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Research Article

The Innovation in Air Plasma Spray for Hardfacing

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Abstract

Thermal spray coating plays a significant role in industry. The wear-resistant deposition helps to provide a longer life cycle for the components. There is an ongoing effort to develop coatings that improve the coefficient of friction. Compared with other deposition techniques, plasma spray coating can be recommended for a wide range of substrate materials to produce a stable, wear-resistant material. The plasma-sprayed deposition not only improves tribological performance but also embeds the desired mechanical and physical properties. In plasma spray technology, the inert gas used is mostly plasma jet. To create the wear-resistant coatings, the engineers apply self-flux or cermet powder, both of which are expensive materials. Some positive results of deposition using the amorphous powder encouraged the engineers and researchers. But in a few of the investigations on the air plasma spray Fe-based powder, the plasma generation gas is ordinary air. This innovation served to save on production costs. The aim of this work is the study of Fe-based spraying, applying the modification of a plasma torch. Both of the innovations help to enhance the hardfacing effect for wear resistance.

Keywords

Wear Resistance
Deposition
Microstructure
Production Cost
Kinetics of Stream

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1. Literature Review

Thermal spraying found wide applications in the struggle against the introduction of the service life of the component operating in a heavy environment. There is a huge demand for this area due to its efficiency, not only in aerospace but also in other branches of industry. The total global coating revenue was raised to USD 9.69 billion in 2021, and it is expected to reach USD 19.02 billion by 2030. (Straits Research Report to 2030) Aerospace coatings with very specific performance can be considered a special solution for eliminating the risk of the degradation of the components due to severe operation in aircraft. It is noted that there is a high demand to design new materials in this industry since the whole cycle of service in the aerospace industry requires a specific standard specification. The operation of the aerospace components required the special depositions assigned to avoid any air instability, thermal fluctuation, or unstable pressures. The protective layers also provide the aircraft with the ability to resist the harmful chemical effects of the environment. The newly developed coating materials show the advantages outlined, helping the aerospace industry save on production costs. The APEC countries are strongly involved in global boom competition, creating new chances and challenges for aerospace coating growth. The main drive for the expansion of the Asia-Pacific region market is derived from the rising aerospace and aviation industries in these countries. The strong stream of passenger circulation and international business contributed to an enhanced huge project of aerospace development in all related aspects. The boom in aircraft production and the new routes are leading to an expansion of the aerospace coatings market. According

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to recent forecasts, the growing capacity and contract between companies in the APEC community created good opportunities for the development and manufacturing of new coatings in the aerospace industry. According to The Insight Partners, the aerospace coating industry will increase from US$ 1.81 billion in 2019 to US$ 2.92 billion by 2027. (Partners, 2023). It is useful to introduce some applications of the thermal spraying process used by big companies such as Boeing and Airbus. Thermal spray coatings of hard chrome are environmentally safe. The newly developed High Velocity Oxygen- Fuel (HVOF)-sprayed coatings are far superior in wear resistance and corrosion resistance compared with the traditional spraying processes. In companies like Boeing and Airbus, metallic carbide coatings like WC-CoCr using HVOF technology are applied to improve the sliding wear resistance of hydraulic actuators and landing gear components. In the jet engine, severe operation conditions like fluctuating temperatures, high levels of oxidation, and strong erosive corrosion caused an intensive degradation problem, leading to the design of specific coating compositions with advanced spraying systems. Thermal spray technologies and processes, like (HVOF) and air plasma spray (APS), are applied to deposit on these components the state-of-the-art layer, increasing their service life. The components in the aircraft engine and landing section became more efficient in terms of higher speed and less fuel consumption due to reliable and advanced spray processes. It is recommended that the entire specific quality standard, including the guidelines and testing procedure, be binding to not only engine manufacturers but also authorized maintenance and repair contractors. Depending on the operating environment, each component of an aircraft engine exhibits specifications that reduce their service life. The Atmospheric Plasma Spraying (APS) process is well known in the industry to reduce the harmful impact of environmental operations. It is useful to nominate these applications, such as the specific deposition that improves the tribology and enhances the corrosive resistance in the engine block. The wear resistance of components plays an important role in saving costs during service life in industry.

