AMORPHOUS PLASMA SPRAYED COATING

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Abstract - The plasma spraying method has wide application in many industries, including the automotive industry, due to its diversity and efficiency. The interest in this technology is increasing as it is possible to replace expensive materials with iron-based alloys and use air instead of inert gas to activate plasma. There are a number of works that have emphasized the importance of properly selected spray parameters, but they used the plasma generation gas, which is an expensive inert gas such as argon, heli, or their gas mixture with a different ratio. The objective of this paper is to study the influence of the most specific parameters that affect the quality of the wear-resistant spray layer using Fe-based powder sprayed onto the steel substrate material. The experiment design with the ANOVA analysis helped to find out the nature of the elevation of the wear resistance under the influence of the particle velocity and the related technological parameters in the process. The research results provide an experimental formula that combines the main spray parameters with the evaluation of wear resistance in relation to the traditional material group.

Key words - Technological parameters; friction properties; iron substrate materials; air plasma spraying; adhesion

1. Introduction

The atmospheric plasma spray (APS) has a specific feature since the environment is the open atmosphere, which involves some limitations in the protection of the feedstock from the influence of oxygen and the disability of the process. [1, 2, 3, 4]. The spray material must be in the form of powder. The wide range of industrial applications of APS is evidence of its advantages (Table 1).

Table 1. *Application of APS in different industries*

N	Area of industry	Application
1	Nuclear	Reactor equipment [5]
2	Aerospace	Gas turbine & Airframe components [6]
3	Cutting tools	Steel cutting tools; non-steel cutting tools equipment [7]
4	Metal processing	Sink rolls; extrusion rolls [8]
5	Biomedical	Orthopedic implants [9]
6	Pulp; paper machinery	Impression rolls; corona rolls; boiler; paper manufacturing rolls [10]
7	Petrochemical; gas & oil	Pump components; valves; tank linings [11]
8	Power generator	Gas turbine blades and components; hydroelectric turbine components; steam components [12]
9	Textile machinery	Stretch tow rollers; thread guides [13]
10	Automotive	Engine & Drive components; moulding [14]
11	Shipbuilding (Marine)	Propeller; shaft; decking [15]

Amorphous coatings by APS have some advantages due to their outstanding performance against similar depositions. That’s why, recently, many publications have focused on this issue. The experiments with the Fe-based coating using APS to evaluate the effect of arc power on the wear resistance in [16] defined the decreasing porosity with increasing the arc power, but the power of plasma was not exceeded at 40 kW. The maximum porosity of the deposition is approaching 5.75%. Fe-based coatings by HVOF Sprayed were investigated for automotive applications [17]. In [18], the authors presented their investigation by using the Fe-based HVOF coating to enhance the tribocorrosion resistance. The significant value of the study consists of the potential recommendation of amorphous Fe-based coatings in the marine industry. However, there are very few publications on the spraying with plasma power exceeding 40 kW applied to the amorphous materials in the case of APS. To ensure the quality of the thermally sprayed coatings, it is necessary to analyze not only the specifications of the powder as the feedstock material but also the mechanical properties of the substrate and, most importantly, the technological parameters of the process. Between the criteria evaluating the operating performance of the coatings, it is useful to focus on the adhesion and cohesion bonding, which consist of strength and dense deposition with a long-lasting resource [19–22].

From this position, the interaction between the technological parameters of the process contributed the significant influence on which the study focused. Concerning the technological parameters in the thermal spraying, in the different publications [23–26], authors investigated the level of their influence on the properties of the final coatings. Some research focused on the material side, such as the morphology of the powder, the chemical composition, and the transition of microstructure under thermal cycles. The other ones focused on the changing of the plasma power and the flow rate in the feeding mode for the primary and secondary gases. A few investigators are interested in the modification of the plasma torch, helping to enhance the efficiency of the process. Anyway, it is necessary to cover the gap between the theoretical research and the experiment in the case of the amorphous Fe-based material, paying attention to the particle velocity as a significant contribution to the wear resistance. The result of this work confirmed that the plasma current plays a very important role in increasing the particle velocity as well as the particle surface temperature, encouraging wear resistance.

2. Methodology

The series of spraying experiments was conducted on the system SG-100 TAFA-Praxair, US. Ordinary air is used for plasma generation. The feedstock was carried by the nitrogen. The author in this study tends to highly evaluate the role of particle velocity and the enthalpy of the stream to establish the high quality of the coating, as specified [27, 28]. The particle velocity was measured by the high-speed camera Shimadzu HPV-1 [29]. The wear resistance is registered using the pin-on-disk test in the equipment UMT-CETR (US) under the requirements of the ASTM G133 standard. The distribution of the particle size of powder was found in the device Cilas-1090 [30]. The level of oxidation is defined by the comparison of the content composition of the feedstock and the coatings using a high-end melt extraction analyzer (G8 Galileo, Germany). The hardness of the coatings is defined using the device FM-100 (Japan) under the guidance of the standard ISO 6507-2. The chemical composition of some Fe-base powders is presented in Table 2. The fraction composition of powders is listed in Table 3.

