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Particle Temperature Fluctuations in Plasma Spraying

S. Goutier, E. Noguès-Delbos, M. Vardelle, and P. Fauchais

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In direct current (d.c.) plasma spray torches, the dynamic behavior of the arc attachment at the anode nozzle results in arc voltage fluctuations and correspondingly power fluctuations. The resulting plasma jet instabilities affect the treatment (heat and momentum) of particles injected in the plasma flow and, thus, the coating quality. However, it is not clear if the experimentally observed fluctuations of particle temperatures are a major phenomena and if their frequencies are always in unison with those of voltage. In this study, two online techniques are used to investigate, respectively, the time variation of particle temperatures and its correlation with voltage variations; the first technique makes it possible to analyze plasma voltage instabilities and the second one to investigate those of particle temperatures. Both allow determining the frequencies and amplitude variations of voltage and particle temperature. Experiments were carried out with three plasma torches (F4-type and two 3MB-type) using, respectively, argon-hydrogen (F4-type and 3MB) and nitrogen-hydrogen (3MB) mixtures (all with restrike mode for the voltage fluctuations) as plasma-forming gases. A good correlation between arc voltage and particle temperature fluctuations is observed when the plasma torch is operated with argon-hydrogen mixtures and high mass flow rate. However, it is not the case when the torch is operated with nitrogen-hydrogen mixtures even if the amplitudes of voltage fluctuations are two to three times higher than those obtained with Ar-H_2.

Keywords arc voltage, diagnostic, particle temperature, plasma fluctuations, zirconia

1. Introduction

It is well known that the quality of plasma sprayed coatings depends on the thermal treatment of particles in the plasma jet. However, the effects of arc root fluctuations on particles are not yet obvious.

The simulation of the plasma spray process integrating the arc root fluctuations phenomenon and the comparison with experimental results (particle temperatures and velocities) have shown a significant scattering of these parameters ($\Delta v \approx 25$ m/s and $\Delta T \approx 1000$ °C) (Ref 1-3).

Actually, the temperature of particles can be measured using DPV-2000, Spray Watch, or Accuraspray systems. These techniques are based on the measurement of the thermal radiation emitted by hot particles. Such measurements give mean values, except DPV-2000, which can give parameters related to a single particle, and the imaging acquisition frequency is too low (about 30 Hz) for time-dependent measurements.

The aim of this study is to establish the relationship, if any, between the arc root fluctuations and the particles heat treatment. So, an experimental setup was developed to detect, for each single particle, its in-flight temperature within the plasma jet. This system is coupled with the device allowing the measurement of arc fluctuations. For the analysis of single particle radiation, the powder mass flow rate must be such that it allows at the maximum the presence of only one particle in the measuring volume each ten or twenty microseconds. The flow fluctuates at frequencies between 1000 and 10000 Hz, and therefore measurements must be carried out in a few μs range.

Very few studies were undertaken to analyze the influence of arc voltage fluctuations on those of particle temperatures. It was shown (Ref 4, 5) by using a modified DPV-2000 and spraying with Sulzer Metco PTF4 torch, working with Ar-H_2 plasma-forming gas mixtures, that alumina particle temperatures and velocities depended strongly on the transient voltage level at which they penetrate into the plasma jet. Correspondingly, their recorded fluctuations had the same frequency (4500 Hz) as that of the arc root. These results were obtained by synchronizing the acquisition of particle signals (using DPV-2000) with the arc voltage fluctuations. The data processing technique required particle signals to be very well defined and separated from the others. So Bisson et al. (Ref 5) have used a low powder mass flow rate (1.5 g/mn).

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S. Goutier, E. Noguès-Delbos, M. Vardelle, and **P. Fauchais**, SPCTS Laboratory, UMR6638, University of Limoges, 123 av A. Thomas, 87060 Limoges Cedex, France. Contact e-mail: simon.goutier@unilim.fr.

