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Analysis of Wire Arc Spraying Process variables on coatings properties

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The objective of the present study is thus to investigate the effect of particles velocity, temperature on the cored wire coatings properties. The results of a systematic investigation of the influence of different nozzles configurations on the coatings properties are presented, including the gas dynamics properties of the spray jet were calculated by using the CFD code, temperature, velocity and diameter of the particles in flight measurements and the effects on the particles properties on coating adhesion, pores and oxide content. The microstructures of arc spray coatings using a new developed thermal spray nozzle, was studied and compared with those of regular arc sprayed coatings. The test results showed that coatings had better properties than those of regular arc sprayed coatings.

1. INTRODUCTION

Wire arc spraying is an inexpensive thermal spray deposition process in which the materials to be deposited are introduced into the plasma as wires in the form of consumable arc electrodes. Arc spray coatings are normally denser and stronger than their equivalent combustion spray coatings. Low running costs, high spray rates and efficiency make it a good process for spraying large areas. Recent equipment and process developments have improved the quality and expanded the potential application range for thermally sprayed coatings. Typical general applications are thermal barriers, wear resistance, corrosion resistance, high dielectric strength, hard dense coating, decorative arts, etc. Arc sprayed coatings are used widely to fight both high and low temperature corrosion. Arc sprayed coatings also provide excellent resistance to atmospheric corrosion and are used on bridges and other infrastructure components. Most major aircraft engine manufacturers specify the use of the arc spray process for repairs of many aircraft engine components. Coatings are applied to various components for dimensional restoration, hot temperature erosion resistance, etc. It is possible to spray a wide range of metals, alloys and metal matrix composites (MMCs) [1-3].

In arc spraying an arc is formed between two wires. The molten ends of the wires are dispersed and accelerated by a gas stream (air or inert gas). The temperature in the arc can reach 5000 °C. The particle velocity lies in the range of 100 to 300 m/s. A combination of high arc temperature and particle velocities gives arc sprayed coatings superior bond strengths and lower porosity levels when compared with flame sprayed coatings. However, use of compressed air for droplet atomisation and propulsion gives rise to high coating oxide content.

2. STUDIES OF THE FLOWS OF JET BY CFD

The software PHOENICS was chosen for numerical calculation. Developed by Company SHAM, PHOENICS is a general programme of mechanics of the fluids intended for the simulation of all types of flows and heat exchange. The original gun exit is composed of a converging nozzle exhibiting a 6 mm exit diameter. The meeting point of the wires (where the electric arc is formed) is situated just at the center of the exit area. The changes that were made on nozzle geometry and were tested included additional extension of the original nozzle (fig. 1). This approach was expected to lead to the first tendency (qualitative comparison) of the effect of these small changes. Many models of nozzles were tested (nozzle of Laval, nozzles with divergences or convergences). The flows of the six new nozzle configurations were modelled. The influence of transporting gas (air) speed, configuration of jet, temperature gradients in jet, enthalpy were calculated. All the results of modelling were compared with the process parameters of original nozzle.

Figure 1 presents a view of these different nozzle exit designs. In each case, the results were compared to those obtained for the original geometry (Figure 1-a). More precisely, criteria such as - the velocity magnitude and the jet divergence in the near exit region were retained. Figure 1-b incorporates a progressive change in the converging angle. Figures 1-c to 1-e show different lengths of constant area nozzle extensions whereas geometries on Figures 1-f and 1-g were built up with a slightly diverging extension.

