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: *metal coatings, gas dynamic spray, metal powder, ceramic powder.*

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 [1, 2].

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

Rocheville [3] declared, that at stagnation air pressure of 1 MPa accelerated in the supersonic nozzle «powder adheres to the surface of workpiece, partly by entering the pores of the surface where it is firmly retained thereon. A thin layer of around 0.0001 inch 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 paper is to discuss the difference between the supersonic blasting [3] and cold spray [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.

Gas dynamic spraying conditions and experimental setup

The main possible reason of the difference between the supersonic blasting [3] and cold spray [1,2,4] processes is the difference in particle velocities. The use of de Laval nozzles in both methods produces particle acceleration. But depending on the carrier gas velocity and density, particles size, 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 – 3 MPa [4] while supersonic blasting is produced at stagnation pressure of 1 MPa [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. To follow the process of supersonic blasting conditions and to reduce drag force substantially the air stagnation pressure of 0.5 MPa was chosen for the experimental procedures.

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 particle and substrate's high rate deformation followed by the adiabatic shear instability [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 [5]. Both deposition efficiency and fraction of bonded area increase drastically by increasing particle velocity over the critical value [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 [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 followed 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.

But 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 then the particle dimensions.

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

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

Table 1. Mass distribution of particles (%).

	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

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

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

The supersonic nozzle with diverging part length of 130 mm and critical section area of 5 mm^2 produces a supersonic jet with a total air flow rate of about 0.3 m^3/min at stagnation pressure of 0.5 MPa. The nozzle exit section produces sprayed line with a width of 5 mm. The powder is injected into the air jet at the diverging part of the nozzle.

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 by long cylinder tubes. The cylinder tubes with a length of 250 mm and internal diameters of 8 mm and 6.5 mm produced jet velocities 130 – 180 m/s and 200 – 250 m/s respectively at stagnation air temperatures 300 ^oK – 900 ^oK.

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.

Experimental results

The supersonic blasting of carbon steel and aluminum samples by aluminum and copper 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 ^{o} K metal particles polished the smooth surface of a carbon steel substrate, but the deposition of both aluminum and copper was observed at the rough surface. The view of deposited aluminum particles is presented at Figure 1. Only slight erosion was observed at the aluminum substrate and preliminarily prepared roughness at the aluminum sample's surface was smoothed.

At the jet stagnation temperature 500 ^{o} K only slight erosion of the aluminum substrate surface still observed without any particle deposition. On the carbon steel substrate aluminum and copper particles quickly form a thin coating at the rough surface, and some aluminum particles depositing at the smooth surface was observed.

At the jet stagnation temperature 600 ^{o} K aluminum particles begin to deposit at the rough parts of the aluminum substrate surface but copper particle deposition on aluminum still was not observed. A thin layer of aluminum 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 steel substrate, producing thin coating layer, and the copper layer thickness did not grow also.