2. Experimental Setup

2.1 Plasma Torches Working Conditions

The investigations presented here were carried out with three Sulzer-Metco plasma spray torches: first a PTF4 torch working with Ar-H_2 and then two 3MB torches, one working with Ar-H_2 and the other with N_2-H_2. The principal torch configurations are summarized in Table 1.

The sprayed powder was 8 wt.% yttria partially stabilized zirconia, with 5-25 μm size distribution. The powder feed rate was 25 g/mn, i.e., close to spray conditions.

Different parameters were studied to determine their effects on particle temperature fluctuations. For each plasma torch, these parameters were the total mass flow rate, the hydrogen flow rate, and the arc current intensity.

2.2 Particle Temperature and Voltage Fluctuations Measurement Systems

The experimental setup for measuring the particle temperature fluctuations and voltage fluctuations is presented in Fig. 1.

It consists of a fast pyrometer (50 ns response time) and a voltmeter. The bichromatic pyrometer (Ref 6) collects the thermal radiation emitted by in-flight particles. Signals are filtered by a monochromator, H10IR-Jobin Yvon with holographic gratings, 600 grooves/mm, with a bandwidth of 16 nm, at two different wavelength bands adapted to the sprayed materials, for example, respectively, 528 and 684 nm for zirconia powders. The two signals obtained are then transmitted by optical fiber to two photomultipliers (Hamamatsu R928) (PM).

An interface (National Instrument) allows the fast acquisition of signals and the data processing under Labview®.

The program running under Labview® includes:

- fast acquisition of the signals (2 μs response time);
- detection of signal peaks that cross a threshold defined by the electric and photonic noise of plasma;
- calculation of the ratio of the intensities of the peaks over the two wavelengths;
- calculation of the evolution of the particle temperature and its Fast Fourier Transformation (FFT).

The fast voltmeter (one megahertz) (Ref 7) includes a digitalization of the arc voltage and data processing (FFT and the root mean square, RMS, of the arc voltage).

Table 1 Principal plasma torch configurations

	Plasma torches	
	PTF4	**3MB**
Anode shape	Cylindrical	
Nozzle internal diameter, mm	6	5.5
Injector location	External	
Internal diameter, mm	1.8	2
Injector location		
Versus torch axis, mm	9	8.5
Versus torch exit, mm	6	5

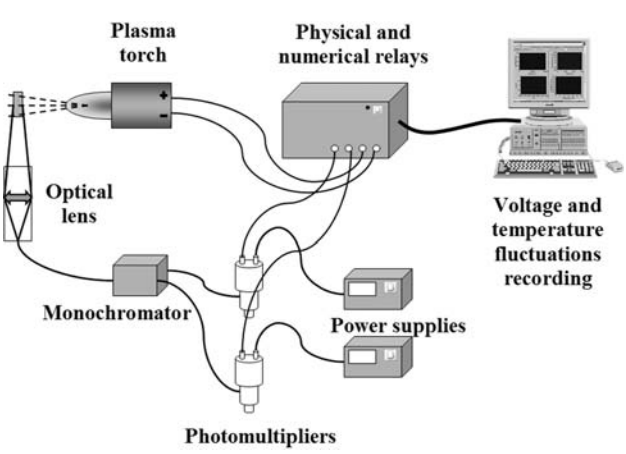

Fig. 1 Experimental setup for measuring the particle temperature and voltage fluctuations

3. Results

3.1 Comparison of Temperature and Voltage Signals

The spray parameters with the PTF4 torch are summarized in Table 2.

Particle temperatures obtained at 110 mm from the nozzle exit along the mean particle trajectory (i.e., 4 degrees relatively to the torch axis (Ref 8)) are shown for case 2 of Table 2 in Fig. 2(a) and (b); the arc voltage signal is represented for the same parameters.

Both signals are periodic and to compare their fluctuation frequencies the corresponding FFT signals are drawn as shown in Fig. 3. The first peak observed at 300 Hz is probably related to the powder feeder working frequency.

