ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 9, No. 4. 2003

Influence of the Particles Velocity on the Arc Spraying Coating Adhesion

I. Gedzevičius*, **A.V. Valiulis**

Department of Materials Science and Welding, Vilnius Gediminas Technical University, Basanavičiaus 28, LT-2009 Vilnius, Lithuania

Received 30 September 2003; accepted 26 October 2003

The article deals with investigation of the influence of spray gun nozzle parameters on sprayed particles velocity and strength of coating adhesion. Four different arc spray nozzles were chosen for research. All variables of the spray process were constant except the air debit. The adhesion of coatings was tested. The results of the test showed the dependence of coating adhesion on particles velocity and contamination.
Keywords: thermal spray, arc spray, coating adhesion.

INTRODUCTION

Thermal spraying is a generic term for a group of coating processes that deposit finely divided metallic or non-metallic materials, such as plastics or ceramics, onto preparation of substrate for coating. The three major categories of thermal spray processes define the type of energy source used: plasma-arc spray, flame spray and electric-arc spray. 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. These coatings have proven their excellence in challenging environments such as boilers, by providing oxidation and heat resistance. 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.

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. The process is simple and can be operated either manually or in an automated manner. It is possible to spray a wide range of metals, alloys and metal matrix composites (MMCs) [1 – 3].

Advantages of the process are minimal facilities large structures can be coated, excellent coating bond required, no combustible gas supply is required, versatile and reliable, easily automated, easy to operate, portable, large structures can be coated, excellent coating bond strength and density, high production spray rates and produces easily machinable coatings.

Disadvantages of the electric arc spray process are that only electrically conductive wires can be sprayed and if substrate preheating is required, a separate heating source is needed.

MATERIALS AND EXPERIMENTAL PROCEDURE

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. 1), 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), four different spray nozzles were studied to evaluate the effects of different nozzle geometries.

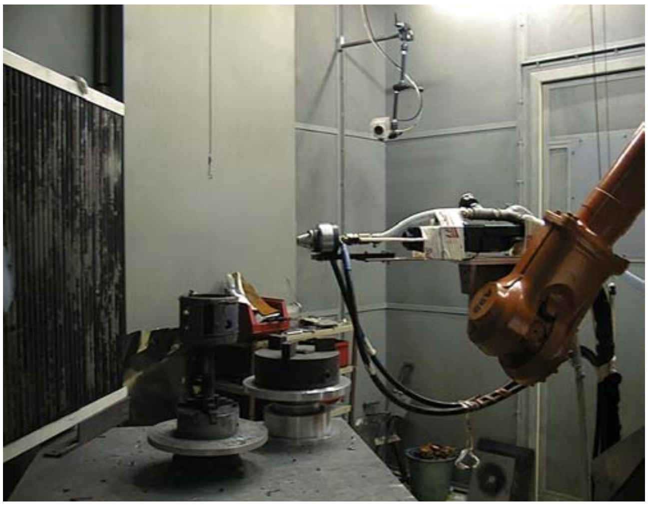

Fig. 1. Experimental set-up

The first nozzle was the standard TAFA 9000 spray nozzle. The second one was the modified Tafa's nozzle. The third one was the original CMES (Chinese Mechanical Engineering Society) nozzle and the last one was the modified CMES nozzle.

*Corresponding author. Tel. +370-5-2744741; fax.: +370-5-2744739.
E-mail address: *irmantas@me.vtu.lt* (I. Gedzevičius)

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

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 (Fig. 2). 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.

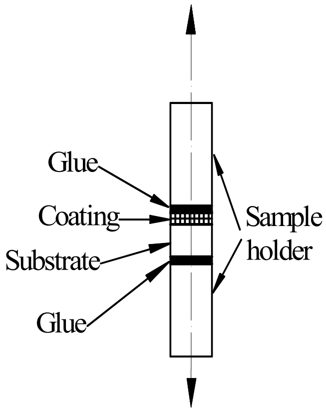

Fig. 2. Experimental set-up for bond test

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 (Table 1) can by defined with high accuracy.

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 [4, 5].

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.

Fig. 3. The samples after bond tensile test (in left rupture occurred in the coating, in right occurred in the glue)

The samples for the tensile test were glued up together to sample holders by the polymer glue FM 1000. For the glue polimerisation the samples that had been assembled were treated by the two - hour heating under the temperature 170 °C. After the glue final hardening prepared samples were ruptured by standard tensile test procedure. The results of these tests are presented in Table 1.

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 “ > ” sign was then used to point it out. The sprayed particles velocity was measured by the diagnostic system DVP-2000. The description of this measurement principles can be found in [6 – 8].

