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The Long-Term Stability of Plasma Spraying

L. Leblanc and C. Moreau

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The wear state of the different gun parts can affect the reproducibility of the plasma spray process. Indeed, this may influence the plasma characteristics and the energy transfer to the sprayed particles resulting in significant changes in the coating attributes. In this contribution, results from a detailed investigation on the stability of plasma spraying are presented.[1] Specifically designed diagnostic tools were used to study the evolution of key parameters of a plasma spray process during a long-term experiment. A comprehensive analysis was carried out on the collected set of data, with an emphasis on the correlation that may exist among the data. Results show significant variations in the particle state and gun characteristics with spraying time. These variations are reflected in the microstructure of the sprayed coatings. The investigation also gives some indication about how the spray process could be controlled.

Keywords arc root fluctuations, electrode wear, in-flight particle state, long-term stability, plasma spraying, process control

1. Introduction

Direct current (DC) plasma spraying is used to deposit coatings on structural materials to protect them against different degradation mechanisms. The reproducibility of coating characteristics during production becomes a crucial attribute as coatings are used in more and more demanding applications.

In DC plasma spraying, the heat source consists of a plasma generated by an electric arc ignited and maintained between two electrodes. Generally, the arc root moves along the anode surface under the combined action of a gas flow and electromagnetic forces. This movement leads to significant fluctuations in the plasma characteristics.[2-5] Torch voltage fluctuations, acoustic emission, high-speed imaging, and plasma light intensity fluctuations have been used to monitor the arc behavior.[2,6] In general, good correlation is found between these signals because they are all sensitive to the arc length fluctuations.[7-9] However, the influence of all related parameters on the arc behavior is not fully understood. Nevertheless, it is well established that the electrode surface condition influences the arc root movement.[2,10-13]

The heating and acceleration of the particles fed into the plasma depend on its actual composition, temperature, velocity, viscosity, enthalpy, etc.[14,15] The plasma fluctuations associated with the arc root movement play an important role because their characteristic period is of the same order of magnitude as the transit time of the particles in the plasma. Therefore, the change of the electrode surface condition with time is likely to affect the temperature and velocity of the sprayed particles. Because these particle characteristics are among the most important parameters influencing the microstructure of the deposited coatings,[16-19] the wear of the electrodes may significantly influence the coating attributes, leading to poor reproducibility of the spray process.

In this contribution, the long-term stability of plasma spraying is investigated using a model F4-MB plasma torch (Sulzer Metco Inc., Westbury, New York) to characterize the evolution of the main torch and particle parameters with spraying time. Specifically designed diagnostic tools were developed to study the evolution of key spray parameters during a long-term experiment. A comprehensive analysis was carried out on the collected set of data, with an emphasis on the correlation that may exist among them. Moreover, strategies for controlling the plasma spray process were also evaluated on the basis of the observed evolution of the in-flight particle characteristics.

L. Leblanc (Current address: Pyrogenesis Inc., 1744 William Street, Suite 200, Montreal, Quebec, H3J 1R4 Canada); and **C. Moreau,** National Research Council Canada, 75 Blvd. De Mortagne, Boucherville, Quebec, J4B 6Y4 Canada. Contact e-mail: christian.moreau@nrc.ca.

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Table 1 Nominal Operating Conditions

Parameters	Settings
Arc gas, L/min	
Primary (Ar)	32.4
Secondary (H_2)	12.6
Arc current, A	550
Powder carrier gas (Ar), L/min	1.7
Powder feed rate, g/min	23
Stand-off distance, mm	140

2. Experimental Setup and Procedure

The investigation was carried out using a model F4-MB plasma gun starting with new electrodes (types 300002 and 300001) using a 1.8 mm diameter external powder injector, the tip of which was located 10 mm away from the gun axis. The sprayed powder, injected from the top into the plasma plume, was a fused and crushed 7 wt.% yttria partially stabilized zirconia powder, −45 + 22.5 µm. The nominal operating conditions are summarized in Table 1.