These two spectra are identical for the low frequency peak (4300 Hz). But there is only one peak on the particle temperature spectra; thus it can probably be deduced that

Table 2 Particle temperature, voltage fineness, and spray parameters for PTF4 torch

Case	Ar, L/mn	H_2, L/mn	Gas mass flow rate, kg/h	Current, A	$F_{temperature}$, s	$F_{voltage}$, s
1	33	10	3.22	600	0.20	0.03
2	45		4.37		0.55	0.12
3	60		5.81		1.24	0.16
4	70		6.77		2.32	0.17
5	33	10	3.22	300	0.71	0.11
6				350	0.58	0.06
7				500	0.25	0.03
8	33	3.7	3.19	500	0.50	0.08
9		8.5	3.21		0.28	0.02

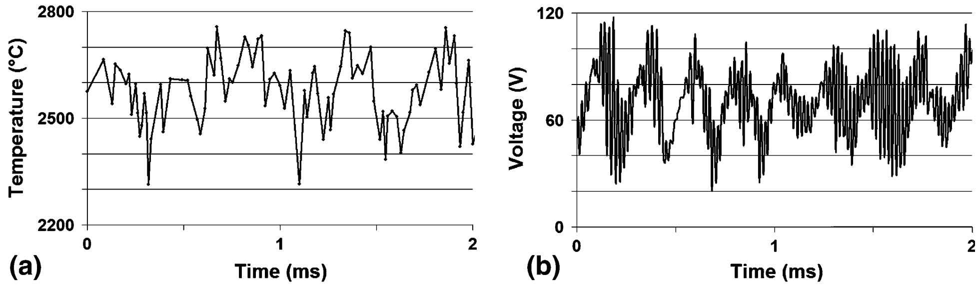

Fig. 2 Comparison between (a) particle temperature and (b) arc voltage signals [case 2/Table 2: Ar = 45 slm-H_2 = 10 slm-I = 600 A]

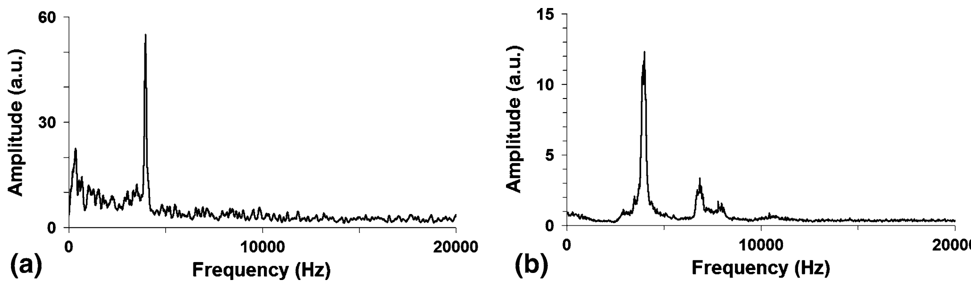

Fig. 3 FFT signals of (a) particle temperatures and (b) arc voltage signals [case 2/Table 2: Ar = 45 slm-H_2 = 10 slm-I = 600 A]

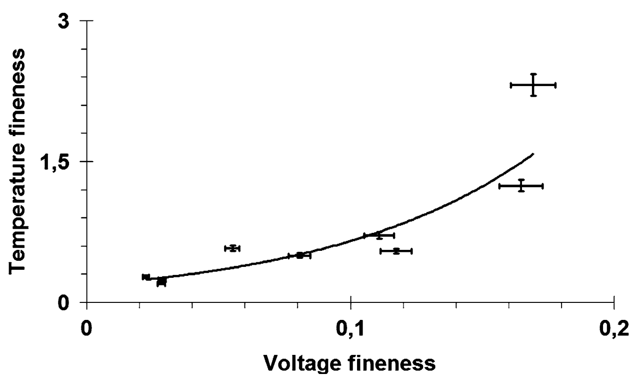

Fig. 4 Particle temperature FFT peak fineness versus arc voltage FFT peak fineness

particles follow mainly the arc fluctuations at the lower frequency.