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. 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 1. Results of investigations

Spray gun	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 TAFA	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
Original CMES	–	220	0.19	14.8	70.1; >56.3; >61.1; >51.0
Modified CMES	–	236	0.46	14.8	56.5; 56.7; >52.1; 50.3

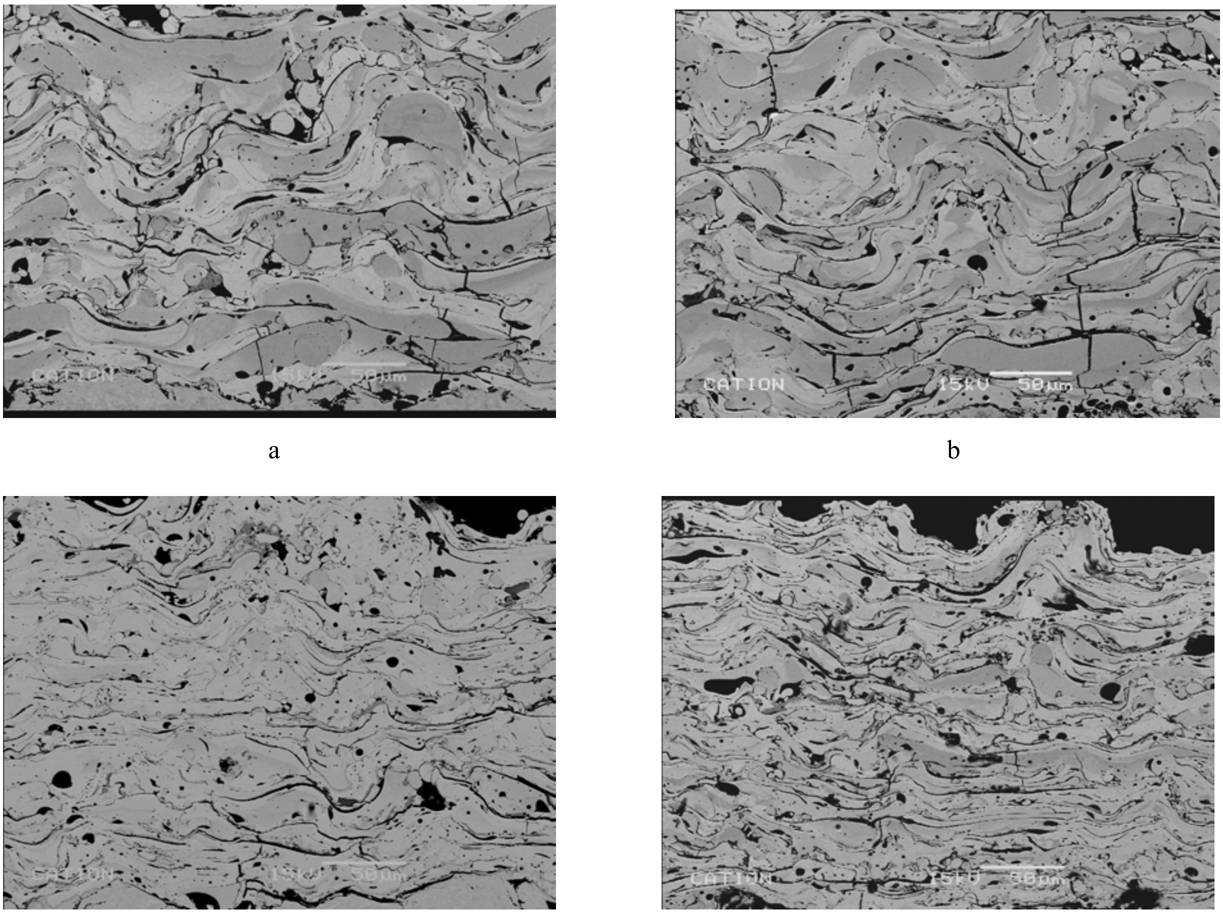

Fig. 4. SEM photographs of micro sections of sprayed coatings: a – standard TAFA 9000 nozzle; b – modified Tafa's nozzle; c – original CMES nozzle; d – modified CMES nozzle

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 inflight 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.

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 to reach the highest strength of adhesion. The optimal coatings were produced when the spray operations were performed by TAFA 9000 and Modified TAFA spray guns with 110 m^3/h air debit. In the case when spray operations were performed by Original CMES and Modified CMES spray guns, the results were worse. This type of spray guns requires very big air debit and this is the reason why spray torch has insufficient space concentration. On the average the velocity of the particles is high, but particles flying in spray periphery have smaller velocity and high surface oxidation degree. For these reasons the properties of coatings are not so high if compared with coatings performed by TAFA 9000 and Modified TAFA spray guns.

