STUDY ON THE NEW SOLUTION OF AIR PLASMA SPRAY FOR IMPROVING THE PERFORMANCE OF AMORPHOUS COATINGS

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Abstract - Thermal spray processes found wide applications in many industries, including the automotive industry due to their versatility and efficiency. There were a lot of publications about the hard-facing of these components using some thermal spray processes: electric arc wire, High Velocity Oxygen - Fuel (HVOF), detonation, and plasma. The decision of the engineer depends on the context based on the specific character of the component, the operation condition, and the availability of the equipment. The typical generation plasma gas is the inert gas, namely the argon, helium, or their mixture. Recent publications have shown the result of deposition using amorphous powder, cermet, and self-flux materials. However, there is a lack of investigation on the air plasma spray using Fe-based powders. The contribution of this work is the new combining solution, including the innovation of a plasma torch, to spray Fe-based powders in the ordinary air for hard-facing provided wear resistance.

Key words - Wear resistance; hard-facing; air plasma spray; self-flux powder; amorphous Fe-based powder

1. Introduction

Coatings are a vital issue in combating solutions of component degradation in many aggressive industrial conditions and constitute a significant market. It is noted the total global revenue accounted for USD 7.58 billion in 2015 and is forecasted to grow at an annual growth rate of 7.79% to reach USD 11.89 billion by 2021 [1] for innovative development. The plasma spray in the atmospheric environment is recommended in many applications to eliminate the aggressive degradation from the operating conditions for many reasons. Some of these applications follow such as the special coatings to improve the frictional coefficient and increase the corrosive resistance in the cylinder–bore of internal combustion engines; it is expected an average enhancement of the corrosion resistance up to 50 % [2, 3].

Wear resistance had been recognized to have a significant economic impact on the operation of components in the industry. The overhaul and/or replacement of components depends on durability. That is why the enhancement wear resistance plays a key role in exploring any mechanical systems [4, 5].

Thermal barrier coatings (TBCs) are a typical example of the application of special materials to reach a very low thermal conductivity when exposed to high heat flow. Due to the requirement for elevated efficiency of machine parts that work in heavy conditions for application in the power, aerospace, and automotive industries, TBCs attract a special worldwide effort from researchers and managers [6].

The development of new applications for APS in detail and thermal spray coatings are strengthening and expanding this market. The list of these new functional coatings consists of super-hydrophobic coatings, coatings as heating elements, biomedical coatings, and coatings in electronics.