To compare the periodicity quality of both signals, the fineness parameter F is introduced. It is defined as the ratio of the peak intensity to its width at mid-height. This very sensitive factor is associated to the signal periodicity quality.

In Fig. 4 the particle temperature fineness has been represented versus the voltage fineness for different plasma spray parameters.

It can be noted that when the voltage fineness is large a high particle temperature fineness is obtained. This means that when the arc voltage fluctuations frequency is strongly marked, the particle temperature follows better this fluctuation. It also means that particles are not influenced by the arc voltage frequency below a certain value of the F parameter (about 0.02). In viewing Table 2, the following question is raised: why does increase in argon flow rate induce an increase of particle temperature fineness?

3.2 Influence of Argon Flow Rate

For different argon flow rates (keeping the hydrogen flow rate constant at 10 L/mn), the time variations of particle temperatures is measured at 110 mm downstream of the nozzle exit. The detector is focused along the mean trajectory (Ref 8). Results are shown in Fig. 5 as a function of time.

First, it can be noted that the periodicity of particle temperatures time evolution is better defined with higher fluctuation amplitudes for high argon flow rate (70 L/mn) than for low argon flow rate (33 L/mn). It also seems that particle temperatures dispersion is weaker for low argon flow rate and so the particle heat treatment is more stable.

To determine whether this effect is due to the arc root fluctuations, variations of the voltage RMS and particle temperature RMS have been represented versus the argon flow rate in Fig. 6.

It can be seen from this figure that the increase in the argon mass flow rate increases the RMS of particle temperatures as well as that of arc voltage. This increase in the RMS of the arc voltage is due to the fact that arc voltage fluctuations depend very strongly upon plasma flow properties. Indeed, when the argon mass flow rate increases, the arc column diameter decreases slightly and the arc attachment at the anode nozzle is pushed farther downstream (Ref 9). The mass enthalpy depends strongly on the arc column length. Its fluctuations are

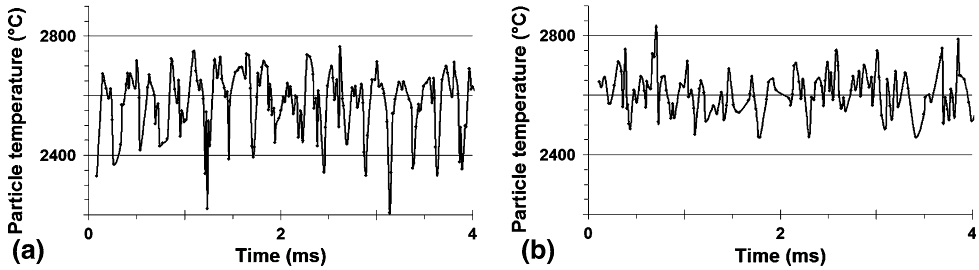

Fig. 5 Particle temperatures: (a) 70 L/mn Argon flow rate [case 4/Table 2: Ar = 70 slm-H_2 = 10 slm-I = 600 A] and (b) 33 L/mn Argon flow rate [case 1/Table 2: Ar = 33 slm-H_2 = 10 slm-I = 600 A]