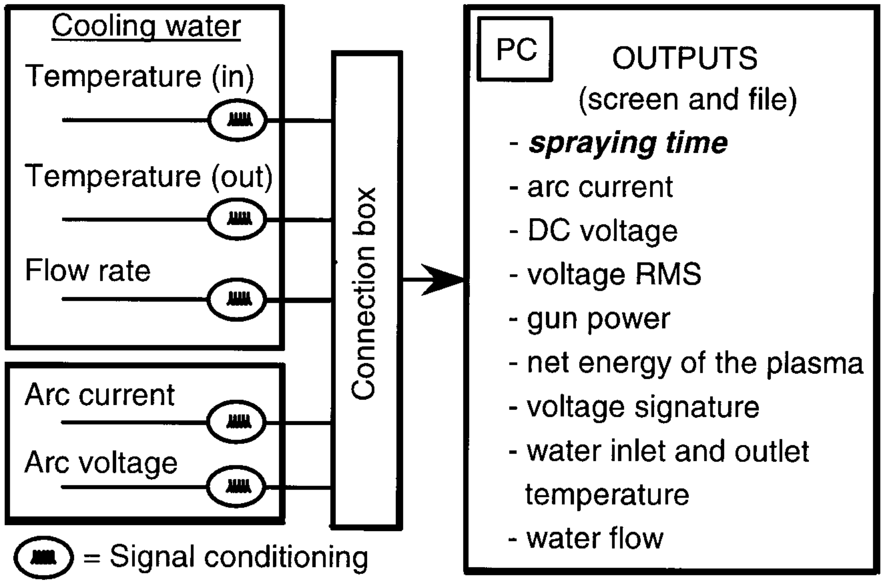

Fig. 1 The DAPRO system monitors, processes, and records key process parameters during plasma spraying.

Those operating conditions were used for more than 50 h of spraying, with an average of 2.5 stops/starts per hour. During that period of time, different diagnostic tools were used to monitor and characterize the spray process, namely the data acquisition and processing system (DAPRO), the DPV 2000 (Tecnar Automation Ltée, St-Bruno, Quebec, Canada), and a camera system designed to take pictures of the electrodes. The DAPRO system was specifically developed to monitor key parameters during long periods of spraying. The system is based on a 12 bit, 1.25 megasamples/s, 8 channel data acquisition board located in a personal computer. A specific application was developed under LabVIEW (National Instruments, Austin, TX) to record, visualize, and process the monitored data on line. The collected signals include the arc current and voltage as well as the inlet and outlet water temperature and flow rate (Fig. 1). These parameters, as well as other calculated process variables, are automatically saved onto the computer hard disk and displayed at a desired rate.

The DAPRO system saved more than 3300 sets of data during the long-term experiment, i.e., an average of one set per minute. Each data set included the value of the five above-mentioned monitored parameters. In addition, the total spraying time since the beginning of the experiment, the voltage root mean square (RMS), the gun power, and the net energy of the plasma were recorded. The net energy was calculated as the difference between the total input electrical power and the power loss to the cooling water. The plasma net energy reflects the energy content of the plasma that is available to heat and accelerate the injected particles.

Arc root fluctuations were studied both in the time domain (RMS voltage) and in the frequency domain (spectral intensity as a function of frequency) by performing a fast-Fourier transform (FFT) of the time domain voltage signals. The DAPRO system includes a module to perform FFT on line and to display and record the calculated voltage signature. The latter is composed of different peaks, which have been associated with different phenomena such as the restrike and the circular motion of the electric arc.[11] The restrike mode usually generates the more intense peak. The position and intensity of that peak have been shown to depend on the wear state of the electrodes and be correlated to some extent to the sprayed particle characteristics.[11-13]

Finally, the DAPRO system was also designed to visualize the acquired and processed data and to manage the different files generated to characterize the spray process (DPV 2000, camera system, deposited coatings, etc.).