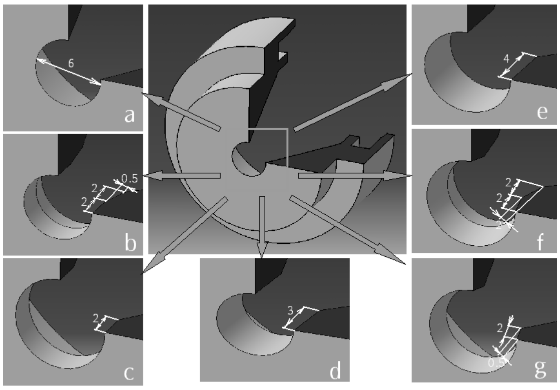


Fig.1. View of the tested diverging nozzles

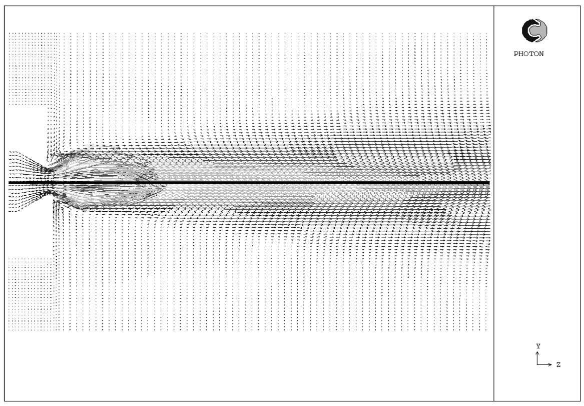


Fig. 2. Vectors of the speed

For the same heating power, the calculated model of the jet temperature fields showed that temperature of jet flowing from origin TAFA nozzle is higher than jet temperature flowing from the modified nozzle. The rate of the flow of air is bigger from the modified nozzle. The speed vectors (fig. 2) shows that the divergence of the jet of the modified nozzle is smaller, than for the jet of the origin nozzle, but the size of the speed vector in the area adjacent to electric arc is larger. This indication enables us to suppose, that the spray of the modified nozzle accelerate particles. The calculations allowed estimate air blow velocity in Y-Z directions. For the modified nozzle the blow speed on the direction *Z* is higher and is smaller in the direction *Y*.

Finally, one of the modified designs was selected on the basis of the numerical modeling results and the corresponding nozzle was machined in order to be tested on the experimental way. The selected design has a 3 mm constant area extension (Figure 1-d). The other designs were modeled to provide either a lower gas velocity or a larger jet divergence (if compared to the chosen one). From the presented results it seems reasonable to investigate dependence of sprayed matter characteristics (temperature, velocity and size of particles) from the nozzles - original and modified. The measurements were provided by measurements system DPV 2000. This system allow to measure size, temperature and velocity of particles in flight and estimate in what degree the measured parameters depend on nozzle orifice.

3. EXPERIMENTAL

3.1. Materials and spray guns

Commercially available Tafa's steel (95MXC) cored wire (1.6 mm. diameter) was used for the spray operations in this research. The spray gun was mounted on at ABB 4400 robot arm so that the spray process (Fig. 3), e.g. meander of the gun and spray time, can be controlled precisely. All the spray operations were performed by a Model 9000 TAFA arc spray system (Tafa Inc., Concord, NH), two different spray nozzles were studied to evaluate the effects of different nozzle geometries.

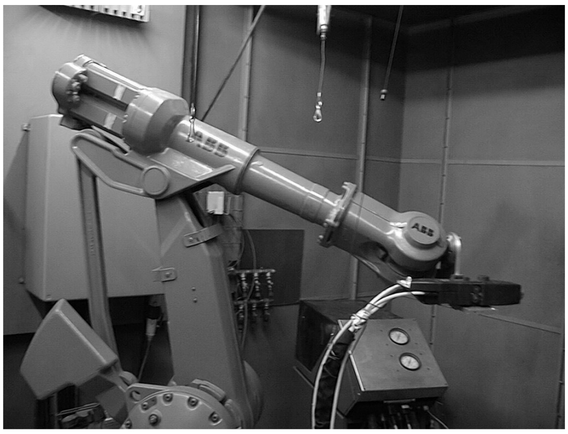


Fig. 3. Arc spray gun on robotic arm

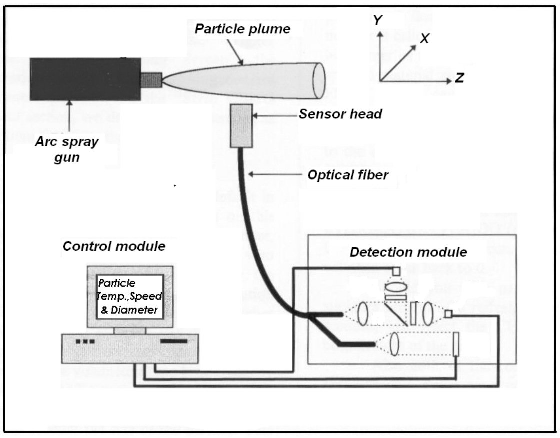


Fig 4. DPV-2000 operation principle

The first nozzle was the standart TAFA 9000 spray nozzle. The second one was the modified Tafa's nozzle.