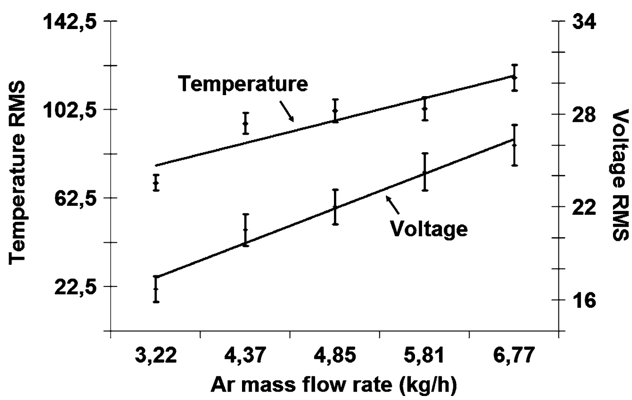

Fig. 6 Particle temperature and arc voltage RMS versus argon mass flow rate

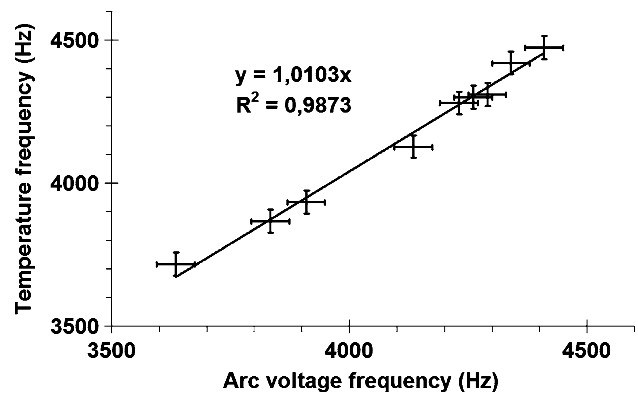

Fig. 8 Particle temperature frequency versus arc voltage frequency [case PTF4]

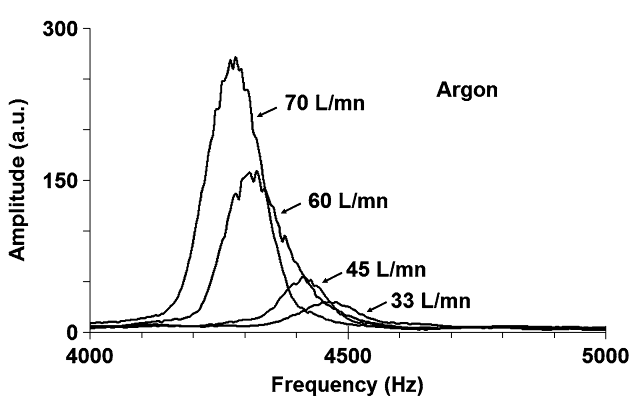

Fig. 7 Particle temperature FFT peak evolution versus argon flow rate

instantaneously followed by the gas velocities and plasma jet length almost as well by particle temperatures due to their rather low inertia (Ref 5).

The evolution of the FFT peak frequency with the argon flow rate is represented in Fig. 7.

A progressive frequency shift from 4500 to 4250 Hz can be noted when the argon flow rate is increased. This phenomenon was previously noted for the arc voltage FFT (Ref 10). Indeed, with the increase of the mass flow rate the cold boundary layer becomes thicker, the time between two successive breakdowns grows, and so the arc voltage frequency diminishes.

In addition, it can be noted that with high mass flow rates, the peak frequency is much more marked than that for low mass flow rates, which confirms the observation carried out on the study of the RMS. This phenomenon indicates that the particle temperature fluctuations seem to be more linked to the arc voltage fluctuations with high argon gas flow rates. In fact, when the argon mass flow rate increases, the intensity of the arc voltage FFT is higher (Ref 9).

3.3 Relationship Between Particle Temperature and Arc Voltage Fluctuations

To check if the fluctuation frequency of particle temperatures is identical to the one of the arc voltage, the evolution of the particle temperature frequency versus that of arc voltage is shown in Fig. 8. The resulting curve of these two parameters is linear with a slope of one. It can be concluded that the particle temperature frequency is identical to the one of the arc voltage.

To determine the parameters that influence the particle temperature periodicity quality, the particle temperature and arc voltage finenesses for different torch working parameters are summarized in Table 2.