Another diagnostic tool, the DPV 2000, was used to monitor the temperature, velocity, size, and trajectory of the sprayed particles at the nominal stand-off distance. The optical monitoring system was described in detail previously.[20,21] When a hot particle passes in the system's measurement volume, its image is formed on a two-slit mask fixed on the end of an optical fiber that guides the radiation to a detection box located away from the plasma booth. Because the distance between the slits as well as the magnification of the detection optics are known, the particle velocity is calculated from the measured time of flight of the particle image between the two slits. The particle temperature is determined from the ratio of the radiation intensities collected at two different wavelengths. Particle size is determined from the calculated temperature and the absolute radiation intensity. The DPV 2000 also includes a linear charge-coupled device (CCD) camera to monitor the particle jet in its entirety.

Coatings were deposited at different spraying times onto mild steel test coupons prepared by cleaning, degreasing, and grit blasting. Surface temperature was measured immediately after deposition using a thermocouple. The test coupons were subsequently infiltrated under vacuum with epoxy, cut with a diamond saw through thickness, remounted, and polished using standard metallographic preparation for characterization under a scanning electron microscope (SEM).

During the 50 h spraying period, the DAPRO system, the DPV 2000, and a camera system were used to regularly characterize the thermal process using the nominal spraying conditions (Table 1).

The response of the thermal spray process to arc current adjustments was also studied. Two different approaches were used. The first approach consisted of adjusting the arc current to keep the total electrical power constant. The second approach consisted of adjusting the current to keep the in-flight particle state the same.

3. Results and Discussion

Results related to the spray process operated under the nominal spraying conditions are presented and discussed first. However, some of the graphs will also exhibit results obtained after adjustment of the arc current was imposed. Those results will be discussed subsequently when the response to input spray parameter adjustment is considered.

3.1 Plasma Gun

The evolution of arc current, DC voltage, gun power, and net energy of the plasma can be seen in Fig. 2, which shows the results obtained using the nominal spraying conditions for a period of 55 h. The arc current (Fig. 2a) was maintained at 550 ± 10 A throughout the whole experiment. During that time, the DC voltage (Fig. 2b) decreased by more than 10 V, which led to a gun power variation of more than 6 kW (Fig. 2c). The net energy of the plasma (Fig. 2d) closely followed the gun power trend.

Three distinct regions can be identified in Fig. 2. The first (region I) extends from the beginning of the experiment up to around 12 h of spraying. During that period the plasma gun parameters stayed approximately the same. In the second region (region II), i.e., between 12 and 45 h of spraying, the voltage and power constantly decreased. However, at 45 h of spraying, a sharp drop of more than 1.5 kW was observed in the gun power and net energy of the plasma (almost 3 V on the gun DC voltage). In a production environment the electrodes would have been discarded and categorized as burnt parts. Despite that, they were used for an additional period of 10 h (region III) to investigate the process in such irregular conditions. After the sharp drop at 45 h, the parameter values continued to constantly decrease, but at a higher rate than observed in region II.

Pictures of the electrodes taken at different times and representative of the three regions mentioned above are presented in Fig. 3. After 6 h of spraying (Fig. 3a), the anode surface was relatively smooth, although not as smooth as a new electrode would be. After 33 h (Fig. 3b), significant signs of wear could be observed, as revealed by the large number of wear spots present on the anode surface. Although a detailed investigation was not conducted, other pictures (not shown) taken between 12 and 45 h of spraying (region II) show that the wear spots qualitatively increased both in size and in number with spraying time. Finally, after 55 h of spraying (Fig. 3c), the anode surface was severely damaged and would have been considered improper for production (region III).