About the design of advanced wear-resistant depositions, many developments have contributed to the elimination of energy losses in the industry over the last decade. This area covers the innovation in design, investigation of properties, and the application of new wear-resistant compositions, including the fabrication of advanced wear-resistant ones. The first traditional group of the wear-resistant materials consists of tungsten carbide (WC), ceramic aluminum oxide (Al_2O_3), titanium carbide (TiC), and ceramic chrome oxide (Cr_2O_3). The hardness of tungsten carbide coating can achieve 70 HRC. The additional advantage of this coating is the ability of grounding to mirror surface and it serves a great substitution for hard chrome plating. The chrome oxide ceramic coatings are used for the environment of particle erosion, and cavitation at temperature below 450 °C. The other recommendation of this coating is the operation in corrosive chemical conditions due to their insolubility in acids, and alkaline. The aluminum oxide ceramic coating is an ideal wear-resistant material and thermal barrier one also when sealed. The next group of advanced wear-resistant material is under the brand “cermet”. There are some differences from the carbide family. Cermet is a composite material, which consists of a ceramic core mainly in form of carbide reinforced by a metallic binder. Such composition and structure bring in a new combination between hardness and toughness enabling the introduction of this type of material in wear-resistant substrate. Cermet material also exhibits superb performance in an erosive environment [7]. From this family, a newly developed cermet from Ti and elements C, N distinguish a unique performance: Good wear resistance, elevated erosive resistance, and high strength at high temperatures. In comparison with cemented carbide, they have better fracture toughness due to the complete solid–solution structure of cermet [8]. However, while they exhibit unique properties, there are still some disadvantages, such as poor oxidation resistance at high temperatures and inherent brittleness. According to the definition of cermet, this issue remains an open gap for any proper metal component to provide suitable ductility and heat conductivity. A hard ceramic phase normally constitutes up to 80% by volume, a remaining is a metal-binding phase [9]. For the continuous improvement of the performance of cermet materials, recent publications are valuable contribution related not only to theoretical but also experimental studies encouraging the progressive technologies, innovative development, and manufacturing processes, that promote their potential role for the industry [10, 11, 12, 13]. The newly developed group of wear-resistant materials is amorphous with sophisticated performance. They have distinguishable properties in comparison with crystalline materials due to a lack of crystal defects, such as grain boundaries and dislocations. They attract a wide range of application in the industry, using a well combination between high elongation limit, superior wear resistance, high corrosion resistance, high strength, and stiffness. Generally, amorphous alloy can be produced by rapid solidification, which is the specific nature of the deposition coating using the thermal spray technology. Gang Wang et al. carefully studied the corrosion resistance of the system (Fe, Mo, Cr, B, C) alloy feedstock for HVAF coating and they concluded that Fe-based amorphous material is considered a surface protective coating at low cost [14]. The relationship between the wear properties of the $FeCoCrNiMo_{0.2}$ coatings and plasma spraying power was investigated by Shitao Zhang et al. [15].

All researchers and constructors in close collaboration with the universities, and institutes, contributed their efforts to improving the efficiency of the deposition of the coatings. These publications focused on: arc stabilization, plasma flow concentration, velocity distribution, and the efficiency of deposition, including the cathode and anode contour design. The existing direct current plasma torch is operating on the principle of self-adjusting arc length. The main drawback of this type of torch is the shunting of the arc results in the limit of its voltage. The shunting of the arc also causes the fluctuation of the plasma stream in the profile. This unstable plasma flow decreases the quality of the coating. The weight loss of the anode and its erosion position depends on the current of plasma, the flow rate of gas, the contour of the anode, and the plasma torch power.

As rule, argon used as a primary plasma gas, since it is the easiest to initiate a plasma and tends to be less aggressive for electrode and feedstock. Nitrogen, hydrogen, and helium are mainly used as secondary gas. Argon and helium are noble gases. Argon plasma has some advantages but in comparison with the binary gases, argon exhibit less thermal conductivity and enthalpy. There is a limited publication on the discharge of plasma, using ordinary air, despite of its cost-saving and advantages in some specific applications of air plasma coatings. Nevertheless, with the innovation of torch construction and the optimal spraying parameters, ordinary air can be recommended for the wear-resistant coating of ceramic materials, especially Fe-based amorphous alloy [16, 17]. Ordinary air is a molecular gas and before ionization, it must be dissociated. That means ordinary air has enthalpy and thermal conductivity considerably higher than argon plasma. Consequently, the molecular gases consume much higher input energy to become partially ionized.

The hardness of the materials mainly depends on the chemical composition and microstructure. Speaking on the wear resistance of the material, it is a specific property since there are many other affected conditions, such as abrasive properties, environment, and test method. This relation is a complex issue, which needs more research and the optimal solution will be defined in the dependence on the operation conditions. When the coating on the surface of the substrate is harder than that of the mating one then there is a reduction of wear in that surface until it exists since the wear of harder material is less than that of the softer ones if the coefficient of friction is the same. The friction and wear are related to the dissipative irreversible processes which reduce the mechanical power and generate entropy.

From this context, the aim of this research is to design the new construction of the plasma torch working on the ordinary air, to spray the amorphous powder and evaluate the performance of the coating in terms of wear resistance and hardness, using the quantitative relations between the spray parameters and material properties.

