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CHARACTERISATION OF FLUCTUATIONS IN A DC PLASMA TORCH USED FOR THERMAL SPRAYING

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Abstract

The fluctuating behaviour of a commercial DC plasma spraying torch has been investigated. The time dependence of the arc voltage and current and of the jet acoustic pressure and optical emission have been acquired. An optical fiber inside the gun allows direct measurements of optical fluctuations of the arc. Analysis of the recorded signals shows significant dependence of the arc fluctuations on the working parameters and on the geometry of gas injection. In addition an optical technique has been used 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, biomedical industries and others. In spite of this success, the underlying fundamentals are still poorly understood [2], in particular the behaviour of the arc inside the torch nozzle which experiences instabilities and restrike [3] giving rise to "surging" and "whipping" motions of the plasma jet [4]. This fluctuating behaviour may lead to a non-uniform heating of the injected powder and consequently adversely affects the quality and yield of the spray deposits. A lot of R&D effort has been put into new torch designs to control arc fluctuations [5] and in process control [6]. However, the intrinsic performance of commercial torches can still be improved. Further developments towards improved 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 acoustic pressure and the optical emission of the plasma jet. In addition, an optical fibre inside the gun measures directly the optical emission fluctuations of the arc . Analysis of the fluctuating signals and of their power spectra is made for various working parameters and for different types of gas injector. The time of flight technique of reference [7] has been set up which measures the propagation of the light fluctuations along the plasma jet axis. This allows an estimation of the plasma jet velocity in the hottest regions.

2. 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, 15-80 SLM (Standard Litre per Minute) of Ar and with 2-4 SLM 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.

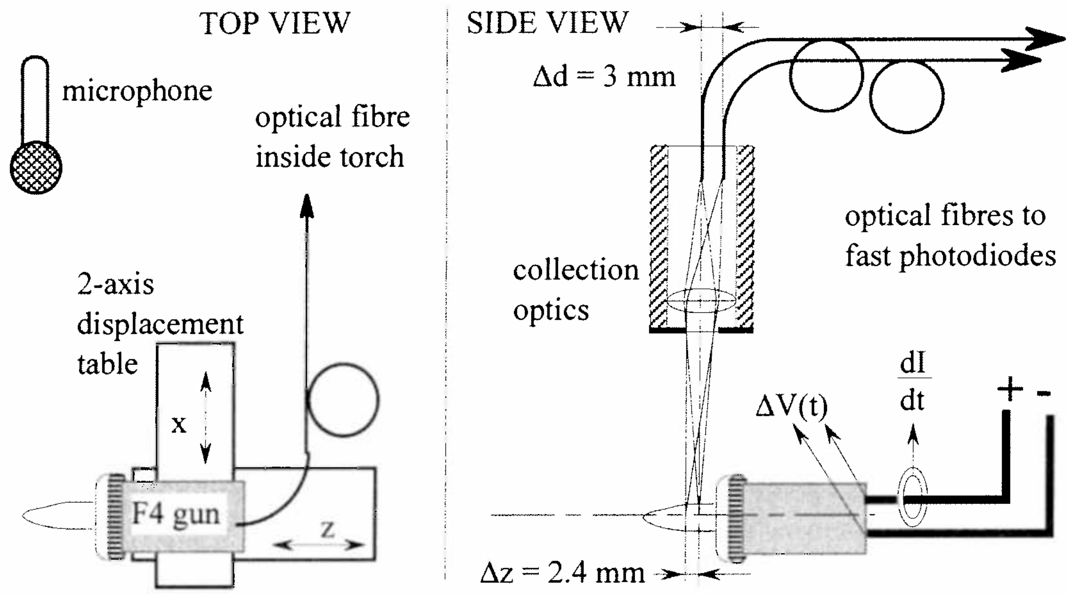

Figure 1 : Top and side views of the experimental arrangement.

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 microphone (10-20 kHz) is positioned 1.2 m from the jet axis. 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 placed Δd = 3 mm apart along the torch axis, collect light from two locations separated by Δz = 2.4 mm (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 propagate with the flow [7]. 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.

