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An Evaluation of the Electric Arc Spray and (HPPS) Processes for the Manufacturing of High Power Plasma Spraying MCrAlY Coatings

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The high power plasma torch (PlazJet) can be used to spray refractory ceramics with high spray rates and deposition efficiency. It can provide dense and hard coating with high bond strengths. When manufacturing thermal barrier coatings, the PlazJet gun is well adapted to spraying the ceramic top coat but not the MCrAlY materials that are used as bond coat. Arc spraying can compete with plasma spraying for metallic coatings since cored wires can be used to spray alloys and composites. In addition, the high production rate of arc spraying enables a significant decrease in coating cost. This paper discusses the performances of the PlazJet gun, and a twin-wire arc spray system, and compares the properties and cost of MCrAlY coatings made with these two processes. For arc spraying, the use of air or nitrogen as atomizing gas is also investigated.

Keywords arc spraying, bond coat, economic analysis, PlazJet

1. Introduction

MCrAlY coatings used as bond coats for thermal barrier coatings (TBCs) can be applied by air plasma spray, vacuum plasma spray, high velocity oxy-fuel spraying,[1] and arc spraying. According to the spray process, coatings exhibit specific properties that make it possible to select the most suitable process for the considered application.

In this study, the bond coat of TBCS is deposited on large-sized substrates and used under specific working conditions. These involve vacuum and corrosion by hot liquids but no thermal cycling. For TBCs that work under vacuum, the oxidation phenomena at the interface between the top coat and bond coat[1] do not take place and the TBC's lifetime depends very little on the internal MCrAlY coating oxidation. To achieve good corrosion resistance from liquids, the surface of the ceramic coating must exhibit a low roughness. It must also be dense without cracks or open porosity. As the thickness of the top coat is limited to 200 μm for this application, the roughness of the bond coat must also be low; *i.e.,* the arithmetic mean roughness value (R_a) must be less than 10 μm and the maximum peak to valley height (R_t) less than 100 μm.

The PlazJet torch can develop electric powers up to 200 kW. This results in high particle velocity[2] producing dense and smooth coatings.[2,3] The high deposition rate (over 12 kg/h) of the PlazJet gun makes it well suited for large parts, as it significantly reduces manufacturing time and deposition cost. Arc spraying exhibits deposition rates in the same order as the PlazJet system for metals. In addition, the use of cored wires enables the arc spraying of superalloys.

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This paper presents a comparison of the coating properties and cost of MCrAlY coatings produced by PlazJet and arc spraying devices.

2. Experimental Procedure

2.1 Coating Deposition

The TAFA PlazJet gun model 7070 (TAFA Incorporated, Concord, NH) was equipped with a 120 mm long anode. Two powder feeders (model 9MPE, Sulzer Metco (US) Inc., Westbury, NY) were used to reach feed rates up to 12 kg/h. The plasma gas consisted of a mixture of nitrogen and hydrogen. Table 1 lists the operating parameters of the torch.

The twin-wire arc spray system used in this study is a TAFA model ArcJet 9000. The push-pull model, which refers to the manner of feeding the wires, was selected for its capability to work with cables and hoses of 7.50 m in length. This condition was mandated for spraying onto the large substrates. The arc system allows the use of a secondary atomizing gas injected around the electrodes, which is associated with the classical atomizing system.

Air and nitrogen were used as atomization gases. The ArcJet 9000 system can use various air caps of exit diameters 8, 7.7, 7, and 6.4 mm. They play a role on the electrode atomization and, thus, on coating properties. The spray conditions are summarized in Table 2.

2.2 Materials

The substrate was a nickel-based superalloy, with a surface area of 100 × 50 mm and a thickness of 2 mm. It was prepared by abrasion with Norton 80 sand paper prior to spraying. The average roughness of the substrate surface after preparation was of the order of 2 μm.

