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Determination of the parameters of the process of gas–dynamic deposition of metallic coatings

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A V SHKODKIN and A I KASHIRIN
Obninsk Centre for Powder Spraying

In industrial practice, special attention is given to the introduction of the new technology of gas-dynamic deposition of metallic coatings using DIMET equipment.[1–3] In this case, the sprayed particles are secured to the substrate utilising their kinetic energy supplied to the particles by the supersonic airflow. According to the experimental results, the efficiency of the process of gas-dynamic spraying is strongly affected by the mutual geometry of the accelerating airflow and the treated surface.

The effect of the angle between the vector of the velocity of the particle and the normal to the surface on the efficiency of bonding metallic particles

It is well-known that the bonding of the particles on the smooth surface takes place when the critical velocity of the particles is exceeded. This velocity depends on the thermal and mechanical properties of the materials of the particles and the barrier.[4,5] The concept of the critical velocity implicitly assumes that the vector of the velocity of the particle in interaction with the barrier is directed normal to the surface of the barrier.

However, in the gas-dynamic method, it is necessary to use the acceleration of the particles in the flow of the carrier gas which, after discharge from the nozzle, is decelerated and expands, mixing with the surrounding gas medium, and is also deflected by the barrier spreading along its surface. These changes in the movement of the gas should result unavoidably in the change of the vector of the velocity of the particles. This may result in the interaction of the particles with the barrier under the angle to the surface differing from the normal.

If the component of the vector of the velocity of the particle, normal to the surface of the barrier, increases the intensity of interaction, resulting in the increase of the degree of deformation of the particle and the barrier, the tangential component of the velocity, which is parallel to the surface of the barrier, leads to the formation of shear stresses and strains in the contact zone, which may cause separation of fracture of the particle. The ratio of these components of the velocity influences the bonding of the particle to the barrier.

Since the variation of the angle between the vector of the velocity of the particle and the normal to the surface may result in changes of the efficiency of deposition of particles, it is of practical interest to examine this relationship.

The processes taking place during the collision of the particle with the barrier under angle will be examined. The process of deformation and bonding of the particle, associated with the component of the velocity, normal to the surface, increases the contact area and bonding strength and the deformation process, associated with the tangential component of the velocity, is directed to displacement of the particle in relation to the contact zone. In this case, a decrease of the strength of the crystal lattice as a result of the generation of heat in the area adjacent to the contact point may result in tensile loading (shear deformation along the surface of the barrier) of the section with reduced strength. Depending on the ratio of the normal and tangential components of the velocity, the strength of the material and its temperature dependence, the interaction may lead to different results.

If the normal component of the velocity is high and the tangential component is small, the particle is bonded to the substrate. The degree of deformation and, correspondingly, the bonding strength are determined by the value of the normal component of the velocity.

If the tangential component of the velocity is high, the force of bonding of the particle with the substrate in the contact spot in the process of formation of the contact may prove to be insufficient for preventing its displacement along the surface of the base. In this case, the partially bonded particle should separate from the substrate. As the strength and melting point of the material of the particle increase, the probability of this taking place also increases. With an increase of the size of the particle, this probability increases together with the probability of separation.

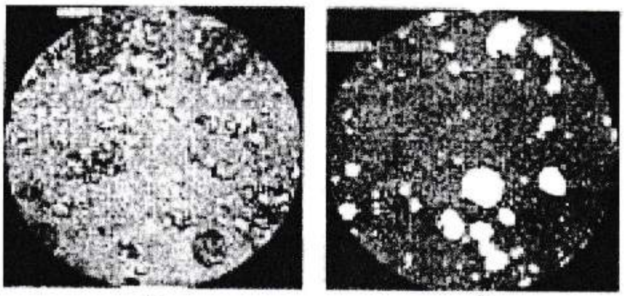
Finally, if the tangential component of the velocity is large and the melting point of the particle material is low, the local decrease of the strength in the vicinity of the contact zone, associated with the generation of heat during deformation, may result in fracture of the partially secured particles. This takes place if the bonding strength of the particle with the barrier in the contact spot is higher than the strength of the material of the particle in the vicinity of the contact zone. In this case, a thin layer of the material of the particle remains on the surface of the substrate.

The examined variants of interaction are found in the effect of the flow of the poly disperse powder of aluminium with a nonuniform velocity on the surface of a glass barrier.