The cathode tip also exhibited significant changes during the 55-hours spraying period. After 6 h, although some fusion spots can be observed on the edges in Fig. 3a, its shape was conical, similar to a new one. After 33 and 55 h of spraying, the cathode tip was nearly flat, showing clear evidence of degradation. This suggests that some tungsten (cathode material) might have been sprayed during the experiment. Presence of tungsten in coatings has been shown to be detrimental to their quality because of the large volume expansion (300%) of the oxides formed during use at high temperature.[22]

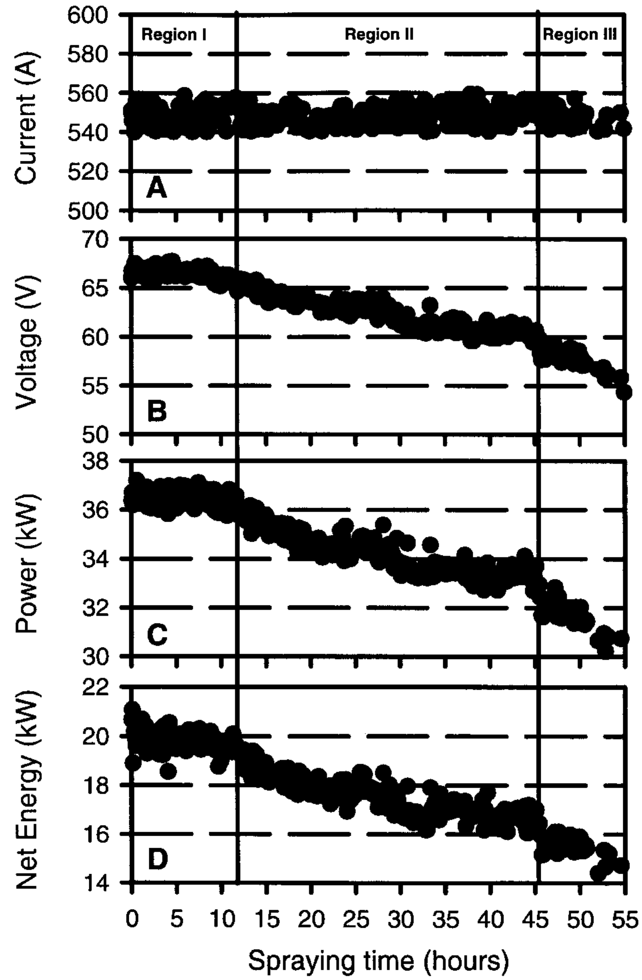

Fig. 2 Evolution of the plasma gun parameters during 55 h of spraying using the nominal operating conditions (constant arc current). **(a)** Arc current and **(b)** DC voltage are used in the calculation of the **(c)** gun power and **(d)** plasma net energy.

The high local energy load to the part generated by the electrical arc causes the electrodes to wear. The surface morphology of the electrodes can influence the arc root motion. Because significant changes in surface morphology are observed on the electrodes in Fig. 3, a variation of the arc root fluctuation characteristics during the experiment is expected.

Arc root fluctuations were studied both in the time and frequency domains. Figure 4 shows an example of a typical measurement. In the time domain, arc root fluctuations were characterized by the RMS of the measured voltage. In the frequency domain, the spectrum is composed of different peaks. The more intense peak, located around 5 kHz, was characterized by its position and intensity.