The atomized NiCrAlY powder used with the PlazJet gun was a Starck Amperit 413.1H.C. (Starck GmbH & Co., KG,

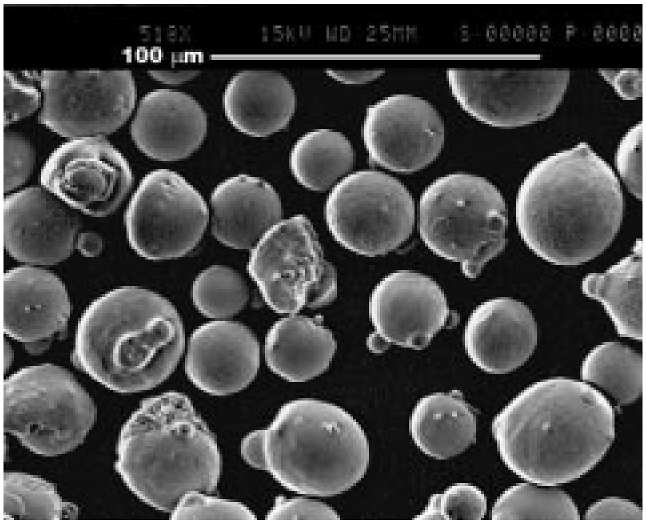


Fig. 1 SEM micrograph of the NiCrAlY powder

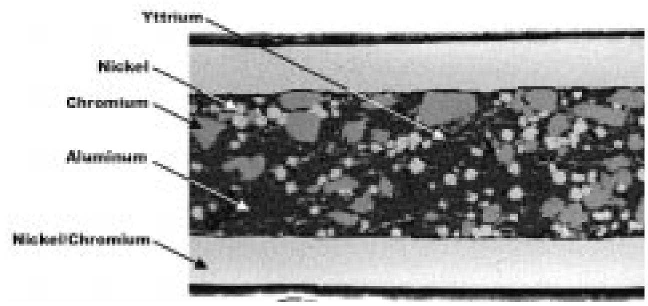


Fig. 2 Polished cross section of the 76MXC NiCrAlY wire

Table 1 Typical spraying conditions for NiCrAlY coatings using the PlazJet gun

Arc current	Nitrogen flow rate	Hydrogen flow rate	Arc voltage	Arc power	Gun thermal efficiency	Powder feed rate	Spray distance
400–500 A	9–15 m^3/h	0–4 m^3/h	250–370 V	100–185 kW	55%	6–12 kg/h	120–200 mm

Table 2 Typical spraying conditions for NiCrAlY coatings using the ArcJet 9000 system

Air cap diameter	Arc current	Arc voltage	Arc power	Primary atomization pressure	Secondary atomization pressure	Spray distance
6.4–7.7 mm	100–350 A (3–12 kg/h)	33–38 V	3–13 kW	0.4–0.7 MPa (60–100 psi)	0.4–0.7 MPa (60–100 psi)	50–150 mm

Table 3 Weight composition of the NiCrAlY powder

Ni	Cr	Al	Y
67%	22%	10%	1%

Table 4 Weight composition of the NiCrAlY wire

Ni	Cr	Al	Y
67%	22%	10%	1%

Goslar, Germany). Particles were of spherical shape and homogeneous composition. The particle size ranged between 22.5 and 45 μm with a mean diameter of 35 μm (Table 3, Fig. 1).

The NiCrAlY cored wire used with the ArcJet 9000 system was TAFA 76MXC, 1.6 mm in diameter. This size was selected to obtain coatings of low roughness. The polished cross section of the 76MXC wire is shown in Fig. 2; the wire consists of a nickel-chrome sheath, 350 μm thick, filled with a heterogeneous mixture of nickel, chromium, aluminum, and yttrium. Its composition is detailed in Table 4.

2.3 Coating Characterization

The NiCrAlY coatings were evaluated using optical microscopy and scanning electron microscopy (SEM). Deposition efficiency (DE) was calculated as follows:

$$\mathrm{DE} = \frac{P_d \cdot K \cdot V}{S \cdot D_p \cdot N_p} \qquad \text{(Eq 1)}$$

where P_d is the coating weight, K the overlapping of the passes, V the traverse speed, S the substrate surface, D_p the powder feed rate, and N_p the number of passes.

The coating roughness was determined as the average of ten measurements with a Perkin-Elmer (Norwalk, CT) profilometer. The oxide content of coatings was determined from coupled energy dispersive spectroscopy (EDS)/wavelength dispersive spectroscopy (WDS) analysis. The granulometry of the particles collected in flight during spraying was measured in aqueous solution using a Malvern (Southborough, MA) laser granulometer.