Correlatively, the evolution of particle temperature fineness versus the particle temperature frequency for

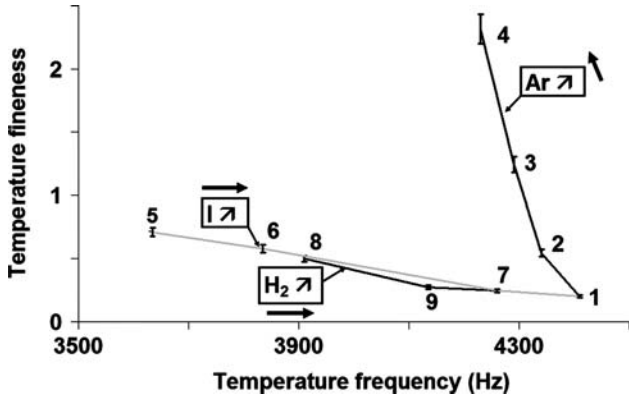

Fig. 9 Particle temperature fineness versus fluctuation frequency [case PTF4, Table 2]

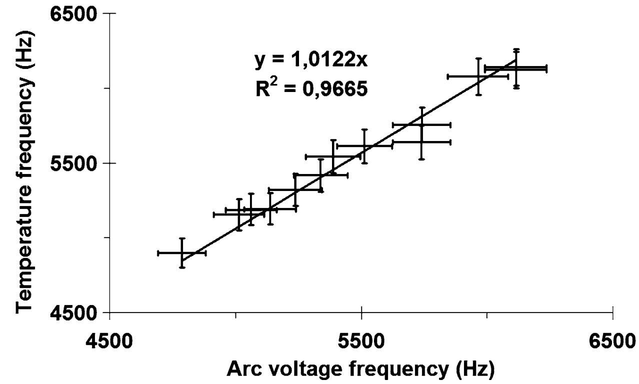

Fig. 10 Particle temperature frequency versus arc voltage frequency [case 3MB, running on argon]

different torch working parameters are represented in Fig. 9.

Figure 9 shows that, for the different torch working parameters (argon flow rate, hydrogen percentage, and arc current) considered, particle temperature fluctuations FFT peak fineness decreases when the arc voltage FFT frequency directly linked to that of particle temperature increases. It is probably due to the better particle heat transfer for a lower frequency of plasma flow pulsations.

It must also be noted that for almost the same arc voltage frequency ($\Delta F = 30$ Hz, between cases 7 and 4), different particle temperature finenesses are obtained. The high particle temperature fineness corresponds to a high argon gas flow rate (70 L/mn). This phenomenon is probably induced by the higher plasma jet velocities when the plasma mass flow rate is increased. As the particle time of flight is lower, particles undergo less plasma puffs, and hence their temperatures depend strongly on the voltage level at which they are injected in the plasma jet core. Thus, their heating directly depends on the arc voltage fluctuations.

On the other hand, when the arc current increases, the plasma velocity also goes up, although the particle temperature fineness goes down. This phenomenon is due to the fact that the increase of the arc current, increasing the arc column diameter $d_a \approx \sqrt{I}$, causes more random voltage breakdowns spoiling the signal periodicity. Thus it induces a decrease of the voltage fineness, and as a consequence, the particle temperature fineness decreases.

However, the following question is now raised: is such a behavior similar when using another plasma spray torch or different plasma-forming gases?

3.4 Comparison Between PTF4 and 3MB

The torch 3MB running on argon and hydrogen and having only one hole vortex injector of plasma-forming gases (against eight for the PTF4 torch) has been used to check whether the particle heating follows the same behavior as that obtained with the PTF4 torch.

As can been seen from Fig. 10, there is an excellent correlation between both fluctuation frequencies. The particle temperature fineness and the arc voltage fineness for different torch working parameters have been summarized in Table 3. For both torches the same evolution of particle temperature fineness is obtained (compare Fig. 9 and 11). However, the fineness variation with the 3MB torch is lower. It can also be seen that for an argon flow rate of 25 L/mn there is no periodic signal for particle temperature with the 3MB torch.