The process parameters remained fixed: voltage - 30 V, arc current - 150A, spraying distance - 15 cm.

2.2. Procedures and measurements

The sprayed particles velocity, temperature and diameter were measured by the diagnostic system DVP-2000. On-line measurement of these parameters, as well as the particle trajectories, is thus an efficient diagnostic tool for characterizing the spray process. The complete monitoring system consists of three main components: a) the sensor head located near the arc spray torch collecting the thermal radiation from the hot sprayed particles, b) the detection module containing the optical components and photodetectors, and c) an IBM-compatible personal computer (control module) equipped with the required digitizing and computing boards.

The sensor head is located near the arc spray gun collecting thermal radiation emitted by the hot in-flight particles. The collected light is transmitted to the detection module through an optical fiber bundle. The radiation from the particles is collected by a 6-element lens specially designed for the present application in order to minimize chromatic and spherical aberrations for wavelengths ranging from 700 to 1000nm. The collected light is focused on the end of the optical fiber bundle constituted of two distinct arrangements of fibers. The first arrangement consists of a group if 50 optical fibers (200 μm core) whose ends are aligned along a straight line forming a 12 mm long linear array. The second arrangement consists of a 200 μm core fiber, located on the sensor head axis, whose end is covered by an optical mask. Only the light impinging on the two transparent slits engraved on the opaque mask can reach the end of the optical fiber and thus be transmitted to the detection module. The light emitted by a hot particle traveling near the focal plane of the collection optics will then be collected twice as the particle moves from the first slit field of view to the second one. The distance between the slits images being known, the velocity of the particle can be computed from its transit time. The particle temperature is determined by measuring the thermal radiation intensity at two different wavelengths [4,5]. Additionally, the sprayed particles microstructures and performance of the coatings were studied by scanning electron microscopy (SEM).

Coating adhesion was measured in accordance with the ASTM C 633-79 standard pull-off tensile test. This is a common method of characterizing the comparable bond strength of thermally sprayed coatings. The results of the tests determine the degree of adhesion of a coating to a substrate in tension normal to the surface. 25 mm diameter coupon was stuck onto two sample holders for testing. The latter ones were set into a tensile machine. A progressive force at a constant speed of 0.075 cm/min was applied to set up until the spallation occurred. Four samples were used for eight spraying conditions.

Polished cross section of the spray deposit was digitised by using a Nikon EPIPHOT® optical microscope with a Nikon Coolpix E955 digital camera. Computer image analysis program Scion Image® based on the image processing toolbox was used to analyse the true-colour image. Instead of using grey level as threshold, the RGB value of the pixels was utilised as criterion to distinguish the different features of the coating microstructure. In this way, the area fraction and distribution of oxide and porosity (Tab. 2) can by defined with high accuracy.

4. RESULTS AND DISCUSSIONS

The sprayed coating is built up particle by particle and, therefore, higher atomizing air pressure results in higher impact velocity of smaller particles on the substrate.

Air atomization is commonly used in the wire arc spray process. The major advantages are the availability and economy of compressed air. In the air atomisation wire-arc spray process, the oxide content of the sprayed coating is relatively high due to oxidation of the molten wire material. This higher oxide content can increase the coating hardness so that the abrasion and wear resistance of the coatings is improved. However, the oxide content may also be detrimental to coating properties because oxides may reduce the adhesion strength between coating and substrate. Also, hard oxide particles embedded in sprayed coatings impose problems during machining. Furthermore, coatings sprayed with air atomisation often contain relatively high porosity, which is frequently detrimental. Another disadvantage of air atomisation is related to the burn off of alloying elements contained in parent wires. These

elements are essential ingredients to produce the required coating characteristics. As a consequence, coatings with specified characteristics cannot be produced reliably [6,7].
The adhesion of the coatings depends upon the interactions between individual lamellae and between lamellae and substrate. The bond strength of a coating is affected by the extent of both physical and chemical interactions between the coating and the substrate material and on the microstructure of the interfacial region. Poor adhesion can be attributed to poor interfacial interlocking, low degree of metallurgical bonding, and high internal stresses. The degradation modes of the coating depend on both the nature of the coating-substrate interface and on the chemical phenomena that occur at the interface during deposition and solidification. The results of particles measurements in-flight are presents in the Table 1.

