretical deposition efficiency is determined directly using the formula:

$$k_{d0} \cong \frac{m_{c2} - m_{c1}}{m_{p2} - m_{p1}} \quad \text{(Eq 28)}$$

Moreover, it is possible to obtain an "effective" induction time using this procedure. For this purpose, it is necessary to find a point of intersection between the x axis and the line constructed through two experimental points obtained: (m_{p1},m_{c1}) and (m_{p2},m_{c2}). This intersection point yields the "effective" induction mass (induction time). Obviously, for a detailed insight into the deposition kinetics, the deposition efficiency should be measured at many points.

11. Conclusions

The article considers the methods of measuring the deposition efficiency and evaluating the measurement accuracy in cold spray. The authors place the primary emphasis for estimating the effect of the delay time on the accuracy of the measurement of deposition efficiency. It is shown that the values experimentally observed are affected by experimental conditions, such as the velocity of substrate motion, the number of passes, the mass of the single powder portion, and the exposure time of a given surface section. If the parameters are chosen incorrectly, erosion is observed instead of deposition, and one may wrongly conclude that there is no cold spray produced under the parameters considered (i.e., at the impact velocity and the particle size for the materials chosen for the substrate and particles). The present article suggests relations that allow one to correct the results of the deposition efficiency determined experimentally and to avoid mistakes in interpreting the data obtained.

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