The reliability of components is determined by the technical criteria setting the schedule for their maintenance. Based on these arguments, it is necessary to increase the wear resistance as the milestone factor in the running of any dynamic combination. (Joshi and Nylen, 2019; Sadeghi et al., 2019).

The thermal barrier coatings (TBCs) deposited by special ceramic materials exhibit significant low thermal conductivity even under high heat flow. The high demand for increased efficiency of machine components operating in heavy conditions in the aerospace and automotive industries using TBC coatings constitutes a specific worldwide effort. (Mondal et al., 2021).

The newly developed APS processes are spreading to the coating market. Cermet, consisting of a ceramic core with the main ingredient carbide, is reinforced by a metallic binder. There is a successful combination between hardness and strength, varying not only the composition but also the structure, providing a well-known wear-resistant material. The other advantage of cermet is that it also recognizes a super characteristic against an erosive environment. (Hussainova and Antonov, 2007). The new type of group-cermet Ti (C, N)-based exhibits state-of-the art performance with heightened high wear resistance and high erosive resistance, especially at high temperatures. They have better fracture toughness against cemented carbide since the solid-solusion phase is costituted (De la Obra et al., 2016).

However, as rules, they also have demerits, such as poor oxidation resistance at high temperatures and inherent brittleness. A core ceramic ingredient commonly constitutes up to 80% of a remain, which is a metal-binding matrix (Jose et al., 2022). Amorphous materials are the most advanced group of wear-resistant materials with outstanding properties. The principle of formation amorphis is the disordered structure of an alloy by rapid solidification; is it worth investigating this process during the deposition coating? (Wang et al., 2016) presented the analysis on the corrosion resistance of the Fe-Cr-Mo-C-B alloy material for High Velocity Air Fuel (HVAF) coating, and the results confirmed the prospective deposition from Fe-based amorphous materials. The recent papers focused on the arc efficiency, the density of the plasma stream, the acceleration of particles, and the productivity of spraying. For the direct-current plasma torch, the arc length is self - adjusting. It is noted the reduction in voltage since the fluctuation of the plasma stream caused the shunting effect. The other side effect is the fluctuation in the plasma power flow, resulting in a negative quality of the surface layer. Some publications focused on the influence of the density of current around the anode and its count on the service life of the torch. On the other side, there are very few publications investigating the possibility of ordinary air as a substitution for the notable inert gas, in spite of its cost savings. The bilateral impact of ordinary air in spraying Fe-based alloys varies depending on the specific tribology condition. The significant result recommends the use of ordinary air in thermal spraying Fe-based alloys due to the new count of plasma torch with the limited range of input parameters (Kuzmin et al., 2021; Kuzmin et al., 2017). The tribology and friction conditions are the subject of many publications relating to the spraying materials since the difference in hardness of the deposition and substrate determines the mutual relationship. Friction and wear are in close relation and could be considered the reducing factor of power in mechanical systems. Based on the above-mentioned analysis, the target of this paper is to develop an innovative plasma torch using ordinary air as plasma generation to deposit the Fe-based material to improve the hardness of the coating. The quality of the surface layer deposited is evaluated, referring to the hardfacing formation. The input factors and characteristics of the feedstock are analyzed by quantitative relations.

2. Methodology

In the experiment on spraying materials, the system SG-100 TAFA-Praxair was involved. The chemical composition of four Fe-based powders (Vu and Thu., 2021) was analyzed using the device SM-6510LV. The results of the analysis are presented in Table 1.

