Effect of HVOF Processing Parameters on the Properties of NiCoCrAlY Coatings by Design of Experiments

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Abstract: The effect of three principal, independent, high-velocity oxygen fuel (HVOF) processing parameters on the properties of NiCoCrAlY coatings deposited using commercial powders is reported here. The Design of Experiments (DoE) technique at a two-level factorial and a central composite rotatable design was used to analyze and optimize the HVOF spraying process. The deposition parameters investigated were 1) fuel flow, 2) oxygen flow, and 3) stand-off distance. The effect of these processing variables was evaluated using selected responses, including porosity and oxide content, residual stresses, and deposition efficiency. Coatings with low porosity as well as with low residual stress were obtained using high fuel-rich conditions at a stand-off distance between 250 and 300 mm. At shorter and longer stand-off distances, respectively, either excessive flattening of splats or un-molten condition occurred, resulting in high levels of porosity and residual stress. The response surface, the empirical relationships among the variables, and the response parameters allowed the selection of optimum deposition parameters and the improvement of coating properties.

Keywords: HVOF Design of experiments, Residual stress, NiCoCrAlY, process parameters

Introduction

NiCoCrAlY alloys are widely used for high-temperature coatings and structural materials, particularly as overlay coatings or bond coats in thermal barrier coating systems (TBCs) in turbine engines due to its oxidation and corrosion resistance (Ref 1, 2). NiCoCrAlY alloys typically consist of c-phase, a f.c.c. Ni-rich solid solution, and b-phase, a b.c.c. (Co,Ni)Al. The microstructure can also include c-N Al precipitates and a-Cr, depending on the composition and temperature (Ref 3). These coatings have been deposited by several techniques, including electron beam physical vapor deposition (EB-PVD) (Ref 4), vacuum and air plasma spray (VPS and APS) (Ref 5, 6), and more recently by high-velocity oxygen fuel (HVOF) (Ref 6–-9). This technique has attracted attention because it produces high bond strength, and dense coatings at a relatively low-cost. By HVOF spraying, metallic alloy coatings can be highly dense and homogeneous; and often present high adhesion strength, and low oxide content owing to the high kinetic energy and relatively low temperature of the powdered feedstock particles fed into the flame (Ref 10, 11). HVOF has been widely employed to produce coatings to protect critical components used in high- and low-temperature industrial applications with aggressive environments such as oxidation, hot-corrosion, sulfidation, and erosion/wear phenomena (Ref 12-14).

Despite the advantages of HVOF, metallic coatings are still prone to oxidize during processing and can develop residual stresses. The combination of oxidation and residual stresses is considered deleterious since it limits coating properties as it produces splat fracture, poor inter-splat adhesive strength, inadequate thickness, spallation, cracking, and buckling (Ref 15–-17). Although, porosity, oxide content, and residual stresses are critical for coating performance, limited information is available in the literature regarding how coatings build up and how their properties are affected during processing and the optimal spraying parameters for NiCoCrAlY coatings deposited by HVOF (Ref 7).

Statistical experimental design methods have been shown to be an efficient technique to systematically optimize the process of thermal spraying, including the Taguchi method (Ref 18, 19), full and fractional factorial designs (Ref 7, 20), and central composite designs (Ref 21, 22). Among them, the central composite design is the most popular response surface method, since it estimates linear and two-factor interactions as well as the surface effects, and also provides insightful information on experiment variable effects and overall experimental errors. This paper aims to correlate how three main HVOF processing parameters, namely fuel and oxygen flow and stand-off distance, change the formation of the coating by evaluating response variables, viz, residual stress, porosity, and deposition efficiency, employing both a two-level factorial and a central composite experimental designs.

Experimental Details

Materials and coating characterization Sulzer Metco DJ2700 Hybrid HVOF gun was used for coatings deposition. Commercial NiCoCrAlY powders (Sulzer-Metco 365-4) were used as feedstock. The particle size distribution of the spherically shaped powder was 45 +20 lm. The nominal chemical composition of the NiCoCrAlY powder as well as the average chemical composition of the coatings is shown in Table 1.

