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Investigation of Particle In-Flight Characteristics during Atmospheric Plasma Spraying of Yttria-Stabilized ZrO_2: Part 1. Experimental

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A detailed investigation of the relationship between the parameters of the spray process and the in-flight properties of the particles was carried out using a multivariate statistical approach. A full factorial designed experiment concerning the spray process was performed, the spray gun parameters' current, argon flow rate, hydrogen flow rate, and powder feed rate being selected to control the process. The particle properties, *viz.* velocity, temperature, and diameter, were determined using an optical measurement system, DPV 2000. In addition, the standard deviations of, and the correlations between, the measured particle properties were analyzed. The results showed current to have the strongest impact on particle velocity and particle temperature and argon flow rate to be the only parameter with an inverse effect on velocity and temperature.

Keywords DPV 2000, particle diameter, particle temperature, particle velocity, plasma spray, yttria-stabilized ZrO_2

1. Introduction

Thermal spraying is a critical material-coating technique, currently being used in numerous applications, such as in producing thermal-barrier, wear-resistant, and abradable coatings. Further improvements in this technique within the present fields of application and expansion into other fields require an increase in the reliability and reproducibility of the process.

The thermal spray coating process is based on powder particles being introduced into a plasma plume, *cf.* Fig. 1. Transfer of heat and momentum takes place while the particles are being melted and accelerated, traveling through the plasma plume toward the target. Due to large temperature and velocity gradients in the plume, small changes in the spray gun parameters and in the powder injection can result in significant changes in the properties of the particles.

Upon impact at the substrate surface, the individual molten or partially molten particles flatten, adhere, and solidify, building up the coating particle by particle. The particle velocity and temperature prior to impact, together with the substrate temperature, determine the degree of flattening and adhesion of the particles. This, in turn, influences the solidification rate and the microstructure of the coating. Thus, the velocity and the temperature of the particles prior to impact are among the most important parameters influencing the microstructure of the coating.[1]

Typically, thermal spray processes have been optimized and controlled by empirically tuning the numerous spray gun parameters and examining the resulting properties of the coating. This approach has major drawbacks, however, since a vast number of parameters need to be monitored and controlled. In addition, other, uncontrollable parameters such as electrode wear and changes in the particle injection conditions significantly affect the process. Accordingly, a high degree of reproducibility and stability of the process cannot be ensured.

Modern techniques have made it possible to observe the particles in flight and to determine their properties. This on-line measurement of particle properties has a potential for becoming an effective diagnostic tool for controlling the plasma-spray process, particularly since it then suffices for a few parameters to be attended to, specifically the particle properties, rather than the numerous spray gun parameters. By moving control of the process one step closer to the coating, uncertainty regarding the uncontrollable parameters is eliminated and an increase in process stability and an improvement in quality standards can be achieved. Such an approach can help eliminate control by trial and error solutions.[2]

In order to improve the reproducibility of the spray process, it is necessary to understand the relations between the spray gun parameters, the characteristics of the sprayed particles, and the properties of the coating. A significant number of investigations have been published concerning relationships between process parameters, on the one hand, and microstructure, mechanical properties, on the other.[3–8] However, no statistical investigation of the influence of the process parameters on the in-flight particle properties has, according to the authors' knowledge, been published. The present paper, Part 1 in a series of two papers, presents experimental results obtained in on-line measurements of particle properties. Statistical methods are used to determine the influence of the spray gun parameters on the particle proper-

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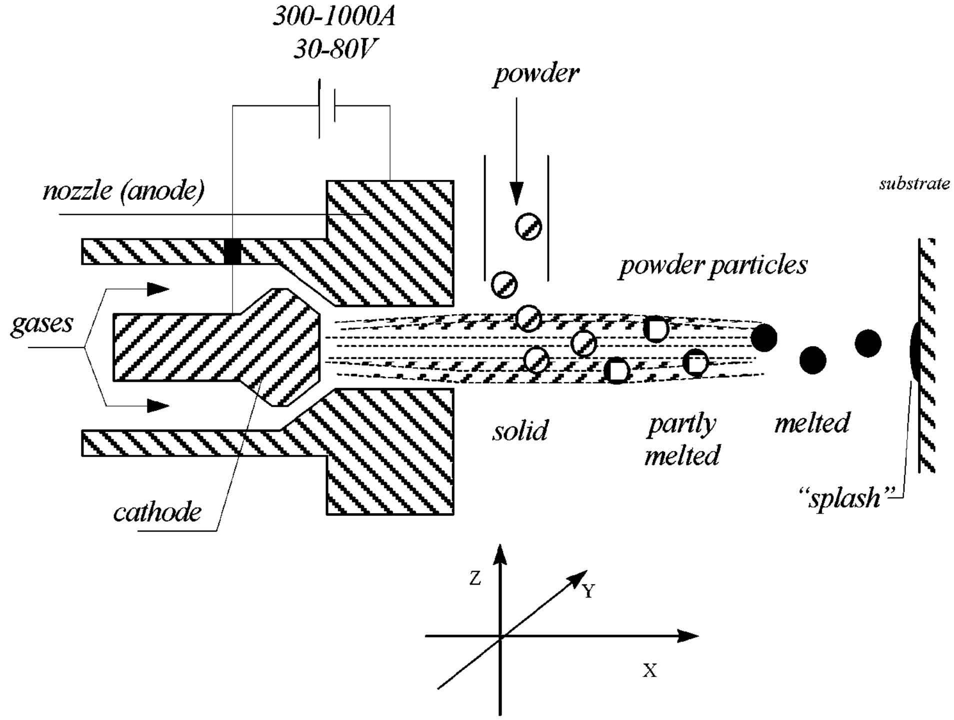


Fig. 1 Schematic diagram of the spray gun

ties. In Part 2,[9] a numerical simulation of the process is presented, using the same spray gun parameters and settings as in Part 1.

2. Coating Material

Yttria-stabilized zirconia (7.7 wt.% Y_2O_3) powder was selected as the coating material. In all 16 of the spray experiments, powder from the same lot, similar in size distribution, was used. The particle size distribution of the powder sample, obtained by calculating the percentage of particles obtained between consecutive steps of screening, as taken from the mass fractions at each step, is shown in Fig. 2. It was found that 85% of the particles were in the diameter range of 10 to 40 μm.