Figure 5 shows the evolution of the voltage RMS, as well as

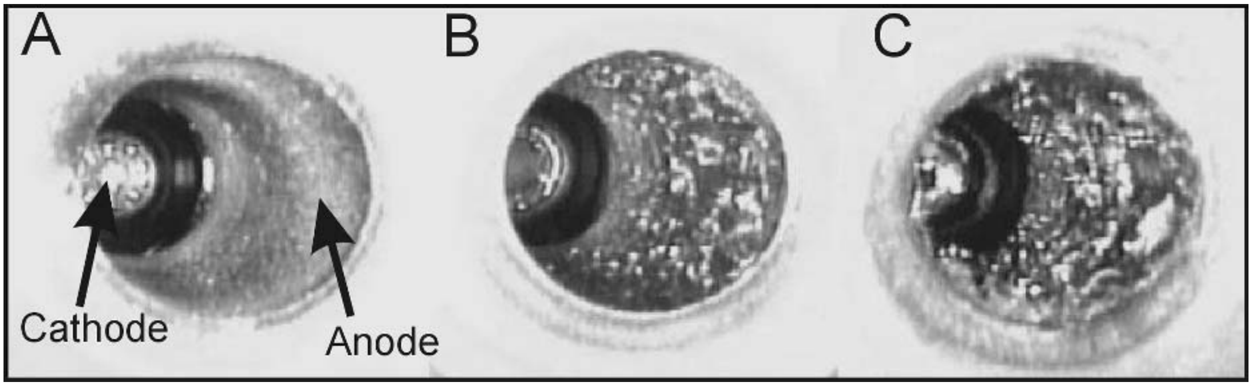

Fig. 3 Anode and cathode pictures showing the evolution of the surface wear state of the parts after **(a)** 6 h, **(b)** 33 h, and **(c)** 55 h of spraying corresponding to regions I, II, and III, respectively

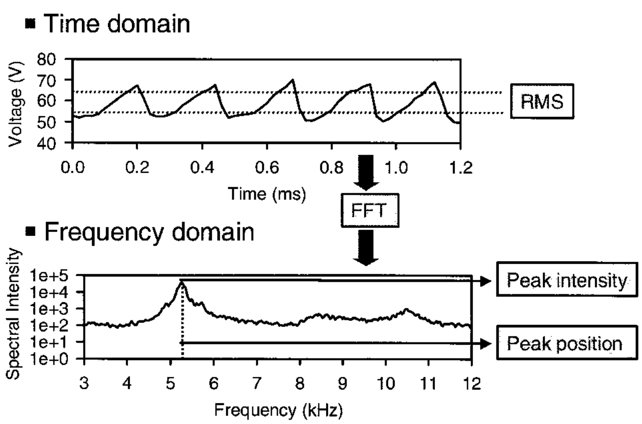

Fig. 4 Arc root fluctuations are characterized using voltage fluctuations in the time or frequency domain. Voltage RMS as well as main peak intensity and position are measured.

the main peak position and intensity of the voltage signature during 55 h of spraying. All of the characterized parameters showed a significant variation during the long-term experiment.

As observed for the gun voltage, power, and net energy (Fig. 2), the 55 h spraying period can be divided in three distinct regions (regions I, II, and III), where the arc root fluctuation characteristic trends are notably different. However, no direct correlation could be observed between the arc root characteristics (Fig. 5) and the plasma gun parameters (Fig. 2).

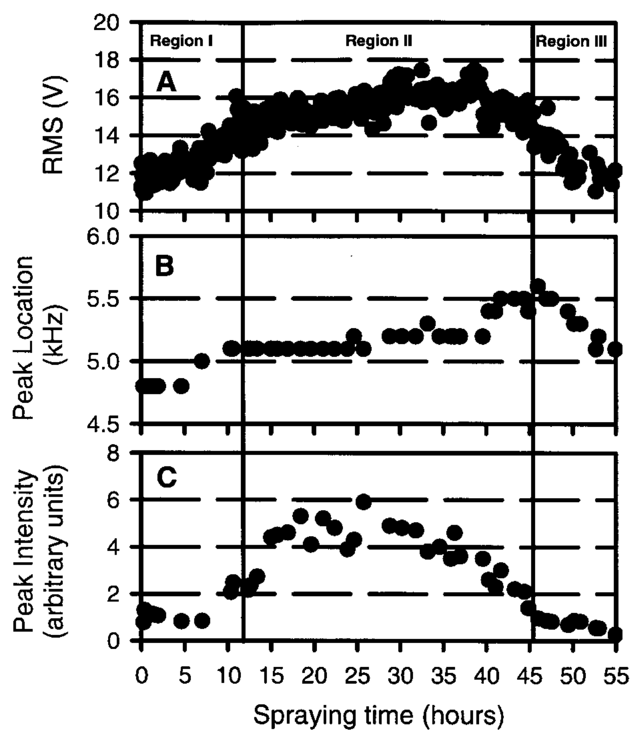

Fig. 5 Evolution of the arc root fluctuation characteristics during 55 h of spraying using the nominal operating conditions. **(a)** RMS value, **(b)** main peak location, and **(c)** intensity are shown.