3. Time dependence of the fluctuating signals

Figure 2 shows a typical time dependence of the torch voltage and jet light emission on axis at 1 mm from the nozzle exit for two gas mixtures. The standard deviation of the voltage signal represents about 5.3% of the rms value of 27.6 V for the pure Ar case, whereas it exceeds 15% of the rms value of 50.4 V for the H_2/Ar mixture. The voltage pattern for pure Ar operation exhibits fluctuations of weak amplitude and small time derivatives (around 120 kV/s), which suggests that the arc experiences the so-called "take-over mode" [3]. In contrast the voltage signal for the H_2/Ar mixture shows a clear sawtooth pattern, which is typical of the "restrike mode" [3, 8]. There are two kinds of voltage drops : the large ones (between 20 and 30 V, with up to 10 MV/s) which might be attributed to the "upstream restrikes" described in reference [8], for which a breakdown of the arc occurs with a new arc root closer to the cathode; and the small voltage drops (typically 5 to 15 V at 1 MV/s) which may originate either from "upstream restrikes" [8] or from short circuiting of the curved part of the arc at the anode root. In the latter phenomenon, which resembles to reconnection, the anode root is maintained at the same position and the arc is not interrupted. This is shown for some of the small voltage drops in Fig. 2B by the absence of a subsequent reduction in the jet emission.

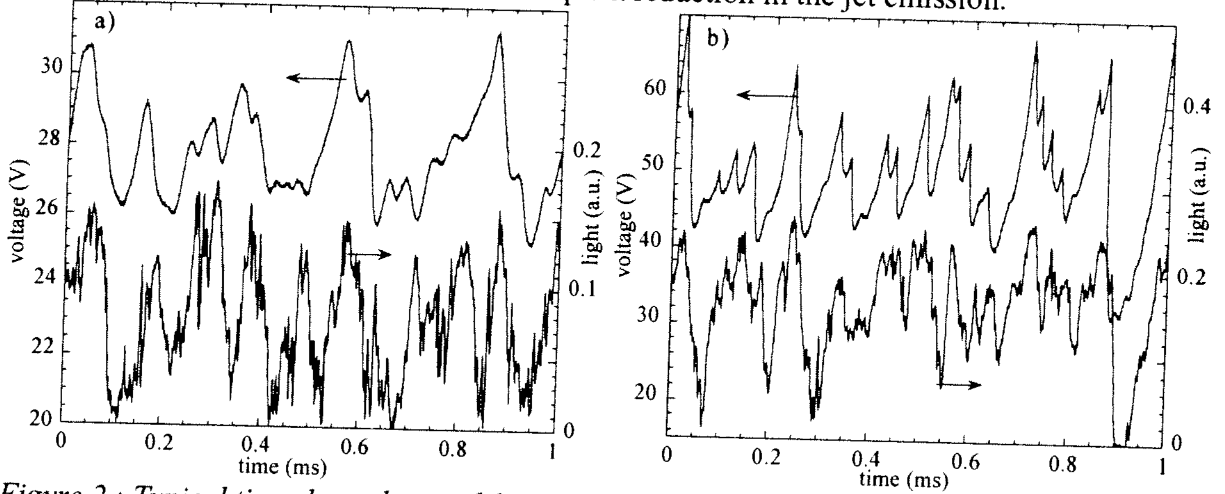

Figure 2 : Typical time dependence of the torch voltage and light emission collected on jet axis at 1 mm from the nozzle exit for two gas mixtures : a) 50 SLM Ar and b) 4/50 SLM H_2/Ar (500 A, straight flow gas injector, sampling time 0.2 μs).