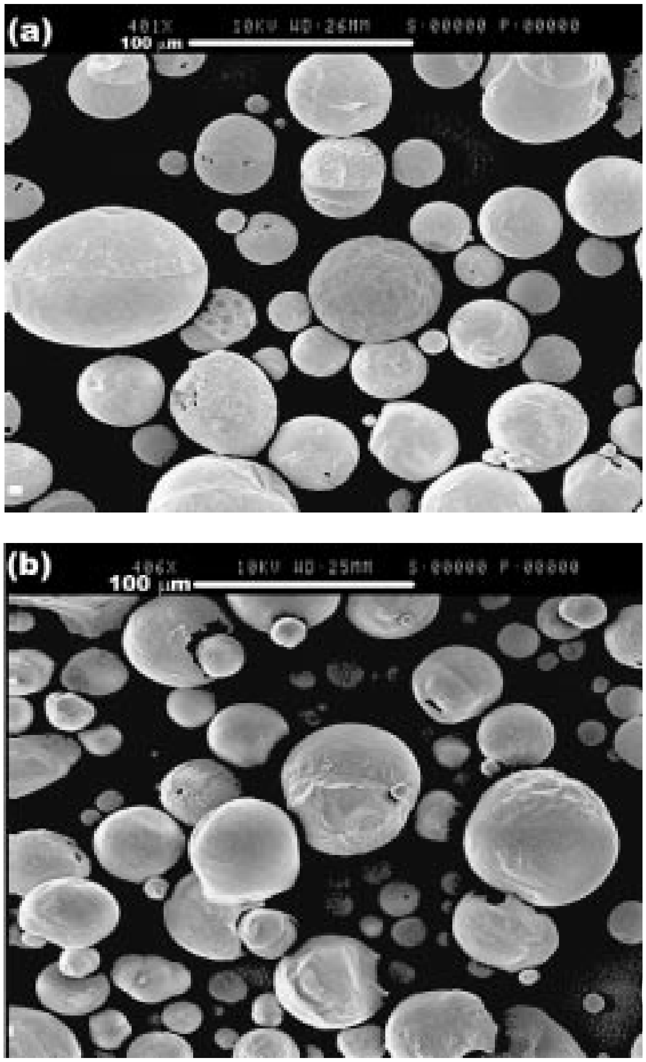


Fig. 3 SEM micrograph of powders collected in flight in the arc spray process using (**a**) air and (**b**) nitrogen as atomizing gases (200 A, 35 V, primary gas pressure: 0.5 MPa, secondary gas pressure: 0.5 MPa, and 7 mm nozzle cap diameter)

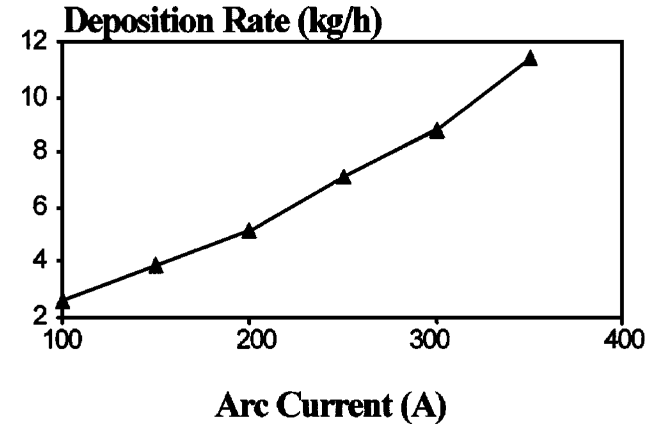


Fig. 4 Deposition rate vs arc current for the ArcJet 9000 using 1.6 mm diameter wire

