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CHARACTERISATION AND ORIGIN OF ARC FLUCTUATIONS IN A F4 DC PLASMA TORCH USED FOR THERMAL SPRAYING

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key words : torch, fluctuations, restrike, plasma spraying, arc

Abstract

The fluctuating behaviour of a Sulzer Metco F4 DC plasma gun has been investigated. The time dependencies of the arc voltage and current and of the optical emission of the plasma jet have been measured. An optical fibre inside the gun allows direct measurement of optical fluctuations of the arc. Spectral and statistical analysis of the recorded signals are presented for various working gas mixtures and for two types of gas injection. There is a dominant fluctuation frequency around 4 kHz which appears to be almost insensitive to the working parameters. It is suggested that the circuit impedance might dominate the arc physics with respect to the fluctuations at this particular frequency. On the other hand, an increase in the amplitude of the fluctuations and the increase of high frequency components in the power spectra are observed as the electrodes become worn. This might be used as a process control tool. An optical technique has been set up to estimate the jet velocity from the time of flight of the emission fluctuations.

1. INTRODUCTION

Plasma spray coating is a well-established industrial technology [1] which has achieved outstanding technological and commercial progress in the aeronautics, gas turbine, and automotive industries, amongst other fields. In spite of this great success, the underlying fundamentals are still poorly understood [2, 3], in particular the behaviour of the arc inside the torch nozzle which experiences instabilities and restrike [4] giving rise to "surging" and "whipping" motions of the plasma jet [3]. This fluctuating behaviour may lead to a non-uniform heating of the injected powder particles and consequently adversely affect the quality and yield of the spray deposits [5]. However, most of the spray torches like the Sulzer Metco F4 require that the arc attachment moves over the surface of the gun electrodes to distribute the large heat load and consequently increase the electrode lifetime. Much R&D effort has been put into new torch designs to control arc fluctuations [6] and in process control [7] to adjust spray parameters to minimise fluctuations. Systematic studies of the electrode wear and its effect on the fluctuations [8, 9] have shown that the frequency spectrum of fluctuations can be correlated with the anode wear. However, the intrinsic performances of commercial torches can still be improved. Further developments towards improved control, reliability and reproducibility of the present processes and for new coatings need, amongst other things, a basic understanding of the arc physics and of the plasma jet dynamics [3].

In this paper we present measurements of the temporal evolution of the torch voltage and current, as well as of the optical emission of the plasma jet. In addition, an optical fibre inside the gun directly measures the optical emission fluctuations of the arc. Analysis of the fluctuating signals and of their power spectra is made for various flows of the H_2/Ar gas mixture and for two different types of gas injectors. The time of flight technique which measures the propagation of the light fluctuations along the plasma jet axis has been set up as described in reference [10]. This allows an estimation of the plasma jet velocity in the hottest regions.

2. EXPERIMENTAL ARRANGEMENT

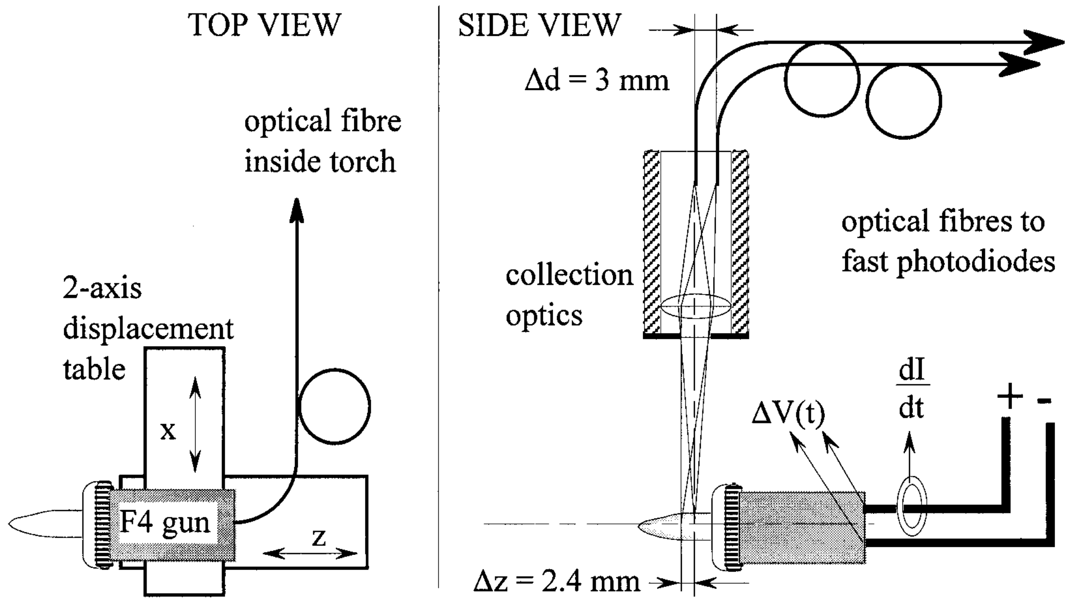

Figure 1 : Top and side views of the experimental arrangement.