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 emissivity is a sensitive function the local temperature variations in the jet (10-15.10^3 K). The mean light intensity is nearly doubled by the addition of only 7 % of H_2 to the plasma gas because the effective power coupled to the plasma jet increases from 6.8 to 14.4 kW. The emission signals are clearly correlated with the voltage fluctuations, especially for the H_2/Ar case. Systematic analysis of the voltage and light signals shows that the deepest voltage drops lead to the strongest reductions in the emission. It seems therefore that the upstream restrikes are responsible for the strongest temperature drops in the jet. Voltage and emission signals are shifted with an average delay of about 15 μs 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 3 shows the arc emission fluctuations measured inside the torch which exhibits much smaller amplitude variations than the plume emission probably because of the absence of spatial resolution, and the fact that visible 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, as opposed to the jet emission signals which are distorted due to turbulence before the nozzle exit. For the low Ar flow case (Fig. 3a) we observe regular, quasi-periodic fluctuation of the signals at about 4.3 kHz with alternating small and large drops, whereas for the high Ar flow the fluctuations are much faster and less regular.

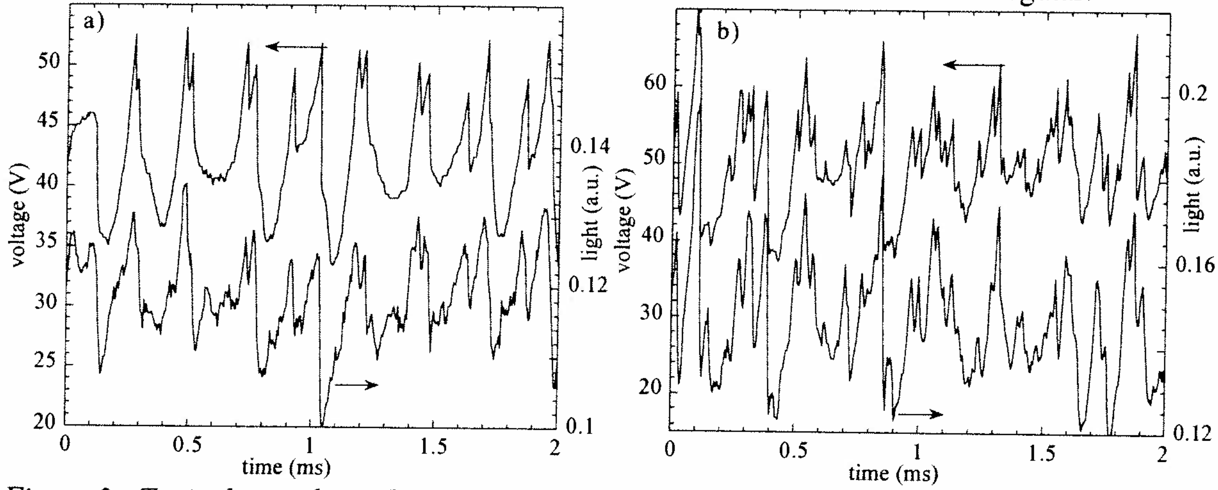

Figure 3 : Typical time dependence of voltage and emission from inside the torch for two gas mixtures : a) 4/15 SLM and b) 4/50 SLM H_2/Ar (500 A, straight flow, sampling time 5 μs).

