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On the dynamic behavior of the anode–arc–root at the nozzle surface in a non-transferred plasma torch

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Abstract The dynamic behavior of the anode–arc–root at the nozzle surface of a plasma torch was experimentally investigated in this work. A gas (N₂) vortex–stabilized non–transferred arc torch with a thoriated tungsten rod (2wt %) cathode (3.2 mm diameter) and a coaxial anode (5 mm diameter, 30 mm length) was used in the experiment. By using a sweeping Langmuir probe in floating condition, the voltage of the plasma jet outside the nozzle was inferred. Arc voltage waveforms were also obtained. Data have been obtained for an arc current of 100 A and a gas flow rate of 30 Nl min⁻¹. A typical sawtooth shape (i.e., restrike mode) (with a fluctuating level of $\approx \pm 25\%$) and a dominant frequency of ≈ 6.5 kHz was observed in the arc voltage waveforms, which is attributed to anode–arc–root movements along the anode surface followed by a restrike at a certain point close to the cathode. By performing a time correlation between the probe and arc voltage oscillograms together with simple estimations, the amplitude of the movement of the arc–root along the anode surface as well its velocity were inferred.

1. Introduction

Atmospheric pressure thermal plasma jets generated in direct current (dc) non–transferred arc plasma torches are used in a number of applications like plasma surface modifications, spray coatings, material synthesis, and waste treatment [1].

The electric arc inside these torches can be divided into three parts: the cathode region (located right in front of the cathode), the arc column, and the anode region (located right in front of the anode). The cathode arc root is quite stable for hot (thermionic) cathodes, but the anode–arc–root usually moves along the anode surface. This movement is in general desirable, as it allows a more uniform heating of the anode surface (increasing its lifetime); but in plasma spray applications it also causes a non–uniform heating of the particles injected in the plasma jet, which is undesirable.

The dynamics of the arc inside dc non–transferred arc plasma torches are mostly the result of the unbalance between the magnetohydrodynamic force, produced by the local curvature of the current path and the arc self-induced magnetic field, and the flow drag, caused by the interaction of the

incoming dense, cold gas and the hot, low density, plasma arc [2]. If the magneto–hydrodynamic force equals the drag force, then a steady attachment is obtained, characterized by a negligible movement of the arc. If the drag force is larger than the electromagnetic force, then the flow will drive the arc downstream. At the same time as the arc moves downstream, the arc length increases and so do the total voltage drop and the magnitude of the electrical field around the arc. If the voltage drop between a certain point of the stretched arc and the anode exceeds the local breakdown voltage value, a new breakdown and, hence, a new arc attachment forms somewhere upstream the original attachment. The corresponding arc voltage exhibits a typical transient restrike mode (sawtooth shape), which is attributed to the above described arc dynamics.

The dynamic behavior of the anode–arc–root at the nozzle surface of a non–transferred plasma torch was experimentally investigated in this work. The amplitude of the movement of the arc–root along the anode surface as well as its time–averaged velocity was inferred by using a floating Langmuir probe and time resolved arc voltage measurements.

2. Experimental set–up

A gas (N_2) vortex–stabilized non–transferred arc torch with a thoriated tungsten rod (2wt %) cathode (3.2 mm diameter) and a coaxial anode (5 mm diameter, 30 mm length) was used in the experiment. The operating torch conditions were: arc current of 100 A and a gas flow rate of 30 Nl min^{-1} .

A schematic of the employed experimental set–up is shown in figure 1.

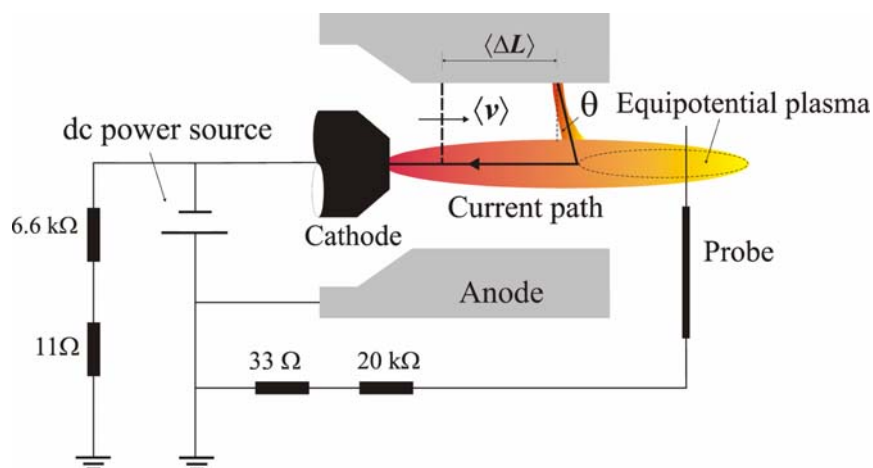


Figure 1. Schematic of the employed experimental set–up.

The employed Langmuir probe system consisted in a rotating aluminum disk carrying one single probe mounted in the radial outward direction of the disk. The cylindrical probe was made of tungsten wire with a radius of $250 \mu\text{m}$. The probe was swept through the arc at constant velocity (17 m s^{-1}) at 3.5 mm from the nozzle exit in unbiased (floating) condition. This condition was obtained by connecting the probe to ground through a large resistance ($20 \text{ k}\Omega$) that limited the collected current to a very low value, and using an additional low value resistance (33Ω) to register a signal proportional to the probe voltage (V_p). The arc voltage waveforms (V_c) were also obtained by connecting the cathode to ground through a large resistance ($6.6 \text{ k}\Omega$), and using an additional low value resistance (11Ω) to register a signal proportional to the arc voltage. Both voltage signals were registered using a two-channel Tektronix TDS 1002 B oscilloscope with a sampling rate of 500 MS/s and an analogical bandwidth of 60 MHz . A detailed description of the employed probe system can be found elsewhere [3].