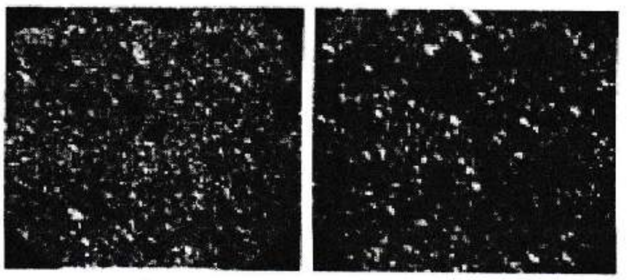
Figure 1 shows the result of interaction of aluminium particles with the glass barrier in the direction of the flow the particle normal to the surface. The deposition process was realised using a poly-dispersion powder of aluminium with the modal size of the spherical particles of 20 μm. The velocity of air on the axis of the flow was approximately 600 m/s.

The surface of the gas at the top shows the bonded particles with different degrees of deformation and the size of 10–50 μm, at the bottom these particles are indicated by large white spots. There are also a large number of indentations with the size of 1–5 μm. These maybe both the bonded small particles and also traces left by the larger partially bonded particles which had separated under the effect of the tangential component of velocity.

When the axis of the flow is under an angle in relation to the surface of the glass, the form of the traces changes. The result of interaction of the aluminium particles with the glass substrate with the flow of the particle under the angle of 45° to the surface is shown in Fig. 2. In the impact of the aluminium particles on the surface of the glass under this angle, there are no bonded particles. Both sides of the glass show only traces of the particles which are mostly (especially with the increase of the size of the trace) elongated in the direction of travel of the particles. This means that the softening of the particle material in the contact zone results in fracture of the particles with the formation of a trace on the surface of the barrier.



1 *The deposition of aluminium particles on glass:* ***a)*** *the view of the glass from the top of the side of the flow;* ***b)*** *the side from the direction against of the flow.*



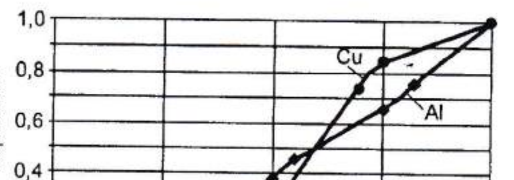
2 *The deposition of aluminium particles on glass under an angle of 45°:* ***a, b)*** *Fig. 1.*

This phenomenon, which is sometimes referred to as spreading, takes place in the treatment of the surface under any angle with large slightly deformed particles of low-melting metals, such as a zinc or tin. When the size of the particles is larger than 50 μm, the surface of the barrier is characterised by the high rate of formation of a thin layer of the material of the particles but there are no bonded deformed particles.

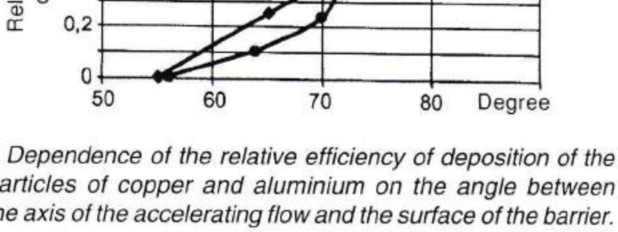
In contrast to the interaction with the glass (in which only the particle is deformed and the barrier does not show the formation of residual strain and only the formation of internal cracks) in interaction of the metallic particles with the surface of the metallic barrier the mutual deformation of the particles and the barrier takes place. Naturally, the size of the crater, formed on the surface of the barrier during the collision with the particle is determined by the ratio of the hardness of the materials of the particle and the barrier and by the strength of the pulse of the particle. It is important to note that the formation of the crater on the surface of the barrier should reduce the strength of the effect of the tangential component of the pulse of the particle, directed to separation of the particle, because the interaction of the particle takes place under the right angle in relation to the actual cross-section of the surface (Fig. 3). Naturally, these angles are determined by the ratio of the size of the particle to the depth of the crater.

However, in the case of a large deviation of the vector of the velocity of the particle from the normal to the surface of the barrier, the value of strain in the particle and the barrier must decrease. This results in a marked change of the efficiency of deposition.