It is necessary to define the impact of the oxygen from the open atmosphere on the composition of the deposition, including the oxygen percentage contained in the feedstock material and coatings. The analyzer G8 Galileo (Germany), working upon the principle of definite melt extraction, was used for this purpose. The kinetic energy of the particle stream plays a significant role in providing a strong adhesion bond between the coating and the substrate. Adhesion can be considered an important criterion for the performance of the deposited layer. That is why the high-speed camera Shimadzu HPV-2 was involved during the experiment. Besides the kinetic energy, the heating of the particle during short-time flight to the substrate makes it more plastic, leading to good deformation and the creation of strong cohesion in the coating. It is better to measure the enthalpy of the plasma stream instead of a separate particle since only the particle stream is the main total thermal factor. The method of enthalpy definition in the system was presented in (Zhang et al., 2012). As mentioned above, the cycle life of the aerospace component depends on its wear resistance since it is in severe conditions. The suitable standard for the evaluation is the ASTM G133 standard. The efficiency of the plasma stream depends on the concentration of heating and accelerated particles in the feedstock, especially under the influence of the atmospheric environment. On the other hand, the method of introduction of the powder onto the plasma torch also impacts the productivity of the deposition. These requirements are solved by the newly developed design of the plasma torch, which consists of a number of intermediate sections that are thermally and electrically isolated. Further innovation is the installation of a special swirler in a cascaded plasma torch, creating a spiral vortex flow.

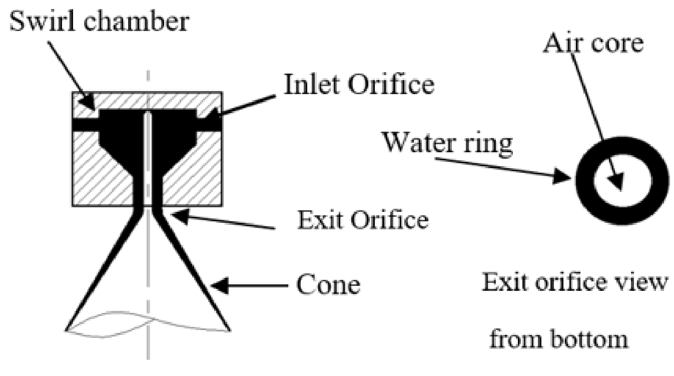

Fig.1. Swirler

The flow under the pessure of the gas stream and the dynamics process will press the arc stream along with the arc column, including the outer space. All these improvements enhance the stability of the plasma stream and the productivity of the deposition cycle. (Fig. 1).

The swirler installed on the plasma torch creates vortex circulation into the chamber, improving the mixture between the feedstock particles and plasma stream. By pressing the plasma stream, it will be isolated partially from the walls of the plasma chamber and encourage the voltage of the plasma jet to be elevated.

3. Experiment & Result

Case study 1:

The aim of the experiment is to enhance the thermal efficiency to increase the specific enthalpy of the plasma stream, including the feedstock material. It can be achieved by varying the injection angle in the swirler simultaneously with the spraying conditions, namely the flow rate of gas, arc voltage, and arc current.

- Current I = 135 A, voltage U = 220 V, and flow rate of air G = 1.2 g/s.
- Current I = 180 A, voltage U = 220 V, and flow rate of air G = 1.35 g/s.

In these spraying experiments, the spraying distance was kept constant at L = 120 mm. The increased enthalpy in the plasma stream also facilitates the oxidation of the Fe-based powder. The level of oxidation can be evaluated by comparing the oxygen content in the feedstock and the coating layer. The results of the experiment are presented in Table 2.

It is found a slightly the oxidation in the deposited layer. The oxidation of the feedstock happened due to the plasma stream generated by ordinary air, and the whole plasma jet with the Fe-based particle was conducted in an open-air environment. The oxygen in the environment reacted with the material of the particle, consequently increasing the oxygen content in the sprayed layer. The elevated hardfacing in this case helped to increase the wear resistance, illustrating a positive effect on oxidation.