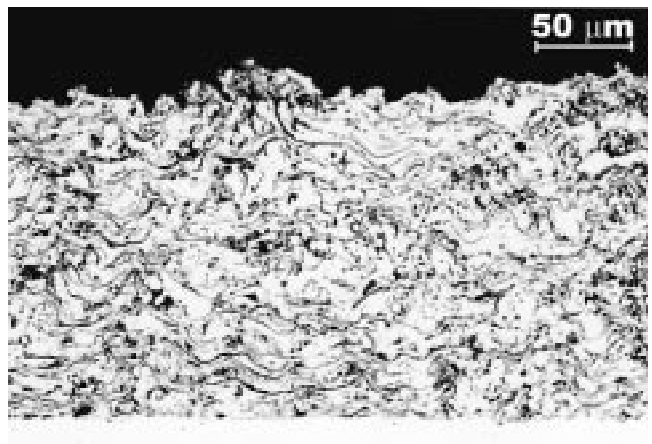


Fig. 5 Optical photomicrograph of NiCrAlY coating sprayed by the PlazJet system

3. Results and Discussion

3.1 Optimization of Process Parameters

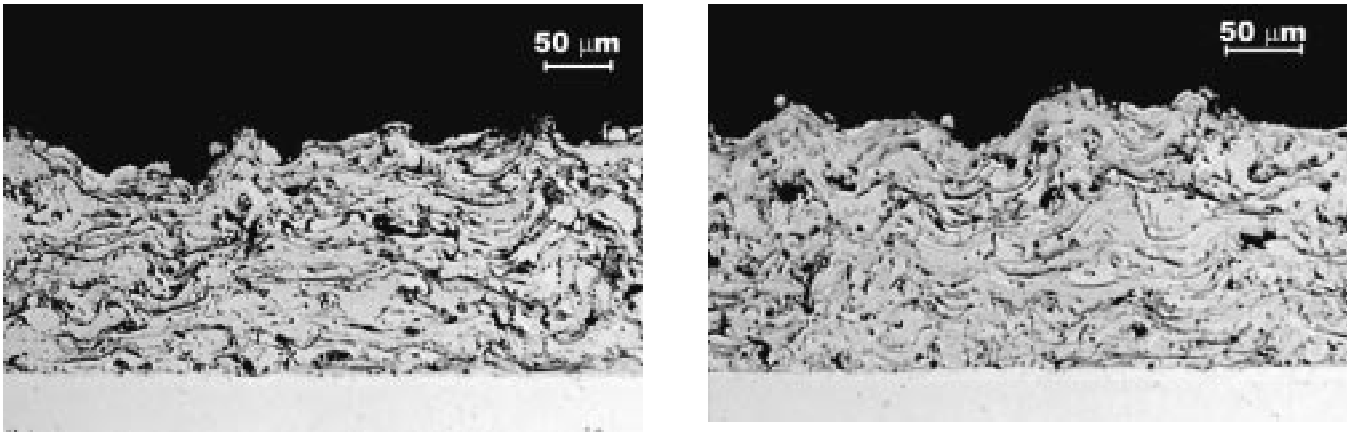
The PlazJet process parameters for NiCrAlY coating were optimized in a previous study (Ref 4) using a Taguchi design of experiments. Table 5 summarizes the range of plasma processing conditions and the parameters used in this study. The optimization of arc spraying parameters was conducted in order to minimize the surface roughness, maximize the material feed rate, and achieve high-quality coatings by decreasing the air cap exit diameter, increasing the primary and secondary atomizing gas pressures, and using an inert atomizing gas such as nitrogen.

In the arc spray process, the molten particles are cooled along their trajectory from gun to substrate. So, a long spray distance can result in solidified particles at impact, whereas a too short distance may favor a splashing phenomenon and a decrease in deposition efficiency. It has been found that a spray distance ranging between 50 and 100 mm will lead to the best coating microstructure.

Using a 6.4 mm diameter nozzle cap improves electrode atomization by an increase in the gas pressure around the arc zone and, therefore, influences the coating roughness, as illustrated in Table 6. Indeed, it has been shown[5] that an increase in atomizing gas pressure leads to a lowering of droplet diameters, resulting in a higher droplet velocity at impact and a lower surface roughness.

The analysis of droplets collected in flight (Fig. 3) showed that, for the NiCrAlY wires, the mean particle diameter decreased by 15% with a pressure of 0.7 MPa instead of 0.4 MPa. In this case, coating roughness decreased from 14 to 10 μm (Table 6). However, it must be noted that atomizing gas pressure above 0.4 MPa with a 6.4 mm diameter nozzle cap lead to arc instabilities due to gas turbulence around the electrode tips.

In arc spraying, inert gas atomization results in a decrease of coating porosity and surface roughness since the in-flight oxidation of droplets is reduced.[6] This enables better flattening of droplets on the substrate. It has also been observed that heavy gases such as argon could improve electrode atomization due to



(a) (b)

Fig. 6 Optical photomicrograph of NiCrAlY coatings sprayed by arc spraying, with (**a**) air and (**b**) nitrogen atomizing gas