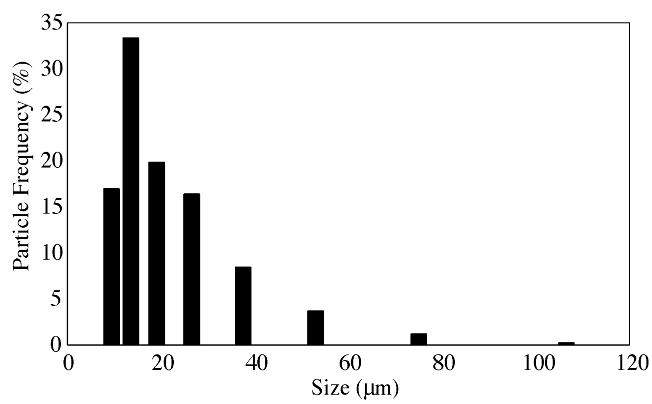


Fig. 2 Size distribution of sintered and agglomerated zirconia. Each bar is drawn at the center of the respective interval. Note that, in reality, the diameter distribution is continuous

3. Experimental

All experiments were performed using a SM-F-100 Connex (Sulzer Metco, Wohlen, Switzerland) gun controlled by an automated and robotized Sultzer Metco (Wohlen, Switzerland) A3000 air plasma unit.

The characteristics of the particles traveling through the plasma flame were determined at a standoff distance of 70 mm from the spray gun nozzle exit. These measurements were made using the optical system DPV 2000, developed by the National Research Council of Canada (Industrial Materials Institute, Boucherville, PQ, Canada) and Tecnar Automation Ltée (St-Hubert, PQ, Canada). Each measurement sequence lasted 1 to 2 min, during which 300 to 1000 particles were detected.

In brief, the DPV 2000 collect radiation from passing particles optically through a lens covered by a two-slit mask. On the basis of the radiation transmitted through these slits, the distance set between the slits and the particle transit time, the particle velocity can be calculated with an error of less than 5%. Particle temperature is determined simultaneously, based on the gray body assumption, by measuring the thermal radiation intensity at two different wavelengths (using a two-color pyrometer). Accordingly, the measured temperature is a gray body temperature, which might differ up to 200 °C if the emissivities at the two wavelengths differ by 5%. The particle diameter is estimated after calibration of the DPV 2000 on the basis of the radiation measured at one wavelength when the temperature of the particle is known. A detailed description of DPV 2000 is available in the literature.[10,11]

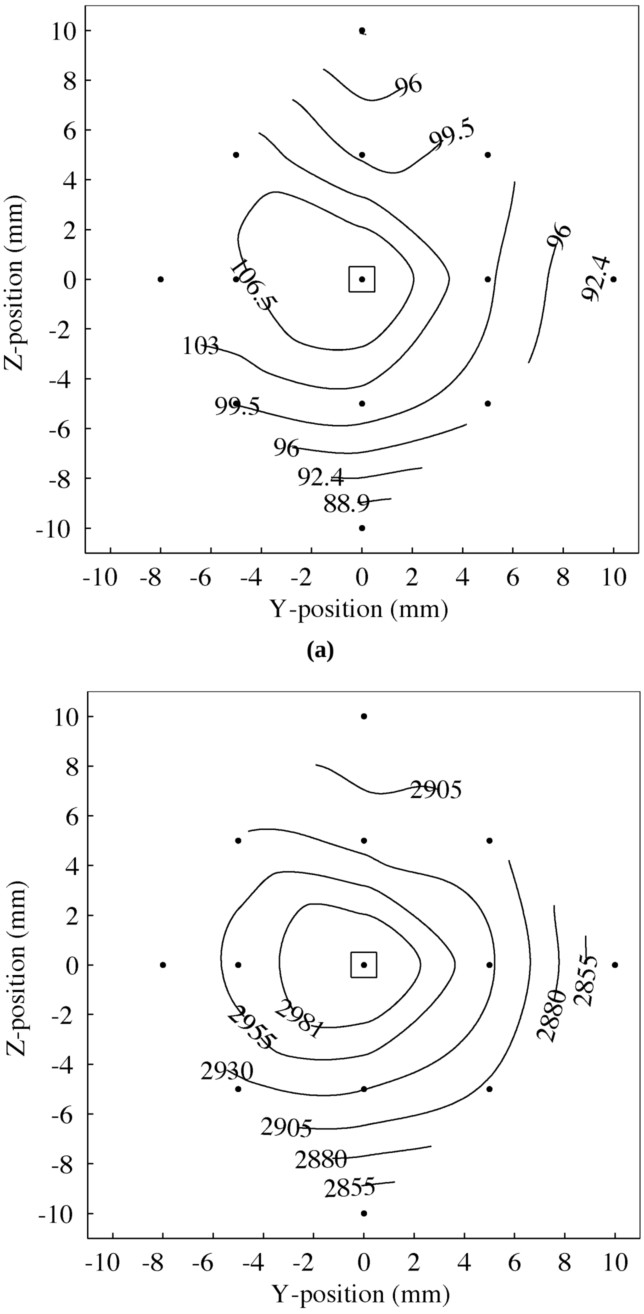


Fig. 3 Contour plots of particle velocity and temperature in a cross section at standoff distance for treatment 14. The gray area indicates the variation of the spatial location (±0.5 mm) of the measure volume between different auto focusing operations. Points indicate measured values: (**a**) particle velocity and (**b**) particle temperature

The DPV 2000 with its current configuration can measure particle velocity in the range 20 to 300 m/s, particle temperature above 1700 °C, and particle size below 130 μm. The performed measurements were well within these limits. Concerning the uncertainty and error of the measurement device, it can be concluded that a systematic error will not affect the statistical analysis; instead, it will only add a constant to the result. The influence of a random error is negligible, since the statistical evaluation is performed based on the mean value of a large (more than 500) number of particles.

The experimental data was obtained while thermal barrier coating (TBC) samples were being prepared. Since the measurement system requires the spray gun to be stationary, the measurements were made prior to and after each coating deposition, resulting in a 16 × 2 data series for each particle property.

Particles of different size will differ in their trajectories through the plasma plume. One could assume that small particles fail to penetrate the core but instead float on top of the plasma plume, whereas large particles penetrate the core and reach the lower part of the plume. Furthermore, the particle trajectories will change with different settings of the spray gun parameters. Accordingly, particle distribution in the plasma plume appears to be very complex.

The DPV 2000 measures particles in a small volume, at a position in the plasma plume that is determined by an auto focus procedure designed to focus on the highest particle density. In order to verify that this location is a proper indicator of particle property variation due to different settings of the spray gun parameters, the following steps were taken.