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

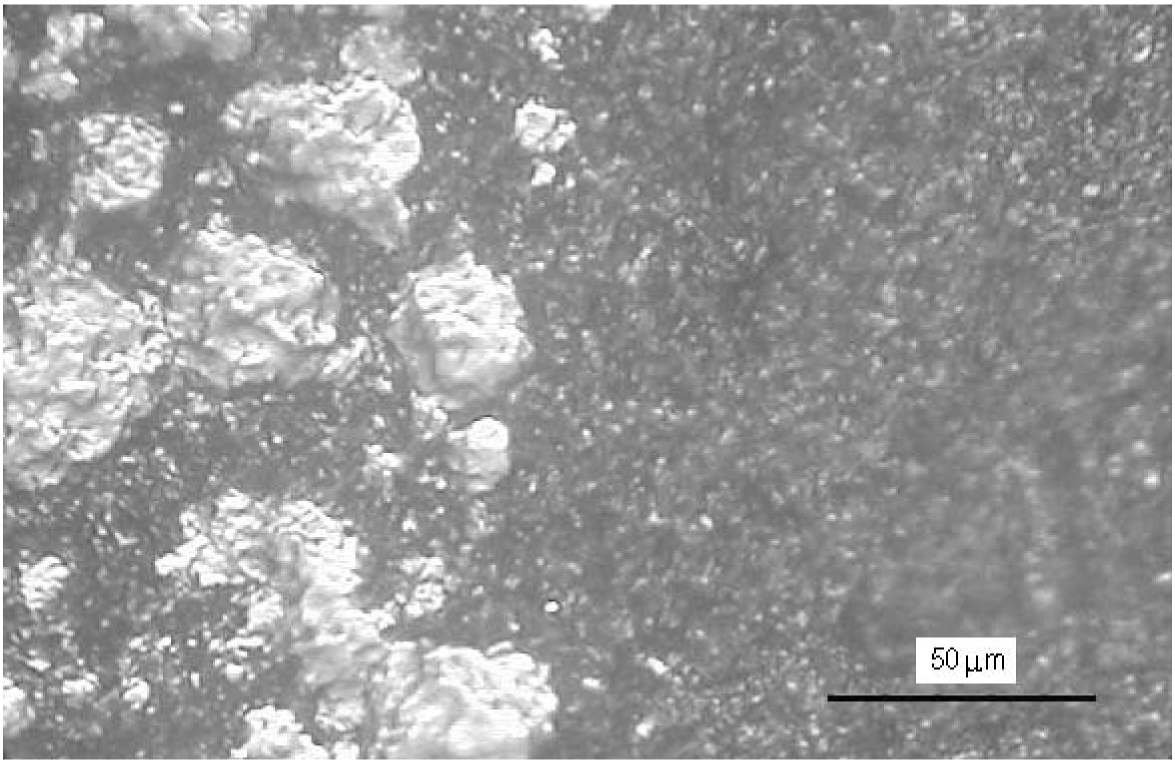

Figure 1. The view of the deposited aluminum particles at the rough carbon steel surface. Left side of substrate was prepared by ceramic particle jet while right side was masked and remained smooth.

The result observed confirms 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.

To reveal the possibility of further deposition onto the thin coating layer under the same circumstances alternated aluminum particles - ceramic particles 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 ^{o}K. The first line was sprayed with the jet of aluminum 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 lines intersection while only a smooth thin aluminum layer developed at the aluminum particle jet line and steel erosion developed at the ceramic particle jet line.