The atmospheric pressure plasma torch investigated is a Sulzer Metco F4 without powder injection equipped with a 6 mm diam. atmospheric anode nozzle and a thoriated tungsten cathode fitted with either a straight or a swirl gas injector. Typical parameters are: 500 A current, 20-60 SLPM (Standard Litre per Minute) of Ar and with 2-14 SLPM H_2. The electrical power is up to 50 kW with a torch efficiency between 30 and 60%. The gun (Figure 1) is mounted on a 2 axis displacement table with the jet axis horizontal.

The arc voltage is measured directly at the gun electrodes with a differential passive voltage probe (÷20, DC-2 MHz). The time derivative of the torch current is measured with a Rogowsky coil (4.3 10^{-7} Vs/A, 50 Hz-100 kHz). A lens positioned 435 mm above the plasma jet focuses the jet light emission onto two optical fibres of 65 μm diam. with a spatial resolution of about 0.08 mm. The fibres collect light from two locations separated by Δz = 2.4 mm along the torch axis (see Fig. 1). This set-up is used for the estimation of the jet velocity by measuring the time of flight of light fluctuations as they are convected with the flow [10]. The collected light is detected by fast Si-PIN photodiodes (bandwidth DC-1 MHz). In addition an optical fibre has been inserted inside the gun to collect the light emission directly from almost the whole arc length. The signals are acquired by a digital oscilloscope and transferred to a PowerMacintosh™ via a GPIB interface for further analysis using Labview™.

3. RESULTS AND DISCUSSION

3.1 Time dependence of the fluctuating signals

Figure 2 shows a time record of the torch voltage and jet light emission on axis at 1.5 mm from the nozzle exit for pure argon and for a H_2/Ar gas mixture. This behaviour is typical of a gun operating with used electrodes and with straight gas injection. The standard deviation of the voltage signal represents about 5.6% of the rms (root mean square) value of 27.8 V for the pure Ar case, whereas it exceeds 17% of the rms value of 50 V for the H_2/Ar mixture. The voltage pattern for pure Ar operation exhibits fluctuations of weak amplitude and small time derivatives (120 kV/s maximum), which suggests that the arc experiences the so-called "take-over mode" [4] for which it has been proposed that the arc root attachment to the anode is diffuse. In this case the jet light emission fluctuations are only weakly correlated with the voltage oscillations. In contrast the voltage signal for the H_2/Ar mixture shows a clear sawtooth pattern, which is typical of the "restrike mode" [4, 11] for which the anode arc root is constricted due to the high thermal conductivity of hydrogen. In this case the jet light emission signal is better correlated with the voltage fluctuations. Voltage and emission signals are shifted with an average delay of about 15 μs (dotted lines on Fig 2B) corresponding to the transit time of the perturbations from the anode arc root to the detection point (about 24 mm in our case which leads to an average velocity of nearly 1600 m/s inside the nozzle).