The transversal HVOF deposition speed was controlled in all the experiments with a 6-axis Kuka KRC2 robot arm. All coatings were deposited onto grit-blasted 5 mm thick 304 stainless steel plates. The substrate temperature and the residual stress buildup of the coating were both monitored by an in-situ coating-property sensor (ICP, Stony Brook, New York) (Ref 17).

The ICP sensor was used to monitor the curvature and temperature of the substrate as a function of time during and after spraying (Ref 17). To measure the substrate temperature two contact thermocouples are placed in the back of the substrate. The curvature during deposition is measured by the deflection of three points measured by laser sensors, which is converted to curvature. The curvature is used to computed the evolving or deposition stress, defined here as the nominal residual stress for a deposited layer includes the effect of quenching and peening of the particles in each layer. The term ‘‘evolving stress’’ is used to generalize the presence of both effects in HVOF. The principle of measurement assumes that each deposited layer is much thinner than the substrate and stress from the measured curvature change is calculated using Stoney´ s equation (Ref 24):

formula

where rev is the evolving stress, E´s is the in-plane elastic modulus of the substrate, ts is the substrate thickness and dj is the change in curvature caused by a change in the coating thickness, dt-dtc is considered after the first or second deposited layer in order to neglect the interaction of the first passes with the substrate.

Thermal stresses are calculated during cooling by measuring the curvature change caused by the cooling temperature gradient, from deposition temperature to room temperature, and using the Brenner and Senderoff formula (Ref 25):

Table 1

The values adopted for elastic modulus are 136 and 193 GPa for the NiCoCrAlY coating and stainless steel, respectively.

The as-sprayed coatings were characterized by X–ray diffraction (XRD) using Cu-Ka radiation on a Rigaku Dmax2100 diffractometer. A cross-section of the coatings was prepared by metallographic methods and observed with a scanning electron microscope (SEM, Philips XL30) equipped with an energy-dispersive X-ray spectrometer (EDS) to quantify the chemical composition. The porosity and oxide content of the coatings was determined by image analysis from 12 optical images recorded at 10x of the cross-section for all samples. These images were processed and the area fraction was calculated using the ImageJ software package.

The deposition efficiency was determined using the method proposed by Shinoda et al. (Ref 26). They defined the deposition efficiency gd as the weight ratio of the deposited coating to the injected powder onto the substrate, that is

formula

where L and W are the length and width of the substrate; Md, Ws, Rf, U, Np are the deposit weight, step width, powder feed rate, raster speed, and number of passes, respectively.

Experimental design

The analysis of the effect of spray processing on the coating properties was divided into three steps. In all the stages, the spray distance, the fuel flow, and the oxygen flow were statistically evaluated. In the first step, a two-level factorial design of experiments was implemented. The high (+1) and low (–1) levels were chosen to give a variation of the flame chemistry. Table 2 shows the parameters used for the initial factorial design trials. The powder feed rate, the robot velocity and the number of passes were fixed in all stages at the values shown in Table 3. No substrate preheating was performed in all experiments.

In order to identify and estimate the effect of the flame conditions on the coatings, porosity and oxides presence, residual stress and deposition efficiency, the coatings were produced using three different flame combinations, stoichiometric, fuel-rich and oxygen-rich. The chemistry of the flame was calculated according to the fuel/oxygen ratio, c,c, using the following equation (Ref 27):

formula

considering that the stoichiometric ratio for the complete combustion of propane is cstoi = 0.2 (Ref 28). The second step was based on the evaluation of the results of the two-level factorial design. In this stage, all coatings were deposited with a fuel-rich flame and the experiments focused on the effect of the stand-off distance. The depositions for the second step were carried out following the processing conditions listed in Table 3.

Table 2

Table 3

Finally, the third step consists of a central composite design (Table 4), developed in the region of optimum settings as defined by the first two steps. The first 8 spray conditions belong to a two-level factorial design, (+a) and (–a) are the star or axial points, and (0) are the central points, where the replicates are used to estimate pure error. To evaluate the effect of the selected spray conditions on the response variables the porosity, residual stress, and deposition efficiency results were fitted using a commercial statistical software (Design-Expert, USA).