3. Experimental results and discussion

Typical V_c and V_p waveforms corresponding to the above torch operating conditions are given in figure 2. The arc voltage exhibits a characteristic sawtooth shape (i.e., restrike mode) with a fluctuating level of $\approx \pm 25\%$, with respect to its time-averaged value, and a dominant frequency ($\langle f \rangle$) of ≈ 6.5 kHz.

This phenomenon is attributed to a motion of the arc root driven by the flow, followed by a sudden restrike near the cathode (indicated in the figure 1 with a dotted vertical line as a cold gas layer breakdown), between some point of the arc column and the anode. This results in sawtooth shaped voltage traces because there is an almost linear relationship between the arc voltage and the arc length [4].

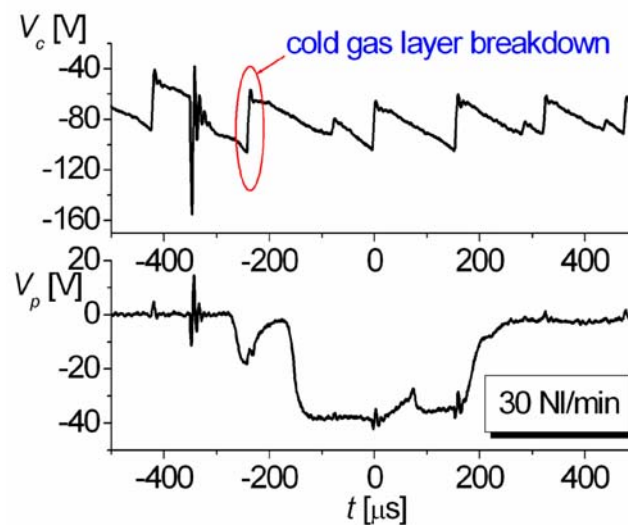


Figure 2. Correlated arc and plasma floating voltages.

The time-correlated V_p signal is also given in figure 2. The relevant part of this signal extends from ≈ -200 μs to ≈ 200 μs , which corresponds to the passage of the probe through the arc. Taking into account that in this kind of torches the difference between the plasma potential and the floating potential is quite small [5], a plasma potential value (V_s) of ≈ -35 V can be inferred for the whole plasma jet emanating from the torch. This voltage value represents the voltage drop between the arc column and the anode-arc-root (see the straight path tilted an angle θ in figure 1). Neglecting the small anode voltage drop, the average electric field strength along such path is given by

$$\langle E \rangle \approx \frac{V_s}{R} \cos(\theta), \quad (1)$$

where R is the nozzle radius. Furthermore, by setting $\langle E \rangle$ equal to the uniform electric field strength along the arc, the time-averaged restrike length (ΔL) can be estimated as

$$\langle \Delta L \rangle \approx \frac{\langle \Delta V_c \rangle}{\langle E \rangle}, \quad (2)$$

where $\langle \Delta V_c \rangle$ is the time-averaged peak to peak value of the sawtooth shape of the arc voltage.

The corresponding time-averaged drift velocity ($\langle v \rangle$) is given by

$$\langle v \rangle = \langle \Delta L \rangle \langle f \rangle. \quad (3)$$

The spatial-averaged arc electric field strength, together with the time-averaged restrike length as well the drift velocity, are shown in figure 3 as functions of the model parameter (θ). As it can be seen, ΔL varies in the range 3–7 mm ($\langle v \rangle$ is around 25–50 m s⁻¹) while $\langle E \rangle$ remains relatively high, in the range of 7–14 V mm⁻¹.

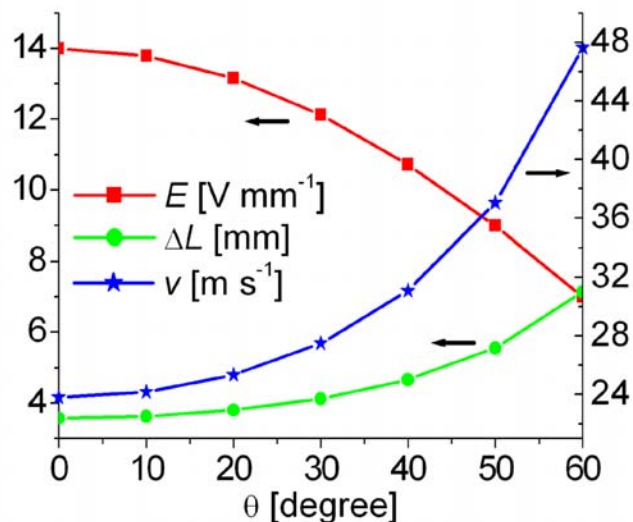


Figure 4. Calculated arc electric field strength, restrike length and restrike velocity.

4. Conclusions

The dynamic behavior of the anode-arc-root at the nozzle surface of a plasma torch was experimentally investigated in this work by using a floating sweeping Langmuir probe and time resolved arc voltage measurements. By performing a time correlation between the probe and arc voltage oscillograms together with simple estimations, a range of values for the arc electric field, the amplitude of the restrike length and the drift velocity of the arc were inferred. The estimated values of the restrike length are in accordance with numerical simulations [6].

Acknowledgements

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