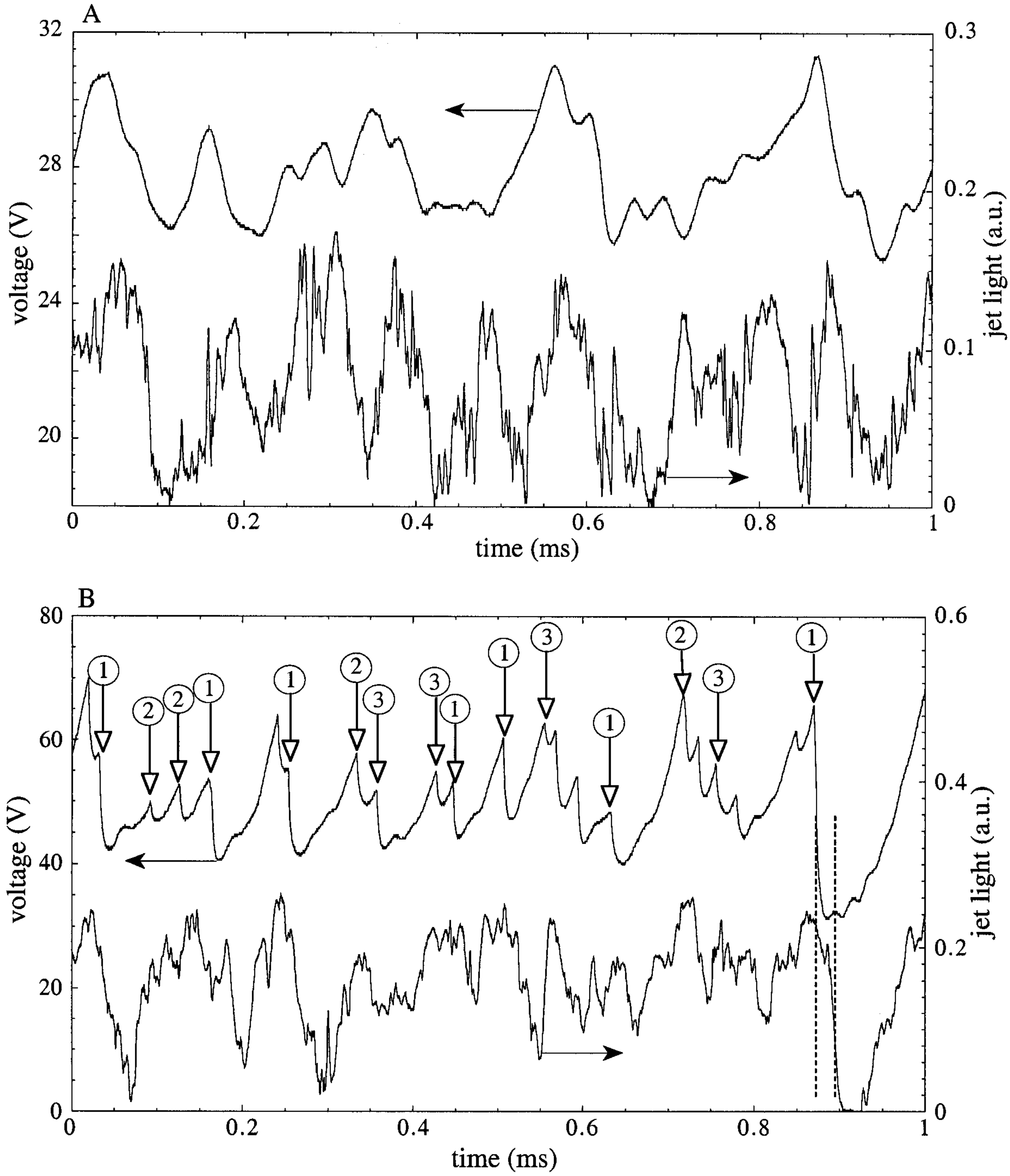

Figure 2 : Typical time dependence of the arc voltage and light emission collected on jet axis at 1.5 mm from the nozzle exit for two gas mixtures : A) 50 SLPM Ar and B) 4/50 SLPM H_2/Ar. The numbered arrows on Fig 2B refer to different categories of voltage drops (see text). Plasma parameters : 500 A, straight flow gas injector, used electrodes, sampling time 0.2 μs.

We have identified three categories of voltage drops (referred to as number 1, 2 and 3 on Fig 2B) which are similar to the ones described in references [2, 11] :

Type 1 : large and fast voltage drops (between 20 and 30 V, with up to 10 MV/s) which might be attributed to "upstream restrikes" [11], for which a breakdown of the arc occurs with a new arc root closer to the cathode. The length of the new arc is strongly reduced, which results in a large drop of the voltage. The corresponding jet light emission exhibits large drops consecutive to these "upstream restrikes" because the jet temperature suddenly decreases due to the transient interruption of the arc. Note that after these restrikes, the voltage re-increases slowly and systematically showing a shoulder during ramp up. This might be because the arc lengthening occurs first by the gliding of the anodic arc root in the direction of the gas flow and then by the bending of the arc termination close to the anode surface [11].

Type 2 : small and relatively slow voltage drops (typically 5 to 15 V at 1 MV/s) which we attribute to "downstream restrikes" [11] for which a breakdown of the arc occurs with a new anodic root farther from the cathode. In this case, the new arc termination does not exhibit an S-shape bending which results in a shorter overall length, and explains the voltage reduction. Note that the jet emission is also reduced consecutively to these restrikes but to a lesser extent than for the type 1 above.

Type 3 : small voltage drops for which a subsequent reduction in the jet emission is not observed. These might originate from a short circuiting of the curved part of the arc at the anode foot [2]. For this phenomenon, which resembles reconnection, the attachment of the anodic root is maintained at the same position and the arc is not interrupted which explains the absence of a subsequent drop in jet emission.