Table 2. *Chemical composition of powder, % by weight (the balance is the Fe content)*

Code	C	Cr	B	Mo	Ni	Mn	Si	Nb	V	W
F-1	0.11	32.9	0.10	3.30	5.0	1.05	0.70	-	-	-
F-2	0.73	5.0	0.25	4.20	-	1.25	0.84	0.54	1.20	-

Table 3. *Distribution of article upon size*

Code	Mean diameter μm	Content of articles upon size fraction, %										
		0 - 1	1 - 1.5	1.5 - 2	12 - 16	16 - 24	24 - 32	32 - 48	48 - 64	64 - 96	96 - 128	128 - 192
F-1	53.9	7.7	18.9	14.1	-	-	-	-	24.9	24.7	3.2	6.1
F-2	72.5	0.9	0.2	0.6	0.5	-	-	14.5	4.5	43.4	5.0	13.8

3. Results and discussion

3.1. Case study I

The sizes of particle powder: 40–100 μm. The distance L= 130 mm. The changes of the main technological parameter in the spraying are following:

Table 4. *Modes of the plasma spraying*

Mode	Plasma current I [A]	Voltage of plasma, U[v]	Feeding rate of air, G [g/s]
1	122	205	1.2
2	182	205	1.25

The result of hardness measuring was presented in Table 5.

Table 5. *The hardness before and after heat treatment*

Code	Mode	Before the heat treatment, HRC	Parameter of heat treatment	After the heat treatment, HRC
F-1	1	41-42	-	-
	2	34-36	4 hours – 800ºC	52-54
F-2	1	41-43	4 hours – 800ºC	44-48
	2	40-44	4 hours – 800ºC	55-57

From Table 5, the hardness of the coating increased after heat treatment. The elevation of the hardness can happen due to the amorphous phase transition, which helps transform the nanocrystalline structure. In turn, it was dispersed in the coating and improved its strength. The other reason can be that, when the temperature reaches 650°C, the rich-chromium and molybdenum structures derived in the deposition encourage the toughening of the solid solution. It is useful to analyze the oxidation impact of the air environment on the behavior of the coatings. The results of this experiment are presented in Table 6.

Table 6. *Content of oxygen in powder and in coating*

Code	Version	Content of the oxygen, %	
		In Powder	In Coating
F-1	1	0.19	1.70
	2	0.19	1.14
F-2	1	0.14	2.15
	2	0.14	1.60

The data in Table 6 shows a significant increase in the oxygen content due to the effect of the APS in the air. The author of the study considers the advantage of this effect in the case of dry tribology since hardness is the positive factor that enhances wear resistance. The content of oxygen in APS is higher than HVOF sparing by 3–4 times [31] since the particle velocity is lower. But the bilateral role of the hardening phase (oxidized iron) is predominant when wear resistance is the main criterion of the coating's performance. Two types (F-1 and F-2) are tested for wear resistance to evaluate the mechanical property. The result of the test is presented in Table 7. From Table 7, the hardness of the coating with the material F-1 did not satisfy the wear-resistant criteria. The content of the Fe element in the material F-2 is significantly higher than in the material F-1. At this stage, the continuing testing of the material F-2 is meaningful.

Table 7. *Result of testing on the wear resistance*

No	Powder	Current (A)	Voltage (V)	Standoff (mm)	Hardness HRC	Wear resistance in relative units	
						wear volumetric	Volumetric cavity indent
1	F-1	122	225	130	42-45	fail	fail
2	F-1	222	235	130	38-44	fail	fail
3	F-1	205	200	130	40-43	fail	fail
4	F-2	120	200	130	47-55	737	116.5
5	F-2	220	248	130	51-53	753	123.3
6	F-2	200	200	130	44-50	732	112.8

Thus, as indicated in Table 7, the wear performance depends on the plasma power, and this parameter increases with the elevation of the plasma power. The increasing wear resistance can be explained by the increasing kinetic energy of the particles since they are accelerated under the thermodynamic forces in the plasma stream. Under the impact of the thermoplastic deformation in the sprayed layers, the porosity decreased, which improved the dense structure of the coating. It is interesting to mention the slowdown of the wear resistance (number 5). Probably some threshold excitation causes the content of oxide in the coating to increase. From one side, this content has a positive effect on the hardness in dry lubricating conditions, but from the other, it also decreases the wear resistance depending on the nature of the friction.