2. Methodology

The experiment was implemented on the system SG-100 TAFA-Praxair, USA. The device 6510 LV(Japan) is used for the analysis of the chemical composition of 4 typical Fe-based powders and the results are shown in Table 1.

Table 1. *Chemical composition of powders, % mass*

Code	C	Cr	B	Mo	Ni	Mn	Si	Nb	V	W
A-4	0.11	32.9	0.10	3.30	5.0	1.05	0.70	-	-	-
B-5	0.06	35.3	0.40	3.50	10.5	1.05	0.91	-	-	-
C-10	0.41	12.5	-	0.70	-	0.54	0.66	0.73	0.35	6.10
D-5	0.73	5.0	0.25	4.20	-	1.25	0.84	0.54	1.20	-

The device Cilas-1090 is used to analyze the distribution of particle size. The high-end melt extraction analyzer (G8 Galileo, Germany) is applied forthe definition of the level of oxidation in the coating. In the experiment, the definition of the particle velocity in the plasma stream was conducted by the special camera Shimadzu HPV-2. It is necessary to measure the average mass enthalpy against the temperature of the individual particle since the coating consists of a melting particle stream by the collision on the substrate. The methodology for measuring the enthalpy was presented in [18]. During the experiment, it is reported the calculation of the consumption of the primary gas and the enthalpy with the error about the value of 2.5% and 7% accordingly. To determine the wear resistance, the typical method is used according to ASTM G133 standard [19]. The special software based on the least square method is used to calculate all experiment values and the plotting graphics.

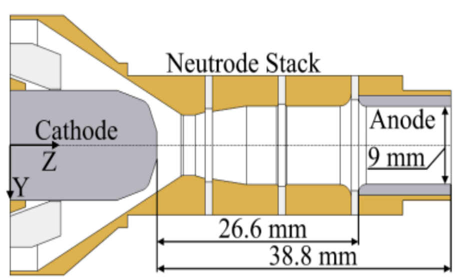

Figure 1. *Cascaded construction*

The new construction of a cascaded plasma torch using a special unit creating a spiral vortex flow that presses the arc stream not only in the arc column but also in the outer part of the nozzle helps the stabilization and efficiency of the spraying process (Figure 1).

In the production and assembling of all components in the cascaded plasma torch, it is strictly required the following criteria:

- The centricity of all intermediate rings with the cathode and anode;

- Good electrical insulation with tightness to avoid water leakage into the plasma chamber during the operation since it can lead to the breakage of the torch immediately;

- During the operation it is necessary to take into account the temperature of the cooling water, since it may impact the different expansion of the copper and insulator material, leading to leakage and sudden shunting.

A powder feeding upon the point scheme either in the area of the cathode spot, or in the area of the anode spot, under the influence of an asymmetric plasma jet, eliminates the sufficient processing of the particle stream, including the formation of clog. The axial feeding of powder into an opening channel in the cathode area was a complex design for the implementation. In this context, the idea of the input of the powder particles through the vortex device is considered the most interesting solution.

The vortex flow by a swirl injection unit improves gas mixing in the arc stream, isolation it from the walls of plasma channel and increasing of the voltage of plasma jet. (Figure 2).

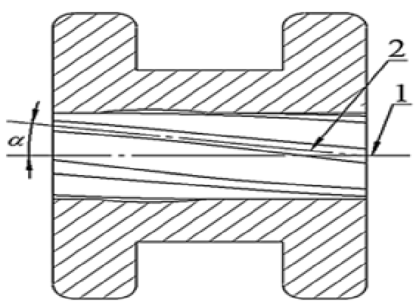

Figure 2. *Cross-sectional view of the gas injection ring*
1- Axis of the gas injection rings; 2- axis of the gas injection grooves

3. Result & discussion

Experiment 1:

The conditions of this experiment are as follows:

Table 2. *Value of the parameters in the plasma spray*

Current of plasma, I [A]	Voltage of plasma, U [V]	Flow rate of the air, G[g/s]	Version
130	220	1.2	1
185	190	1.3	2

The distance from the plasma torch to the substrate in the two versions is 130 mm. This experiment was set up to evaluate the influence of oxygen in the plasma stream on the deposition. The results of the analysisof the oxygen content are shown in Table 3. The result of measuring the particle velocity was described in Figure 3.