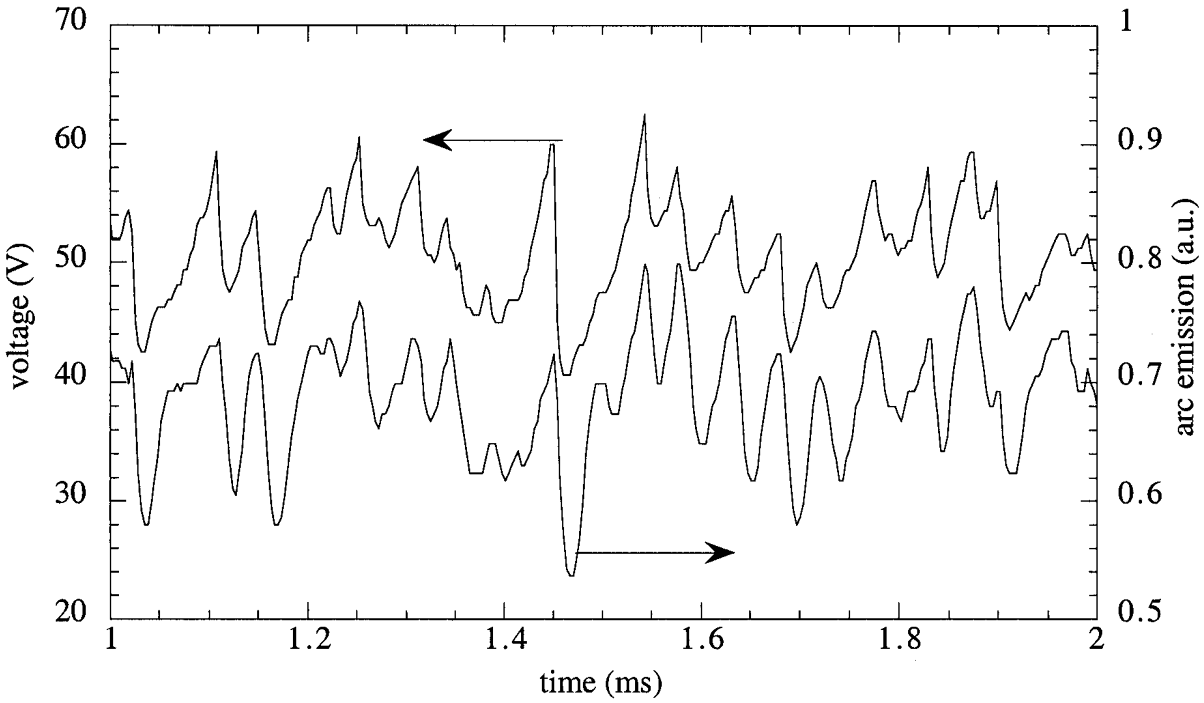

Figure 3 : Typical time dependence of voltage and emission from the arc inside the torch. Plasma parameters : 2/50 SLPM H_2/Ar, 500 A, swirl flow gas injector, used electrodes, sampling time 3 μs.

The jet emission signals show strong fluctuations for both gas mixtures (35 to 45 % standard deviation from the rms value). This is because the plasma visible emission is a very sensitive function of the local temperature variations in the jet ($8\text{-}15.10^3$ K). The mean light intensity is nearly doubled by the addition of only 8 % of H_2 to the plasma gas because the effective power coupled to the plasma jet increases from 5.7 to 14.2 kW.

Figure 3 shows the arc emission fluctuations measured inside the torch which exhibit variations of much smaller amplitude than the jet emission probably because of the absence of spatial resolution, and the fact that visible light emission is less sensitive to temperature variations at the high arc temperatures (above 20'000 K). Moreover the arc emission signal closely follows the voltage fluctuations, in striking comparaison to the jet emission signals which are distorted due to turbulence before the nozzle exit.

3.2 Power spectra

Figure 4 shows power spectra of the voltage, jet light emission and current for the same plasma conditions as in Fig 2. These spectra are obtained numerically using a FFT algorithm on a record of 2^{14} data points sampled every 3 μs, corresponding to a 49.15 ms time history and a frequency resolution of 12.2 Hz. The signals are numerically band-pass filtered (20 Hz - 60 kHz) and a Hanning window is applied prior to the FFT. The above procedure is performed on 30 consecutive time records, and the spectra are averaged. The torch current spectrum is obtained by dividing the spectrum of the current time-derivative by the frequency. It shows prominent peaks at 300 Hz and harmonics which come from imperfect smoothing of the torch power supply. The 300 Hz is also clearly visible on the emission and on the voltage spectra.

The voltage for the pure Ar case shows about five times less fluctuations than for the H_2/Ar mixture which is consistent with Fig 2. Except for the current, there are prominent peaks on the power spectra in the frequency range 2-12 kHz. Note that the high frequency peaks are not harmonics of the low frequency ones. These fluctuations are related to the arc motion and restrike [9, 11]. On the current spectrum, these fluctuations are damped by the large smoothing inductance of the power supply, which explains the qualitative difference in voltage and current signals. For both gas mixtures the power spectrum of the jet light emission shows a significant continuous background level, which is not observed for the arc emission measured inside the gun. We attribute this to the turbulence of the plasma jet, and the entrainment of the surrounding air. This effect is more pronounced for the H_2/Ar mixture because the jet velocity is much higher (see Fig 8 below).

The emission and voltage spectra show a strong peak at a nearly identical frequency for the two gas mixtures (around 4 kHz). A significant contribution to the fluctuations is almost always observed in the form of a peak around this particular frequency, regardless of the working parameters, provided that the electrodes are not new (see below for the effect of electrode wear). Changing the working parameters, such as current, gas injector geometry, gas composition or flows, leadto only a slight shift of this frequency. This suggests that its value is determined mainly by the impedance of the electrical circuit components and to a lesser extent by the arc dynamics. However there are other peaks in the frequency spectra, in the range 5 to 12 kHz, also reported in reference [9]. These peaks strongly depend on the working parameters and electrode wear. This behaviour might be more representative of the arc itself.

