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Relation Between the Arc-Root Fluctuations, the Cold Boundary Layer Thickness and the Particle Thermal Treatment

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In plasma spraying, the arc-root fluctuations, modifying the length and characteristics of the plasma jet, have an important influence on particle thermal treatment. These voltage fluctuations are strongly linked to the thickness of the cold boundary layer (CBL), surrounding the arc column. This thickness depends on the plasma spray parameters (composition and plasma forming gas mass flow rate, arc current, etc.) and the plasma torch design (anode-nozzle internal diameter and shape, etc.). In order to determine the influence of these different spray parameters on the CBL properties and voltage fluctuations, experiments were performed with two different plasma torches from Sulzer Metco. The first one is a PTF4 torch with a cylindrical anode-nozzle, working with Ar-H_2 plasma gas mixtures and the second one is a 3MB torch with either a conical or a cylindrical anode-nozzle, working with N_2-H_2 plasma gas mixtures. Moreover, arc voltage fluctuations influence on particle thermal treatment was studied through the measurements of transient temperature and velocity of particles, issued from an yttria partially stabilized zirconia powder with a size distribution between 5 and 25 μm.

Keywords arc voltage fluctuation, particle thermal treatment, plasma spray, spray parameter influence

1. Introduction

In d.c. plasma spray process, the arc is generated between two electrodes (Ref 1). The arc column emanating from the cathode tip does not directly hit the anode, because they have the same axis. Thus the arc attaches at the anode wall through a connecting column (Fig. 1), crossing the cold boundary layer (CBL) surrounding the arc column. The arc column corresponds to the area where the electrical conductivity is high enough to let the current go through, which, for conventional plasma forming gases, correspond to temperatures over 7500-8000 K. The connecting column strikes at the anode wall, where the CBL, between the arc column and the anode wall, has been sufficiently heated (Ref 2).

This connecting column is submitted to two forces: the Drag force issued from the gas flow in the CBL and electromagnetic forces ($\vec{j} \wedge \vec{B}$ where $\vec{j}$ is the current density and $\vec{B}$ is the induced magnetic field), resulting in its continuous fluctuation along the anode wall. Under the action, mainly of the drag force, the connecting column lengthens, when the voltage increase within it, reaches the breakdown voltage, a new arc root, upstream or downstream of the previous arc, is created resulting in voltage drop. The voltage at which this breakdown occurs is very difficult to determine, because first, a few studies (except in circuit breakers) have been devoted to the evolution of the breakdown voltage with temperature, and second, because the temperature distribution within the CBL is unknown. This movement, depending on the CBL thickness, induces a periodic variation in the arc voltage, thus in the torch power when supplied by a current source. Such fluctuations modify the enthalpy input to the gas, the plasma-jet velocity, length and width, and the way it mixes with the surrounding atmosphere when exiting the torch. The plasma temperature is generally less affected by the enthalpy variations, due to the ionization of the plasma which behaves as an ''inertia wheel'' (about 2000 K increase if the enthalpy is doubled).

Three different principal fluctuation modes have been identified by Duan and Heberlein (Fig. 2): the steady mode, for which the anode lifetime is very short and thus not recommended at all, the takeover mode, mainly with monoatomic plasma gas mixture, and the restrike mode, for polyatomic gas mixture (Ref 3-5). For a relatively thick CBL, a downstream motion of the arc anode attachment is

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observed until the voltage gradient across the connecting column becoming higher than the breakdown voltage, results in a periodic variation of the arc length: restrike mode (Ref 3). The thick CBL, for a given anode-nozzle internal diameter (i.d.), is promoted by using hydrogen as secondary gas or nitrogen as primary with argon as well as when diminishing the arc current. A thin CBL facilitates the breakdown between the arc column and the anode surface resulting in a more random variation of the arc length: takeover mode. This mode is promoted by using high current and monoatomic gases (Ar-He) (Ref 3).

Intermediary modes exist between the restrike and the takeover modes, again depending on the CBL thickness, which can be calculated from the voltage curves. Duan and Heberlein (Ref 4) have defined a shape factor S and an amplitude factor A, calculated as follows:

$$S = \frac{t_{up}}{t_{down}} \quad \text{and} \quad A = \frac{\Delta V}{V} \times 100\% \qquad \text{(Eq 1)}$$

where: t_{up} is the time duration of the uprising slope of the waveform; t_{down} is the time duration of the down slope of the waveform; ΔV is the amplitude of the arc voltage fluctuation and V is the mean arc voltage.

