EXPERIMENTAL APPROACH OF THE INTERACTION BETWEEN A SUB-MICROSCOPIC CATHODE TIP AND THE PLASMA

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Abstract: **The interaction between electrical arc and cathode represents a crucial problem in the conception of arc jet thrusters, circuit breakers, and plasma torch or arc heaters. At the cathode surface, the current and energy transfers are controlled by the current emitting site (cathodic spot). Theories and experimental observations, at macroscopic and mesoscopic scale, deal with the erosion of the cathodic surface. Under micrometer range, theories refer to the arc root to describe the erosion of the surface. The works presented here propose an original method to evaluate the arc-cathode interaction at micrometric scale. A nanotechnology is used in order to control the roughness of the electrode surface and to deposit the microscopic tip. After discharge, the influence of the tip in the cathodic erosion process is studied. Scanning Electron Microscopy images show that a good reproducibility of the erosion zone is obtained by using this experimental method.**

Keywords: **Nanotechnology; tip; cathode surface, cathode erosion.**

1. Introduction

Electrical arc appear in relays, circuit breaker or plasma torch. Physic phenomena of the interaction between the plasma and the cathode are an important problem for industrial device. A large literature deals with this subject and is divided into two approaches.

The 'post-mortem' approach consists to observe the cathode surface after discharge extinction and highlights the existence of craters with dimensions 5 µm to 100 µm [1].

Post-mortem traces of a spotlight are characterized by a sudden high localised current going through the surface. Spotlights (current emittive site) play a major role in the electric arc. Indeed, they feed on the electrode neighbourhood plasma of atoms by electrode erosion [2-5] and of electrons by thermo-emission.

The 'in vivo' approach consists to observe the electrode surface using a high speed camera during the discharge. Oscilloscopes are used to monitor the current and the voltage time evolution. Thus, Jüttner proposes a hierarchy of the spotlights associated to the current emittive site [6].

The paper presents the development of an experimental method to study the interaction plasma/surface at sub-microscopic scale. A nanotechnology is used in order to control the roughness of the electrode surface and to deposit the microscopic tip (on the middle of the surface). Then, this electrode contributes to obtain a reproducibility of the erosion space repartition.

The design of the tip and the set-up of the discharge apparatus are described. Then, the experimental results are exposed and discussed.

2. Design of the structured nano tips

The tips are deposited on the electrode surface by adsorption of carbon.

A sample is placed in the vacuum chamber of a Scanning Electron Microscope (SEM). Then, a spot of contamination is realized on the surface in order to adsorb carbon. The quantity of carbon deposited on the sample is characterized by the diminution of the current measured on the sample. A calibration is performed according to this diminution to quantify the size of the tip. To design the tip and locate the central site of the spot of contamination on the samples, an electron microscope JEOL 6500 is used. This apparatus has a turntable motorized with a precision of about 500 nm. It allows identifying precisely the site of release of the arc. Adsorptions carried out will be less important than with the SEM JEOL 840A because this one use a turbo-pump and not an oil-pump. This involves fewest carbons in the column and thus restricts adsorption.

In the first aspect of this experimental process, a Cu-layer is deposited on a glass substrate by cathode sputtering. Then, the sample is placed in the vacuum chamber of a SEM (JEOL 840A). After the development of a fine image, the mode "spot" is chosen to stop the scanning of the electron beam. The total energy of the electron beam (20 keV) is entirely focused on a precise point of the sample. This allows the adsorption of carbon. The height of the tip is then controlled by the measurement of the diminution of the current, expressed in pico-ampere. The time of

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adsorption is variable according to the quantity of carbon present in the SEM column.

Table 1: Dimension of the tips obtained

Fall of current	Height of tip	Base of tip
45 pA	500 nm	450 nm
25 pA	400 nm	350 nm
20 pA	350 nm	285 nm
17 pA	345 nm	210 nm
15 pA	205 nm	208 nm
10 pA	110 nm	312 nm

Then the result can be observed and quantified as shown on figure 1. Thus, from smallest with largest, we obtain for a loss of 10 pA, a tip of 110 nm high for a base of 312 nm and we obtain for a loss of 45 pA a tip of 500 nm high for a base of 450 nm.

The whole of measurements is indexed in table 1. Thus, the profile of these tips is conical and their dimensions do not vary in a linear way with the loss of current. These results show that this technique is viable for the fabrication of tips. If the highest tips are not taking into account, it requires slightly rough copper substrates.

In this case, the diminution of the maximum current realized is about of 10 pA and the associated higher tip is about of 120 nm (figure 1). These values are limited but they are compatible with roughness obtained by polishing. Theoretically, the effect of tip should be sufficient and the electric arc is attracted by the carbon spots present on each electrode.