Case study 2:

In this experiment, the loss of alloy elements by the variation of the input parameters will impact the hardness of the deposited layer. The range of setting parameters is as follows:

- Current I = 130 A, voltage U = 203 V, flow rate of air G = 2.35 g/s.
- Current I = 170 A, voltage U =220 V, flow rate of air G = 2.35 g/s.

In both modes of spraying, the spraying distance was keep constant at L = 130 mm.

It is interesting that in version 2, when the particle velocity increased, the flight time of the particle in a rich oxygen environment reduced, but it is also noted that the elevated oxidation level in the plasma jet, since the power of the plasma jet caused the high temperature, resulted in the strong activation of the alloy composition. The bilateral effect of the acceleration of the feedstock particle was found, taking into account the influence of the plasma jet power.

The result of the analysis of the chemical composition and hardness definitions presented in Table 3.

In all experiments, the loss of elements happened since the spraying process was implemented in the open atmosphere using ordinary air as the plasma generation. However, the increased power of the plasma jet (version 2) is the additional reason for the greater loss of elements. It is easy to observe the slight loss of some elements, such as Cr, Mo, and Ni, which can originate from an error in the chemical analysis. Thus, the violation is considered acceptable. For the powders H4 and H10, the increased nitrogen content (N2) is noted. It is assumed that the chemical interaction between the melted metallic particles and the environment leads to the definite involvement of nitrogen from the surrounding atmosphere.

The target of this experiment is to evaluate the wear resistance and bonding strength of the coating layer under the variable current of the plasma jet and its flow rate in the air. The feedstock in this case study was nominated for material X5 since its hardness reached the highest in comparison with all remaining alloys in the previous experiment. That is why it is useful to access the habit of this alloy material under the changing main conditions of the spraying process, such as the power of the plasma jets via the current of plasma and the flow rate of the air.

From of all four materials, powder X5 exhibits the highest hardness.

Case study 3:

In this case study, the wear resistance of the deposited layers will change under the varying flow rate of the air without changing the plasma current. All the parameters of these experiments are shown in Table 4.

Data in Table 4 shows a tendency that the elevating current of plasma (plasma power) has accelerated particles, which results in an increasing wear resistance of deposition from materials X5.

Table 1. Chemical composition of powders.

Code	C	Cr	B	Mo	Ni	Mn	Si	Nb	V	W
H4	0.11	32.9	0.10	3.30	5.0	1.05	0.70	-	-	-
B5	0.06	35.3	0.40	3.50	10.5	1.05	0.91	-	-	-
H10	0.41	12.5	-	0.70	-	0.54	0.66	0.73	0.35	6.10
X5	0.73	5.0	0.25	4.20	-	1.25	0.84	0.54	1.20	-

Table 2. Evaluation of the oxidation level.

Code	Case	Content of the oxygen, %	
		Feedstock materials	Deposited layer
H4	1	0.20	1.75
	2	0.21	1.16
B5	1	0.29	1.35
	2	0.31	0.08
H10	1	0.19	1.25
	2	0.20	0.92
	1	0.13	1.60
	2	0.15	1.55

Table 3. Result of the experiment in case study 2.