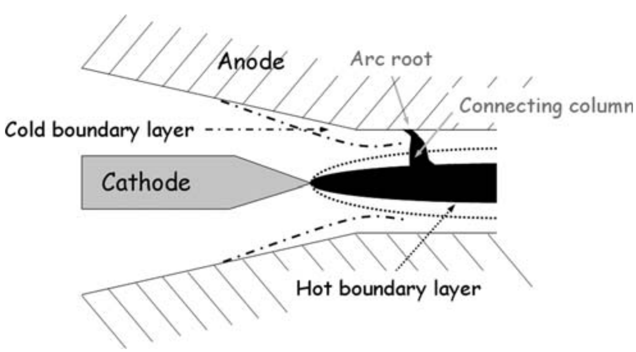

Fig. 1 Plasma-jet generation

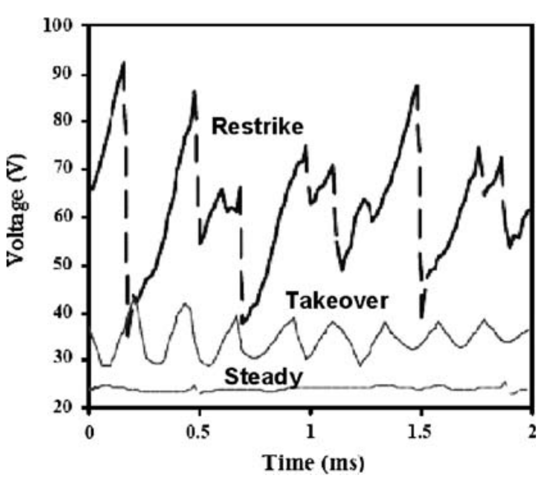

Fig. 2 Different modes of voltage time evolution linked to the arc-root fluctuations at the anode. Takeover mode was obtained for an Ar-He plasma while restrike mode resulted from an Ar-H_2 plasma, both with the same arc current (Ref 5)

According to Duan and Heberlein: for $A \geq 10\%$ and $S \geq 5$, the arc fluctuation mode is a perfect restrike; for $A \geq 10\%$ and $S < 1.1$, the arc fluctuation mode is a perfect takeover and for $A < 2\%$, it is the steady mode, and otherwise it is a mixed mode.

During the process, particles are injected within the plasma jet with a constant momentum, defined, for their mean diameter, by the injector i.d., carrier gas nature (Ar or N_2), and flow rate. Their penetration within the plasma jet and their trajectories depend on the momentum imparted to them by the plasma jet ($S_p \rho v^2$ where S_p is the particle surface areas (m^2), ρ the specific mass of the plasma (kg/m^3) and v its velocity (m/s)), varying continuously, as calculated for a stationary jet, along its jet radius (Ref 5, 6). Due to the connecting column fluctuations, the momentum density (ρv^2) of the jet also drastically varies with the power fluctuations affecting particularly the square of the jet velocity along its radius, thus inducing particle trajectory fluctuations and correlatively particle temperature and velocity fluctuations. The measurements of Bisson and Moreau (Ref 7, 8) performed on alumina particles with a size distribution between 32 and 45 μm for an Ar-H_2 plasma (35 SLPM/10 SLPM), working at 550 A, have shown that, due to the arc root fluctuations, at the same location, particle temperatures vary between 2400 and 2900 K, while their velocities range between 260 and 430 m/s.

The aim of this article is to determine the relationship existing between the arc root fluctuations, the CBL thickness and the particle thermal treatment, for different plasma torches, anode shapes and plasma gas mixtures. Successively will be presented:

- the experimental set-ups,
- the results and discussion about CBL thickness, voltage fluctuations and particle treatments.

2. Experimental Set-ups

2.1 Cold Boundary Layer Thickness Measurement

2.1.1 Plasma Torches. The investigations were carried out with two Sulzer Metco torches (Switzerland): the PTF4 torch, with a cylindrical anode-nozzle shape and the 3MB torch both with cylindrical and conical-shaped anode-nozzles. The main characteristics of torch configurations are summarized in Table 1.