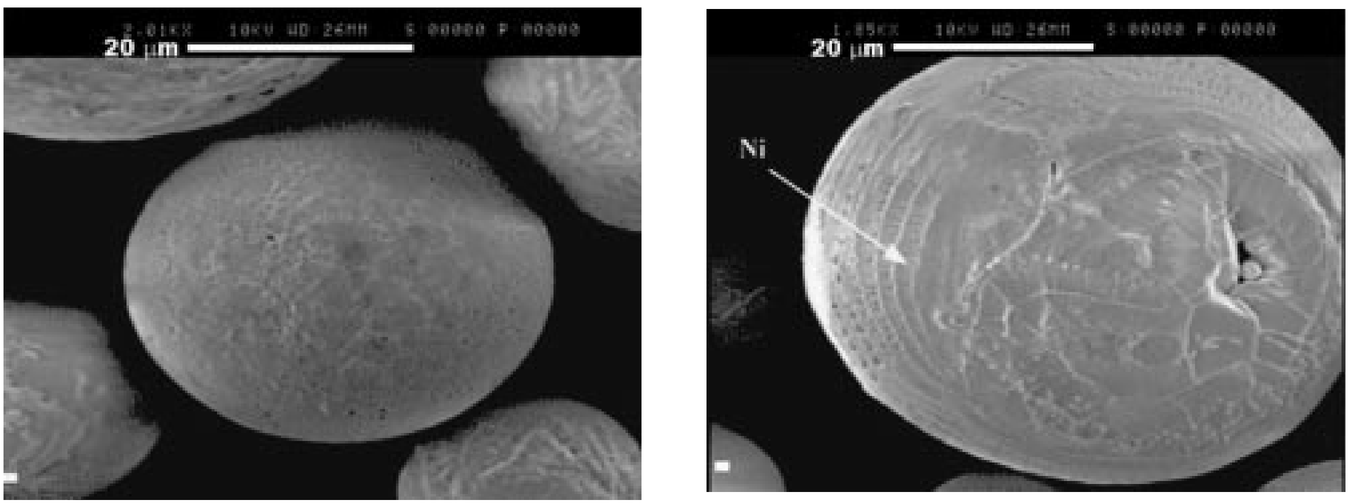


Fig. 7 SEM micrograph of homogeneous particles collected during arc spraying

higher viscous drag forces compared to that of lighter gases such as nitrogen.[7] This could contribute to the reduction of coating roughness and porosity.

In this study, the use of nitrogen as atomizing gas instead of air led to a reduction of the NiCrAlY coating roughness by about 20% (Table 6), although the droplet sizes with air and nitrogen atomization were nearly the same (Fig. 7 and 8).

The droplets were collected in a vessel filled with distilled water. The EDS/WDS analysis showed a reduction of about 10 wt.% of the oxygen content of the NiCrAlY coatings with nitrogen gas. Therefore, the decrease in NiCrAlY coating roughness can be related to lowering of the in-flight oxidation.

With a 1.6 mm diameter NiCrAlY wire, the ArcJet 9000 system can reach feed rates near 12 kg/h, for a 350 A arc current (Fig. 4). The deposition rate can be increased by using higher wire diameters, but this may produce high-roughness coatings because of a less effective atomization. Considering the size of the parts to be covered in this study, 7.50 m long electric cables had to be used for arc spraying. It was necessary to raise the system voltage by 3 to 5 V to compensate for the voltage drop in the cables. However, this increase could bring about arc instabilities when working with high arc currents, since the electric generator worked close to its design limits. Consequently, the arc current was limited to 250 A during coating manufacturing, and the deposition rate was 7.2 kg/h.

Under these conditions, two sets of parameters were found to produce satisfactory coatings with air and nitrogen atomization. These parameters are summarized in Table 7.

3.2 Coating Characterization

Table 8 lists the results for coating characterization. The NiCrAlY coatings sprayed by HPPS (Fig. 5) have a low surface roughness due to high particle velocity and low particle diameter at impact. The bond strength, higher than 40 MPa, is satisfactory considering the surface preparation of substrates and a pass thickness of 50 μm. The oxygen content of the coating was 15 wt.% and no inclusion of unmolten particles was observed. The