Table 1. Results of measurements of particles in-flight with diagnostics systems DPV 2000

Spray gun nozzle	Air debit m^3/h	Particle speed m/s	Temperature C^0	Diameter μm
TAFA 9000	90	118	2185	32
	110	141	2210	28
	130	157	2220	25
Modified	90	136	2191	29
	110	175	2217	24
	130	189	2217	20

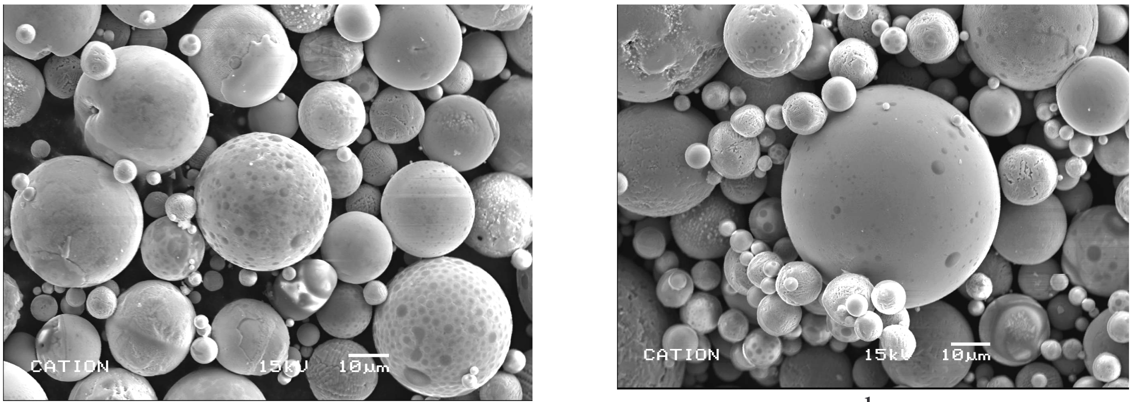
The samples for the tensile test were glued up together to sample holders by the polymer glue FM 1000. For the glue polymerisation the samples that had been assembled were treated by the two - hour heating under the temperature 170 ^{0}C. After the glue final hardening prepared samples were ruptured by standard tensile test procedure. The results of these tests are presented in Table 2.

It sometimes happened during the test that spallation did not take place at the interface coating /substrate but within the coating or in the glue. For instance, when rupture occurred in the glue, the real adhesion of the coating onto its substrate was higher than the recorded value. The " > " sing was then used to point it out.

Sprayed coatings are formed by the impact, deformation, and rapid solidification of individual molten droplets so that coating structure consists of a series of overlapping lamellae. Faster molten particles with higher kinetic energy spread and deform more readily on impact, thus increasing coating density and reducing porosity. The particle velocity and the particle temperature determine the coating structure at the instant of impact on the substrate. Completely molten particles impinging on the substrate spread out radially in the form of thin disks. In reality, however, the deposit is not uniform in thickness, and the periphery of the flattened particle is not circular.

Table 2. Sprayed coatings properties

Spray gun nozzle	Air debit (m^3/h)	Particle speed (m/s)	Porosity (%)	Oxides (%)	Adhesion (MPa)
TAFA 9000	90	118	0.77	13.1	52.7; 49.2; 62.0; 53.8
	110	141	0.57	15	>59.4; >63.1; >55.5; 57.2
	130	157	0.37	14.2	>67.1; >68.3; 56.0; 48.8
Modified	90	136	1.23	12.3	>54.0; >64.3; 50.9; 67.0
	110	175	0.63	14.4	>71.0; >68.6; >55.0; >50.5
	130	189	0.31	15	>53.2; >58.9; >51.8; 63.9



a b

Fig. 5 SEM photographs of the sprayed particles (air debit 130m^3/h, particles quenched in water): a - standard TAFA 9000 nozzle; b - modified Tafa's nozzle