The experimental set-up for measuring the CBL thickness is depicted in Fig. 3. End-zone imaging is used to observe the cross-section of the plasma jet inside the

Table 1 Principal plasma torch configurations

	Case 1	Case 2	Case 3
Plasma torch	PTF4	3MB G	3MB GE
Anode shape	Cylindrical	Cylindrical	Conical
Internal diameter	6 mm	5 mm	6.3-7.9 mm
Powder-injector location	External	External	External
Internal diameter	1.8 mm	2 mm	2 mm

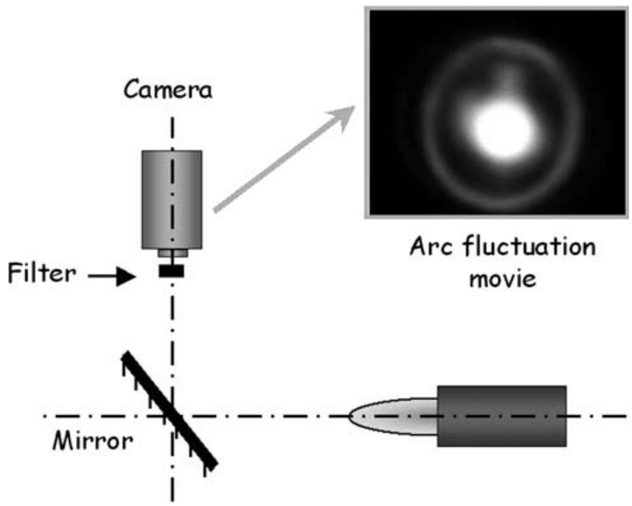

Fig. 3 Experimental set-up scheme to capture movies of the arc root fluctuations

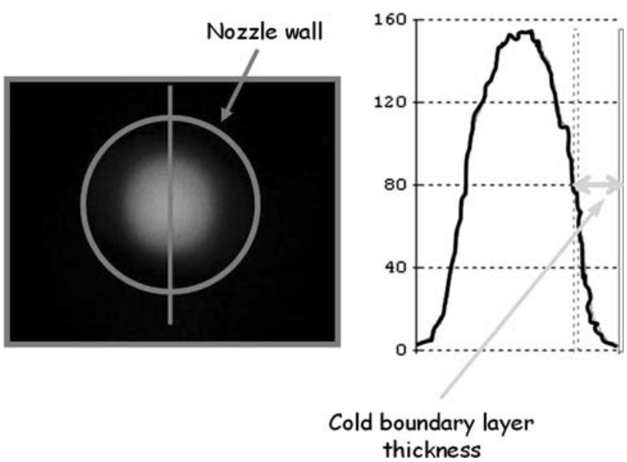

Fig. 4 Measurement of the cold-boundary layer in an end-zone image

nozzle and estimate the CBL thickness. The filters used work in the 0.4-0.8 μm wavelength range. According to the plasma total volumetric emission coefficient calculated for Ar-H_2 and N_2-H_2 mixtures in this wavelength range (Ref 9), for temperature under 8000 K, the emission coefficient is below 2.10^5 W/m^3 ster. Two filters have been used, one allows seeing the anodic-arc root, which requires that the camera is saturated by the light emitted by the plasma core (see the image in Fig. 3) and the other one which cuts all emissions over 5.10^6 W/m^3 ster (see Fig. 4). With the first filter and the saturated image it is not possible to define precisely the boundary of the arc column. On the contrary with the second filter, the end-zone image is well defined, and the light intensity profile along the line which crosses the arc column center can be represented (Fig. 4). The edge of the CBL has been located at the point where the intensity is half of the highest one inside the nozzle channel. The camera response time is about 10^{-4} s which corresponds roughly to the half period of the voltage fluctuations. Thus to account for the plasma jet fluctuations and improve the precision of measurements, the thickness of the CBL was measured 11 times for each individual experimental condition to obtain an average value. Each image was taken with a time delay of 4×10^{-2} s between each.

Table 2 **Spray parameters chosen to study their influences on the arc voltage fluctuations**

PTF4	Ar flow rate (L/min)	33	45	70
	H_2 flow rate (L/min)	1	3.7	10
	Current (A)	200	400	600
3MB GE	N_2 flow rate (L/min)	25	35	45
	H_2 flow rate (L/min)	1	4.5	6.6
	Current (A)	300	400	500
3MB G	N_2 flow rate (L/min)	45	71	90
	H_2 flow rate (L/min)	1	4.5	6.6
	Current (A)	300	400	500

The values in grey have been taken as reference parameters
G: cylindrical anode nozzle GE: conical anode nozzle

The surface of the area targeted by the camera being 9×9 mm^2 and the camera resolution being 288×288 pixels, it means that one pixel correspond to 31.2 μm which is the precision of the measurement for the CBL thickness. In order to compare values obtained with the different torches, the CBL thickness has been divided by the nozzle internal radius. For the conical-shaped nozzle the internal radius of the nozzle throat has been chosen. Of course, it means that comparatively to the two torches with cylindrical nozzles, only the relative variations can be compared.