Figure 4 shows the dependence of the relative efficiency of deposition of the particles of copper and aluminium



3 *The diagram of interaction of the particle with the surface in the absence* ***(a)*** *and in the presence* ***(b)*** *of a crater on the surface of the barrier.*



4 *Dependence of the relative efficiency of deposition of the particles of copper and aluminium on the angle between the axis of the accelerating flow and the surface of the barrier.*

of comparable sizes on the surface of the aluminium sheet on the angle between the axis of the accelerating flow and of the surface of the barrier. The effect of small deviations from the normal on the efficiency of bonding of the particles is smaller than the efficiency of bonding of the latter particles of aluminium. However, with increase of the deviation from the normal, the ratio changes. Evidently, the bonding of the smaller particles takes place with a lower degree of deformation of the particle and the substrate.

Since the increase of the depth of the crater on the surface of the barrier results in bonding of the particle moving under the angle to the plane of the surface of the barrier, the formation of large craters on the surface may result in an increase of the efficiency of deposition of metallic particles. This should be carried out by preliminary treatment of the surface of the barrier.

To ensure the constant formation of the large craters in the process of growth of the layer during the deposition of the particles, the deposition process should be accompanied by partial erosion of the surface as a result of the introduction of abrasive (ceramic) particles into the flow.

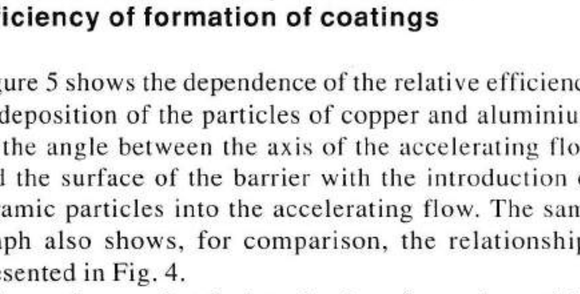
The effect of ceramic particles on the efficiency of formation of coatings

Figure 5 shows the dependence of the relative efficiency of deposition of the particles of copper and aluminium on the angle between the axis of the accelerating flow and the surface of the barrier with the introduction of ceramic particles into the accelerating flow. The same graph also shows, for comparison, the relationships presented in Fig. 4.

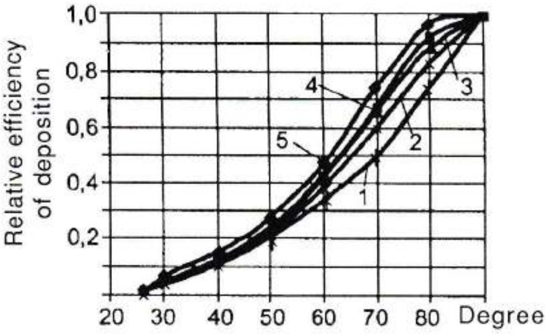
It may be seen that the introduction of ceramic particles into the flow widens the range of the angles of deposition for both the particles of aluminium and copper, and the difference in the dependence of the relative efficiency of the position on the angle for the particles of different materials is greatly balanced.

However, it may be expected that the presence of craters on the surface should have a different effect on the efficiency of bonding of the particles of both different hardness and different size.

The increase of the temperature of the accelerating flow reduces the hardness of the particles moving in the flow. In this case, the general efficiency of deposition of the particles increases, mainly as a result of the large particles taking part in the deposition process. The increase of the flow temperature should result in the increase of the efficiency of deposition in the entire range of the angles between the axis of the accelerating flow and the barrier, but it should also result in a smaller increase of the contribution of the large particles with the increase of the angle of deviation.



5 *The dependence of the relative efficiency of deposition of copper and aluminium particles on the angle between the axis of the accelerating flow and the surface of the barrier in introduction of ceramic particles into the flow: 1) A1+ ceramics; 2) Cu + ceramics.*



6 *The dependence of the relative efficiency of deposition of copper particles (with the ceramic particles introduced into the flow) on the aluminium barrier of the angle between the axis of the accelerating flow and the surface of the barrier for different temperatures of the flow (T 5 > T 4 > T 3 > T2> T 1).*

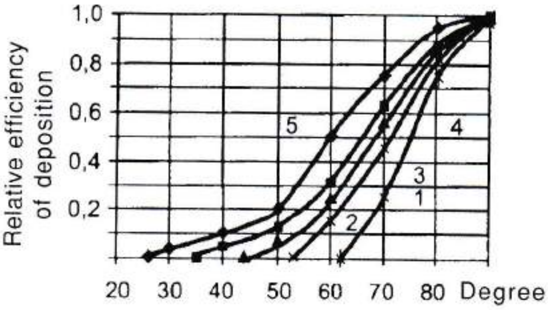
Figure 6 shows the dependence of the relative efficiency of deposition of the copper particles of the aluminium sheet with the variation of the deposition angle. As in the previous case, ceramic particles were introduced into the flow of the copper particles. The curves 1–5 correspond to different temperatures of the accelerating gas from T1 to T5.