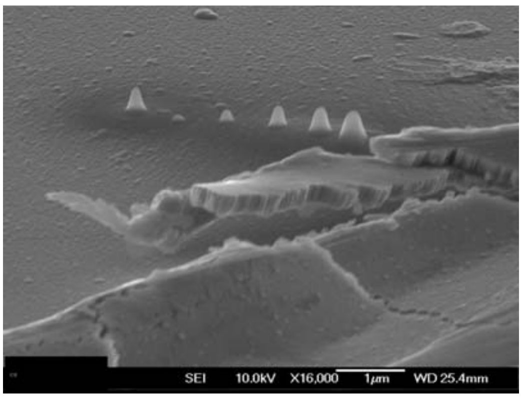

Figure 1: SEM image of several carbon tips (Magnification 16000)

In order to obtain a surface quality whose roughness is in adequacy with the height of the tip, we carried out a polishing of the copper electrodes. The copper sample is placed in an acrylic resin to allow good mechanical stability during polishing. The sample undergoes several stages of polishing of which the last is the use of an alumina felt of 1 μm.

A SEM observation (JEOL 6500) allows an evaluation of the roughness of produced surfaces (figure 2). The roughness of surface is about 30 nm and is quite lower than the dimension of the tip. The diminution of current being relatively difficult to maintain constant (fluctuation in order to 10 pA), a thin layer of gold is deposited (approximately 20 nm) by cathode sputtering. This increases the conductivity (without modifying the thermal properties of the layer) and thus increases the adsorption of carbon on the surface of the electrodes. In addition, the layer of gold allows "revealing" the zones where the electric arc struck. Thus, the fabrication of the electrodes led us to use the spots of contamination in order to deposit the tip. Experiments of electric arc were carried out on a copper electrode surmounted of a tip

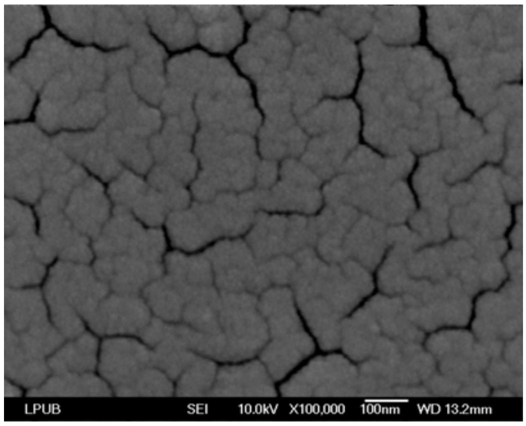

Figure 2: An observation with the SEM (JEOL 6500). Evaluation of the roughness of produced surfaces

of carbon of 110 nm high and three copper electrodes surmounted of a layer of gold with on each one a tip of 105 nm high. For the calibration of the distances from breakdown during the tests of electric arc, a polished electrode without tip is used.

3. Electrical apparatus

Figure 3 represents the electrical apparatus used to obtain the breakdown. It is composed of three stages. A high voltage transformer and a Graetz diode bridge allow the AC-DC conversion. The second stage consists to a capacitor bank with a load resistance R1. The discharge of the capacitor bank is controlled by a HV switch (denoted K_{HT}). The next element is a resistance R2 to control the intensity of

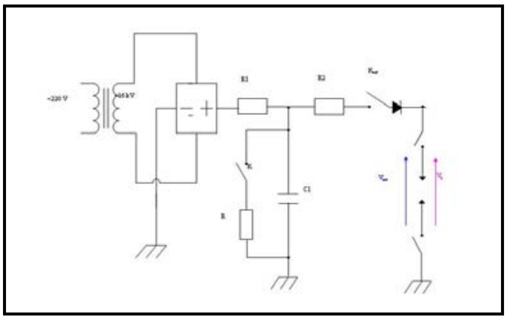

Figure 3: Scheme of the electrical apparatus

the current pulse and the current time.

This set up allows (in accordance with the electrode gap) to realize current pulses with a time in the range of10 µs-100 ms.

4. Results

The first experiment consists to define the duration of the discharge which assure the presence of multiple eroded zones without a large erode zone (macro-spot). The duration is estimated to 50 µs. In this case, the distribution of the eroded zones on the surface indicates that the arc root moved by "jump" and not in a continuous way [7]. It is possible to return to the centre of the surface where the deposited cathodic point is located by following the discontinuous way of the arc.

In comparison with figure 4, which represents the cathodic surface of an electrode after arc, the deposition of gold ensures a more detailed description of the eroded zones. Thanks to that, the displacement of the arc along the surface can be followed.

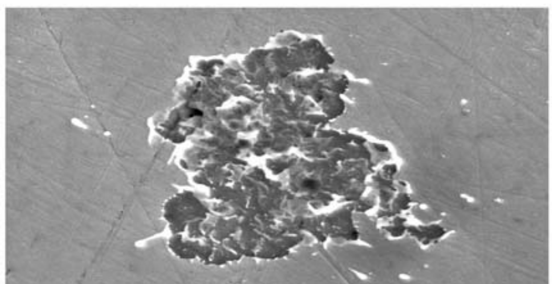

Figure 4: Example of eroded area

Fine SEM observations of the edge of one of these zones allow evaluating the importance of this layer of gold. The periphery of the eroded zone shows that the layer of gold was not vaporized but puffed up without liquefaction, leaving copper without any trace of erosion.