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

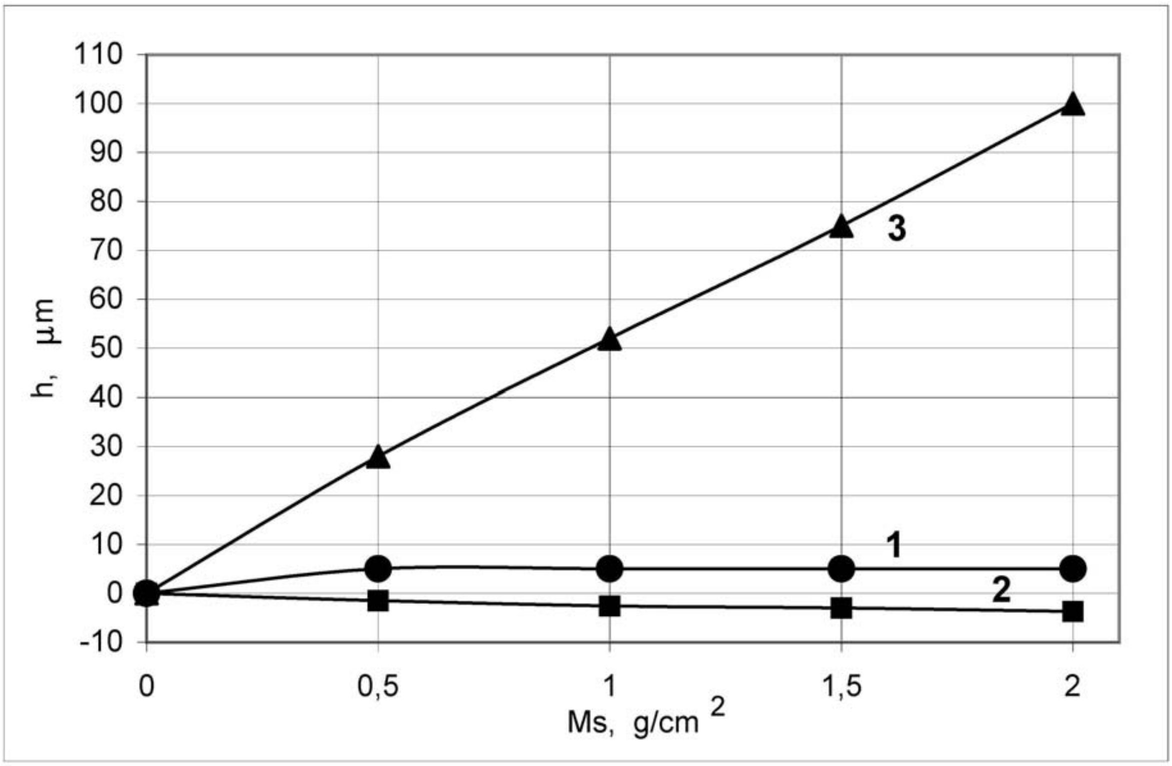

Figure 2. The coating thickness produced by the aluminum particles jet (1), ceramic particles jet (2) and alternated aluminum particles - ceramic particles jets (3) as a function of sprayed powder amount.

Just as in the former experiment, the 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 [2, 7]. In the case of surface activation one should observe the time dependence of the activation process. The results obtained by alternated crossed aluminum 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 aluminum jet-sprayed layer thickness on the sprayed powder amount must be obtained. But the result observed shows the aluminum 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 particles 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 particles and substrate materials will reduce the value of pressure required the intensive plastic deformation to occur. The particles and surface preheating improves the deposition efficiency. Well-heated aluminum particles may be deposited far below the critical velocity for cold spray.

The deposition efficiency of aluminum powder and mixed aluminum-ceramic powder at different jet velocities at various accelerating air stagnation temperatures is shown at Figure 3. For this experiment long cylindrical tubes were used instead of the divergent part of the nozzle. The subsonic air flow inside these tubes produced particle velocity and temperature equal to that of the air jet.

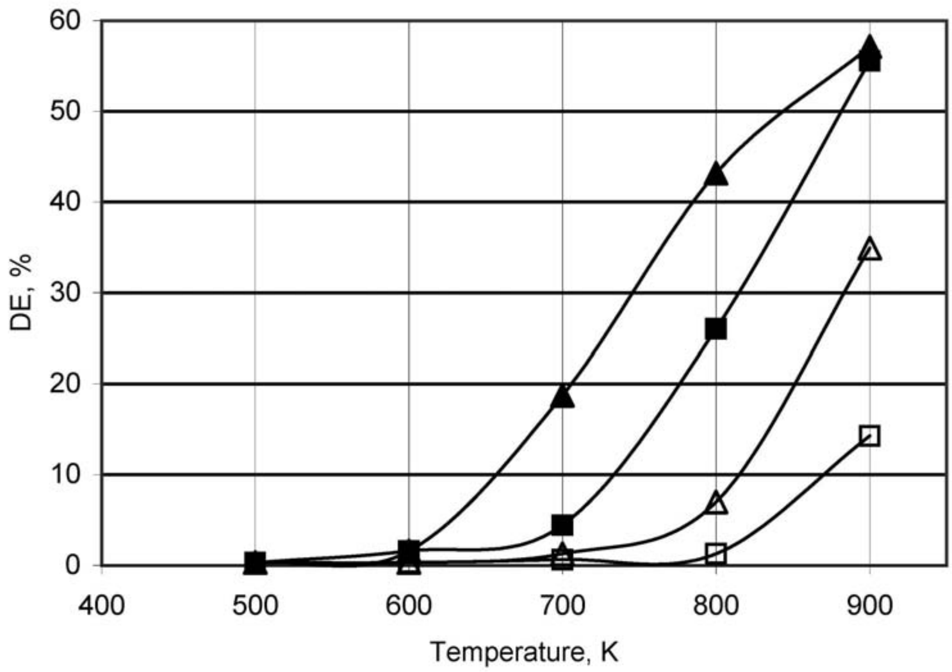

Figure 3. Deposition efficiencies of aluminum (1,2) and mixed aluminum-ceramic (3,4) powders at different air stagnation temperatures and velocities 130 - 180 m/s (1,3) and 200 - 250 m/s (2,4).