Table 3 Particle temperature, voltage fineness, and spray parameters for 3MB torch (running on argon)

Case	Ar, L/mn	H_2, L/mn	Gas mass flow rate, kg/h	Current, A	$F_{temperature}$, s	$F_{voltage}$, s
1	25	4.5	2.42	500	…	0.003
2	35		3.38		0.016	0.006
3	40		3.86		0.049	0.01
4	45		4.34		0.315	0.017
5	50		4.82		0.583	0.032
6	55		5.3		0.857	0.04
7	35	4.5	3.38	350	0.165	0.032
8				400	0.021	0.024
9				450	0.03	0.012

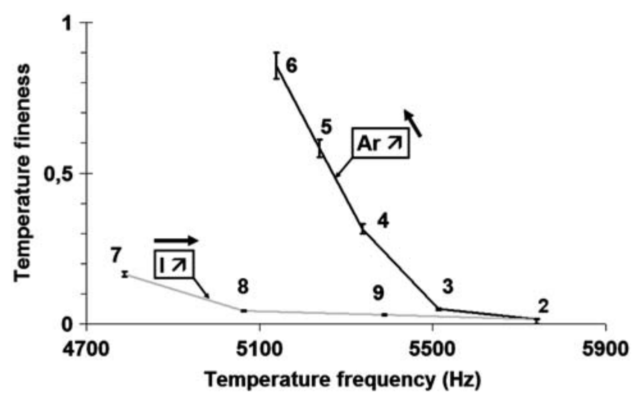

Fig. 11 Particle temperature fineness versus fluctuation frequency [case 3MB, Table 3]

In general, for this torch the periodicity quality of particle temperature is rather poor. This phenomenon is probably due to the fact that in this torch (3MB), the plasma gas injection is made only with one vortex hole. Indeed for PTF4 torches, the plasma arc column shrouding, thanks to the eight-hole vortex gas injection, stabilizes well the fluctuations of the plasma flow, which is not the case with the one hole of 3MB torch and a bad periodicity of arc voltage induces a bad periodicity for particle temperature.

3.5 Comparison Between Nitrogen and Argon as Primary Gases

The arc voltage fineness for the 3MB torch working with nitrogen (to be compared with those obtained when it is working with Ar-H_2: Table 3) have been summarized in Table 4.

Table 4 Voltage fineness and spray parameters for 3MB torch (running on nitrogen)

Case	N_2, L/mn	H_2, L/mn	Gas mass flow rate, kg/h	Current, A	$F_{voltage}$, s
1	25	4.5	2.42	500	0.002
2	35		3.38		0.001
3	40		3.86		0.001
4	45		4.34		0.001
5	50		4.82		0.002
6	55		5.3		0.003
7	35	4.5	3.38	350	0.001
8				400	0.001
9				450	0.001

It can be seen from Fig. 12(a) that the particle temperature FFT peak, corresponding to the arc voltage frequency (see Fig. 12b), does not exist anymore in spite of the high plasma primary forming gas flow rate (see Table 4). The only peak that can be observed is at very low frequency (300 Hz), which could correspond to the fluctuation of powder mass flow rate.

The calculation of the parameter F in this case gives a value of 0.003, which is very weak.

Torches working with nitrogen as primary gas have quite a different behavior from those working with argon. With nitrogen at atmospheric pressure, the minimum temperature to sustain the arc column is 7500 K, and it corresponds to a strong increase of the thermal conductivity. Thus the nitrogen arc column is self-constricted, and its diameter is almost independent of the gas mass flow rate and hydrogen percentage (Ref 9). Moreover, the radial plasma-forming gas injector used results in no plasma shrouding at all. Thus, the mass flow rate of the nitrogen primary forming gas has no effect on the particle temperature fluctuations for the 3MB torch running with nitrogen.

As can be seen from Fig. 13, there is no correlation between the arc voltage fluctuation and the particle temperature time evolution when nitrogen is used. In fact, for the 3MB torch running on argon, the voltage RMS is much lower (8.32 V) than that obtained with the 3MB torch running on nitrogen (25 V). But the particle temperature RMS values are similar for both torches.