Table 3. *Comparison of oxygen content*

Code	Version	Content of the oxygen, %	
		In Powder	In Coating
A-4	1	0.20	1.75
	2	0.21	1.16
B-5	1	0.29	1.35
	2	0.31	0.08
C-10	1	0.19	1.25
	2	0.20	0.92
D-5	1	0.13	2.20
	1	0.13	1.60
	2	0.15	1.55

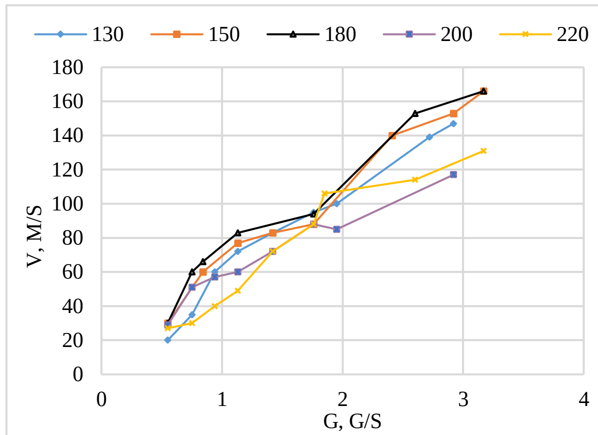

Figure 3. *Influence of flow rate and current on the velocity*

The result of the analysis from Table 3 shows the increased content of oxygen in the coating. Thus, this change had a dual effect on the wear resistance. The plasma spray process is carried in an open-air environment, the ordinary air freely intensified the oxidation of the material. Subsequently, it facilitates the oxidation of particles in the plasma jet and results in increasing the oxygen content in the coatings. On one side the elevated oxidation leads to an increase in the hardness of the coating, event negatively influences the wear resistance. On the other side, in some lubrication environments, it could bring a positive influence if the coating is working on the wear resistance. The wear resistance depends also on many other parameters of the operation condition, such as the loading, the type of lubrication, the properties of the counter surface, etc. It is useful to mention that the hardness degrades the bending, since it can be considered a cracking initiator. As reported in this experiment (version 2), the oxygen content in the coating is slightly decreased. It happened under the less influence of the oxygen in the plasma jet on the particles. Namely, the increased velocity limited the flight time of the particle.

Experiment 2:

This experiment is used to evaluate the influence of the current on the wear resistance and the adhesion bond. All parameters and results of the experiment are shown in Table 4.

Table 4. *Condition of spraying of coating D-5, using cascaded torch without gas injection ring*

Sample	Value of current - I, A	Value of flow rate- G, g/s	Value of wear resistance, in relative unit
1	120	1,42	58
2	150	1,42	53
3	180	1,42	42

Experiment 3:

In this experiment, the changing of spray parameters is shown in Table 5. It is suggested to use the cascaded plasma torch (Figure 1) without the gas injection ring (Figure 2).

Table 5. *Plasma spray of powder D-5, using cascaded torch, without the gas injection ring*

Number of sample	Value of current I, A	Value of flow rate G, g/s	Results of measuring of wear resistance, in relative units	Value of adhesion bond, MPa
1	160	0.55	22	23
2	160	1.13	54	40
3	160	1.76	39	35
5	185	0.75	30	46
6	185	1.42	68	56
7	185	1.76	40	54

Results of the experiment in Tables 4 and 5 certified that the increasing current of plasma (plasma power) helps to increase the velocity of particles in the plasma stream. In turn, the velocity enhances the wear resistance of coating D-5, since the kinetic energy of the system is elevated.