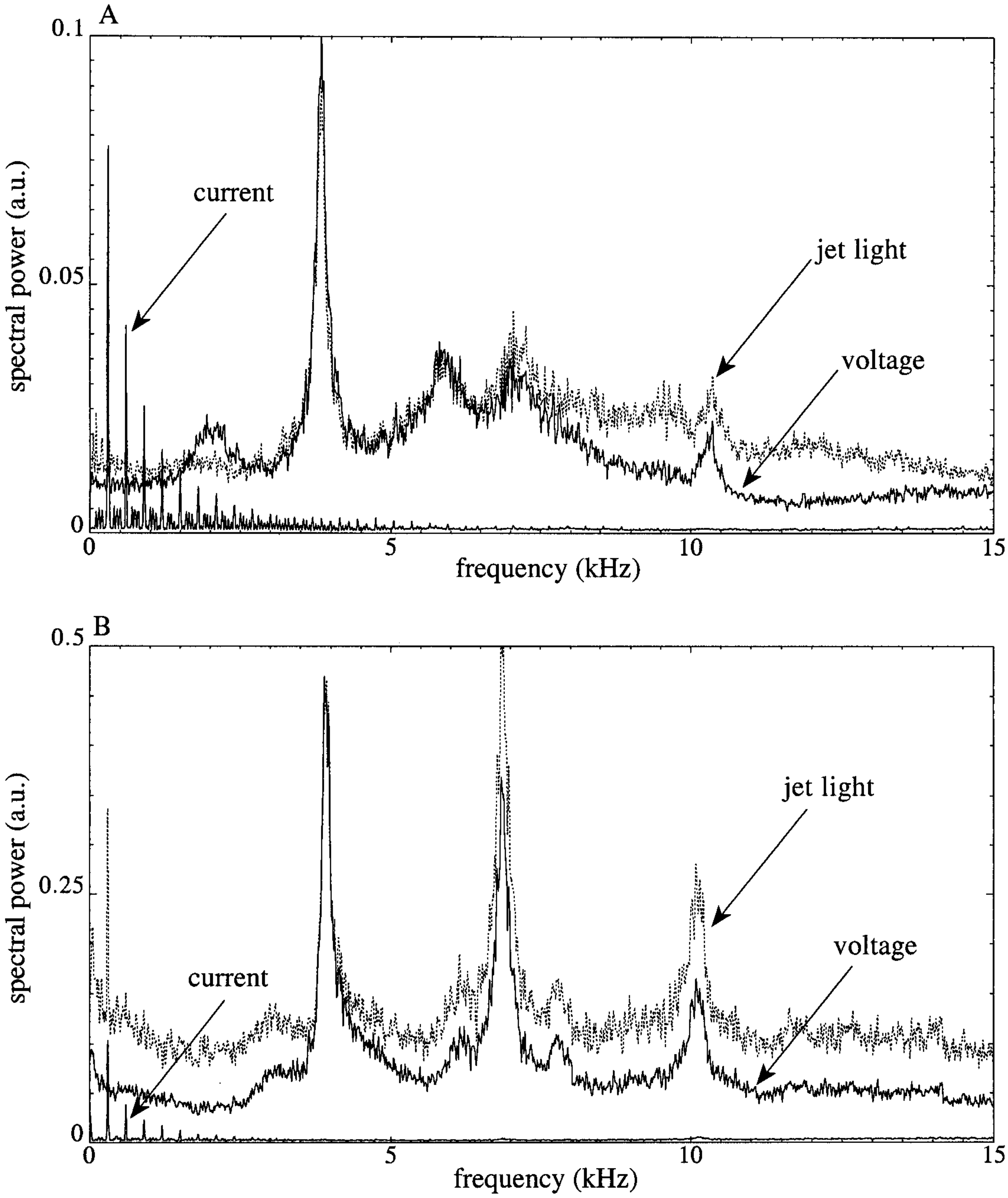

Figure 4 : Power spectra of voltage, current, and emission on jet axis at 1.5 mm from the nozzle exit for two plasma conditions : A) 50 SLPM Ar and B) 4/50 SLPM H_2/Ar. Other plasma parameters as for Fig 2.