The spatial position of the measure volume was observed for the measurements performed prior to and after each coating deposition. The deviation of the *z* and *y* positions was less than ±0.5 mm along each axis (Fig. 1 shows the axis reference). Considering that the size of the measure volume is approximately $\Delta z = 200$, $\Delta x = 330$, and $\Delta y = 2000$ μm,[10] the *y*-axis deviation can be neglected. The *z*-axis deviation, however, is of the same magnitude as the measure volume height, which indicates that there might exist a deviation between the measurements performed prior to and after each coating deposition. To investigate how sensitive the particle property values are to variation of the spatial location of the measure volume, a cross section of the plasma plume at standoff distance was examined for one of the experimental parameter settings. Selecting the focus spot as the origin of coordinates, 12 other spots were manually located and measured. From Fig. 3(a) and (b), it can be seen that the variation of particle velocity and particle temperature due to spatial deviation of the focusing point is very small, indicating that the focused volume well represents the particle property variation.

Furthermore, a hypothesis testing at the 99% confidence level was performed to evaluate whether the difference between the particle data obtained before and after each deposition was significant. This test was performed for all 16 treatments. The test showed the difference between the two measurements to be negligible. Thus, the repeatability of the auto focusing procedure and, thereby, the reproducibility of the experiment were found to be good.

Concerning the statistical analysis, the data series obtained prior to and after each coating deposition were merged and were randomly reduced to consist of the same number of observations as the shortest series. This resulted in 16 series, each containing 596 measured values.

4. Design Parameters

The objective of the experiment was to investigate how the spray gun parameters, namely, current (*C*), argon flow rate (*A*),

Table 1 The factors investigated and their high and low levels

Factor		+ Level	− Level	Unit
C	Current	420	300	A
A	Argon	32	23	slpm(a)
H	Hydrogen	5	3	slpm
P	Powder feed rate	70	40	g/min

(a) Standard liters per minute

Table 2 The 2^4 factorial design matrix

Treatment	C	A	H	P
1	−	−	−	−
2	−	−	−	+
3	+	−	−	−
4	+	−	−	+
5	−	+	−	−
6	−	+	−	+
7	+	+	−	−
8	+	+	−	+
9	−	−	+	−
10	−	−	+	+
11	+	−	+	−
12	+	−	+	+
13	−	+	+	−
14	−	+	+	+
15	+	+	+	−
16	+	+	+	+

hydrogen flow rate (*H*), and powder feed rate (*P*), influence the velocity, temperature, and size of the particles. These parameters are known to yield significant variation in the TBC microstructure, a fact that puts these specific parameters in focus for investigation. The ranges of the parameters were chosen to vary around a standard production setting with the aim of producing porous coatings. These different parameters and their ranges are given in Table 1.

The experiment was designed as a full 2^4 factorial design, each of the four factors having 2 levels and there being 16 treatments altogether. Thus, there are 15 different treatment effects that show the influence of all factors and of all possible factor combinations, *i.e.,* two-, three- and four-factor interaction effects. The design matrix is given in Table 2, a plus sign there denoting high-level value and a minus sign a low-level value of factors *C, A, H,* and *P* according to the figures shown in Table 1.

5. Statistical Analysis

The statistical analysis of the experimental data is presented in terms of three separate investigations.

5.1 Investigation 1: Mean Values of the Particle Properties

The experimental data were analyzed using the multivariate analysis of variance (Manova),[12] aimed at testing appropriate hypotheses regarding the possible treatment effects of *f* factors at *n* levels and estimating these effects. Thus, the Manova assesses the impact of the *f* different factors on the response, the

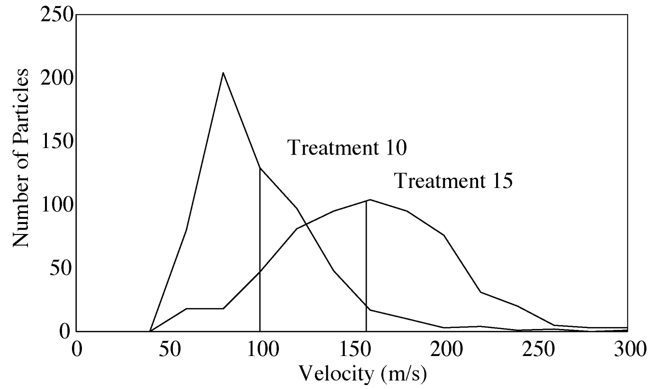


Fig. 4 Example of the difference between the mean values for two treatments

impact of the different factor interactions on the response, and the correlation between the responses. The term *f* in the present case represents the four spray gun parameters and *n* denotes high and low level, respectively.

The Manova provides hypothesis testing concerning which of the treatments have a significant effect. This requires that the data be normally distributed and that each treatment contain the same number of observations. To this end, each of the individual particle properties was transformed to a normally distributed series. Using an iterative method for each property, a proper transformation rule was determined and was successively refined.

The variation in particle velocity, temperature, and diameter was analyzed using a model that included the effects of the spray gun parameters and of their interactions. The *r* observed values (1 to 596) in each treatment could be described in terms of the following relation:

$$\begin{aligned} \boldsymbol{X}_{klmnr} &= \boldsymbol{\mu} + \boldsymbol{C}_k + \boldsymbol{A}_l + \boldsymbol{H}_m + \boldsymbol{P}_n + \\ &\boldsymbol{CA}_{kl} + \boldsymbol{CH}_{km} + \boldsymbol{CP}_{kn} + \boldsymbol{AH}_{lm} + \boldsymbol{AP}_{ln} + \\ &\boldsymbol{HP}_{mn} + \boldsymbol{CAH}_{klm} + \boldsymbol{CAP}_{kln} + \boldsymbol{CHP}_{lmn} + \\ &\boldsymbol{AHP}_{lmn} + \boldsymbol{CAHP}_{klmn} + \boldsymbol{e}_{klmnr} \end{aligned} \quad \text{(Eq 1)}$$

where $\boldsymbol{X}_{klmnr}$ is the vector response consisting of the components particle velocity, temperature, and diameter. The vector $\boldsymbol{\mu}$ denotes the mean values of all the treatments. The vectors $\boldsymbol{C}_k$, $\boldsymbol{A}_l$, $\boldsymbol{H}_m$, and $\boldsymbol{P}_n$ are the effects of current, argon, hydrogen, and powder feed rate, with indices *k*, *l*, *m*, and *n* representing high and low levels of each factor, according to Table 2. Interactions between the parameters, such as between current and argon, are represented in the form $\boldsymbol{CA}_{kl}$. The remaining terms are interpreted similarly. The random error is denoted by $\boldsymbol{e}_{klmnr}$.