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.

But 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 aluminum coating obtained at jet temperatures above 800 ^{o}K is about 30 % and, in contrast to the liquid particle spray, the coating ultimate tensile strength is less then 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 aluminum – ceramic particle jet produces a dense aluminum 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 ^{o} K is presented at Figure 4.

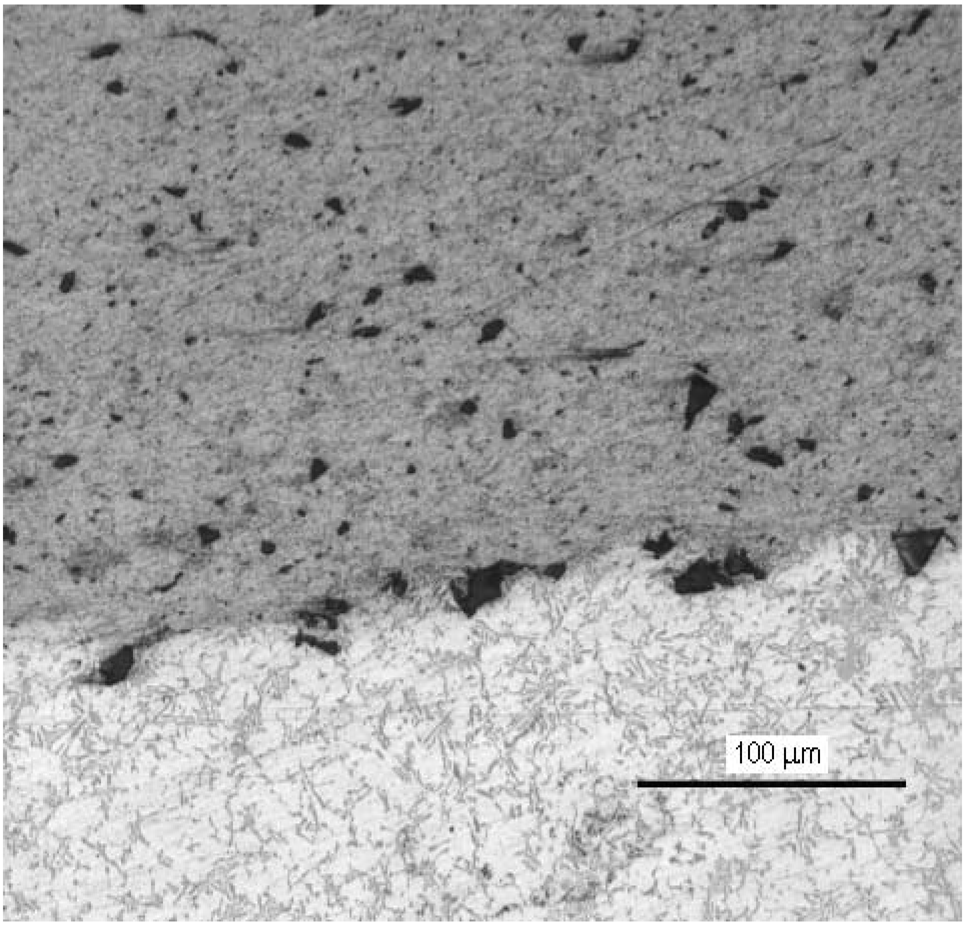

Figure 4. The cross section of aluminum coating with ceramic inclusions at the carbon steel substrate.

Only a small portion of ceramic particles impinges the coating. Most of 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 aluminum – ceramic powder mixture deposition efficiency dependencies on the ceramic powder mass content at different stagnation temperatures of accelerating air.