3.3 Effect of electrode wear

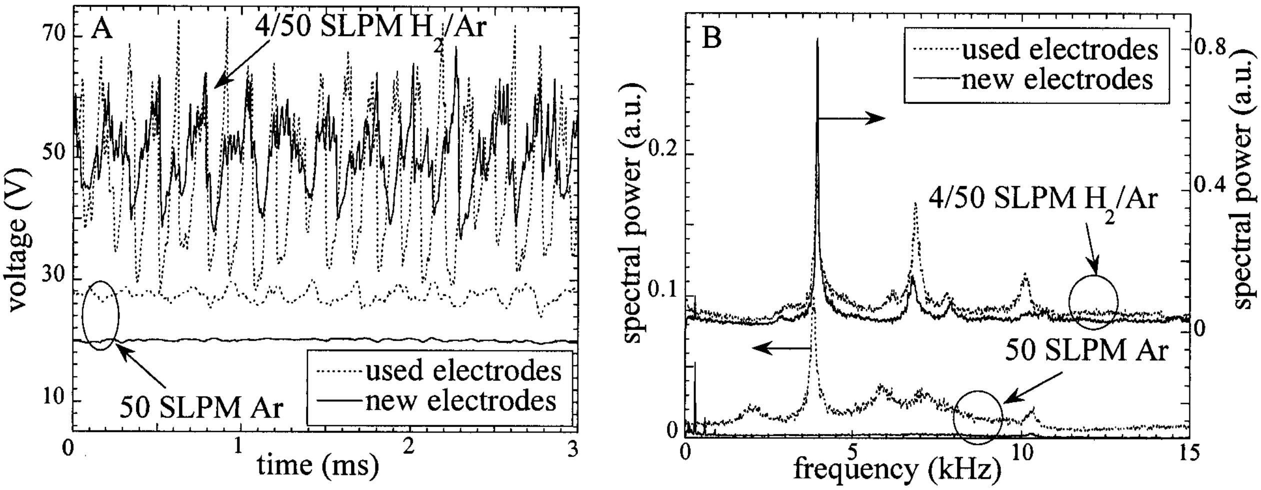

Figure 5 : Time dependencies (A) and corresponding power spectra (B) of the voltage fluctuations for new (-) and used (...) electrodes and for two gas mixtures. Plasma parameters, 50 SLPM Ar or 4/50 SLPM H_2/Ar, 500 A, 3 μs sampling time.

Figure 5 shows voltage signals and corresponding power spectra for a new electrode compared with a worn electrode, and this for two gas mixtures using the straight gas injector. For the pure argon case, the voltage signal is significantly affected by the electrode wear, both on its mean value (which increases by about 7 V) and on the fluctuation amplitude.

It appears that for new electrodes and pure argon the arc is quiescent and does not exhibit fluctuations. This situation has been described as the "stagnation" mode in reference [4] and interpreted as the result of fixed anodic arc root position resulting in a rapid localised electrode wear. The corresponding power spectrum, which only shows 300 Hz and harmonics, illustrates this absence of arc fluctuations. This means that for pure argon the electrode wear plays a key role in triggering the torch fluctuations.

In contrast, the voltage signal for the H_2/Ar mixture exhibits ample fluctuations regardless of electrode wear. Here the effect of wear is to reduce the mean voltage value by about 6 V and to nearly double the fluctuation amplitude. The power spectrum for the unworn electrodes is dominated by a peak at 4 kHz and shows weak contributions at higher frequency, whereas for the worn electrodes, this peak is reduced in favour of fluctuations in the range 5 - 12 kHz. This effect has been reported in a previous study of electrode wear [9]. It should be emphasised that this behaviour is observed for a straight gas injector and that the situation is different for a swirl injector (see below).

3.4 Effect of gas injector geometry

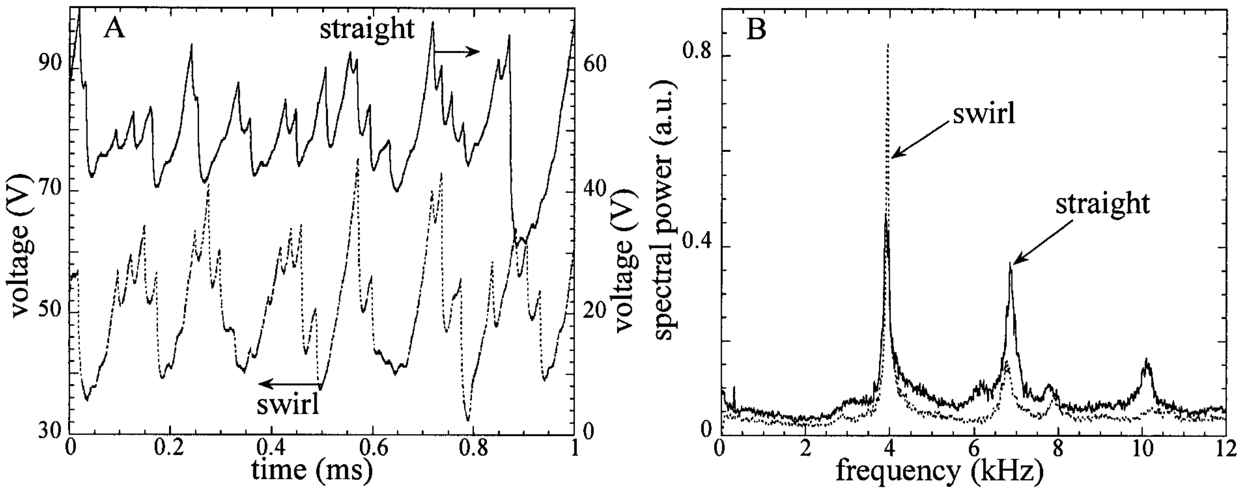

Figure 6 : Time dependencies (A) and corresponding power spectra (B) of the voltage fluctuations for swirl (...) and straight (-) gas injection. Plasma conditions : 4/50 SLPM H_2/Ar, 500 A, worn electrodes, 0.2 μs sampling time, 12.2 Hz frequency resolution.