2.1.2 Torch Working Conditions. Many parameters influence the plasma process. In order to limit the study, only three main spray parameters were studied: the total mass flow rate, $\dot{m}_g$, (linked mainly to Ar or N_2), the hydrogen volume percentage, $\%H_2$, and the arc current, I. Table 2 shows the spray parameters chosen for the experimental designs. The PTF4 torch is equipped with a vortex plasma forming gas injection (eight holes with an angle of 45°), while the 3MB torch, it is a radial injection with two holes.

It has to be noted that N_2 gas-mass flow rates with 3MB G torch (cylindrical nozzle) are, according to the manufacture recommendation, almost twice those of 3MB GE torch (conical-shaped nozzle).

2.2 Voltage Fluctuations Measurement

The experimental set up for measuring the arc voltage fluctuations is depicted in Fig. 5. The voltage fluctuations were measured between the anode and the cathode and recorded using the LabVIEW (National Instrument, France) application, especially developed for this purpose. Using a Fast Fourier Transform (FFT) method, a frequency analysis could be calculated, and different characteristic frequency peaks were observed, for each spray condition.

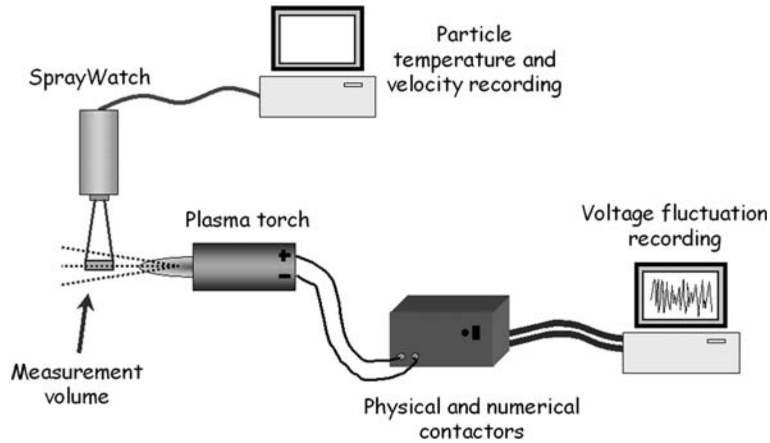

Fig. 5 Experimental set-up for measuring and recording the arc voltage fluctuations and the temperature and velocity of particles

This program runs with a sampling rate of 6000 at 150 kHz. For each measurement, it runs 100 cycles and calculates the mean value of different output parameters: the mean voltage, the voltage fluctuation (standard deviation/mean voltage), the amplitude and frequency of the characteristic peak on frequency curve. The maximum and minimum voltages are also recorded.

At the same time, in-flight ensemble particle temperature and velocity were measured, with the SprayWatch® system, developed by Oseir (Finland) (Fig. 5). This system is constituted by a CCD (Charge-Coupled Device) camera. It allows calculating the hot particle velocity, by measuring the displacement track during the shutter aperture time (25 μs). For each measurement about 30 particle images are recorded. Two measurements are made during 1 s and thus during 8 s, about 1000 particle images are recorded. It allows calculating the velocity distributions and the mean values. Velocity measurements are not synchronized with the voltage fluctuations, but the dispersion of velocities randomly measured during 1/6th to 1/8th of the voltage fluctuation period is characteristic of the effect of the voltage fluctuations on particle velocities.

The particle temperature is obtained with the same method using two filters at two different wavelengths. However, the spray system only gives the mean temperature of 1000 particles recorded. Thus, to study the temperature distribution, a set-up comprising a monochromator and two photomultipliers working in the visible wavelength range has been used. Each photomultiplier has a response time of about 1 μs and the wavelength ranges for the two color pyrometry have been chosen to avoid the presence of high intensity Ar, N or H lines. These wavelength ranges are 520-536 nm and 676-692 nm, respectively. It has been checked that the mean temperatures given by the SprayWatch and the set-up with photomultipliers were the same within ±2%. However, in both cases the emission coefficient of zirconia has been assumed to be one which lowers the results obtained by about 300 K in the temperature range 2200-2500 °C.

The sprayed powder, used for this study, was 8 wt% yttria partially stabilized zirconia, with 5-25 μm size distribution (fused and crushed powder from Medicoat, Switzerland).

