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Metal Particle Deposition Stimulation by Surface Abrasive Treatment in Gas Dynamic Spraying

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Processes of supersonic blasting for producing thin metal coatings and of cold spray for producing thick coatings by solid metal particle jets are based on the particle plastic deformation. Extensive plastic deformation of accelerated metal particles at the surface roughness was observed. The possibility of stimulation of metal particle deposition by the substrate and coating blasting by ceramic particles was experimentally confirmed. The process of thick coating creation by the mixed metal-ceramic powder supersonic jet is presented.

Keywords ceramic powder, gas dynamic spray, metal coatings, metal powder

1. Introduction

It is well known that gas dynamic sprayed metal particles must undergo an extensive deformation to be deposited at the substrate surface. The cold spray process produces particle acceleration above critical velocity to cause the necessary deformation (Ref 1, 2).

The impact below critical velocity only causes the densification and abrasion of the substrate (Ref 1). According to Alkhimov et al. (Ref 2), the deposition efficiency of the order of 10^{-3} to 10^{-4} may be observed at velocities below critical value. However, the process of supersonic blasting (Ref 3), known for almost 50 years, produces a thin coating at the surface treated by the supersonic jet of metal particles.

Rocheville (Ref 3) declared that at stagnation air pressure of 1 MPa accelerated in the supersonic nozzle "powder adheres to the surface of the workpiece, partly by entering the pores of the surface where it is firmly retained thereon. A thin layer of a few micrometers thickness forms on the part and is uniform over the entire surface. This occurs because the coating will build up over the surface of the part, but will not build up upon itself."

The aim of this article is to discuss the difference between the supersonic blasting (Ref 3) and cold spray (Ref 1, 2, 4) processes and to demonstrate the possibility of creating a thick coating instead of a thin one at the spraying conditions of supersonic blasting.

2. Comparison of Supersonic Blasting and Cold Spraying

The main possible reason for the difference between the supersonic blasting (Ref 3) and cold spray (Ref 1, 2, 4) processes is the difference in particle velocities. The use of de Laval nozzles in both methods produces particle acceleration. However, depending on the carrier gas velocity and density, particles size, and nozzle profile and length, the maximum velocity may be both above and below the value of critical velocity. Declared necessary stagnation jet pressure for cold spray is 1 to 3 MPa (Ref 4), while supersonic blasting is produced at stagnation pressure of 1 MPa (Ref 3). So, at the same accelerating gas velocity, the gas densities and, accordingly, drag forces, proportional to the gas density, will differ for the processes in question.

The intensive research of cold spray in the last decade revealed the main features of this process. Particle bonding in the cold spray process is due to the high rate deformation of the particle and the substrate followed by the adiabatic shear instability (Ref 1). Large deformations caused by the jetting of both substrate and particle materials from the crater created promotes bonding of the particle to the substrate (Ref 5). Both deposition efficiency and fraction of bonded area increase drastically by increasing particle velocity over the critical value (Ref 6). On the other side, the process of thin coating formation or supersonic blasting at velocities below critical value is partly related to powder entering the pores of the surface where it is firmly retained thereon. As declared in (Ref 3) a thin adherent coating layer will build up over the surface of the substrate, but will not build up on itself. To separate surface abrasion and thin coating creation at velocities below critical value, surface roughness should be taken into consideration.

Shear flow at the interface causes kinetic energy dissipation, reducing the rebound force, and produces close surface connection to induce short-range force influence. The value of extensive plastic deformation following the shear flow is obviously dependent on the material hardness and the value of the contact pressure. To cause shear flow on impact, the material may be softened by the thermal softening or the contact pressure has to be enlarged by the impact force rise or by reduction of the impact contact area.

The cold spray process utilizes both the impact force enlargement by the rise of particle velocities above critical value and the rise of the contact interface temperature as a result of adiabatic heating.

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Table 1 Mass distribution of particles

	Mass distribution, %			
	1-10 μm	10-20 μm	20-30 μm	30-50 μm
Al	12	21	24	43
Cu	8	44	38	10
Al_2O_3	8	72	18	2

However, at velocities below critical value the impact force is insufficient to cause the shear flow. It has been supposed that the necessary impact pressure may be obtained by reducing the contact interface area in this case. Substitution of multiple peaks instead of the flat substrate surface may cause the extensive plastic deformation at the peaks. A rough surface may be considered as multiple peaks if the roughness scale is less than the particle dimensions.