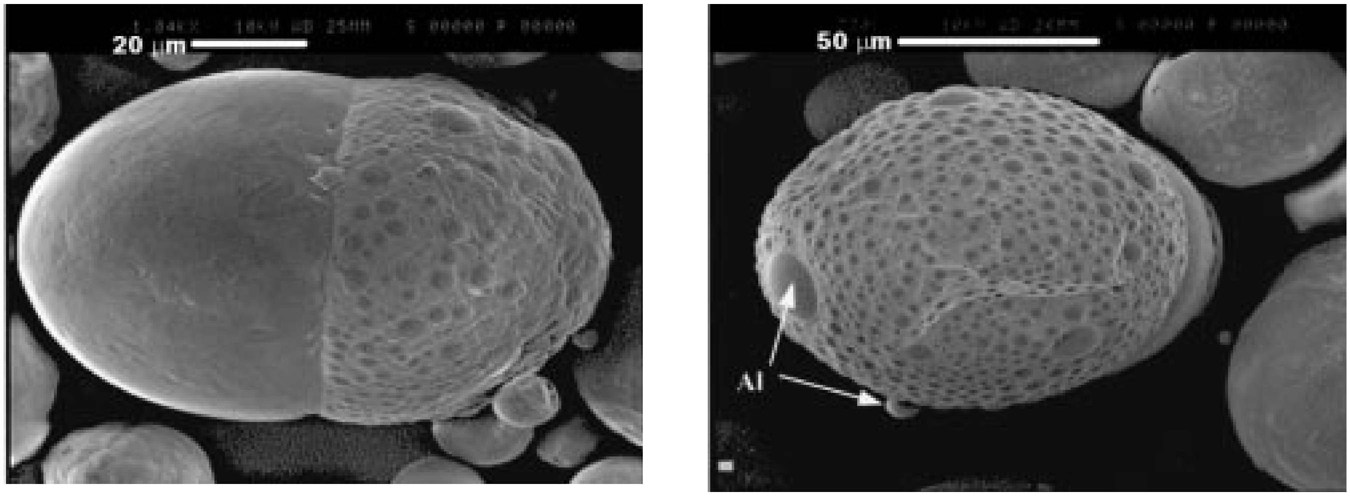


Fig. 8 SEM micrograph of heterogeneous particles collected during arc spraying

Table 5 Typical variations for Taguchi design of experiments and optimized parameters for NiCrAlY coating (HPPS)

Arc current	Nitrogen flow rate	Hydrogen flow rate	Arc voltage	Power	Powder feed rate	Spray distance	Relative speed gun/substrate
370–420 A	9.6–10.8 m^3/h	0–2 m^3/h	270–310 V	100–130 kW	9.6–12 kg/h	160–180 mm	0.75–1.5 m/s
400 A	9.6 m^3/h	…	290 V	115 kW	12 kg/h	160 mm	1.5 m/s

Table 6 Influence of arc spraying parameters on coating roughness in μm (200 A, 35 V)

Air cap exit diameter, atomizing gas pressure and nature											
ϕ7.7 mm 0.4 MPa, air		ϕ6.4 mm 0.4 MPa, air		ϕ6.4 mm 0.4 MPa, N_2		ϕ6.4 mm 0.7 MPa, N_2		ϕ7.7 mm 0.55 MPa, air		ϕ7.7 mm 0.55 MPa, N_2	
Ra	Rt	Ra	Rt	Ra	Rt	Ra	Rt	Ra	Rt	Ra	Rt
22 ± 3	160 ± 20	13 ± 1	100 ± 8	14 ± 1	105 ± 7	10 ± 0.5	80 ± 5	15 ± 2	110 ± 15	12 ± 2	90 ± 8

Table 7 Optimized parameters for NiCrAlY coatings produced by the arc spray process

Nozzle cap diameter	Atomization gas	Arc current	Arc voltage	Power	Primary atomization pressure	Secondary atomization pressure	Spray distance
6.4 mm	air	250 A	38 V	10 kW	0.4 MPa (60 psi)	0.4 MPa (60 psi)	100 mm
7 mm	nitrogen	250 A	38 V	10 kW	0.7 MPa (100 psi)	0.7 MPa (100 psi)	100 mm

Table 8 Characterization of the NiCrAlY coatings

Spraying system	Thickness μm	One-pass thickness μm	Deposition efficiency %	Bond strength MPa	Roughness Ra μm	Roughness Rt μm	Oxygen content wt%
HPPS	150	50	60	>40	7 + 0.5	65 + 5	15
Arc spray	120	40	60	>40	12 ± 2	90 ± 8	15

deposition efficiency of HPPS leveled off at 60% and corresponded to a powder feed rate of 12 kg/h at a deposition rate of 7.2 kg/h.