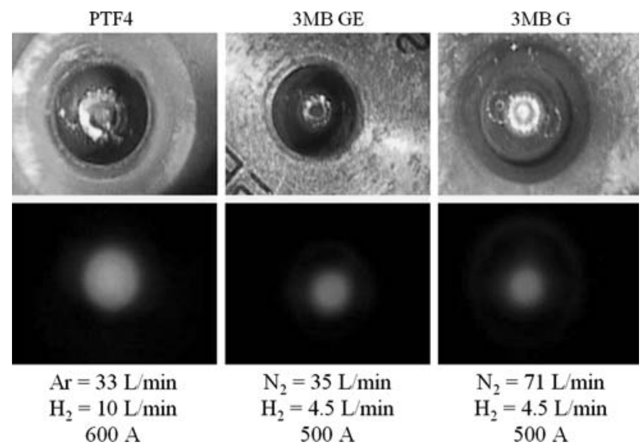

Fig. 6 Views of nozzles before and during experiments for the three different plasma torches: PTF4, 3MB GE and 3MB G, working at the reference parameters

3. Experimental Results and Discussion

3.1 Cold Boundary Layer Thickness Measurement

According to previous works (Ref 3-5), the voltage fluctuations of the plasma torch drastically depend on the CBL properties. So the influence of the torch working parameters, on its thickness has been first studied. Figure 6 shows typical pictures of the torch, anode-nozzle and cathode without plasma (top view) and of the plasma column (bottom view) for the reference parameters (see Table 2 where reference parameters are on gray background).

Table 3 summarizes the torch-working parameter influence ($\dot{m}_g$, I, $\%H_2$) on the CBL thickness. Whatever may be the plasma-torch type and the plasma-gas

Table 3 Influence of primary gas-flow rate, hydrogen percentage and electrical current on CBL thickness (expressed in % of the anode-nozzle radius)

	Boundary layer thickness		
	PTF4	3MB GE	3MB G
↗ mass flow rate	23,6 ⬈ 25,2	30,4 ⬈ 31,0	32,1 ⬈ 33,0
↗ $\%H_2$	23,8 ↘ 23,4	31,4 ↘ 29,8	33,6 ↘ 32,7
↗ arc current	32,3 ➘ 23,5	36,7 ➘ 32,0	38,3 ➘ 33,3
➘: high influence ⬈: mean influence ↘: low influence			

composition, the CBL thickness variation presents the same evolution.

The CBL thickness strongly varies with I, especially with the Ar-H_2 plasma, 37% at the maximum between 200 and 600 A, and with N_2-H_2 less than 15% for both torches, but between 300 and 500 A, only a little with $\dot{m}_g$—7% with Ar-H_2 between 59 and 130 g/min and less than 3% for N_2-H_2 cylindrical nozzle between 56 and 112 g/min—and has practically (in the precision limit) no variation with the $\%H_2$ both for Ar and N_2. In all cases, with Ar, the different parameters influence more the CBL thickness than with N_2. This is probably due to the fact that with nitrogen, 7500 K corresponds to the temperature over which the electrical conductivity is sufficient for the arc column to exist and also to the nitrogen dissociation increasing drastically the thermal conductivity of the gas. Thus the plasma column is self constricted, which is not in the case of argon, where the heat transfer between the arc column and its CBL depends strongly on the hydrogen.

3.2 Voltage Fluctuation Measurement

3.2.1 Voltage and FFT Curves. Figures 7 and 8 show the voltage and FFT curves for the PTF4 and the 3MB reference parameters. Three peaks can be seen on FFT curves, their location and intensity differ for the different plasma torches, due to the geometry of the anode chamber and the power of these torches. For more legibility, the voltage curves were filtered at 30,000 Hz to eliminate the acoustic resonance phenomenon.

For this study, only the first peak was taken into account, i.e., neglecting fluctuations due to turbulences or breakdown within the connecting column, corresponding to the second peak and acoustical signal (third peak, above 40,000 Hz). The first peak corresponds to the largest voltage fluctuations related to the connecting arc column lengthening. These fluctuations probably have the most important influence on the particle thermal treatment, as well as on the anode wear. Its frequency corresponds to the lifetime of the arc root, and its intensity to the amplitude of voltage jumps.