4. Power spectra

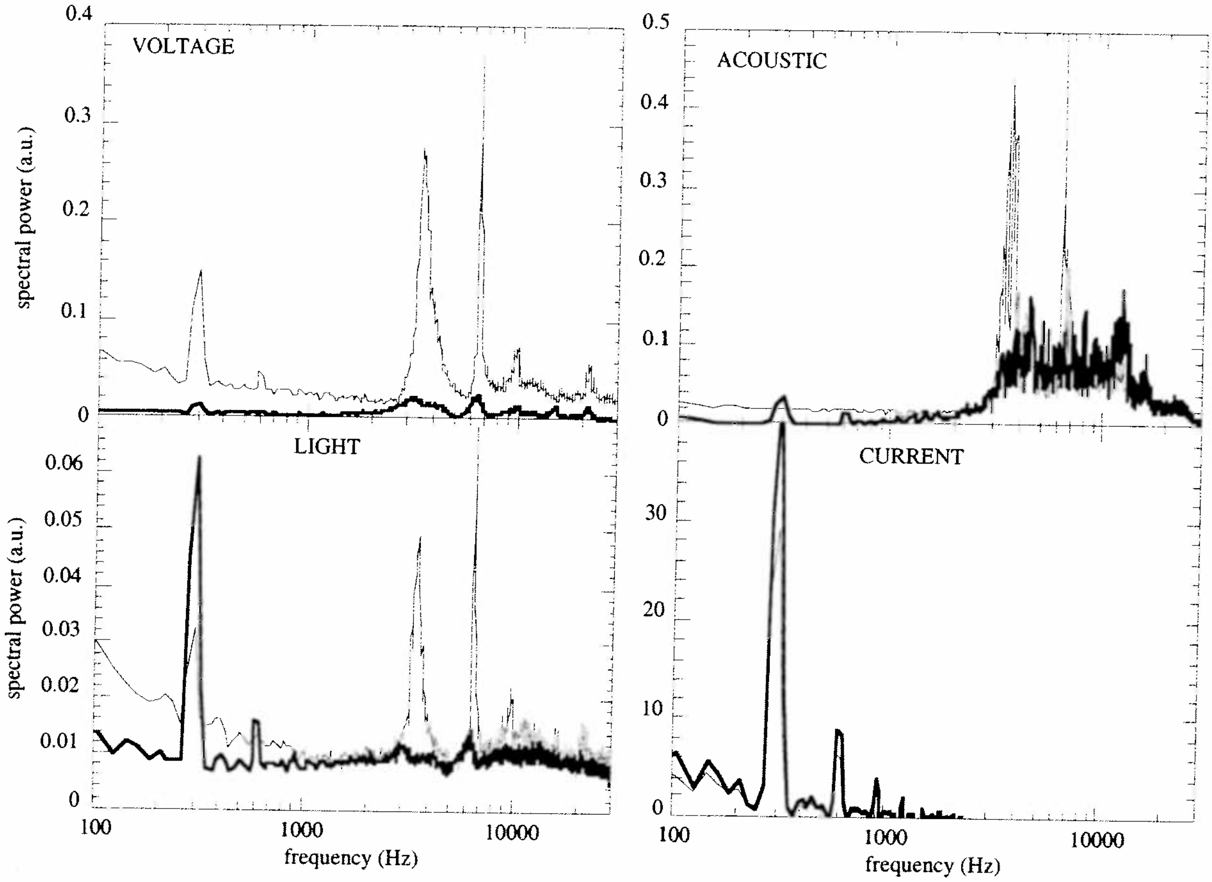

Figure 4 : Power spectra of voltage, current, jet acoustic pressure and emission on axis at 5 mm from the nozzle exit for two plasma conditions : 2/50 SLM H_2/Ar (plain) and 50 SLM pure Ar (bold) (500 A, swirl flow gas injector, frequency resolution 20.35 Hz).

Figure 4 shows the power spectra of the voltage, light emission, acoustic pressure and current for two gas mixtures. These 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. The signals are band-pass filtered (10 Hz-100 kHz) and a Hanning window is applied prior to the FFT. The above procedure is performed on 50 consecutive 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 rectification of the torch DC power supply. The 300 Hz is also clearly visible on the light spectrum for the pure Ar case and on the voltage spectrum of the Ar/H2 mixture.

Except for the current, the pure Ar case shows much less fluctuations and no clearly-defined frequencies in comparison with the H_2/Ar mixture for which the power spectra of voltage, light and acoustics are dominated by high frequency peaks in the range 3-12 kHz. These fluctuations are due to the arc motion and restrike which is a quasi-periodic phenomenon. The amplitude and frequency of these peaks change with torch ageing due to electrode wear. On the other hand, the light emission power spectrum shows a significant continuous background level which increases at low frequencies. This is attributed to the turbulence of the plasma jet, and the consequent entrainment of the surrounding air.