The coatings sprayed by arc spraying (Fig. 6) exhibited a higher surface roughness due to a relatively low particle velocity compared to that obtained with the HPPS process. The deposition efficiency reached the same value as that obtained with the PlazJet gun, for both air and nitrogen atomizing gas. As previ-

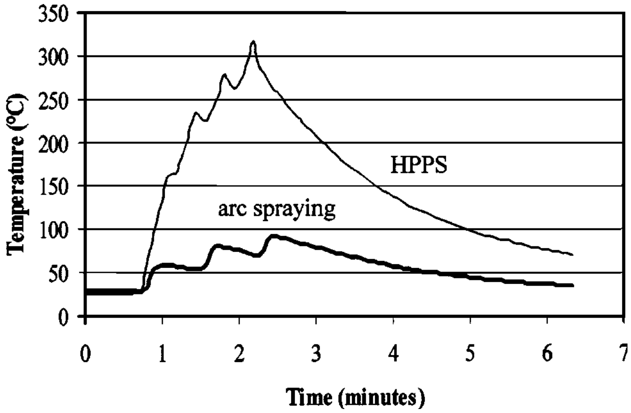


Fig. 9 Evolution of substrate temperature during spraying

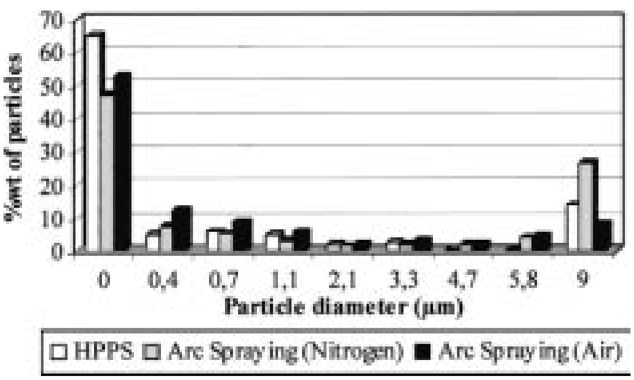


Fig. 10 Size distribution of fumes and dusts

ously observed, the use of nitrogen atomization resulted in a 10 wt.% reduction of the oxygen content, but no changes were observed in the bond strength. The latter was higher than 40 MPa.

The WDS analysis of the arc-sprayed NiCrAlY coatings showed that the composition was very heterogeneous because of the wire manufacturing method. As illustrated in Fig. 2, the NiCrAlY cored wire was composed of a Ni-Cr sheath filled with a heterogeneous powder of nickel, chromium, aluminum, and yttrium.

The observation of the droplets formed by the atomization of the wire showed two different types of particles. Type 1 particles were composed of pure nickel or aluminum-chromium. These homogeneous particles resulted from the melting and alloying of some elements of the powder filling the sheath (Fig. 7). Type 2 particles consisted of pure aluminum coming from the powder, with nickel-chromium coming from the sheath, as illustrated in Fig. 8.

3.3 Advantages and Drawbacks of Both Techniques

Differences in the design of HPPS and arc spray processes lead to specific operating conditions. The arc spray system does not allow the spraying of nonelectric conductor materials such as ceramics. However, the use of cored wires makes it possible to spray most of the existing alloys and composites.

Table 9 Fume concentration in atmosphere during spraying

Spraying technique	Fume concentration
HPPS	75 mg/m^3
Arc spraying (N_2)	100 mg/m^3
Arc spraying (air)	130 mg/m^3

The wire feed system requires a translation speed of the gun less than 1 m/s to avoid arc instabilities due to a nonconstant wire speed. In correlation with the high deposition rate, process parameters must be carefully chosen in order to achieve a reasonable pass thickness.

One of the advantages of arc spraying is the low thermal energy transferred to the substrate. Figure 9 shows the evolution of the Ni-base alloy substrate temperature with HPPS and arc spray processes, using the same one-pass-torch thickness. It has been observed that the temperature can vary by a factor of 2 between both techniques. Cooling of the substrate is not required for arc spraying.

From a safety point of view, the level of noise and light emissions from the arc spray process allows the use of lighter ear and vision protection than with the HPPS process. Nevertheless, due to the high temperature of wire tips, the emission of fumes and dusts of nickel and chromium is important. This requires the use of adequate respiratory protection. Table 9 shows the results of air analysis conducted in a ventilated spray booth, at a height of 1 m from the floor, using filters of different meshes. Most of the particles present in the dusts have a diameter below 0.4 μm (Fig. 10).

One drawback of plasma spraying is the time needed to achieve stationary working conditions, especially when using fluidized powder feeders. The design of the arc spray process makes it possible to start spraying instantaneously and, therefore, to avoid feed stock losses when using a deposition rate of 12 kg/h.

When the arc spray gun is handled by a multiaxis robot, it can be synchronized with the robot to stop spraying during substrate transfer or repositioning, and this reduces feed stock losses and coating cost.