3.2.2 Fluctuation Mode. For each case, according to the criteria of Duan and Heberlein (see Eq 1), the fluctuation mode is a mix between the takeover and the restrike modes. For the PTF4 torch, the fluctuation mode is composed of 90% of the takeover characteristic and 10% of the restrike characteristic. For the 3MB GE and G

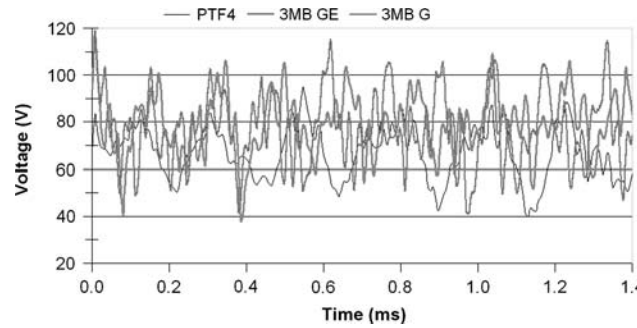

Fig. 7 Voltage filtered curves for PTF4 and 3MB reference parameters

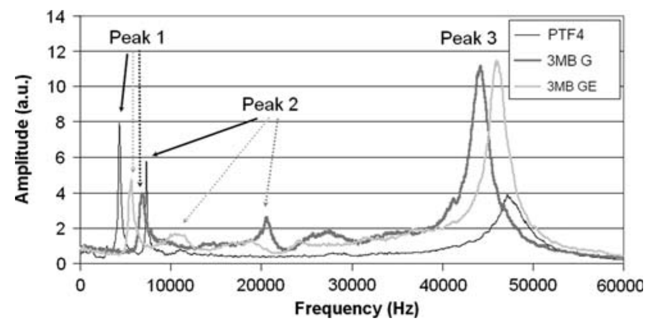

Fig. 8 FFT curves for PTF4 and 3MB reference parameters

torches, these are, respectively, 95 and 80% of the takeover characteristic and 5 and 20% of the restrike characteristic. These fluctuation modes are also linked to the swirl gas injection. Experiments are in progress with the 3MB torch to check the influence of radial and vortex injections on transient working conditions with Ar-H_2. Of course, they vary with the working parameters as summarized in Table 4, but it is difficult to conclude about the spray parameter effect on the restrike percentage.

3.2.3 Torch Working Conditions Influence on the Voltage Fluctuations. According to the experimental design, the effects of the spray parameters can be obtained. Results are summarized in Table 5.

In order to illustrate the importance of voltage fluctuations, Fig. 9 represents the evolution of the quantity $\Delta V = V_{max} - V_{min}$ (which is about seven times that of the voltage standard deviation) with the enthalpy of the different plasma jets. It can be seen that this variation is very important (>160 V), for the 3MB torches (cylindrical and conical), but it almost does not depend on the enthalpy values. For the PTF4 torch, the ΔV values are less important than those of the 3MB torches (<160 V), but the enthalpy value, and so the spray parameters, has very influence: ΔV varies between 20 and 160 V.

For both torches, two other points can be noted: the $\%H_2$ is the most influential parameter on the voltage fluctuations for, and the 3MB torch voltage fluctuations are larger than those of the PTF4 torch, but they are less affected by the variations of torch working parameters.

Table 4 Parameters influence on the restrike mode percentage, in fluctuation modes

	Restrike, %		
	PTF4	3MB GE	3MB G
↗ mass flow rate	➚	➚	➘
↗ H_2 vol%	➚	➘	➚
↗ arc current	➘	➘	➘

Table 5 Influence of the primary gas-flow rate, hydrogen percentage, and electrical current on FFT curves, mean voltage and voltage fluctuations

		Intensity Peak 1	Frequency Peak 1	Mean voltage	Voltage fluctuations
PTF4	↗ Ar flow rate	➚	↗	➚	➚
	↗ % H_2	⬈	➚	⬈	⬈
	↗ current	➘	⬈	➘	➘
3MB GE	↗ N_2 flow rate	⬈	⬈	⬈	➚
	↗ % H_2	➚	➚	➚	⬈
	↗ current	➚	➚	➘	➚
3MB G	↗ N_2 flow rate	↘	⬈	➚	➚
	↗ % H_2	➚	➚	⬈	⬈
	↗ current	⬈	➚	↗	↗
⬈: high influence ➚: mean influence ↗: low influence					