3.2 Particle State and Coating Characteristics

The state of the sprayed particles was monitored regularly at the position of the maximum particle flux in the center of the particle jet. This location was maintained 3 mm below the gun axis by adjusting the powder carrier gas flow rate. Characteristics (temperature, velocity, and size) of a few thousand individual particles were averaged for each reported measurement.

Figure 6 depicts the measured values during the 55 h spraying period as obtained both under the nominal operating conditions, i.e., at constant arc current (circles), and after adjustment of the arc current (squares and triangles).

During the 55 h period, the temperature (Fig. 6c) and velocity (Fig. 6d) of the particles sprayed using the nominal spraying conditions varied by more than 200 °C and 30 m/s, respectively. Similar variations have been observed using a different plasma gun.[12,23] It is interesting to note that after the rapid gun power drop at 45 h of spraying, the particle state showed significant variation in short periods of time.

To illustrate the importance of the particle state before impact on the substrate, Fig. 7 represents the porosity level (as measured using image analysis) as a function of the measured in-flight particle temperature for five coatings sprayed during the long-term experiment. The surface temperature was the same for all

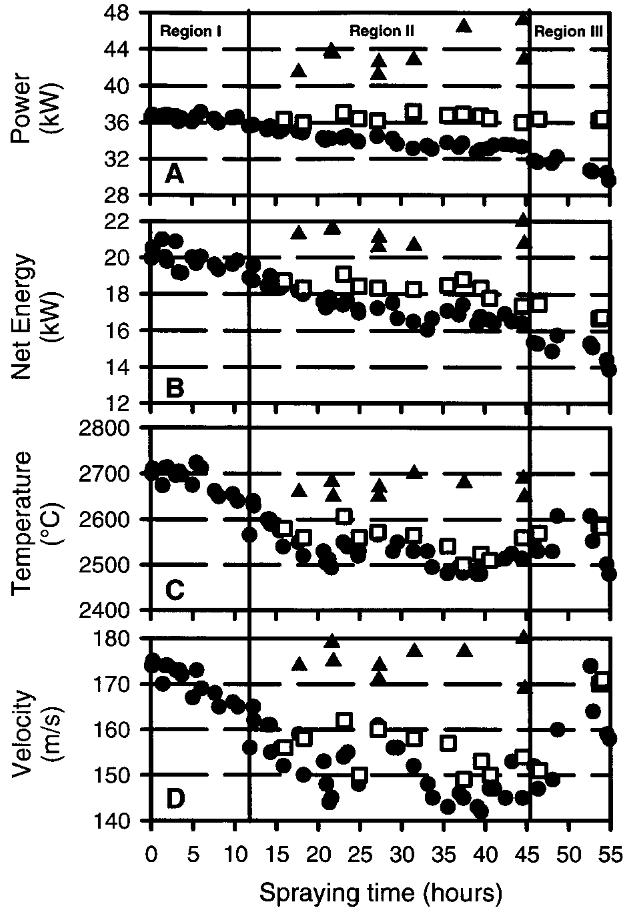

Fig. 6 Evolution of the plasma **(a)** gun power and **(b)** net energy, **(c)** in-flight particle temperature, and **(d)** velocity during 55 h of spraying. Nominal operating conditions (circles); constant power (squares); and constant in-flight particle state (triangles)