The analysis by photonic micro-probe of eroded surface (figure 5) indicates that there is only copper. While approaching the centre of eroded surface, droplets are observed. The analysis indicates that they are made up of gold and copper. The weak difference between vaporization and liquefaction enthalpy of copper and gold leads us to suppose that the influence of gold on the erosion of the cathode is not significant. The blowing and the setback per pieces of plates of the layer of gold in periphery are explained by the effect of pressure applied by the arc foot on the gold depot. The observation of the central zone shows a consequent eroded zone lower 1 µm. The presence of carbon must be due to the nano-structured point. Thus, the latter underwent erosion consequently to the vaporization of a part of carbon constituting it.

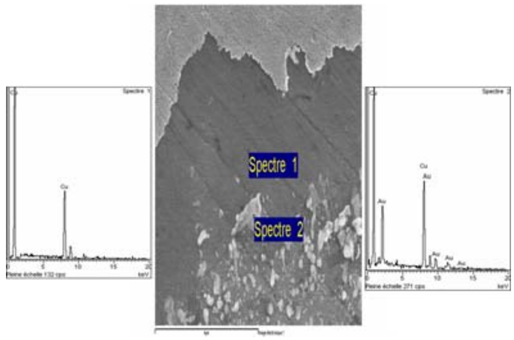

Figure 5: SEM observations with photonic survey of materials on the surface

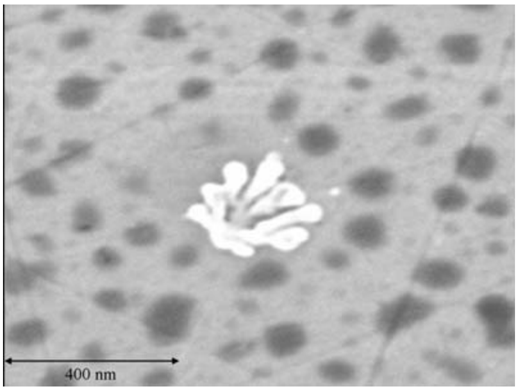

Figure 6: Observation of the central zone, place of the cathode tip

5. Short time of discharge

By means of discharges at short duration (>20µs) the same experiment is renewed to obtain only one emissive site of current corresponding to the structured nano point.

The SEM observations of several surfaces (figures 7 and 8) subjected to the arc indicate the existence of only one emissive site of current via the setting in contrast by the layer of gold.

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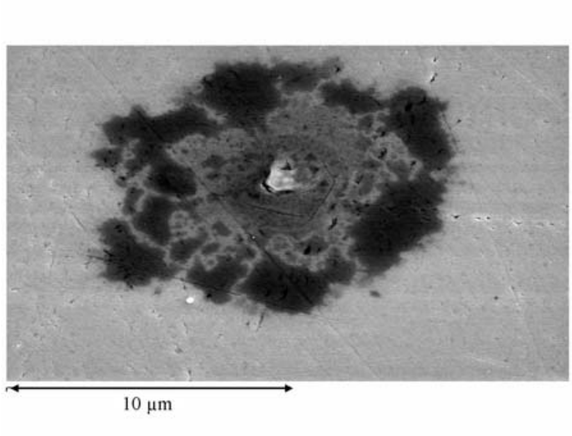

Figure 7: Image of the central eroded zone of the first electrode

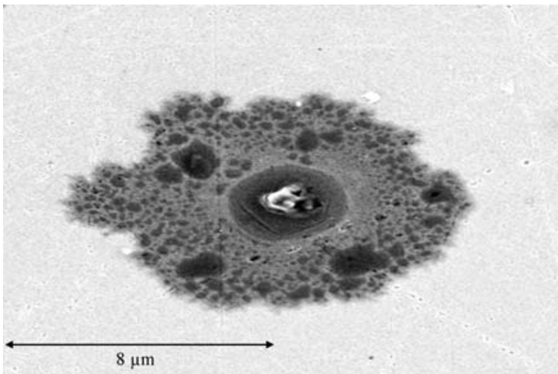

Figure 8: Image of the central eroded zone of the second electrode

Micro-probes measurements show that the site of the electrode (in the centre) corresponds to the site of a carbon cathodic point. The reproducibility is noted by the glance of the various tests. However, SEM image explains the surplus of energy of the discharge provided to obtain only one microspot: it is possible to start an arc with weaker energy and then have an emissive site of single current.

Future measurements require a device of discharge with a shorter time of discharge in order to have a single microspot and not of a small group of microspots.

6. Conclusion

In this article, we proposed an original experimental method to study the interaction plasma/cathode at sub-microscopic scale. A nanotechnology is used to depose a microscopic tip with a controlled design on the centre of a cathodic surface. To eliminate other possibilities of current ignition, the surface is treated with a gold layer (10 nm). Gold is choosen because of its thermophysical properties similar to the thermophysical properties of copper. The gold layer produces an appreciable contrast which allows SEM observations of the erosion on the cathode surface. The results demonstrate a reproducibility of the erosion trace with a short duration arc.

The present analysis should be continued with different sizes of tips and different materials. A numerical model of the cathodic heating by the arc will be also realized.

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