CONCLUSIONS

1. The spray gun nozzle design has a strong influence on spray geometry, its dynamics characteristics and influence on coating properties. The minor modification of spray gun nozzle design can strongly improve the coating characteristics.

2. The precise estimation of adhesion quality of thin coatings is difficult task. Samples preparation (especially sort of glue, heating time to polymerise the glue) is of prime importance to obtain good results of the bond tensile test.

3. In the case of optimal spray process characteristics in several cases, it was difficult to estimate the coatings adhesion strength. This cases were when the strength of coating adhesion was bigger than glue bond between sample holder and substrate.

4. For a more precise and detailed analysis of the quality of coatings, the investigation of different coating properties – tribology, hardness, surface roughness, modulus of elasticity- is necessary.

Acknowledgments

This work was supported by the LERMPS - Research Laboratory on Materials, Plasmas and Surfaces (France).

REFERENCES

1. **Huchin, J. P.** The Place of Thermal Spraying in Industry Today and the Prospects for the Future *Proceedings of 15th International Thermal Spray Conference*, 25 – 29 May, 1998: pp. 925 – 931.
2. **Ducos, M., Durand, J. P.** Thermal Coatings in Europe: a Business Prospective *Thermal Spray 2001: New Surfaces for New Milennium*, Ohio, USA, 2001: pp. 1267 – 1271.
3. **Rigney, R. W., Grubowski, A., McCaw, R., Scandell, K.** Component Repair and Chrome Plating Replacement with New Thermal Spray in the United States Navy: Successes and the Future *Materials Characterization* February - March 2001: pp. 975 – 979.
4. **Wang, X., Heberlein, J., Pfender, E., Gerberich, W.** Effect of Nozzle Configuration, Gas Pressure and Gas Type on Coating Properties in Wire Arc Spray *Journal of Thermal Spray Technology* December, 1999: pp. 565 – 575.
5. **Wang, X., Heberlein, J., Pfender, E., Gerberich, W.** Effect of Gas Velocity and Particle Velocity on Coating Adhesion in Wire Arc Spraying *Thermal Spray: Practical Solutions for Engineering Problems* Ohio, USA, 1996: pp. 807 – 811.
6. **Moreau, C., Gougeon, P., Lamontagne, M., Lacasse, V., Vaudreuil, G., Cielo, P.** On-Line Control of the Plasma Spraying Process by Monitoring the Temperature, Velocity, and Trajectory of In-Flight Particles *Proceedings of 7th International Thermal Spray Conference*, 20 – 24 June, 1994: pp. 431 – 437.
7. **Gougeon, P., Moreau, C.** In-Flight Particle Surface Temperature Measurement: Influence of the Plasma Light Scattered by the Particles *Proceedings of the 1993 National Thermal spray Conference,* 7 – 11 June, 1993: pp. 13 – 18.
8. **Yamada, H., Kuroda, S., Fukushima, T., Yumoto, H.** Capture and Evaluation of HVOF Thermal Sprayed Particles by a Gel Targent *Thermal Spray 2001: New Surfaces for New Milennium*, Ohio, USA, 2001: pp. 797 – 804.
9. **Liu, G., Roniatowski, K., Kurzydowski, K. J.** Quantitative Characteristics of FeCrAl Films Deposited by Arc and High-Velocity Arc Spraying *Materials Characterization* February – March, 2001: pp. 99 – 104.
10. **Gibbons, G., Wimpenny, D.** Mechanical and Thermo-mechanical Properties of Metal Spray Invar For Composite Forming Tooling *Journal of Materials Engineering and Performance* December 2000: pp. 630 – 637.
11. **Dickey, H. C., Meek, T. T.** Active Electronic Devices Fabricated by DC Plasma Arc Spray Process *Vacuum* October 2000: pp. 179 – 184.
12. **Newbery, P., Grant, P. S.** Droplet Splashing during Arc Spraying of Steel and the Effect on Deposit Microstructure *Journal of Thermal Spray Technology* June, 2000: pp. 250 – 258.
13. **Steffens, H. D., Nassenstein, K.** Influence of the Spray Velocity on Arc-Sprayed Coating Structures *Journal of Thermal Spray Technology* September, 1999: pp. 454 – 460.
14. **Kuroda, S** Properties and Characterization of Thermal Sprayed Coatings – a Review of Recent Research Progress *Proceedings of 15th International Thermal Spray Conference*, 25 – 29 May, 1998: pp. 925 – 931.

DOI: 10.5755/j02.ms.26732