Results and Discussion

Part I. Two-level factorial experiment Figure 1 shows the XRD patterns of the as-received feedstock powder and one of the as-sprayed HVOF coatings (coating sprayed under condition C2, in Table 2). The typical NiCoCrAlY phases, which consist of c and b phases, are maintained after the HVOF deposition for all spraying conditions. The lattice parameters measured from the XRD patterns are 0.358 and 0.286 nm for the c- and the b-phase, respectively (JCPDS: 44-1115/44-1187 and 09-0097). Similar values have been previously reported (Ref 29, 30). The b-phase is essential for coating protection since this phase acts as an aluminum reservoir to form a protective a-Al_2O_3 layer, known as the TGO (thermally grown oxide) (Ref 1).

To determine how the spraying process affects the coating formation, the curvature evolution and the residual stresses were monitored by the ICP sensor for all conditions. As it can be observed from Fig.

2a, high quenching stresses are developed for all coating conditions denoted as a large positive curvature change during the first and second passes, the curvature change is associated also to a positive curvature change and tensile stresses, but of a lower value. The curvature change is associated to a constant slope in the ICP curve provided that every layer is deposited with similar amount of residual stress. The first one or two passes are dissimilar as they show the interaction with the substrate surface. The evolving stress reported in this paper is obtained from the layers after the first forty seconds of the spraying sessions, where the stress per layer denotes a nominal value of stress per pass.

Table 4

Furthermore, the slope of the curvature vs. time (which is computed later, as a curvature change per deposited thickness, and from there by equation 1 as evolving stress) during spraying decreases as the spray distance increases from 150 mm to 250 mm (Fig. 2b). This decrease implies a reduction in the evolving stresses, as a result of a decrease of quenching (tensile) or an increase of peening (compressive) stresses. (Ref 27, 31). The evolving stress is a combination of both occurring simultaneously in HVOF (Ref. 27, 31, 32).

Theses stresses are mainly dependent on the particle state and deposition temperature. As can be observed in figure 2a, the change in the curvature per pass (slope) is lower for coating C2 than for C1 or other conditions because fuel-rich conditions generates higher particle velocities which increases the peening stress and lower particle temperature that promotes a decrease or reduction in the quenching stress. Otherwise, stoichiometric and oxygen-rich flames cause high temperature and low velocities of particles increasing the quenching stresses, and therefore the evolving stress.

Similarly, it has been mentioned in previous (Ref 17, 32) studies that high deposition temperatures increase quenching stresses, and therefore the evolving stress in HVOF, since the cohesion between the particles improves as a result of rapid heat transfer, better wetting, etc. (Ref 19). Particularly, coatings deposited at shorter spray distance (150 mm) are deposited at higher substrate temperatures and therefore develop higher values of evolving stress.

Regarding thermal stress post spraying, high thermal stresses are favored by large temperature differences between deposition to room temperature, and also on the coefficients of thermal expansion (Ref 27). The final residual stresses developed in the coatings seem to be most sensitive to the spray distance. As can be observed in Fig. 2b, the residual stresses of the coatings sprayed at 150 mm are all tensile, tending to lower values for fuel-rich conditions. Conversely, coatings deposited at 250 mm are under compressive residual stress showing a minimum (absolute value) for the fuel-rich flame deposition conditions.

Irrespective of the spray distance, high fuel/oxygen ratios (e.g. C2) generate a decrease of the evolving stress and consequently of the residual stress, as a result of low particle temperature and high particle velocity (Ref 27). In contrast, high residual stresses are developed for the stoichiometric (i.e., C1) and the oxygen-rich flames (i.e., C3) due to high particle temperatures, as a consequence of high-energy flames, and low particle velocities (Fig. 2).