For the 3MB torch running on nitrogen, the arc voltage frequency is high (near 7000 Hz). Thus, particles undergo more plasma puffs, and as the voltage fineness is weak (below 0.01), the plasma jet fluctuations are more random.

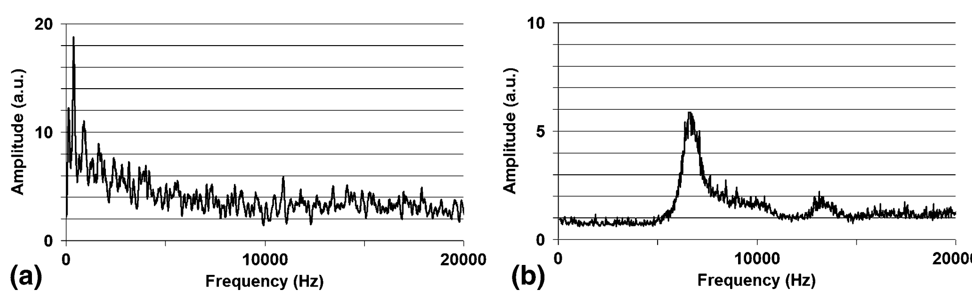

Fig. 12 (a) Particle temperature FFT and (b) arc voltage FFT [case 6/Table 4: $N_2 = 55$ slm-$H_2 = 4.5$ slm-I = 500 A]

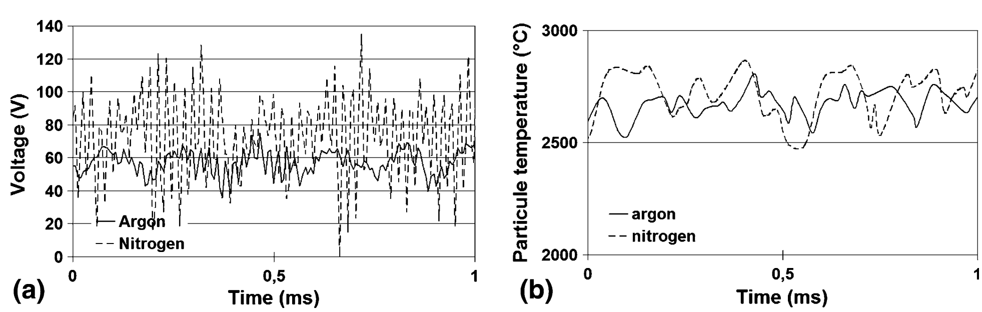

Fig. 13 (a) Arc voltage signals and (b) particle temperature evolution for 3MB torches [Ar/$N_2 = 35$ slm-$H_2 = 4.5$ slm-I = 500 A]

As a consequence, the large voltage RMS does not induce a high particle temperature RMS.

4. Conclusion

For the PTF4 plasma torch, the arc voltage fluctuations strongly influence the heat treatment of the particles. However, experimental results have shown that this influence strongly depends on the arc voltage signal quality. Thus, this influence is linked to the torch working parameters and design. For example, the 3MB torch, running on nitrogen with its arc column self constricted, does not impose its arc voltage fluctuations frequency on the particle heating. In spite of its high voltage RMS (about 25 V), the particle temperature RMS is close to that of the 3MB torch running on argon. So there is no link between the arc voltage fluctuation and the heat treatment for the 3MB torch running on nitrogen.

For the PTF4 and 3MB torch running on argon, the parameter that has the main influence on the particle temperature fluctuations is the plasma-forming gas mass flow rate. This is because on one hand the plasma shrouding is more important and stabilizes the plasma jet fluctuations, and on the other hand the velocity of the plasma jet being more important, particles also undergo less plasma puffs.

With these torches, the influence of the other plasma spray parameters (current, hydrogen percentage) depends first on the quality of arc voltage fluctuation and then on the value of arc voltage fluctuation frequency. For example, with the PTF4, the more stable heat treatment is obtained for the following plasma spray parameters: $Ar = 33$ slm, $H_2 = 10$ slm, $I = 600$ A.

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