Figure 4 shows a typical example of how the mean value of the particle characteristics (in this case, velocity) can differ as a result of different settings of the spray gun parameters. In the diagram, particle velocity versus particle frequency is plotted for treatments 10 and 15.

5.2 Investigation 2: Dispersion of Particle Velocity and Temperature

The standard deviations for particle velocity, σ_V, and for temperature, σ_T, were calculated for each of the 16 data series. The

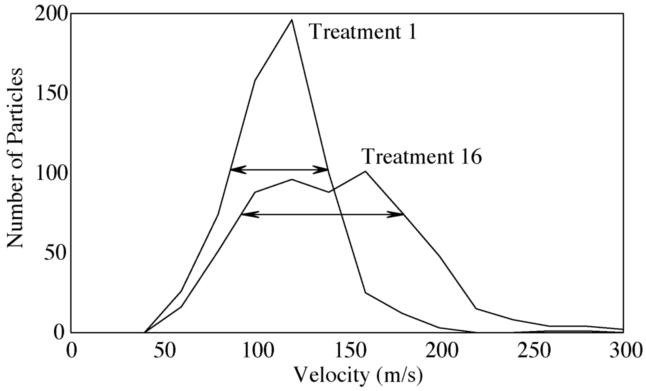


Fig. 5 The difference in standard deviation between two different treatments

standard deviation is defined as

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \bar{y})^2}{n-1}} \qquad \text{(Eq 2)}$$

where y_i denotes the particle characteristic, n the number of observed particles, and $\bar{y}$ the mean value of the respective particle property for each treatment.

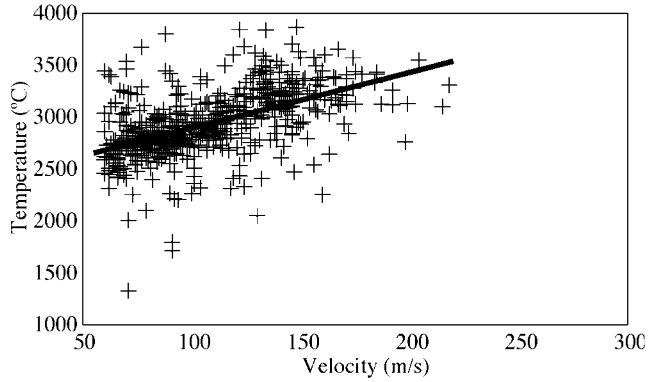
Of interest here was the impact of the main factors on the particle property dispersion, the impact of the factor interactions being neglected. The observed values can be described in terms of the following model, where $\boldsymbol{X}_{klmnr}$ is either σ_V or σ_T:

$$X_{klmnr} = \mu + \boldsymbol{C}_k + \boldsymbol{A}_l + \boldsymbol{H}_m + \boldsymbol{P}_n + \boldsymbol{e}_{klmnr} \qquad \text{(Eq 3)}$$

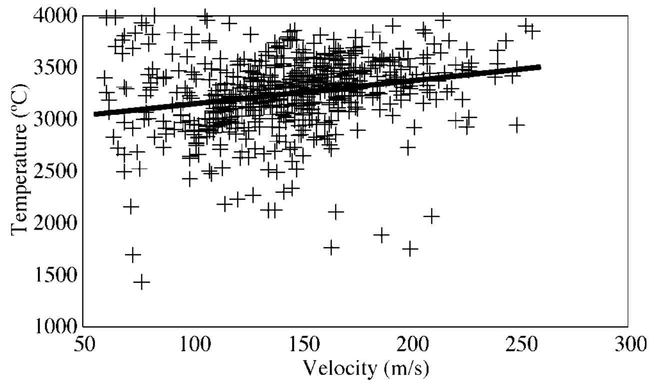
An example of how the dispersion of the particle velocity varies with different settings of the spray gun parameters is shown in Fig. 5. A clear difference in dispersion can be seen between treatments 1 and 16.

5.3 Investigation 3: Correlation between Particle Properties

The third investigation concerns the influence of the spray gun parameters on the correlation between the particle properties. Correlation is a measure of the linear association between two variables and varies between +1 and −1. A positive correlation between two variables implies that, if one variable has a high value, the other one also tends to have a high value. Negative correlation implies that, if one variable has a high value, the other one tends to have a low value. Correlation coefficients were calculated for each of the 16 data series. Figure 6 shows the correlation between particle velocity and temperature for treatments 6 and 11.



(a)



(b)

Fig. 6 Scatter plots of particle velocity vs temperature for treatments (**a**) 6 and (**b**) 11

6. Results

Figure 7 shows the mean velocity, temperature, and diameter of the particles. Clear differences in particle properties between the different treatments can be seen. The largest difference in mean particle velocity (59 m/s) is between treatments 10 and 15. Concerning particle temperature, the largest difference (310 °C) is found between treatments 6 and 11. The difference in particle diameter between treatments 6 and 12 is 7.3 μm. Obviously, the mean sizes of the particles in the most radiant spot can differ, depending upon the spray gun setting.

In analyzing the measured values shown in Fig. 7, certain patterns can be recognized. These are shown in Fig. 8. In using the design matrix (Table 2) to interpret Fig. 8(a), a rather clear distinction between different groups appears. All treatments inside the left dotted ellipse have the low current-level setting, while those inside the right dotted ellipse have the high current-level setting. In addition, the upper solid ellipse shows the argon set at the low level, while the solid ellipse below this shows the argon set at the high level. The triangles denote low-level setting of the powder feed rate, while the dots denote the high level. The difference between the high and the low level of hydrogen is not shown in the diagrams, since it was not as consistent as the difference obtained between the high and the low levels of the other parameters, and Fig. 8(b) should be interpreted in a similar way, since the treatment groupings are the same. In Fig. 8(c), only the current and powder feed rate are marked, since the influence of argon is unclear. One can definitely suspect that the spray gun parameters' current, argon flow rate, and powder feed rate have a strong influence on the particle characteristics.