In figure 6, the time dependences and power spectra of the voltage fluctuations are compared for the swirl and straight gas injection for the same electrode wear. For the swirl flow the voltage signal shows small, fast oscillations superimposed on larger, regular fluctuations. This could be explained by the reduced axial gas velocity with the swirl injector (45° helical angle) and the consecutive reduction of the anode foot drag in the axial direction which would slow down the restrike process. In addition, the tangential component of the flow might drive the anodic arc root in an orbital gliding motion without lengthening the arc column therefore increasing the lifetime of the arc between consecutive restrikes. The power spectrum shows the dominance of the characteristic frequency around 4 kHz for the swirl flow, whereas multiple higher frequency components are present for the straight flow. Note that, although the electrodes are worn in the swirl flow case of Fig 6B, the power spectrum resembles the one for new electrodes and straight flow of Fig 5B. This would make an eventual diagnostic of the electrode wear based on fluctuation analysis less straightforward if a swirl injector were used. This difficulty of interpreting the fluctuation measurements for the case of a vortex flow, compared to axial flow, was already mentioned in previous work [5].

3.5 Effect of gas composition and flows

Figure 7A shows the effect of the argon flow for a fixed hydrogen flow on the power spectrum of the voltage fluctuations. Figure 7B represent the same but as a function of the hydrogen flow for a fixed argon flow. For both figures the gun was equipped with new electrodes.

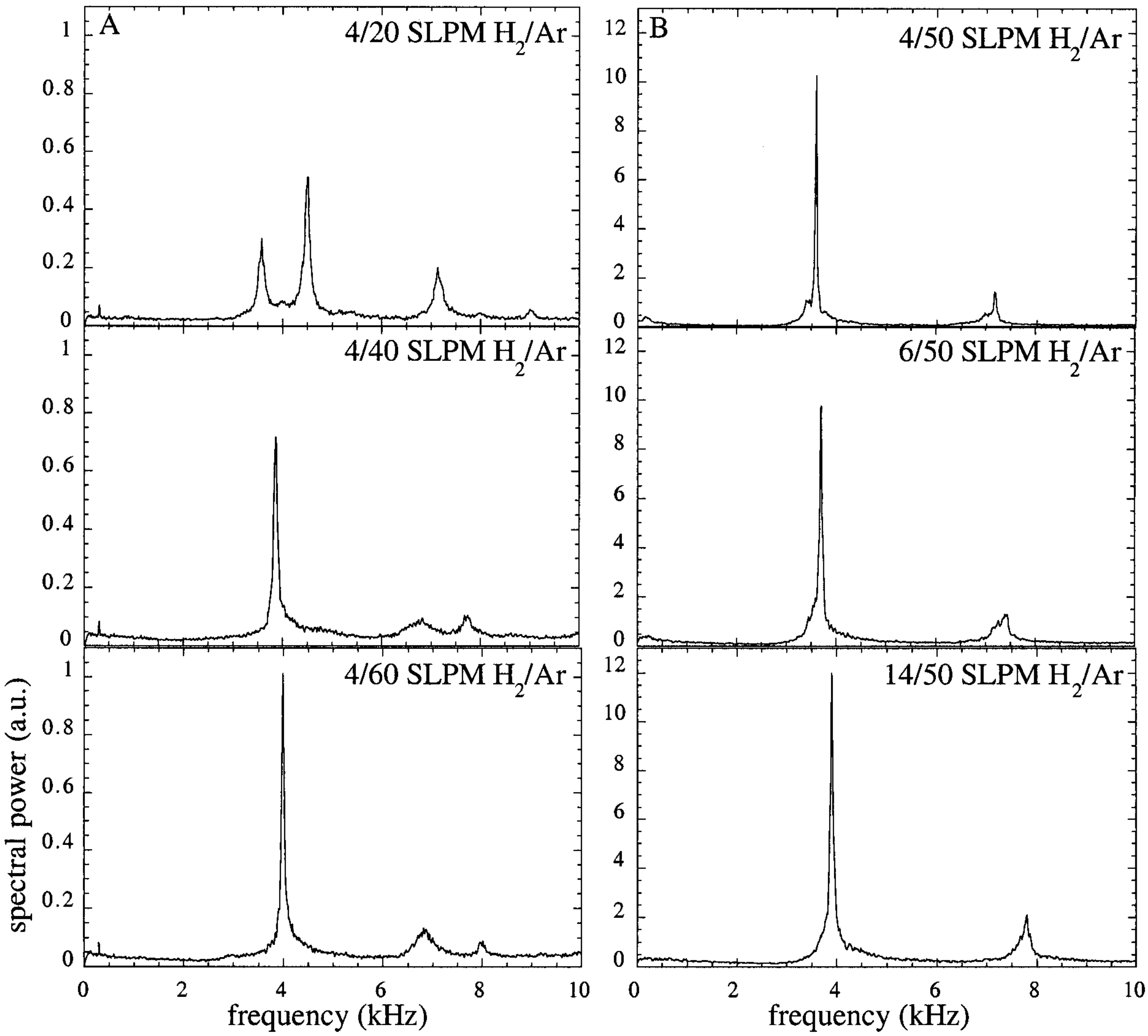

Figure 7 : Effect of the argon (A) and hydrogen (B) flows on the power spectrum of voltage fluctuations. Plasma parameters 500 A, new electrodes, straight (A), respectively swirl (B) gas injection.