4. Economical Aspect

The HPPS and arc spray systems exhibit higher deposition rates than other thermal spray systems. This decreases the production time and coating cost. However, the latter depends on the intrinsic working principle of both systems.

Table 10 shows an economic evaluation of NiCrAlY coatings sprayed with the PlazJet high power plasma gun and the ArcJet 9000 system. The production cost was calculated per kilogram of coating at a deposition rate of 12 kg/h and a deposition efficiency of 60%. The total production was set to two tons per year. Coatings were sprayed without substrate cooling.

This calculation shows that the arc spray process, using air or nitrogen atomization, is about 40% less expensive than the HPPS process. As with the majority of spraying systems, the material feed stock is the most expensive parameter for both systems. In this study, it represents about 84% of the total coating price for HPPS and 97% for arc spraying, while, since the deposition rate is high, the labor cost represents less than 5% for

Table 10 Evaluation of the NiCrAlY coating cost for HPPS and arc spray processes

	PlazJet system	ArcJet 9000 system using N_2 atomization	ArcJet 9000 system using air atomization
Gases	Nitrogen	Nitrogen	Air
System cost	198,500 USD	23,800 USD	23,800 USD
Amortization time	5 years	5 years	5 years
Amortization cost per kilogram of coating	**19.83 USD**	**2.38 USD**	**2.38 USD**
Material feed rate	12 kg/h	12 kg/h	12 kg/h
Spraying time per year	278 h	278 h	278 h
NiCrAlY powder and wire cost per kilogram	90 USD	63 USD	63 USD
Material feed cost per kilogram of coating	**150 USD**	**105 USD**	**105 USD**
Electric power	115 kW	10 kW	10 kW
Cost per 100 kWh	7.90 USD	7.90 USD	7.90 USD
Energy cost per kilogram of coating	**1.26 USD**	**0.11 USD**	**0.11 USD**
Plasma and atomization gas flow rate	9.6 m^3/h	105 m^3/h	65 m^3/h
Gas cost per 100m^3	3.40 USD	3.40 USD	0.50 USD
Gas volume used per year	2,670 m^3	29,200 m^3	18,000 m^3
Electrodes and tips costs	635 USD	6 USD	6 USD
Electrodes and tips lifetime	12 h	6 h	6 h
Expenditure cost per kilogram of coating	**7.39 USD**	**0.63 USD**	**0.18 USD**
Production cost per kilogram of coating	162.10 USD	154.80 USD	107.30 USD
Labor cost per kilogram of coating	8.45 USD	8.45 USD	8.45 USD
Total Production cost without amortization	**158.65 USD**	**105.74 USD**	**105.29 USD**
Total Production cost per kilogram of coating	**178.48 USD**	**108.12 USD**	**107.67 USD**

HPPS and of the order of 7% for arc spraying. The major cost point of the HPPS system is its purchasing cost. It represents 11% of total production cost, whereas it is about 2% for the arc spray system.

The difference in the electric power shows that arc spraying is more thermally efficient than plasma spraying, as it requires a power of 10 kW to spray 12 kg of NiCrAlY material per hour, whereas HPPS needs, at least, 110 kW.

5. Summary and Conclusion

A technical and economic investigation of high power plasma spraying and electric arc spraying was conducted for the manufacture of NiCrAlY coatings used as bond coats in a specific TBC's application.

These bond coats were sprayed on large substrates (100 × 50 mm) and used in specific working conditions (*e.g.,* liquid corrosion, under vacuum and no thermal cycling). The latter requires NiCrAlY coatings with a low surface roughness and tolerates internal oxidation and porosity. For the arc spray system, both air and nitrogen atomizing gas were used to achieve the best quality/cost ratio of the NiCrAlY coating.

This study showed that both processes produced coatings with similar properties, except for roughness. The roughness was lower with HPPS because of finer particle sizes and higher particle velocity at impact. But inherent working conditions of the arc spray process, as the possibility of synchronizing with the handling system or the low thermal energy transferred to the substrate, should make the system well suited for complex, large, and thin substrates. Comparing air and nitrogen atomization, the NiCrAlY coatings arc sprayed using nitrogen exhibit a lower roughness due to the lower oxide content.

From an economic point of view, arc spraying is a less expensive process because of the lower capital equipment cost. If the HPPS process makes it possible to obtain refractory ceramic coating with a high deposition rate, it is not the more suitable process for the spraying of NiCrAlY-like materials. Arc spraying provides NiCrAlY coatings with similar properties at a lower cost for the specific application of this study.

Acknowledgments

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