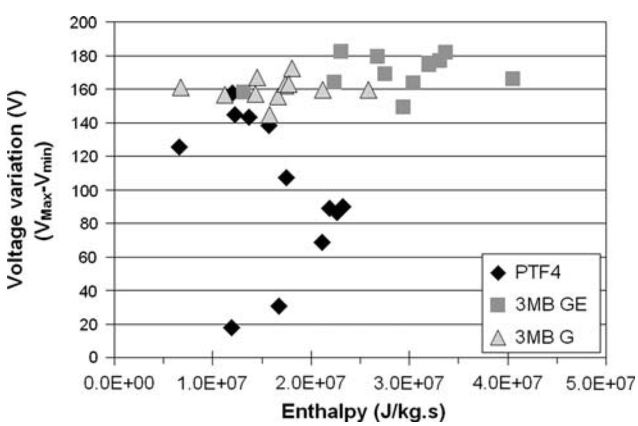

Fig. 9 Voltage variation evolution in function of the mean mass enthalpy

For the different plasma-gas mixtures, the influences of the spray parameters on the mean voltage are as follows:

- Due to the nitrogen dissociation at 7000-8000 K, corresponding to the electrical conductivity sufficiently high to allow current carrying in arc column, its diameter is strongly linked to this dissociation and almost independent on the hydrogen percentage which is not the case of the Ar-H_2 mixture.

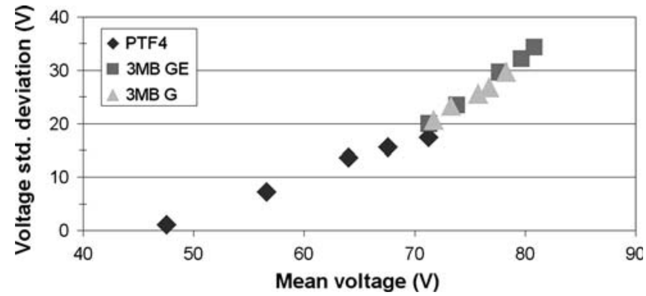

Fig. 10 Arc voltage standard deviation evolution as in function of the mean voltage value

- When the mass flow rate increases, the arc root is pushed farther downstream, thus increasing the mean voltage.
- When the arc current I rises, with both cylindrical anodes, due to the arc column diameter increase (roughly as $\sqrt{1}$ (Ref 10)), the arc root slightly moves upstream towards the cathode and the mean voltage decreases, all other parameters being constant. With the conical anode, it probably moves slightly downstream according to the slight increase of the voltage.
- When the hydrogen percentage rises, the mean voltage increases for both nozzle shapes. According to the research works of Murphy (Ref 11), H_2 diffuses in the plasma arc column periphery, increasing the thermal losses, compensated by a rise in the electrical field and hence the arc voltage.

Figure 10 shows the evolution of the voltage standard deviation versus the mean voltage. For each torch the standard deviation increases with the mean voltage, but for the PTF4 torch, the amplitude of this evolution is more important. In both cases the standard deviation has the same evolution, practically linear, than that of the mean voltage, but with different slopes for Ar and N_2 plasma.

In the case the PTF4 torch (Ar-H_2 gas mixture), the arc-column diameter increases, when the arc current increases. So, the CBL thickness is reduced and hence the mean voltage (the arc attachment being closer to the cathode). Furthermore, thinner the CBL is, lower are the voltage jumps and lower are the arc root lifetimes. Therefore, the Peak 1 frequency increases. However, for both 3MB plasma torches, the Peak 1 intensity grows with the arc-current intensity, phenomenon for which no clear explanation was found. However, the nature of the primary gas (monoatomic or diatomic) seems to have a drastic influence on the current effect on voltage fluctuations.

3.2.4 Particle Thermal Treatment. Figures 11 and 12 show the evolution of the particle velocity and temperature with the plasma enthalpy (the enthalpy is deduced from the torch parameters measured). The experimental data trend has been calculated by using a nonweighted least squares method. For the PTF4 and the 3MB GE plasma torches, the particle velocity increases faster than