It appears that the increase of the hydrogen flow has only the effect of slightly increasing the fluctuation frequencies and amplitudes in the conditions of Fig 7B. The effect of the argon flow is the same, provided that the overall flow exceeds 30 SLPM (Fig 7A). This reveals that, for relevant spraying parameters (high gas flows), the fluctuating behaviour of the arc is probably governed by the fluid dynamics and the fluctuation frequencies are determined more by the circuit impedance than by the arc physics. However at low argon flow one can observe a quite different frequency pattern at the top of Fig 7A. This might correspond to a different operation regime where the arc behavior is no longer dominated by the fluid dynamics. In this case, arc instabilities induced by magnetic effects may lead to some of the observed fluctuations and the circuit impedances play a less important rôle.

3.6 Velocity estimation by TOF of light fluctuations

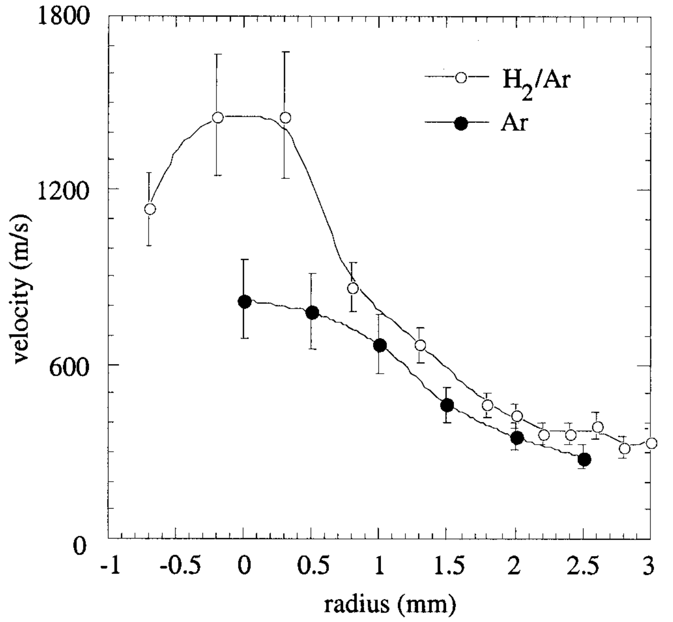

Figure 8 : Plasma jet velocity profiles for two plasma conditions (2/50 SLPM H_2/Ar (o) and 50 SLPM Ar (•) at 500A, swirl injector, used electrodes)

The time of flight (TOF) technique of reference [10] has been used to estimate velocity profiles in the hottest regions of the plasma jet. The technique is based on the assumption of convective transport of emission fluctuations with the axial velocity of the jet.

The TOF of these successive hot/cold puffs is measured by the cross-correlation of the emission signals collected by two optical fibres (Fig 1). The velocity is obtained from the ratio of the flight distance to the time shift of the cross-correlation maximum. A better cross-correlation is obtained if the signals are bandpass-filtered in the frequency range related to the arc movements and restrike (5-12 kHz). Figure 8 shows a radial velocity profile obtained between 1 and 3.4 mm from the nozzle exit for two plasma conditions. Addition of only 4 % H_2 nearly doubles the velocity which then exceeds 1300 m/s on axis. The velocity profile is peaked (3 mm FWHM for 6 mm nozzle diam.) which has implications for the powder injection geometry in plasma spraying applications.

4. CONCLUSIONS

The fluctuations of a Sulzer Metco F4 plasma gun have been characterised by measuring the time dependence of the arc current and voltage signals as well as of the light emission of the plasma jet outside the gun. The recorded signals have been analysed and FFT power spectra have been calculated for various plasma conditions, types of gas injection and electrode wear. Different modes of fluctuations have been identified in agreement with previous works. For most of the operation parameters relevant for spraying processes the torch exhibits the restrike mode for which a detailed analysis of the voltage and emission signals has allowed the identification of three different categories of voltage drops.

Measurement of the arc emission by means of an optical fibre inside the gun has shown that it accurately follows the voltage fluctuations down to the smallest details, in contrast with the jet emission behaviour which is strongly "distorted" by the turbulence. There is a dominant frequency component of the fluctuations in the vicinity of 4 kHz which is almost always present, regardless of the operation parameters. We attribute it to a resonance effect of the system (power supply circuit+electrodes+arc), in which the component impedances dominate the arc physics.

For straight gas injection the electrode wear can be diagnosed by means of a high frequency signature on the voltage and emission power spectra. However if a swirl injector is used, the frequency pattern of the fluctuations is much less sensitive to electrode wear.

Further work is still necessary to understand the fluctuating behaviour of DC plasma torches, and in particular the effects of the arc physics and circuit impedance on the fluctuations.

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