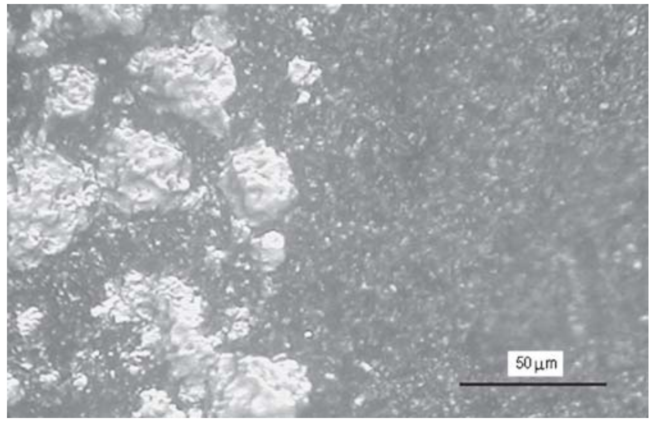

Fig. 1 View of the deposited Al particles at the rough carbon steel surface. Left side of substrate was prepared by ceramic particle jet while right side was masked and remained smooth.

3. Experimental

To follow the process of supersonic blasting conditions and to reduce drag force substantially, air stagnation pressure of 0.5 MPa was chosen for the experimental procedures.

The experimental procedure included aluminum (Al) and copper (Cu) particles spraying to the smooth and rough surfaces of different substrates.

Ceramic particles of aluminum oxide were used to produce surface roughness. The Al powder and Cu powder were used for spraying experiments. All powders have a particle size range from 1 to 50 μm. The powder mass distributions are presented in Table 1.

Samples of carbon steel and Al were used as substrate. Certain parts of the surfaces of the samples were blasted by the jet of ceramic particles to produce roughness. To avoid the possible activation effects, some of the prepared substrate samples were kept 1 h in water and 48 h in the ambient atmosphere.

To produce the supersonic jet of particles, commercial gas dynamic spraying equipment DYMET (Obninsk Center for Powder Spraying, Russia) was used. It includes a spray gun with an air heater and supersonic nozzle, two switched powder feeders, and a control unit (Ref 7).

The supersonic nozzle used has throat diameter of 2.5 mm, exit diameter of 5 mm, and diverging part length of 130 mm. The powder injection point is located at the diverging part of the nozzle 10 mm behind the throat. This nozzle produces a supersonic jet with a total airflow rate of about 0.3 m^3/min at stagnation pressure of 0.5 MPa.

To investigate the possibility of particle deposition at the subsonic jet velocities in some cases, the supersonic nozzle has been modified by replacing the diverging nozzle part after the powder injection point by long cylinder tubes. The cylinder tubes with a length of 250 mm and internal diameters of 8 and 6.5 mm produced jet velocities 130 to 180 m/s and 200 to 250 m/s, respectively, at stagnation air temperatures 300 to 900 K.

Total powder feed rate of 0.4 g/s and 10 mm distance from the nozzle exit to the substrate surface were kept in the experiments. The traversing speed of spray gun with respect to substrate was maintained in the range of 1 to 3 cm/s.

4. Results

The supersonic blasting of carbon steel and Al samples by Al and Cu powder jets was investigated at the first experimental step. The jets were produced by the supersonic nozzle at air stagnation pressure 0.5 MPa and various stagnation temperatures. By the nozzle motion along the substrate surface, both smooth and preliminarily prepared rough surfaces were treated by the metal particle jet.

At the jet stagnation temperature 300 K, metal particles polished the smooth surface of a carbon steel substrate, but the deposition of both Al and Cu was observed at the rough surface. A view of deposited Al particles is presented in Fig. 1. Only slight erosion was observed at the Al substrate, and preliminarily prepared roughness at the surface of the Al sample was smoothed.

At the jet stagnation temperature 500 K, only slight erosion of the Al substrate surface was observed without any particle deposition. On the carbon steel substrate, Al and Cu particles quickly formed a thin coating at the rough surface, and some Al particle deposition at the smooth surface was observed.