No	Mark	Lot	Chemical composition of alloy / level of loss in relative %											Hardness
			C	Cr	B	Mo	Ni	Mn	Si	N	Nb	V	W	HRC
1	H4	1	0.1	29.6	0.09	3.36	4.37	0.69	-	0.4	-	-	-	44
		2	9.1	10.1	10.0	(1.82)	12.6	34.3	-	33.4	-	-	-	
2	H4	1	0.1	29.6	0.08	3.35	4.5	0.55	0.35	0.5	-	-	-	46-52
		2	9.1	10.1	20.0	(1.52)	10.0	47.6	50.0	66.7	-	-	-	
3	H10	1	0.09	34.1	0.88	3.4	10.5	0.27	0.67	0.5	-	-	-	41-45
		2	(50)	3.4	16.2	2.9	20	46	26.4	0.0	-	-	-	
4	H10	1	0.09	35.1	0.27	3.49	10.5	0.92	0.67	0.5	-	-	-	41-43
		2	(61.7)	0.45	46.0	0.3	0.0	12.4	26.4	(0.2)	-	-	-	
5	B5	1	0.38	11.1	-	0.66	-	0.5	-	-	0.56	0.27	5.9	34 -42
		2	6.1	11.2	-	5.7	-	7.4	-	-	23.3	22.9	3.3	
6	B5	1	0.37	10.5	-	0.7	-	0.4	-	-	0.48	0.27	5.9	46-52
		2	9.8	16.0	-	0.0	-	25.9	-	-	34.3	22.9	3.3	
7	X5	1	0.52	5.25	0.15	4.0	-	1.2	-	-	0.56	1.06	-	50-54
		2	28.8	(5.0)	40.0	4.8	-	4.0	-	-	(3.7)	11.7	-	
8	X5	1	0.41	5.2	0.1	4.0	-	1.0	-	-	0.55	1.1	-	45-52
		2	43.8	(4.0)	60.0	4.8	-	20.0	-	-	(1.9)	8.4	-	

The low velocity encouraged deep melting of the particles, which subsequently strengthened the cohesion bond between particles in the coating, significantly improving the wear. But unfortunately, if the flow rate of gas continuously increases, it will have a negative influence on the cohesive bond, reducing its wear resistance because of the uncomplete heating state.

The continued acceleration of particles over the definite threshold positively improves the cohesion and adhesion bonds, resulting in increased wear resistance. This is evidence of the velocity factor (kinetic energy) over the thermal (heating) channel. In other words, it is suggested that the general tendency of wear resistance is changing significantly along with the flow rate of the air. This relationship almost coincides with the changing adhesion bond, excluding the case of the very low flow rates of the air. The reason for this case is probably the fact that the low velocity affects not only the good coherence bond but also the poor adhesion bond. The fifth mode in Table 4 simultaneously presented a high value for the wear resistance and the adhesion bond. It is recommended to continue the investigation in more detail in the future.

4. Conclusion

The newly developed plasma torch construction, using cascaded intersections between anode and cathode with the injection annular swirler, is a valuable contribution to a significant improvement in the wear resistance of the coating. Plasma spraying of the Fe-based powder using an advanced torch helps to increase the productivity of the deposition process. The final aim is enhanced hardness, which helps increase the service time of the components operating in a hostile environment, such as in aerospace and aircraft systems. The result of the preliminary study using newly developed amorphous Fe-based powders for atmospheric plasma spray opened up prospective ways of saving production costs and attracted the managers, constructors, and contractors who made suitable recommendations in industry.

In the future study, it is expected to conduct a complete experiment with multiple target functions of the spray process. It is expected to open up a new advanced performance of the plasma coatings since the hardfacing plays a significant role in improving production costs for the aerospace industry. The intensive mode of spraying (number 5 in Tab.4) is the most successful.

Table. 4 Wear resistance and adhesion bond of coatings X5 upon the flow rate of the air.

Number	Current I, A	Flow rate G, g/s	Wear resistance in relative units	Adhesion bond, MPa	Assessment
1	160	0.55	22	23	Fail
2	160	1.13	54	40	Good
3	160	1.76	39	35	Fair
4	185	0.75	30	46	Fair
5	185	1.42	68	56	Very good
6	185	1.76	40	54	Good

Nomenclature

APEC : Asia-Pacific Economic Cooperation

TBC : Thermal barrier coating

HVOF : High Velocity Oxygen- Fuel

APS : Air plasma spray

HVAF : High Velocity Air Fuel

ASTM : American Society for Testing Materials

CRediT Author Statement

Vu Duong: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Review & Editing, Supervision.

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