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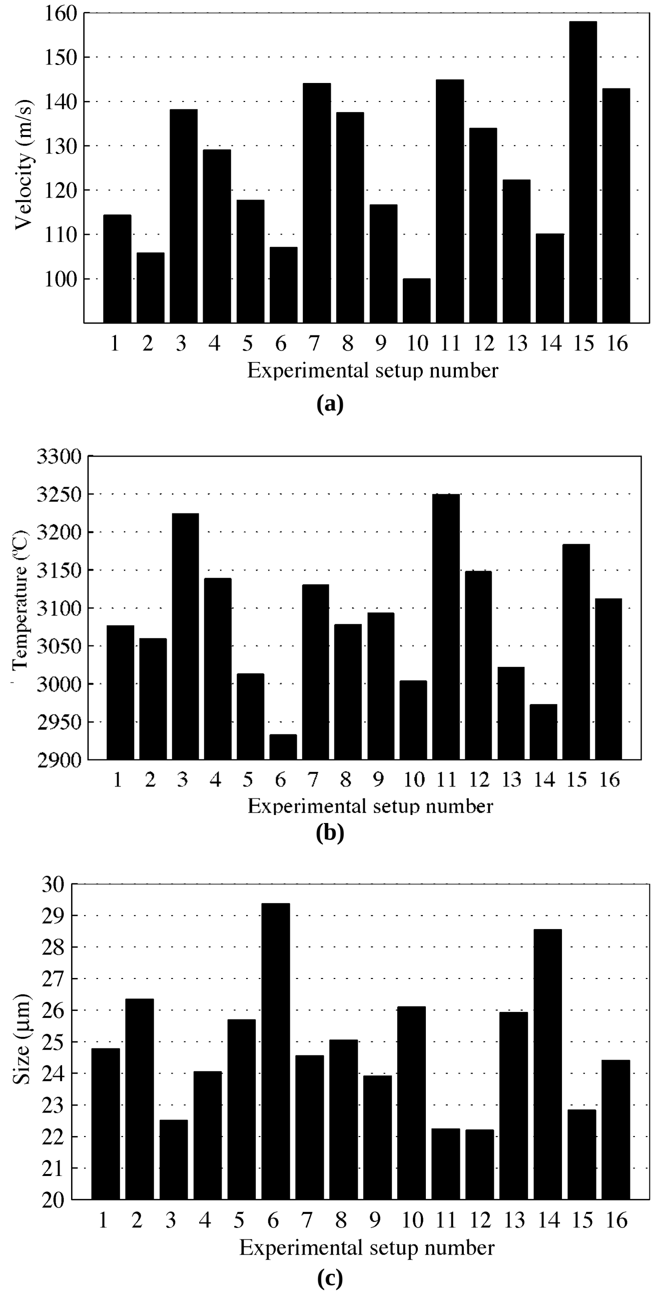


Fig. 7 (**a**) Mean velocity, (**b**) temperature, and (**c**) diameter for the 16 experimental settings

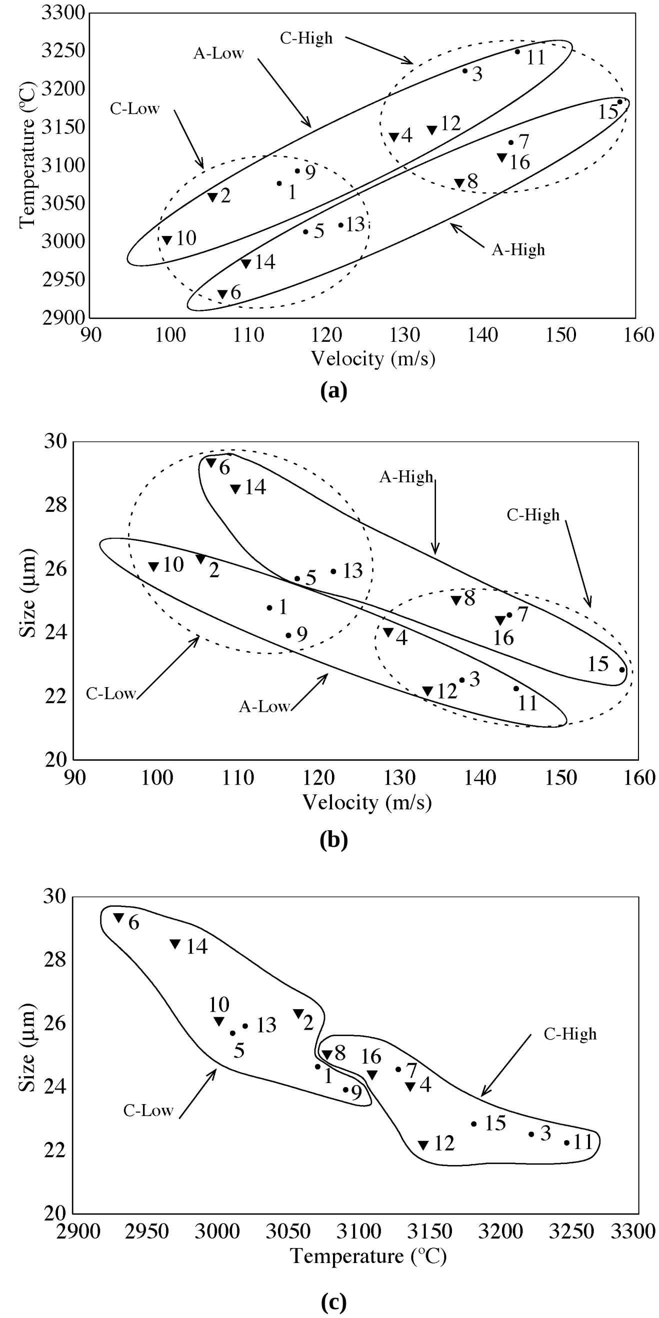


Fig. 8 Mean values of the 16 different treatments, showing trends in the particle properties

6.1 Investigation 1

The first investigation (Section 5.1) concerned the influence of the spray gun parameters and their interactions on the mean particle values. The hypothesis testing at the 99% confidence level showed factors C, A, H, and P and the two-factor interactions CA, CP, AH, and HP to have a significant influence on the response.

The treatment effects calculated for the factors and the two-factor interactions that were significant are shown in Fig. 9 (black squares), calculated in terms of the total mean value for each response. In Fig. 9, the low and high levels of each parameter are connected by a solid line. A solid line inclined to the right (/) shows that an increase in the factor level leads to an increase in the variable, and a line inclined to the left (\) shows that an increase in the factor level leads to a decrease in the variable. An interaction effect is defined as the average difference between the effect of parameter A when parameter B is high (B_+) and the effect of parameter A when parameter B is low (B_-). For example, the interaction effect CP in Fig. 9(a) describes the difference in the influence of current on the particle velocity when the powder feed rate is high and when it is low. Obviously, the