At the jet stagnation temperature 600 K, Al particles began to deposit at the rough parts of the aluminum substrate surface, but Cu particle deposition on aluminum was not observed. A thin layer of Al was formed both on the rough and smooth surfaces of the carbon steel substrate, but the layer thickness did not grow. Copper particles deposited only on the rough parts of the steel substrate, produced a thin coating layer, and the Cu layer thickness also did not grow.

The difference of results observed for carbon steel and Al substrates indicates that the heat conductivity of substrate becomes significant, and the particles plastic deformation process is not adiabatic at the jet velocities used (compared with the high-rate adiabatic process at cold spray, Ref 1).

The results observed confirm the influence of surface roughness on the deposition efficiency of soft metal particles. After the entire rough substrate surface is filled with the striking metal particles, it will become smooth and further deposition will cease. The rise of the heat sink to the surface also prevents particle deposition by limiting the plastic deformation at the contact interface.

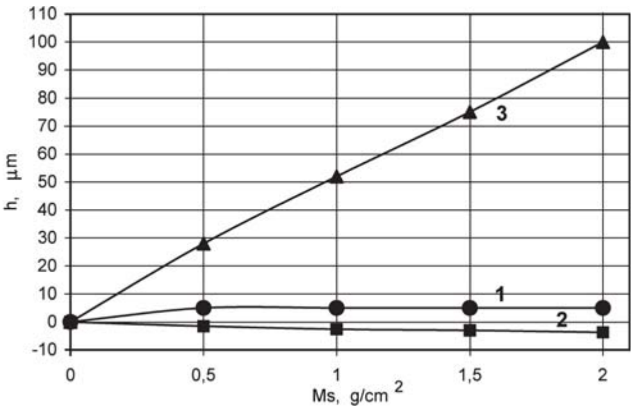

Fig. 2 Substrate thickness change produced by (1) the Al particle jet, (2) ceramic particle jet, and (3) alternated Al-particle/ceramic-particle jets as a function of sprayed powder amount

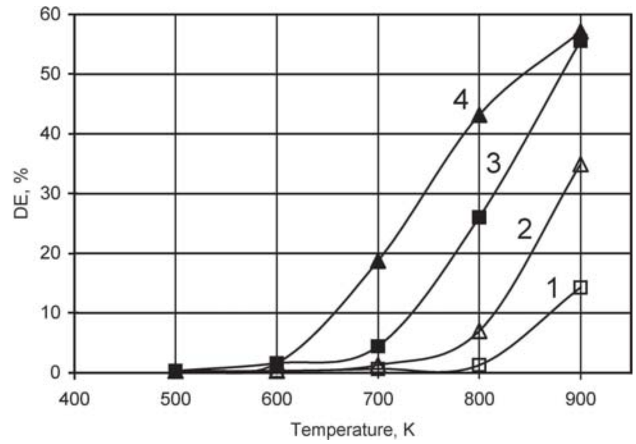

Fig. 3 (1) and (2) Deposition efficiencies of aluminum and (3) and (4) mixed aluminum-ceramic powders at different air stagnation temperatures and velocities (1) and (3) 130 to 180 m/s and (2) and (4) 200 to 250 m/s

To reveal the possibility of further deposition onto the thin coating layer under the same circumstances, alternated Al-particle/ceramic-particle spraying was tested.

Two wide crossed lines were sprayed alternately to the surface of a sand-blasted steel sample by jets with accelerating air stagnation temperature 600 K. The first line was sprayed with the jet of Al particles, and the second, perpendicular line was sprayed with the jet of ceramic particles. The coating thickness was measured at the lines and at the center of their intersection. The thick coating growth was observed at the line intersection, while only a smooth thin Al layer developed at the Al particle jet line, and steel erosion developed at the ceramic particle jet line.

Figure 2 demonstrates the results of thickness development for (1) aluminum particle jet line, (2) ceramic particle jet line, and (3) center of line intersection.