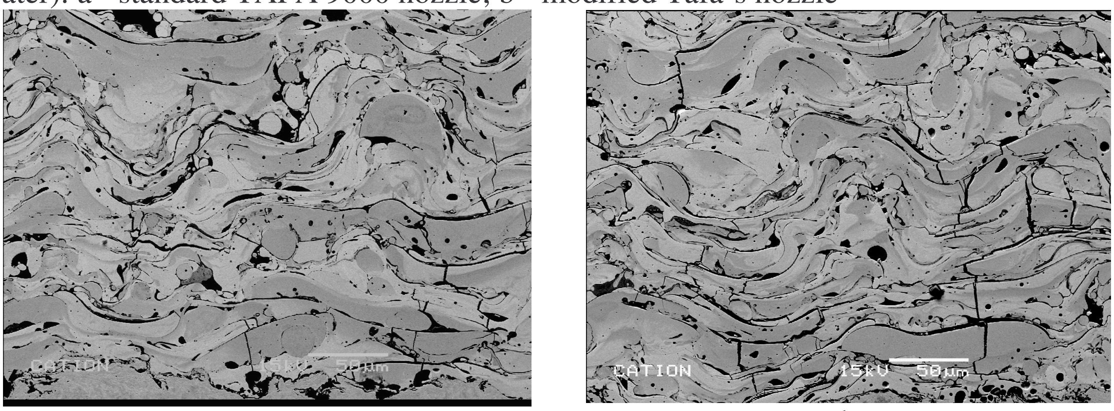


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Fig. 6 SEM photographs of micro sections of sprayed coatings: a - standard TAFA 9000 nozzle; b - modified Tafa's nozzle

Arc sprayed metal coatings contain a certain amount of oxides. During spraying, the effect of atomising air and the entrainment of the surrounding air into the spray stream caused significant in flight oxidation of the molten metal particles. Increasing the atomising air pressure leads to higher gas stream velocities, which in turn break up the molten particles into smaller droplets. The smaller droplets react more readily with oxygen than the larger droplets, because of their greater specific surface area. The Table 1 shows that size of particles is evidentely decreasing whereas air debit increases and the temperature of particles variates very insignificantly within possible eror range in measurement. That allows stating that the temperature remains constant. Fig.5 confirm that under constant air debit the particles sprayed by Modified gun nozzle are smaller than ones by TAFA 9000.

Investigation of coatings microstructure revealed dependence of structure morphology on sprayed particles velocity. The density and dispersity of the lamellar structure increases with the increase of particles velocity. With the increase of particles velocity the size of droplets decrease. Small size droplets have a relatively big surface area; during the flight they are oxidised on bigger degree in comparison with big size droplets, and in these coatings bigger probability of increase of oxide inclusions is possible. On the other hand, the small particles have bigger velocity, shorter fly duration and less time for oxidation reactions. The more particles velocity is, the bigger coating density and less developed porosity is. The optimal selection of spray parameters in matching with the degree of oxidation and adhesion of coating allows reaching the highest strength of adhesion. The optimal coatings were produced when the spray operations were performed by Modified TAFA spray guns with 110 and 130 m^3/h air debits.

5. CONCLUSIONS

1. CFD models can predict the influence of nozzle geometry on flows of jet ant heat transfer. It also helps to choose an optimal nozzle configuration.
2. The spray gun nozzle design has a strong influence on spray geometry, its dynamics characteristics and coating properties. The minor modification of spray gun nozzle design can strongly improve the coating characteristics.
3. Modified configuration of the nozzle allows the increase of the speed of the particles by ~20% and kinetic energy of particles impacts by~40%.
4. The precise estimation of adhesion quality of thin coatings is a difficult task. Sample preparation, sort of glue, heating time to polymerise the glue is of the prime importance to obtain good results of the bond tensile test.
5. In the case of optimal spray process characteristics in several specimens it was difficult to estimate the coatings adhesion strength. This happened when the strength of coating adhesion was bigger than glue bond between sample holder and substrate.

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