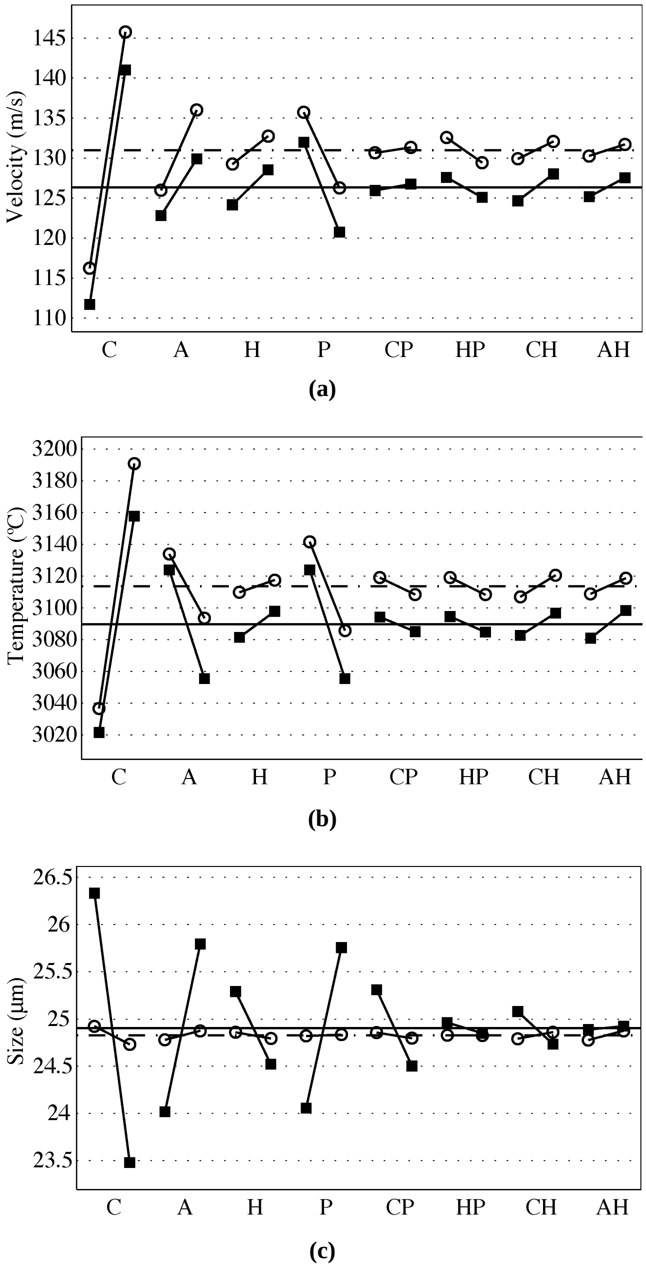


Fig. 9 Response of the particles in terms of (**a**) velocity, (**b**) temperature, and (**c**) diameter to variations in the level of single factors and to two-factor interaction effects. The black squares show effects based on the total mean value of all the particles, whereas the circles show effects based only on particles in the size range of 20 to 30 μm

largest effects on the particle properties originate from the main factors, especially current, argon flow rate, and powder feed rate. Regarding particle velocity, current was found to have the largest influence. The current being set at the high level results in a 29 m/s higher particle velocity than in the case of the low-level setting. The corresponding values for argon, hydrogen, and powder feed rate are 7, 4, and −11 m/s. The most favorable parameter settings for achieving the highest [+ + + −] and the lowest [− − − +] particle velocities result in a difference in particle velocity of 51 m/s due to the direct effects of the main parameters and of 8 m/s due to the interaction between the main parameters, a difference of 59 m/s altogether. Using a similar approach regarding the particle temperature shows the main parameters to yield a temperature difference of 288 °C and the parameter interactions to yield a difference of 22 °C, resulting in a total temperature difference of 310 °C between the highest and lowest particle temperatures, as achieved with the parameter settings [+ − + −] and [− + − +].

Note that, although an interaction between the factors is found, its influence is small compared with the direct influence of each factor separately. Nevertheless, in controlling the spray process, one should be aware of the effect this interaction can have.

An important result to be seen in Fig. 9 is that the argon flow rate is the only parameter affecting particle velocity and temperature in opposite directions. A high level of argon flow rate has a positive effect on particle velocity and a negative effect on particle temperature.

Figure 8 shows the trends found for particle properties, smaller particles having a higher temperature and velocity than larger particles. In Fig. 9 (black squares), the same inverse relationship can be seen.

Despite all the powder used in the 16 treatments being taken from the same lot and being similar in each case in size distribution, Fig. 7(c) shows the treatments to differ nevertheless in mean particle size. The explanation of this could possibly be that the degree of particle evaporation and/or agglomeration varied with the parameter settings. However, modeling of the plasma spray process[9] has shown that the particle temperature is too low and the dwell time in the plasma too short for particle evaporation to be significant.

Another explanation could be that differences in the settings of the spray gun parameters altered the properties of the plasma plume and thus the trajectories of the particles, making the particle distribution passing through the measured volume different for each treatment. To exclude the possibility that the velocity and temperature effects derive simply from measurements made on particles of differing size distributions, treatment effects were calculated for particles in the size range of 20 to 30 μm, which included 45% of the particles. The circles in Fig. 9 show that mean particle size is constant and is only 25 μm, there being no variation due to the spray gun parameters. However, the particle velocity and temperature effects obtained were similar. Results for the particle size ranges of 10 to 20 μm and 30 to 40 μm (the range 10 to 40 μm includes 85% of the particles) were also similar. It can thus be concluded that the variation in particle velocity and temperature between different treatments derives from variation in the parameters.

6.2 Investigation 2

The hypothesis testing shows factors C, A, H, and P to have a significant influence on the standard deviation of the particle properties. The effects of the different treatments were calculated, and the results are shown in Fig. 10. The current and the argon flow rate are the factors that influence the particle velocity dispersion most. An increase in current and in argon flow rate increases the dispersion.

The particle temperature dispersion is most strongly affected by the current and the powder feed rate. An increase in