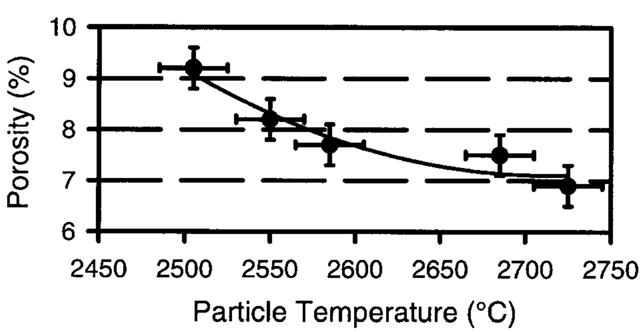

Fig. 7 Coating porosity as a function of in-flight particle temperature

of the sprayed coatings within ±25 °C. It can be observed in Fig. 7 that the porosity level of the coatings decreases as the particle temperature increases. Similar observations have been reported earlier.[12,17,24]

3.3 Correlation and Process Control

As seen in Fig. 7, coating characteristics are correlated to the state of the impacting particles. Note that this investigation is

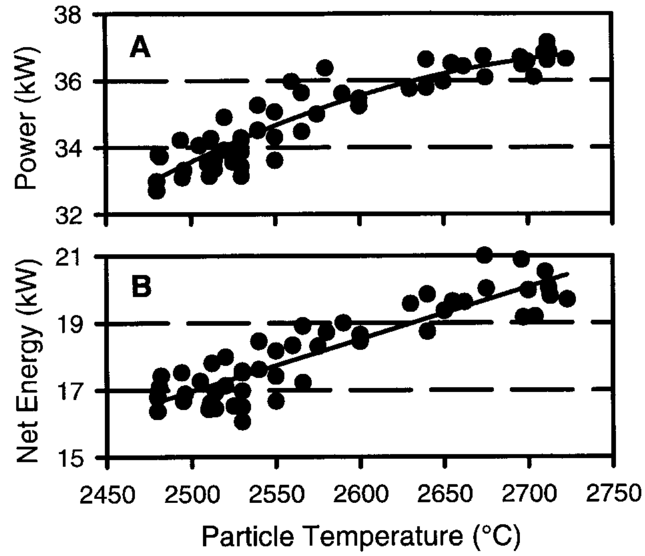

Fig. 8 Correlation between particle temperature, **(a)** gun power and **(b)** plasma net energy

based on the mean particle temperature and velocity measured at the position of the maximum particle flux in the center of the particle jet. The influence of the width of the particle temperature and velocity distributions at the measurement location and/or within the spray jet itself has not been investigated. Nevertheless, current and previous results based on averaged values seem to indicate that regulating the state of the sprayed particles is a good approach to control the plasma spray process.[12,17,24]

Possible correlation between in-flight particle state and other parameters will now be discussed. Good correlation is found between particle temperature and both the gun power and plasma net energy using the nominal operating conditions, i.e., using a constant arc current of 550 A (Fig. 8). A similar correlation is observed for particle velocity.

From Fig. 7 and 8, it can be deduced that coating porosity decreases with increasing gun power and plasma net energy when the arc current is constant. These results suggest that gun power and/or plasma net energy could be of interest for process control. However, results from Fig. 6 show that when the gun power is kept constant at 36 kW (circles for the first 15 h of spraying, squares for the rest, Fig. 6a), the state of the sprayed particles can significantly change with spraying time. Indeed, the temperature and velocity (Fig. 6c,d) of the sprayed particles using constant gun power (squares) varied by nearly 200 °C and 25 m/s, respectively. The magnitude of the observed variation can lead to different coating characteristics (Fig. 7). Thus, maintaining the gun power to a constant value does not seem to be an efficient way to control the process. In fact, results from Fig. 6 show that to maintain the same particle state during the whole experiment (triangles), the gun power had to be raised by more than 10 kW.

On the other hand, Fig. 6 also reveals that a variation of less than 2 kW in the plasma net energy was necessary to preserve the particles at a similar state during the long-term experiment (triangles). Therefore, maintaining the plasma net energy at a constant value appears to be an efficient means of controlling this particular spray process.