Figure 3 shows the main effects of each tested parameter on the response variables. These values are calculated by averaging the results of the response variables moving from the high to the low setting of each variable, irrespective of the level of the other two variables (Ref 33). Focusing on the residual stress and the deposition efficiency, it seems that the spray distance is the parameter that has the highest influence on these responses (Fig. 3a and 3b), probably because of its large effect on particle state and substrate temperature. Regarding the residual stresses, short spray distances such as 150 mm favor tensile residual stresses (*72 MPa), meanwhile the use of longer distances such as 250 mm, shows a change from tensile to compressive residual stress, *-25 MPa. A decrease in fuel and oxygen flow barely affects the final values of residual stresses, always keeping them tensile.

Concerning the deposition efficiency, a change from the lower to the upper value of the spray distance decreases the deposition efficiency at around 6.5 %. As can be seen in figure 3b, an increase in fuel and oxygen maintains the deposition efficiency within 65.5 to 68.5%. Regarding the flame chemistry, high deposition efficiency is obtained at higher energy flames (stoichiometric and oxygen-rich flames) where high particle temperature is reached (see Table 2).

Conversely, porosity and oxides content is significantly and almost equally influenced by all three parameters. An increase of fuel and oxygen flow results in enlarged porosity and oxidation, but by increasing the spray distance the porosity and oxides are reduced.

The porosity decreases when moving from oxygen-rich to fuel-rich conditions. High fuel-rich chemistry conditions cause high particle velocities and low energy flames, which in turn decreases the particle temperature resulting in more desired characteristics for the coatings, specifically for this case, low porosity and low oxide content.

It is well known that the level of oxidation and porosity is greatly influenced by flame chemistry (Ref 7). High fuel-rich compositions lead to the lowest coating oxidation and porosity. The results of porosity from the first four coatings, deposited at 150 mm are the following: C1 = 8.2%, C2 = 6.9%, C3 = 12.9% and C4 = 16.3%. These results are attributable to the in-flight particle characteristics. High particle velocities imply that the powder particles spend less time in the flame reaching lower temperatures, which results in low porosity and oxidation. These characteristics have also been previously observed by Saaedi et al. (Ref 34). Their results show that the oxidation of metallic particles is avoided in fuel-rich flames as a consequence of the low temperatures reached and because the oxygen that is fully reacting is no longer available to oxidize the particles. These observations are also consistent with those reported by Valarezo et al. (Ref 27) for Ni-20Cr coatings deposited by HVOF. The authors mention that oxidation depends considerably on the inflight characteristics of the particles, including velocity and temperature. Their results show that for the stoichiometric and the oxygen-rich conditions, oxidation increases as the residence time of the powder particles in the flame is longer as a consequence of their low velocities. The fuel-rich coatings resulted in lower oxidation and porosity because the residence time in the flame is shorter and also the flame protects the particles from oxidation, as the oxygen present in the surrounding air is burned with the excess of fuel in the flame.

Part II. Coating properties as a function of spray distance

Based on the output of the two-level factorial design, it was found that the stand-off distance has a strong effect on the coating properties. For this reason, this section will particularly focus on the analysis of how the response variables are affected by varying spray distances in more discrete intervals.