Just as in the former experiment, attention was paid to the problem of surface activation. Substrate surface processing by multiple particle impacts has formerly been discussed as a surface activation process for cold spray (Ref 2, 8). In the case of surface activation, one should observe the time dependence of the activation process. The results obtained by alternated crossed Al particle jet and ceramic particle jet spray did not reveal any influence of the time delay between the jet runs. For the case of the activation process, the linear dependence of Al jet sprayed layer thickness on the sprayed powder amount must be obtained. However, the observed result shows that the Al coating does not build up on itself. It indicates that the particle velocities did not exceed the value of critical velocity, and the activation process was not efficient for the process discussed.

For the sake of statistically uniform and continuous surface treatment by metal and ceramic particles, the mixed metal-particle/ceramic-particle jet instead of separate jets alternated runs may be used. The use of mixed jet will also shorten the time intervals between the ceramic and metal particle impacts and can lead to local increase of surface temperature at the impact point.

The temperature increase reduces material resistance to shear flow. The heating of particle and substrate materials will reduce the value of impact pressure required for intensive plastic deformation to occur. The particle and surface preheating improves the deposition efficiency. Well-heated Al particles may be deposited far below the critical velocity for cold spray.

The deposition efficiency of Al powder and mixed Al-ceramic powder with ceramic content of 28% at different jet velocities and various accelerating air stagnation temperatures is shown in Fig. 3. For this experiment, long cylindrical tubes were used instead of diverging cone downstream of the powder injection point of the nozzle. The subsonic airflow was set inside these tubes with calculated velocities of about 130 to 180 m/s or 200 to 250 m/s and calculated temperature of about stagnation temperature. The length of elongating tubes was chosen so as to be long enough to produce particle velocity and temperature close to that of the airflow.

It is clearly seen that the metal particle softening caused by higher temperatures significantly increases the deposition efficiency even at subsonic jet velocities. The coating surface treatment by ceramic particles in the mixed jet improves the deposition efficiency of metal particles.

However, metal particle deformation at high jet temperatures in this case is very small because of low velocity and intensive heat sink at the contact interface. The porosity of an Al coating obtained at jet temperatures above 800 K is about 30%, and, in contrast to the liquid particle spray, the coating ultimate tensile strength is less than 10 MPa.

The coating quality improves substantially at the jet supersonic velocities obtained with a de Laval nozzle. The higher velocity and lower temperature of the mixed Al-ceramic particle jet produces a dense Al coating with small inclusions of ceramic particles. The cross section of the coating obtained with the supersonic jet at air stagnation pressure 0.5 MPa and stagnation temperature 700 K is presented in Fig. 4.

Only a small portion of ceramic particles embeds the coating. Most of the ceramic particles press the coating and leave the surface. High hardness and low heat conductivity of ceramic particles cause the most impact energy dissipation to occur in the top layer of the formed coating. The proportion of metal to ceramic powders in the jet determines the coating properties and metal particle deposition efficiency.

Figure 5 shows the Al-ceramic powder mixture deposition efficiency dependencies on the ceramic powder mass content at different stagnation temperatures of accelerating air supersonic jet.

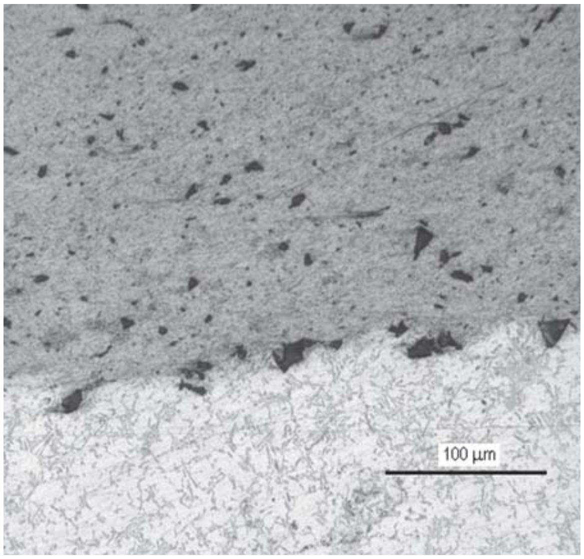

Fig. 4 The cross section of aluminum coating with ceramic inclusions at the carbon steel substrate. Powder mixture sprayed contained 28% wt. of ceramics.