Table 8. *Results from wear resistance test on some compositions of materials*

Material in testing	Average friction coefficient	Morphology of surfaces
(NiAl) + (NiCrBSi) /Al alloy	0.026	Uniform wear on whole surface
F-2 / Al alloy	0.075	Uniform wear on whole surface
F-2 +15% wear resistance alloy/Al alloy	0.086	Linear wear 0.1 mm
F-2 + 30% wear resistance alloy/Al alloy	0.064	Linear wear 0.1 mm
F-2 + 15% soft alloy /Al alloy	0.032	10% surface wear
F-2 + 30% soft alloy /Al alloy	0.048	55% surface wear
Cast iron/Al alloy	0.073	Linear wear 0.4 mm
Cast iron + 15% wear resistance alloy/Al alloy	0.032	N/A
F-2 + 10% graphite /Al alloy	0.032	Linear wear 0.3 mm
F-2 +20 % carbon/Al alloy	0.031	N/A

For the comparison, a set of depositions was done with the powder F-2 and other compositions to study the friction performance and analyze the morphology of the surface. The results of this experiment are presented in Table 8. The data of the experiment helped to introduce the finding: the tribology performance can be improved by mixing the soft alloy of graphite powder by 10–15% with the F-2 powder due to the reduction of the friction coefficient. This reduction is comparable with the traditional antifrictional materials (NiAl or self-flux alloy).

3.2. Case Study II: *Investigation on the behavior of particle velocity*

Material of powder: F-2; size of particle: 40–100 μm; The conditions of this experiment are presented in Table 9. The data of the velocity measurement show an increasing velocity according to the elevation of the current. By using the square-least method for the projection, is it useful to introduce the empirical formula for calculating velocity:

$$V = 11 \text{ x } I^{0.3} \text{ x } G^{0.9} \quad (1)$$

Where I is the current and G is the flow rate of the air. Since the particle velocity is one of the main parameters used to obtain the adhesion strength, it is useful to note that the operating performance of the coatings depends on the technological spraying process via an intermediate parameter such as the particle velocity.

Table 9. *Variation of parameters for F-2 spraying*

Current (A)	Voltage (V)	Flow of air (g/s)	Velocity of particle (m/s)
120	140	0.46	10
120	160	0.55	25
120	170	0.75	30
120	180	0.94	43
120	195	1.42	58
120	205	1.76	66
120	225	2.6	96
150	145	0.55	25
150	155	0.75	29
150	200	1.13	39
150	210	1.76	51
150	240	1.95	100
150	250	2.92	105
180	155	0.75	40
180	170	0.94	52
180	200	1.13	60
180	250	2.92	117
220	207	1.76	88
220	225	1.85	106
220	240	2.60	114
220	250	3.17	131

The result of the analysis of variation using MINITAB software is presented in Table 10.

Table 10. *Analysis of variation (ANOVA)*

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	6	36488.7	6081.44	4302.16	0.000
Linear	3	27602.7	9200.89	6508.93	0.000
I	1	1642.1	1642.08	1161.65	0.000
In the	1	193.5	193.49	136.88	0.000
G	1	736.6	736.61	521.10	0.000
Square	2	113.3	56.63	40.06	0.000
I^2	1	47.4	47.41	33.54	0.000
G^2	1	34.5	34.45	24.37	0.000
2-Way Interaction	1	63.4	63.37	44.83	0.000
IU	1	63.4	63.37	44.83	0.000
Error	32	45.2	1.41		
Total	38	36533.9			

The regression equation in Uncoded Units:

$$V = 3.39 - 0.4498\, I + 0.0992\, U + 32.98\, G + 0.001158\, I^2 - 2.520\, G^2 + 0.001215\, IU \quad (2)$$

The analysis of the coefficients for the evaluation of the consistency of the regression equation (2) presented in Table 11.

Table 11. *Analysis of the consistency*

S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**
1.18894	99.88%	99.85%	99.82%

From the regression equation (2), it can be noted that the particle velocity depends not only on the plasma current but also on the flow rate of the plasma generation gas. The results of the measurement of velocity and spraying parameters in Table 9 demonstrated that the intensive mode has a strong effect on the particle's velocity, and the maximum velocity can reach approximately 180 m/s. The velocity of the particle acts as the mail channel to enhance the kinetic energy of the impact on the substrate and initiate the adhesion bond. The reason for choosing only powder F-2 is because the content of Fe reaches a maximum value of 85%, which exceeds that of any commercial brand.

In Figure 1, the above- mentioned interaction was verified again.

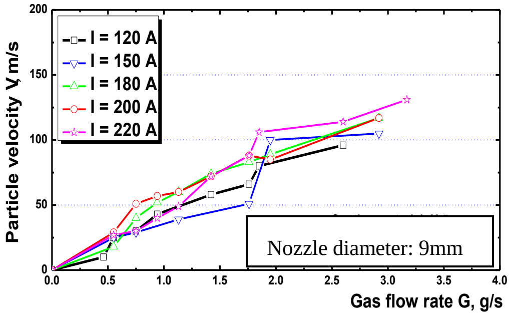

Figure 1. *Relation: Particle velocity- Gas flow rate*

4. Conclusions

It is recommended to use ordinary air as a plasma generation gas to spray amorphous material containing a high content of Fe, providing a reasonable process to regulate the content of oxide while saving on the cost of the deposition.

By the experiment design and ANOVA analysis, the influence of the particle velocity on the operating performance of the coating prevailed in the case of the amorphous materials.

The mathematical model for the prediction of particle velocity is well suited to the experimental results derived from the empirical formula.

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