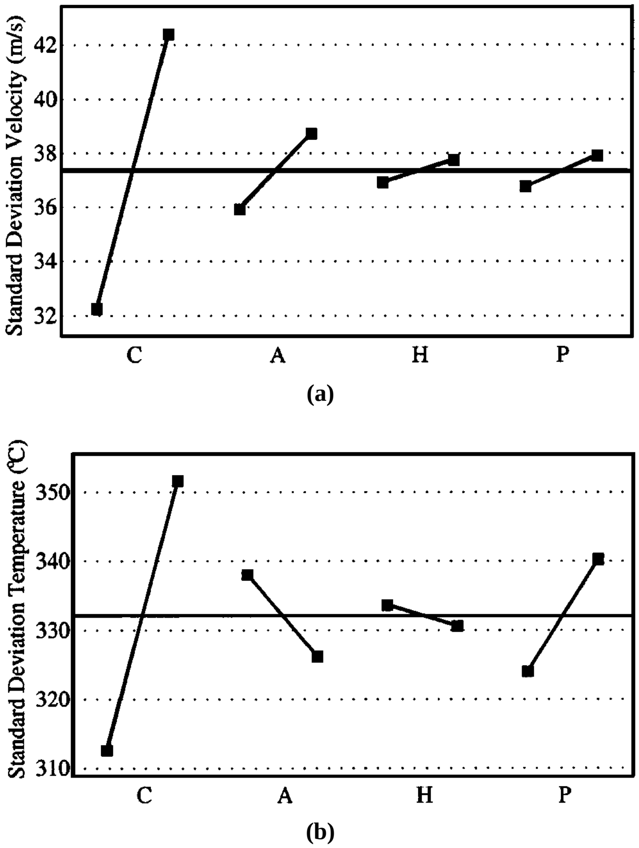


Fig. 10 Response in terms of standard deviations of the (**a**) particle velocity and (**b**) temperature due to variations in the level of the main factors

either or both of these results in an increase in the temperature dispersion.

On the basis of Fig. 10, it can be concluded that the smallest velocity dispersion is achieved when all the parameters are set at their low level, as is the case in treatment 1. The highest velocity dispersion is obtained when all the parameters are set at their high level, as in treatment 16, *cf.* Fig. 5.

6.3 Investigation 3

Investigation 3 concerns the influence of the spray gun parameters on the correlation between particle velocity and temperature.

The hypothesis testing indicates the main factors C, A, H, and P to all have a significant influence on the correlation of the particle properties. The treatment effects are shown in Fig. 11. The parameters having the largest effect on the correlation between particle velocity and temperature were argon mass flow and hydrogen mass flow, the effect of the former being greater. The average correlation for the 16 treatments was 0.40. To achieve a maximum and a minimum correlation, the spray gun parameters C, A, H, and P were set as shown in Fig. 11, *i.e.,* at [− + − +] and [+ − + −]. Figure 6 presents these treatments as scatter plots, treatment 11 showing the lowest correlation, one of 0.24, and treatment 6 showing the highest correlation, one of 0.54. As

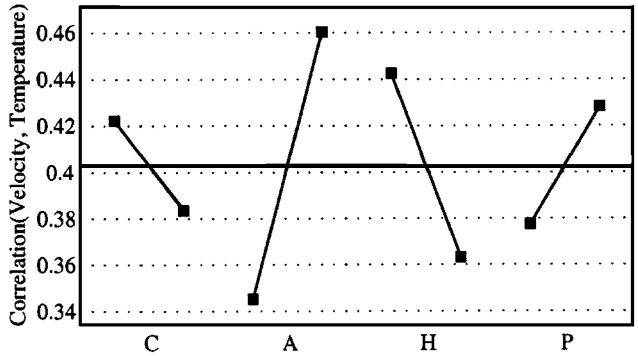


Fig. 11 Response in terms of correlations between particle velocity and temperature due to variations in the level of the main factors

can be seen in Fig. 6, particles of high temperature tend to have a high velocity, and particles of low temperature show a low velocity. These trends were stronger for the data shown in Fig. 6(a) than for the data shown in 6(b), as indicated by the respective inclinations of the straight lines fitted to the data by the least-squares method. The correlation between particle velocity and temperature can thus obviously be controlled by the spray gun parameters.

6.4 Coating Characteristics

Microstructural evaluation of the coatings produced with the different process parameter conditions was performed. A comprehensive investigation is given in Ref 13.

The evaluation was performed by the method of point counting, and two of the treatments, namely, treatment 2 with a total porosity of 31% and treatment 15 with a total porosity of 21%, are here presented as examples of the resulting microstructures.

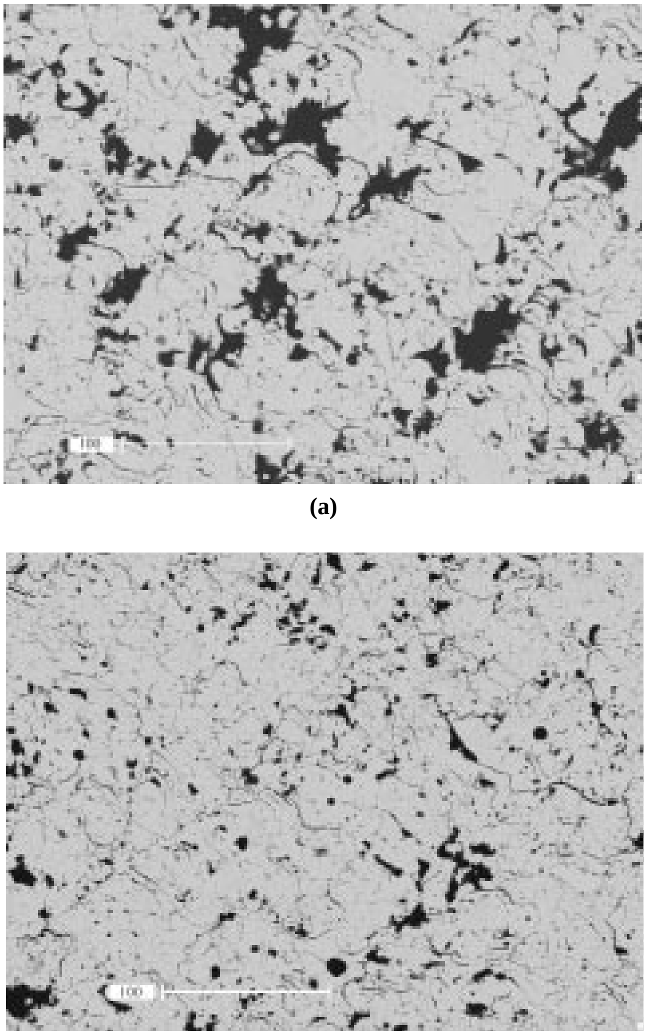
The setting of the parameters C, A, H, and P are inverse in treatment 15 as compared to treatment 2 (Table 3). This is reflected first in the in-flight particle properties, as given in Table 3, and finally also in the resulting microstructures. As can be seen, the more porous coating in Fig. 12(a) corresponds to the lower particle velocity and temperature of treatment 2, while the higher particle properties of treatment 15 correspond to the denser coating in Fig. 12(b), all in accordance with the findings of Prystay *et al.*[1]

7. Discussion

The spray gun parameters of most and second most importance as regards the impact on the two particle properties' velocity and temperature are summarized in Table 4.