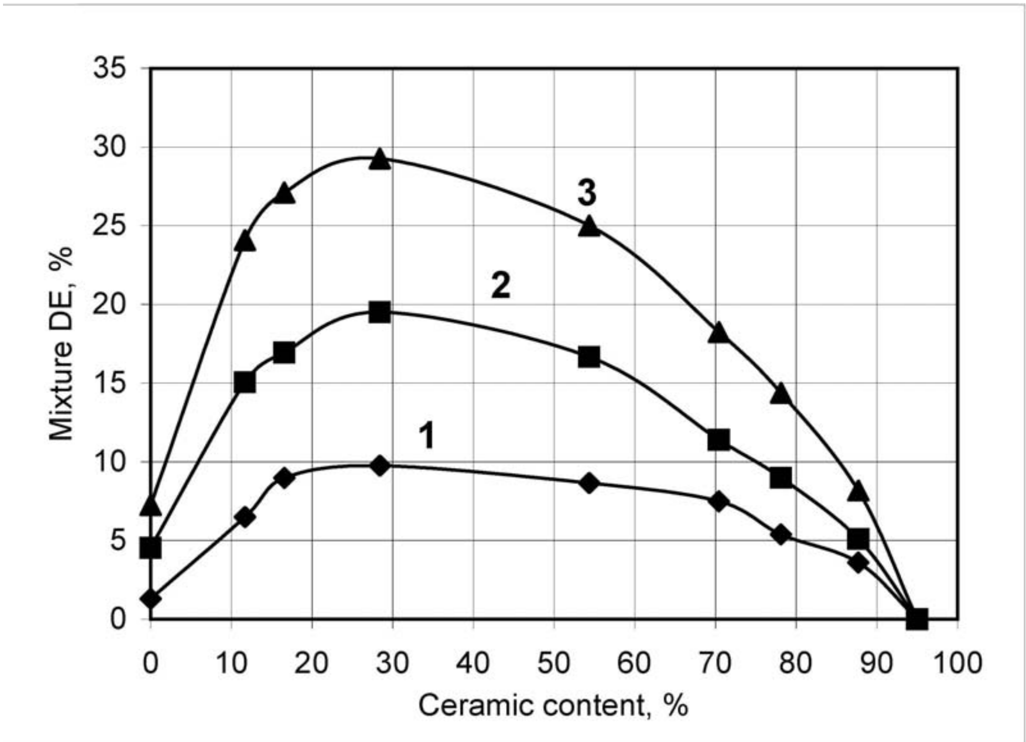

Figure 5. The mixture deposition efficiency dependencies on the mass ceramic content in aluminum-ceramic powder mixture at different air stagnation temperatures (1 - 600 ^{o} K, 2 - 700 ^{o} K, 3 - 800 ^{o} K).

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

Discussion

The comparison of cold spray and supersonic blasting processes shows that they have the same basis but differs only by the jet velocities used. Being both the gas dynamic spray processes they use the solid metal particles plastic deformation to produce coating.

Supersonic blasting is restricted by the use of soft metal powders and rough substrates with low heat conductivity to deposit thin coatings. Cold spray uses the particle and substrate high rate deformation 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. 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 shows the possibility of thick coating formation by producing the roughness of the sprayed coating. And because of statistical nature of erosion processes the thick coating growth becomes statistically determined. 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 cause the rise of pure metal deposition efficiency. But because most of 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. But the particles deformation value is rather low at high jet temperatures and subsonic velocity. The coating densification by the ceramic particles impacts improves coating quality. To produce dense coating with reasonable value of mixture deposition efficiency the optimal ratio of ceramic to metal powder in supersonic jet have to be used.

The process of thick coating creation by the mixed ceramic – metal powder supersonic jet was called dynamic metalisation (DYMET) [8, 9]. Wide industrial use of this process is obviously restricted by relatively low deposition efficiency and rate. But because of low requirements it can be widely used in repair and production of specific high cost products.

Conclusions

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