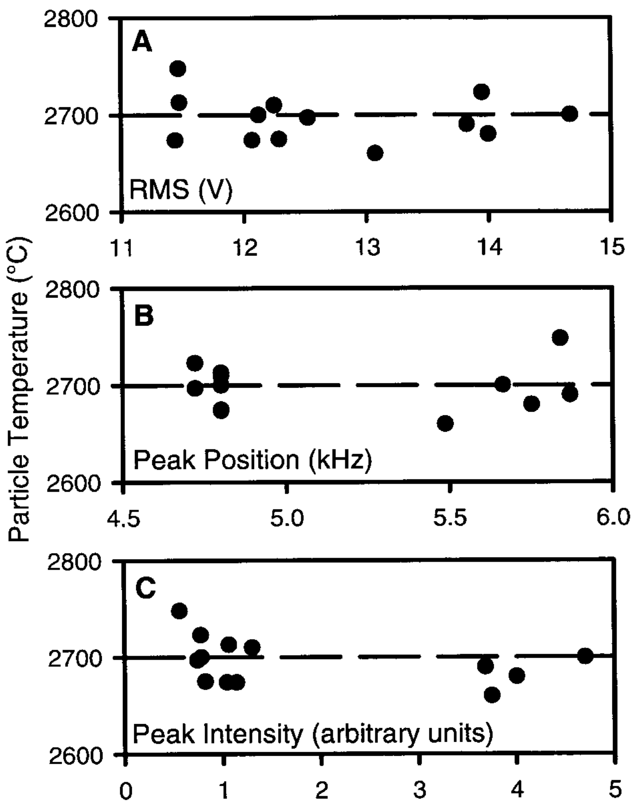

Fig. 9 Arc root fluctuation characteristics when particle state is kept the same. **(a)** RMS value, **(b)** main peak position, **(c)** and intensity are shown.

A similar investigation was conducted to find possible correlation between the state of the sprayed particles and the arc root fluctuation characteristics. A correlation seems to exist between the voltage RMS value, the main peak position and intensity (around 5 kHz), and the state of the sprayed particles using the nominal operating conditions. However, those parameters were found to be of limited use for process control. Indeed, the arc root characteristics changed significantly when the state of the sprayed particles was maintained constant by varying the arc current during the 55 h spraying period (Fig. 9).

4. Summary and Conclusions

Results from a detailed investigation on the stability of plasma spraying were presented. Specifically designed diagnostic tools were used to study key parameters during an experiment that lasted for 55 h of spraying using a model F4-MB plasma gun. Arc current, gun voltage, and power as well as net energy of the plasma were monitored continuously during that period of time. Arc root fluctuations were characterized through the voltage fluctuations, and pictures were used to qualitatively characterize the wear state of the electrodes. The state of the sprayed particles was monitored regularly during the long-term experiment during which coatings were sprayed.

An analysis was carried out on the extensive set of collected data, with an emphasis on the correlation that may exist among them. From that analysis, the following observations were made:

- Coating characteristics are correlated to the state of the sprayed particles before impact on the substrate, suggesting that regulating the state of the sprayed particles could be a good approach to control the plasma spray process.
- The state of the sprayed particles significantly changes with spraying time when the arc current or the gun power is kept constant. Therefore, maintaining those parameters to a constant value does not appear to be an efficient way to accurately control the process.
- Conversely, only a small variation in the plasma net energy was observed when the particle state was kept the same by changing the arc current during the long-term experiment, suggesting that maintaining the plasma net energy to a constant value is a good means to indirectly control this particular spray process.
- Correlation between gun power, arc root fluctuation characteristics, and in-flight particle state was identified when the process is used at constant arc current. Those parameters could possibly be used as indicators of the process condition. However, the observed correlation does not permit the accurate control of the process.

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