The particle temperature was found to depend on both the surrounding plasma temperature and the dwell time of the particles in the flame, the latter being directly related to the particle velocity. A high velocity yields a short dwell time and thus a low particle temperature. The velocity, in turn, increases with increasing flame linear momentum.

An increase in current (*C*) yields an increase in both particle velocity and temperature. A higher power input results in an increase in temperature and an expansion of the plasma, which



(a)

(b)

Fig. 12 The microstructure of (**a**) treatment 2 and (**b**) treatment 15

leads to a higher gas velocity and thus to a shorter dwell time, which in turn results in a lower particle temperature. In the present case, however, the effect of the increase in plasma temperature overtakes the decrease in dwell time.

Increasing the argon flow rate (*A*) leads to an increase in the linear flame momentum and thus to a higher particle velocity. The particle temperature decreases due to both a stronger cooling effect and a shorter particle dwell time.

An increase in hydrogen flow rate (*H*) results in an increase in both particle velocity and temperature. The change in the linear flame momentum due to the increase in the total gas flow rate can be disregarded since the hydrogen flow rate is only 1/7 the flow rate of argon. Instead, the major change is due to the increase in enthalpy as the hydrogen content increases. This results in a higher plasma temperature, a greater expansion of the plasma, and thus an increase in the linear flame momentum. As in the case of increasing the current, the increase in plasma temperature overtakes the effect on the particle temperature of the decrease in dwell time.

Table 3 Setting of treatments 2 and 15 and the resulting particle properties and total porosity

Treatment	C	A	H	P	V (m/s)	*T* (°C)	Total porosity (vol.%)
2	−	−	−	+	105	3055	31
15	+	+	+	−	159	3180	21

Table 4 Summary of the results of investigations 1 to 3

Property	Primary parameter	Secondary parameter
V_p	Current	Powder feed rate
T_p	Current	Powder feed rate
$Ø_p$	Current	Powder feed rate
σ_V	Current	Argon
σ_T	Current	Powder feed rate
Correlation (V, T)	Argon	Hydrogen

Increasing the powder feed rate (*P*) increases the number of particles to be heated and accelerated, resulting in the particle temperature and velocity being lowered. Although the difference in energy required to melt a larger or smaller amount of ZrO_2 is only a small fraction of the energy available in the plasma, the effect is still noticeable in accordance with the findings by Vardelle *et al.*[14] This is most probably due to a local loading effect, since the particles travel in a fairly small volume fraction of the jet.

The torch voltage has been shown to be influenced by the process parameters and is specifically sensitive to the amount of hydrogen.[15] However, the measured voltage variation in this work did not show any statistically significant influence on the particle properties.

8. Conclusions

The results clearly show that the temperature and velocity of the particles can be controlled by the spray gun parameters that were selected here. In addition, the dispersion and the correlation of the particle properties respond to variations in the parameter setting of the spray gun.

The experimental approach and the statistical evaluation presented in this paper, complemented by numerical simulations,[9] constitute a method for optimizing the plasma spray method in a cost-effective and powerful way.

- The factors with the strongest influence on particle velocity are current, argon flow rate, and powder feed rate.
- The factors with the strongest influence on particle temperature are current, argon flow rate, and powder feed rate.
- Argon flow rate is the only spray gun parameter with an inverse effect on particle velocity and temperature. Setting argon flow at a high level yields an increase in particle velocity and a decrease in particle temperature.

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References

1. M. Prystay, P. Gougeon, and C. Moreau: in *Thermal Spray: Practical Solutions for Engineering Problems,* C.C. Berndt, ed., ASM International, Materials Park, OH, 1996, pp. 517-23.
2. L.Pejryd, J. Wigren, and N. Hanner: in *Thermal Spray: A United Forum for Scientific and Technological Advances,* C.C. Berndt, ed., ASM International, Materials Park, OH, 1997, pp. 445-50.
3. D.J. Varacalle, Jr. Wilson, D.E. Crawmer, and P.A. Didier: in *Thermal Spray: Industrial Applications,* C.C Berndt and S. Sampath, eds., ASM International, Materials Park, OH, 1994, pp. 211-20.
4. M.P. Planche, R. Bolot, O. Landemarre, and C. Coddet: in *Thermal Spray: Meeting the Challenges of the 21st Century,* C. Coddet, ed., ASM International, Materials Park, OH, 1998, pp. 355-60.
5. L. Leblanc and C. Moreau: in *Thermal Spray: Meeting the Challenges of the 21st Century,* C. Coddet, ed., ASM International, Materials Park, OH, 1998, pp. 773-78.
6. C. Moreau, P. Gougeon, M. Prystay, and L. Leblanc: *85th Meeting Structures and Materials Panel,* NATO, Workshop 3 on TBCs, Aalborg, Denmark, Oct. 13-17, 1997.
7. P. Fauchais, M. Vardelle, A. Vardelle, and J F. Coudert: *Metall. Trans. B,* 1989, vol. 20B, pp. 263-76.
8. L. Pejryd, J. Wigren, P. Gougeon, and C. Moreau: in *Thermal Spray: Meeting the Challenges of the 21st Century,* C. Coddet, ed., ASM International, Materials Park, OH, 1998, pp. 785-90.
9. Per Nylén, Martin Friis, Anita Hansbo, and Lars Pejryd: *J. Thermal Spray Technol.,* 2001, vol. 10(2).
10. P. Gougeon, C. Moreau, V. Lacasse, M. Lamontagne, I. Powell, and A. Bewsher: in *Advances in Powder Metallurgy & Particulate Materials,* C. Lall and A.J. Neupaver, eds., Metal Powder Industries Federation, Toronto, 1994, vol. 6, pp. 199-210.
11. C. Moreau, P. Gougeon, M. Lamontagne, V. Lacasse, G. Vaudreuil, and P. Cielo: in *Thermal Spray: Industrial Applications,* C.C Berndt and S. Sampath, eds., ASM International, Materials Park, OH, 1994, pp. 431-37.
12. Richard A. Johnson and Dean W. Wichern: *Applied Multivariate Statistical Analysis,* 3rd ed., Prentice-Hall International Editions, Englewood Cliffs, NJ, 1992, pp. 219-84.
13. M. Friis, C. Persson, and J. Wigren: Licentiate Dissertation, Lund University, Lund, Sweden, 1999.
14. A. Vardelle, M. Vardelle, P. Fauchais, P. Proulx, and M. I. Boulos: in *Thermal Spray: International Advances in Coatings Technology,* C.C. Berndt, ed., ASM International, Materials Park, OH, 1992, pp. 543-47.
15. B. Doussoubs: Ph.D. thesis, Limoges University, Limoges, France, 1998.