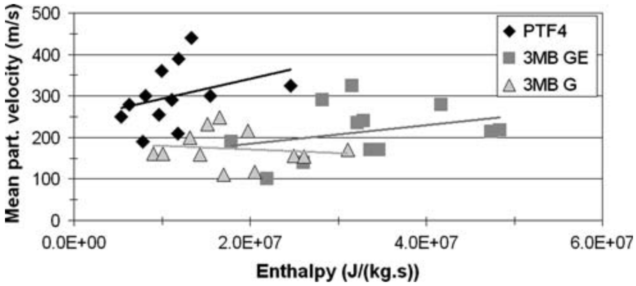

Fig. 11 Evolution of the particle velocity versus the plasma enthalpy

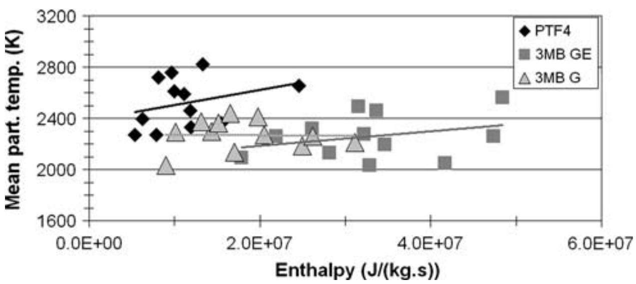

Fig. 12 Evolution of the particle temperature versus the plasma enthalpy

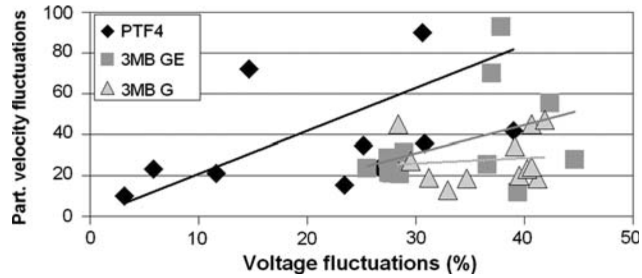

Fig. 13 Evolution of the particle velocity fluctuations (in ‰) as a function of the torch voltage fluctuations (in %)

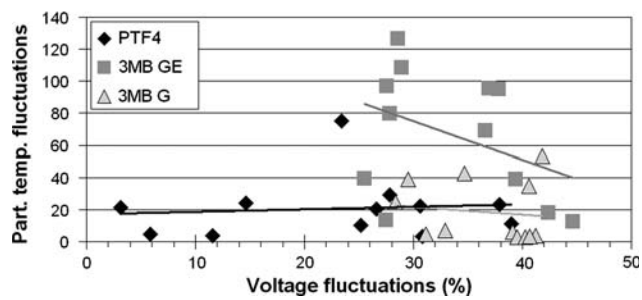

Fig. 14 Evolution of the particle temperature fluctuations (in ‰) as a function of the torch voltage fluctuations (in %)

the particle temperature. This is due to the "inertia wheel" behavior of the enthalpy, which, over 10,000 K, has to be more than doubled to increase the gas temperature by 2000 K. Thus, most of the enthalpy increase is dissipated in kinetic energy within the gas, resulting in better particle acceleration. The particle temperature increase with the enthalpy is essentially linked to the fact that the enthalpy increase corresponds to the lowering of the heavy-gas flow rate and the rise of the hydrogen percentage. However, for the 3MB G plasma torch (cylindrical nozzle), the mean particle velocity and temperature seem to decrease slightly with the plasma enthalpy (according to the precision of the measurements).

In Fig. 13 and 14, the velocity and temperature fluctuations of particles were compared with voltage fluctuations. The experimental data trend has also been calculated by using a nonweighted least-squares method. The particle velocity fluctuations seem to be almost linearly linked to the increase of the voltage fluctuations, whatever the plasma torch may be, but velocity fluctuations are lower with the 3MB torches, in spite of the fact that the voltage fluctuations are higher with these torches than with the PTF4 torch. It is also worth noting that voltage fluctuations increase with $\%H_2$, also rising the plasma jet velocity. The voltage fluctuations do not have a large influence on particle temperature fluctuations for the PTF4 torch, because the particle mean temperature is around the melting point. For the cylindrical 3MB torch, the particle temperature fluctuations seem to decrease with the voltage fluctuations. However, one has to keep in mind that the precision of temperature measurements is about ±15%, thus this decrease is not very significant.

4. Conclusion

As already shown by Bisson et al. (Ref 8), the torch-voltage fluctuations-induced-sprayed particle velocity fluctuations and smaller temperature fluctuations. This has been checked both for the Ar-H_2 and N_2-H_2 plasmas produced with two different plasma torches (PTF4 and 3MB from Sulzer Metco). In spite of the fact that the voltage fluctuations are higher with the N_2-H_2 plasmas, the particle velocity fluctuations are lower, while it is the contrary fot the temperature with the divergent anode-nozzle. These fluctuations are linked to the thickness of the CBL surrounding the arc column and the hydrogen percentage. The CBL thickness is the most influenced by the arc current and much less by the mass flow rate, while it does not vary with the hydrogen volume percentage.

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