The increase of the flow temperature increases the relative efficiency of deposition of the particles in the range of the angle of deviation of 30–90°. At the same time, the largest the lattice increase takes place in the range of 60–90°.

With the change in the dimensions of the craters, the effect of the craters on the efficiency of deposition should also change. The increase of the depth of the craters on the surface of the barrier results in the bonding of the particles, moving under the angle to the plane of the surface of the barrier. As the depth of the craters increases, the efficiency of bonding of relatively large particles increases and, on the other hand, as the size of the crater decreases, the particle size becomes smaller. The size of the craters on the surface of the growing coating may be changed by changing the dispersion of the ceramic particles added to the flow.

Evidently, the dimensions of the craters, generated by the ceramic particles in impact with the barrier, depend on the hardness of the process material. In the initial stage of formation of the coating, the dimensions of the craters are determined by the hardness of the barrier material.

Figure 7 shows the dependence of the relative efficiency of deposition of the copper particles on the surface of a steel bar, coated with the layer of chromium, with the



7 *The dependence of the relative efficiency of deposition of copper particles (with the ceramic particles introduced into the flow) of the barrier produced from a chromium-plated steel on the angle between the axis of the accelerating flow and the surface of the barrier for different temperatures of the flow (T 5 > T 4 > T 3 > T2> T 1).*

addition of ceramic particles into the flow. The individual curves also correspond to different temperatures of the accelerating gas.

If the deposition of copper particles of the surface of aluminium at all examined temperatures of the flow is interrupted only when the angle is smaller than 25°, then on the surface of chromium this angle depends on the temperature of the accelerating gas flow. Within the framework of the examined approach, this may be explained as follows.

The size of the craters generated by the ceramic particles and the surface of the harder chromium is considerably smaller in comparison with the size of the surface of aluminium. Therefore, in oblique incidence in the initial stage of deposition (i.e. in the stage of deposition directly on the surface of the substrate), these craters result in bonding of only fine particles. The probability of deposition increases as the hardness of the particles decreases. The hardness depends on the temperature of these particles. Consequently, the angle indicating the start of bonding of the metallic particles (critical angle) depends on the flow temperature. After bonding of the fine particles, further formation of the craters and deposition of the particles already takes place on the material the coating. Therefore, under the angles of incidence of the particles, greatly differing from the critical angle, the form of the dependence of the relative efficiency of deposition of the metallic particles on the angle of interaction of the flow with the barrier becomes similar to that obtained for the aluminium substrate.

In all cases, the efficiency of deposition of the metallic particles is maximum when the vector of the velocity is normal to the surface of the barrier, and the deviation of the vector of velocity from the normal results in the increase of the efficiency of deposition with the development of surface roughness of the barrier.

It may be expected that in the ideal case of monodispersion particles with the same vector of velocity, the dependence of the efficiency of deposition on the angle between the vector of the velocity of the particles and the plane of the barrier is of the threshold nature. For the actual process of gas-dynamic deposition of the metallic particles, this dependence is determined by the integration of the distribution of the particles in respect of the size, velocity and the angles of the velocity vector.

Conclusions

1 The process of deposition of the metallic particles by the gas–dynamic method is strongly affected by the value of the angle between the vector of the velocity of the particles and of the plane of the barrier. The higher values of the momentum of the particles result in bonding of the particles in deposition under the angles close to the normal to the surface, and prevent bonding in the case of a large deviation from the normal.
2 The introduction of a certain amount of ceramic particles into the accelerating gas flow together with the metal particles reduces the dependence of the efficiency of deposition of the metal particles on the angle and eliminates the difference between these relationships for the particles with different values of the momentum.
3 In the practical application of the method of gas–dynamic spraying in different deposition conditions, it is possible to realise the relationships of different type, but in all cases the deviation of the axis of the flow from the normal to the surface of the barrier by more than 30–40° results in a large decrease of the efficiency of deposition of the particles.

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