Consistent with the first set of experiments, all the coatings retained the c- and b-phases, and no presence of oxides and/or secondary phases were observed in the XRD patterns. However, the cross-sectional microstructure of the NiCoCrAlY coatings presents several differences that can be associated with the variation of stand-off distances (Fig. 4). Depending on the distance, the substrate temperature, the residence time, and the characteristics of the powder particles in the plume differ. This results in different velocities and temperatures of the particles when impacting the substrate. For instance, the coatings deposited at 150 mm show high porosity and oxides content (around 13% quantified by image analysis), with some visible surface cracking, scarcely present semi-molten particles. At this spraying distance, the highest substrate temperature (410 C) is registered. Short spray distances allow the particles to reach the substrate with high temperature and velocity conditions. Here, the microstructure of the coatings is the result of having predominantly overheated particles that may cause splashing (enlarged flattening), fragmentation or cracking due to quenching resulting in high levels of porosity and oxidation (Ref 35). Debonding of splats by the impact of particles at high velocity as well as splat oxidation in its surface during deposition are also possible scenarios. The latter may occur because of the high heat input from the flame. The coatings sprayed at 250 and 300 mm, (Fig. 4b and 4c) have low porosity, a homogeneous microstructure, and few partially-molten particles. This conditions show lower substrate temperatures 270°C and 272.5°C at 250 and 300 mm, respectively. At these spray distances, the particles seem to reach the optimum velocity and temperature at the moment of impingement onto the surface, resulting in a balance of flattening, impact and solidification. At longer spray distances (350 mm, Fig. 4d), the coatings exhibit a large amount of partially-molten particles and pores, which are associated with re-solidified or cooled particles, and the concomitant formation of oxides from interaction with entrained air in the surroundings (Ref 36). Also, the substrate temperature decreased slightly at this spray distance, 205 °C. The porosity does not approach the levels observed in samples coated at 150 mm, at 350 mm and reaches a value of 4.8%.

In general, as the distance increases porosity and oxidation decreases given that coating formation is optimized with reduced splashing, reaching nominal particle impact velocities, and substrate temperatures (see Fig. 5a). At the largest spray distance (350 mm) some particles re-solidify before reaching the substrate resulting in a coating with a high amount of partially molten or un-molten particles, which necessarily implies a slight increment in the porosity and oxide content (Ref 36).

This can be observed in Fig. 5a where the porosity and oxidation decreases as the spray distance increases, but a slight increment at longer stand-off distances (350 mm) is observed.

Splat oxidation has been reduced at long stand-off distances because heat input from the flame to the substrate is reduced (Ref 7). The porosity and oxidation also increases because the residence time of the particles increases which increases the contact time with oxygen and therefore the oxide content.

For this study, since coating porosity and oxidation decrease as the stand-off distance increases, from 150 to 300 mm, oxidation and porosity can be mainly attributed to splat oxidation and re-solidification and/or cooling of the particles prior to impact. Moreover, at longer distances, 350 mm, the oxidation process also arises during in-flight (Ref 37).

Relatively high deposition efficiencies are obtained for all spray distances tested in this work. However a decrease, from 78 to 62%, is observed as the spray distance increases from 150 to 300 mm (Fig. 5b). This decrease is associated mainly to the re-solidification of the feedstock material.

Similar to the previous section, the ICP sensor was used to determine how the stand-off distance affects coating formation. Figure 6a and 6b illustrates the curvature evolution and the variation of the evolving, thermal and residual stresses as a function of time.

As can be observed, quenching stresses are developed for all spray distances, however, as the stand-off distance increases from 150 to 350 mm, in 50 mm increments, the slope of the curvature decreases almost monotonically. For instance, the curve at 150 mm presents a greater change in curvature (Dcurvature = 0.58) than at 300 mm (Dcurvature = 0.27).

This implies a reduction in the evolving stresses since these are proportional to the slope of the curvature. A similar result is also observed for the values of thermal stresses (less negative), see Fig. 6b. However, as can be seen in image 6b, there is not a clear correlation between the residual stresses and the spray distance, and this should be associated to the initial stress state of the substrate. Regarding the substrate conditions some aspects should be considered, such as, the stresses generated during the grit-blasting process, the final surface finish (roughness) and its dimensions. Altogether these variables affect the peening stresses of the substrate. It should be noted that for the present study and in order to compensate the stress state left after the first grit blasting at one side, a second grit-blasting on the other side was carried out. However, due to its length and thickness (9'' and 3/32'', respectively) it is quite difficult to fully compensate the stresses along the entire substrate and thus an effect on the final state of residual stresses is expected.

From these results, it can be concluded that preferred coating properties such as low porosity and oxide content, uniform and homogeneous microstructure and good deposition efficiency, are obtained for stand-off distances between 250 and 300 mm.