At the very low flow rate of gas, it is noted the relatively low wear resistance. When the flow rate is increased, the value of the wear resistance changes in non-linear relation. At slow velocity, the melting of particles is favorable and it strengthens the cohesion bond of the deposition. The wear resistance is improved also. But over the definite threshold, the increasing flow rate without changing the power of the plasma stream will cause the decrease of the cohesive bond in the coating, also the wear resistance due to poor melting conditions for the particle in the plasma stream. The increase in the velocity of particles elevates the cohesion and adhesion bonds with slight changing in plasma power, providing favorable improvement in the wear resistance since the velocity factor (kinetic energy) begins to play a significant role over the heating factor. This feature is described in the high-velocity oxygen-fuel (HVOF) spray or cold spray processes. The general tendency of change of the wear resistance depending on the flow rate of the air almost coincides with the changing of the adhesion bond, excluded a very low flow rate. It can be explained probably due to a reason that the low velocity provided a good cohesion bond, but also a poor adhesion bond.

Experiment 4:

The series of next experiment is conducted with the new design gas injection ring, installed in a plasma torch (Figure 2). The injection angle varied on 20°, 30º, and 40°. By changing the injection angle in different spraying conditions, including the flow rate of gas, the arc voltage, and the arc current, it is established the flexible regulation of spraying parameters to enhance the thermal efficiency in general and the specific enthalpy in detail.

For the evaluation of the new design of plasma construction on the velocity of particles, the wear resistance, and the adhesion bond, it is a set the experiments, parameters, and results which there are shown in Table 6 and Figure 3. Note the injection angle of 30°. Material – powder D-5; average size: 40 µm; distance of spray: 130 mm.

Table 6. *The plasma spray of powder D-5 in cascaded torch, using the gas injection ring*

Sample	Value of current I, A	Value of flow rate G, g/s	Value of wear resistance, in relative units	Value of adhesion bond, MPa
1	150	0.55	27	25
2	150	1.13	63	45
3	150	1.76	49	38
4	150	2.42	78	32
5	180	0.75	35	47
6	180	1.42	88	58
7	180	1.76	52	55
8	180	1.95	78	32

The comparison of the results from Table 5 and 6, shows the elevation of the wear resistance of the coating by about 20% accordingly. At the same time, the adhesion bond just slightly increased. It happened due to the stabilization of the plasma stream using the injection ring, which facilitates the efficiency in melting of particles, kinetic energy (velocity) of particles and reduction of the porosity in the coating, finally improving the wear resistance.

It is necessary to recognize the following valuable conclusions:

- The voltage in arc discharge, thermal efficiencies and specific enthalpies all increase when the angle of the gas injection increases, but spray parameters are unchanging.

- The specific enthalpy of the plasma jet decreases overall when the flow rates of the gas increase at the same angle of gas injection.

- There is an angle of 30° as the substantial limit for changing the tendency with the jet length and the angle of the gas injection. Consequently, the decreasing axial velocity of gas causes a prevailed effect over the influence of the increasing power of the electric discharge when the angle of gas injection is larger 30°. But the length of the plasma jet decreases with the increase of the angle of gas injection when it is larger 30° also.

4. Conclusions

- The new design of the plasma torch, using the cascaded construction and the injection annular unit help to significantly improve the efficiency of the plasma stream containing the feedstock powder and enhance the performance of the coating, especially the wear resistance.

- The preliminary investigation of some new amorphous Fe-based powders in air plasma spray encourages the prospective solution in terms of saving the production cost, on which the managers, constructors, and contractors focus to make recommendation in the industry.

- In the future, it is useful to continue the investigation for the optimization of the spray process based on the complete evaluation of all main spray parameters regarding the microstructure and phase transitions under the influence of size effect of the powder.

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