5. Effect of gas injector geometry

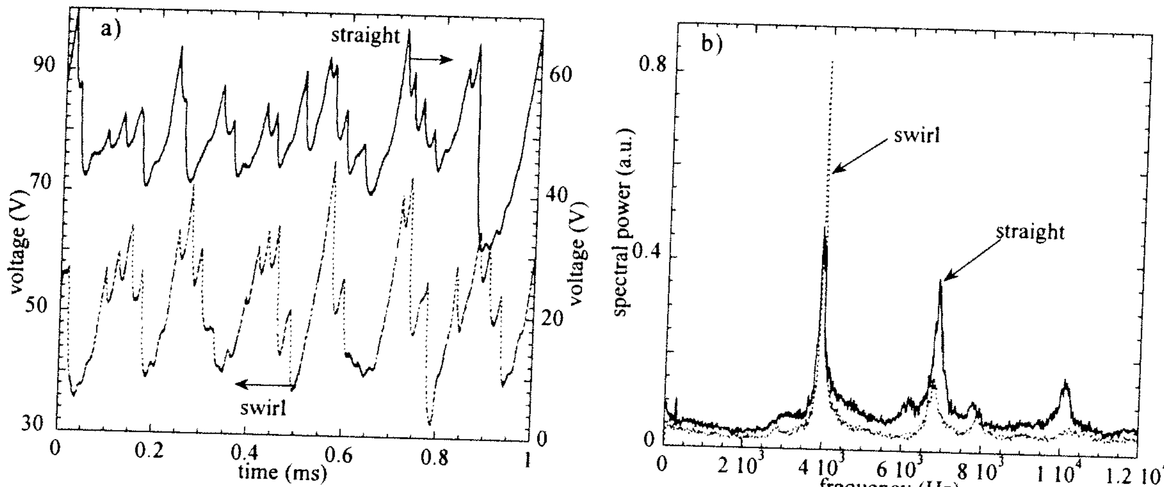

Figure 5 : Time dependencies (a) and corresponding power spectra (b) of the voltage fluctuations for swirl (...) and straight (-) gas injection (4/50 SLM H_2/Ar, 500 A, 0.2 μs sampling time, 12.2 Hz frequency resolution).

On figure 5 the time dependence and power spectrum of the voltage fluctuations is compared for the swirl and straight gas injection. For the swirl flow the voltage signal shows a behaviour similar to the low Ar flow case of Fig. 3, with fast small fluctuations superimposed on regular larger fluctuations. This could be explained by the reduced gas axial velocity with the swirl injector (45° helical angle) and the consecutive reduction of the gas drag on the anode foot in the axial direction. The power spectrum shows the dominance of a characteristic frequency around 4 kHz for the swirl flow, whereas multiple higher frequency components are present for the straight flow.

6. Velocity estimation by TOF of light fluctuations

The time of flight (TOF) technique of reference [7] 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 (3-12 kHz). Figure 6 shows a radial velocity profile obtained between 1 and 3.4 mm from the nozzle exit for two plasma conditions. An addition of only 4 % H_2 nearly doubles the velocity 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.

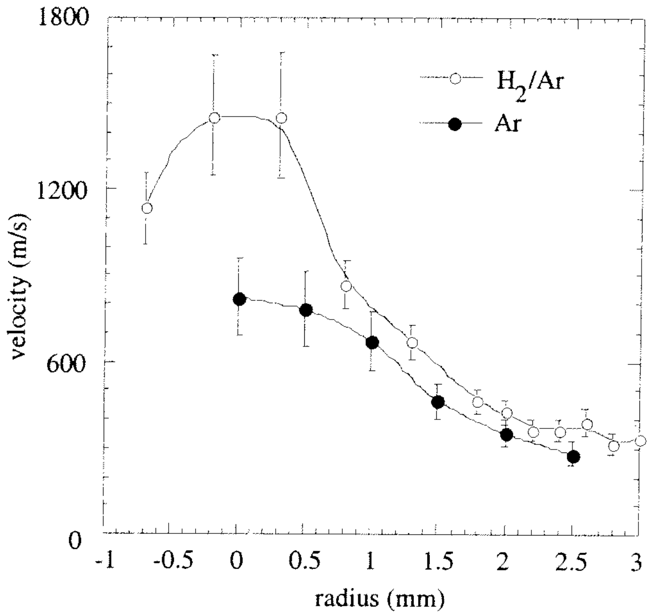

Figure 6 : Plasma jet velocity profiles for two plasma condition (2/50 SLM H_2/Ar (o) and 50 SLM Ar (•) at 500A, swirl injector)

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