Part III. Central composite design

The combination of factors shown in Table 4 were determined based on the results obtained in the first and second experimental steps. Evaluation of these results showed that the optimum coatings, i.e, lower porosity and oxide content, low residual stress and good deposition efficiency, are obtained by:

1) Using high fuel-rich flames, as a consequence of higher particle velocities and lower flame temperatures, which reduce the particle temperature and its oxidation.

2) Using intermediate stand-off distances, from 250 to 300 mm, 300 mm, where the particles reach the optimal conditions of velocity and temperature.

With this combination, a homogeneous and uniform coating can be formed.

The main objective of the final step in this paper is to correlate the process parameters, i.e., fuel flow, oxygen flow and spray distance, and each response variable to determine the combination of factors that are likely to be considered as optimal.

In order to predict and model the responses based on the experimentally measured values, a quadratic model was fitted by using Design Expert software (Ref. 38). The second-degree polynomial model includes the effects of the main and interaction effects of all factors, and is expressed as:

formula

where b0 is the average of the responses, bi, bii , and bij are the regression coefficients that depend on the main and interaction effects of the parameters, respectively.

The predicting equations as a function of fuel flow (FF), oxygen flow (OF) and spray distance (SD), are given below:

formula

The ANOVA analysis for the residual stresses is shown in Tables 5. No significant lack of fit and values of the prob > F below 0.05 were obtained, implying that the empirical relationships are satisfactory (Ref 38, 39). Statistics of the quadratic models show high values of R-squared and adjusted R-squared (near 1), see Table 5 and 6. The model adequacy and reliability of the fit, for each response variable, are shown in Fig. 7 and Fig. 8, respectively. Both, the data-points of the normal probability plot of residuals and the matching between the model-predicted values and the measured values for all the response variables fall approximately on a straight line. This indicates that the errors follow a normal distribution and confirms the validity of the regression model (Ref 38).

Figure 9 shows contour plots, which display in 2D-representations the quadratic fit model of each response variable (residual stress, deposition efficiency and porosity) as a function of the two spray parameters that affect them the most. Such graphs are helpful provided that the optimal parameters of a region can be readily visualized. Each contour in Fig. 9 represents an infinite number of combinations of values of the process variables.

For instance, considering Fig. 9, in the region between 275-287.5 mm spray distance and low to medium fuel flows (114-118 scfh) the deposition efficiency is maximized, the residual stresses and the porosity and oxide content are relatively low.

As a final step in the optimization of NiCoCrAlY deposition process, an estimation of the most optimal settings as well as optimum response point was predicted. A combination of processing parameters [Error hx0200B][Error hx0200B]that satisfies the selected criteria for each response variable was generated to determine the predicted point. The criterion to define the optimum combination of responses was to minimize residual stresses and porosity-oxide content and maximize the deposition efficiency. The combination of fuel flow, oxygen flow and a stand-off distance obtained after the numerical optimization are 115.6 scfh, 332 scfh and 300 mm, respectively. To validate this combination of values obtained by the DoE, a final set of coatings was deposited. The cross-section of this coating showed a homogeneous microstructure with no visible partially-molten or unmolten particles (Fig. 10). A comparison of the experimental and predicted response values are is shown in Table 7. As it can be observed, the experimental results of the deposition efficiency are consistent with the predicted value. The experimental porosity and oxide content was lower than the expected value; meanwhile the residual stress is the variable that shows a larger difference between the experimental and expected value. The value of the residual stress reported in Table 7 was calculated from a lineal extrapolation. This extrapolation was carried out using data near to the optimal point (e.g. condition 4) from the central composite design.

The combination of values obtained for the optimal point conditions (115.6 scfh, 332 scfh and 300 mm of fuel flow, oxygen flow and spray distance) almost coincides with condition 4 of the central composite design (114 scfh, 332 scfh and 300 mm of fuel flow, oxygen flow and spray distance). If we compare the response variables, residual stress (40 MPa), porosity (1.9 %) and deposition efficiency (72 %), of the optimal point with the values obtained for condition 4 (residual stress of 40, porosity of 2.5 %2.5% and deposition efficiency of 70 %) these agreed well confirming the repeatability and reliability of the results.