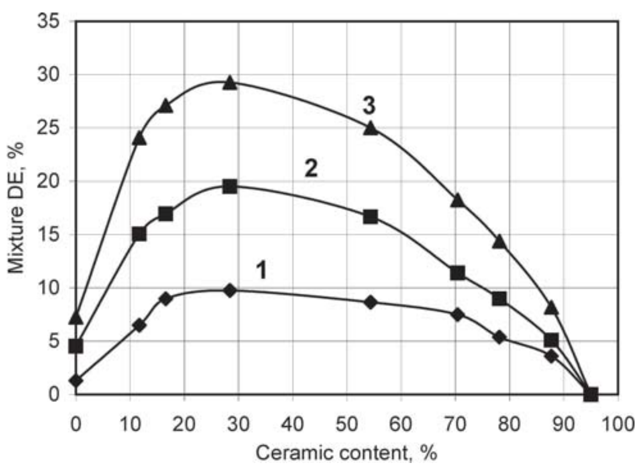

Fig. 5 The mixture deposition efficiency dependencies on the mass ceramic content in Al-ceramic powder mixture at different air stagnation temperatures (1, 600 K; 2, 700 K; 3, 800 K) of the supersonic jet

The pure metal deposition efficiency rises both with temperature and ceramic content in the powder mixture. However, the increase of the ceramic particle portion causes the decrease of total mixture deposition efficiency.

5. Discussion

The comparison of cold spray and supersonic blasting processes shows that they have the same basis, and differ only by the jet velocities used. Both use the solid metal particles plastic deformation to produce coating. Because both processes use gas flow to accelerate the particles, they may be defined as gas dynamic processes.

Supersonic blasting is restricted to use of soft metal powders and rough substrates with low heat conductivity to deposit thin coatings. Cold spray uses the particle and substrate high deformation rate followed by the adiabatic shear instability and needs the high stagnation pressures to exceed the jet critical velocity.

The experiments showed that, at the same spray settings, metal particles may be deposited at the rough surface and do not deposit at the smooth surface. This result confirms the suggestion of impact pressure increase at the peaks of the substrate roughness. At the same time, the influence of heat conductivity of substrate indicates that the deposition process at low velocities is not adiabatic.

The alternating runs of surface abrasion and thin coating deposition distinctly show the possibility of thick coating formation by increasing the small-scale roughness of the sprayed coating. Due to random distribution of ceramic and metal particles in the jet and random location of the impact points, the thick coating growth becomes statistically dependent. The change of ceramic particle jet density will cause the change of metal particles deposition efficiency.

The statistically continuous surface treatment by ceramic particles and coating creation by deposited metal particles is produced by mixed ceramic-powder/metal-powder supersonic jet. The increase of ceramic content in the mixture causes the rise of pure metal deposition efficiency. However, because most of the ceramic particles do not enter into the coating and bounce from the surface, the total mixture deposition efficiency reaches maximum value and then reduces with the rise of ceramic content. The process of erosion of a coating by ceramic particles will also reduce the deposition efficiency.

Both impact velocity and contact interface temperature influence the deposition efficiency. However, the extent of particle deformation is rather low at high jet temperatures and subsonic velocity. The coating densification by the ceramic particle impacts improves coating quality. To produce dense coatings with a reasonable value of mixture deposition efficiency, the optimal ratio of ceramic to metal powder in supersonic jet has to be used.

The process of thick coating creation by the mixed ceramic-metal powder supersonic jet is called dynamic metallization (DYMET) (Ref 9, 10). Wide industrial use of this process is obviously restricted by relatively low deposition efficiency and rate. However, due to low requirements, it can be widely used in repair and production of specific high cost products.

6. Conclusions

The substrate surface roughness may stimulate metal coating deposition in the gas dynamic spraying process at relatively low accelerating air stagnation pressures. Substrate surface smoothing and heat sink to the coating prevent the coating thickness rise.

To produce thick coatings instead of thin ones at particle velocities below critical value, mixed ceramic-powder/metal-powder supersonic jets have to be used. The rise of ceramic content in the mixture causes the increase of mixture deposition efficiency followed by the total efficiency decrease with the decrease of metal content.

Further investigation is necessary to obtain quantitative evaluations of the particle impact statistics based process, but the results presented indicate the possibility of the common approach to the supersonic blasting and cold spray processes.

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