Even when the porosity and residual stresses do not match precisely with the predicted values, an interesting reduction in porosity was obtained (regarding that was one of the original goals). Although the minimum residual stress is not achieved for this particular condition, the use of ICP sensor, specifically the evolving stress, provide insightful information about Ni-CoCrAlY coating formation. According to the results, it is possible to establish that quenching stresses prevails along coating build up indicating good interparticle bonding as a result of good heating and high degree of melting of the particles. Based on this, it can be established that the optimum spray conditions enable an adequate in-flight particle state which leads to the deposition of low porosity and oxide content, residual stress, and high deposition efficiency for NiCo-CrAlY coatings. The conditions found of fuel and oxygen flow and stand-off distance for the optimum condition produce a flame, which generates the required energy leading to an adequately molten particle state (satisfactory in-flight characteristics) during its residence time in the flame. When the particles impact the surface, their degree of flattening allows them to spread and solidify uniformly, resulting in high deposition efficiency by increasing the splat – splat contact, low porosity content and at the same time maintaining high particle cohesion.

Table 5

Table 6

Table 7

Conclusions

A two level factorial and a central composite design have been employed to study the effect of fuel flow, oxygen flow and spray distance on the properties residual stress, porosity and oxide content, and deposition efficiency of NiCoCrAlY coatings.

The results suggest a correlation between the fuel and the oxygen ratio flow, and the porosity and oxide content on the coatings based on the interaction between particle and the flame (its power and chemistry). Using fuel-rich flames results in coatings with low porosity and oxidation, low residual stresses, and high deposition efficiency due to the high velocity and low temperature attained by the particles.

The two-level factorial design results show that the spray distance has a large influence on the residual stresses and deposition efficiency; while the porosity and oxide content is dependent not only on spray distance but also on the other two tested variables (oxygen and fuel flows).

Spray distances between 250 and 300 mm produce coatings that are homogeneous, dense, with high intersplat cohesion coatings. At these spray distances, the particles reach their optimal velocity and temperature resulting in a balance of spreading, flattening, and solidification.

Lastly, as an outcome of the central composite DoE, a specific condition was used to deposit a coating considered optimized. Although the predicted and the experimental results for this optimized parameter showed slight differences, a clear evidence of the effectiveness of the optimization procedure is confirmed by the reproducibility of the previous results obtained within the central composite DoE. However, additional studies are required to refine the prediction of the optimization model employed.

Based on the responses of the tested parameters, it can be stated that the methodology enables to attain the optimal spray condition and particle state for NiCoCrAlY deposits with good properties.

References

Fig. 1 XRD patterns of as-received NiCoCrAlY feedstock powder and C2 as-prayed coating

Fig. 2 (a) Curvature evolution during spraying and cooling of the coatings and (b) evolving, thermal and residual stresses generated during spraying for coatings deposited under all conditions with its respective substrate temperature at 150 and at 250 mm spray distance

Fig. 3 Effect of fuel flow, oxygen flow, and spray distance on the (a) residual stress, (b) deposition efficiency, and (c) measured porosity and oxidation for the two-level factorial design

Fig. 4 Cross-section images of as-deposited NiCoCrAlY coatings at spray distances of (a) 150 mm, 150 mm, (b) 250 mm,250 mm, (c) 300 mm, and (d) 350 mm

Fig. 5 (a) Porosity-oxide content and (b) deposition efficiency as a function of spray distance

Fig. 6 (a) Curvature evolution and the (b) variation of the residual, thermal, and evolving (deposition) stresses as a function of spray distance

Fig. 7 Normal probability plots for (a) residual stress, (b) deposition efficiency, and (c) porosity and oxide content

Fig. 8 Correlation among the values predicted by the model and the measured (actual) values for (a) residual stress, (b) deposition efficiency, and (c) porosity and oxide content

Fig. 9 (a) Residual stress, (b) deposition efficiency, and (c) porosity-oxide contour plots

Fig. 10 Microstructure of a NiCoCrAlY coating using the optimal processing parameters