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Experimental assessment of the surface temperature of copper electrodes submitted to an electric arc in air at atmospheric pressure.

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Abstract. This paper concerns the assessment of the surface temperature of copper electrodes submitted to an electric arc in a non stationary regime in air. An infrared camera is used to measure the decrease of the temperature surface just after a controlled and very fast arc extinction. In the first part, the experimental method is described. In the second part, results are presented for 60-70 A with an electric arc duration in the range 3-4 ms. The temperature decrease after the arc extinction allows to reach an assessment of the surface temperature just at the arc switching off. In the present experimental conditions the mean temperatures reached for copper cathodes and anodes are in the range 750 – 850°C.

1. Introduction

Understanding of arc-electrode interaction in air at atmospheric pressure is still incomplete because of the lack of information concerning the evolution of surface characteristics during the arc. Among these important informations, the surface temperature remains in the case of non stationary electric arcs in air an experimentally relatively unknown parameter. Many researches have been conducted in the case of stationary arcs burning in argon with refractory electrodes (tungsten, thoriated tungsten, hafnium …) [1]-[3]. In these cases, the methods used to measure surface temperature depend strongly on the stationary character of the arc. In [1]-[5] optical methods were used such as single color and a double color pyrometry. The stability of the arc root on the electrode surface and the arc column symmetry were often an essential parameter to allow the temperature measurement.

This paper deals with the surface temperature distribution study on copper (low melting temperature) anodes and cathodes in the case of a switching arc (non stationary regime) burning in air at atmospheric pressure with an electric arc current around some tenths of amperes. In this case the use of a pyrometric method is difficult. Indeed, the arc may be very unstable on the electrode surface, and then no symmetry considerations can be used and a very short integration time for the measurement is then required.

The paper is organized as follows:

- In the first part, the experimental device used to create opening electric arcs is described.
- In the second part, the experimental method used to measure the temperature is presented and discussed.
- In the third part, we present results concerning copper anode and cathode surface temperature measurements at different instant after the arc extinction. An assessment of the surface temperature at the time of the arc extinction is also proposed.

2. Description of the experimental device

The experimental device used to measure the temperature of the electrode surface may be divided into two sets:

- the electrical device which consists of the power supply, the load circuit and the switching off electronic system. It is presented in figure 1.

- the electromechanical system which opens the contact and the different cameras used to observe the arc behavior and to measure the surface temperature. It is schematically presented in figure 2.

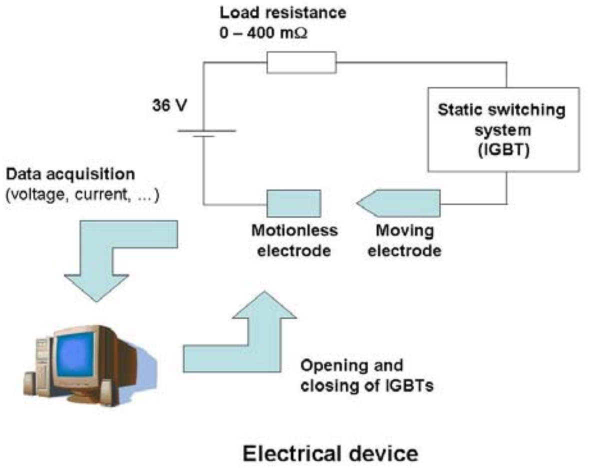

Figure 1. Schematic description of the electrical part of the experimental device

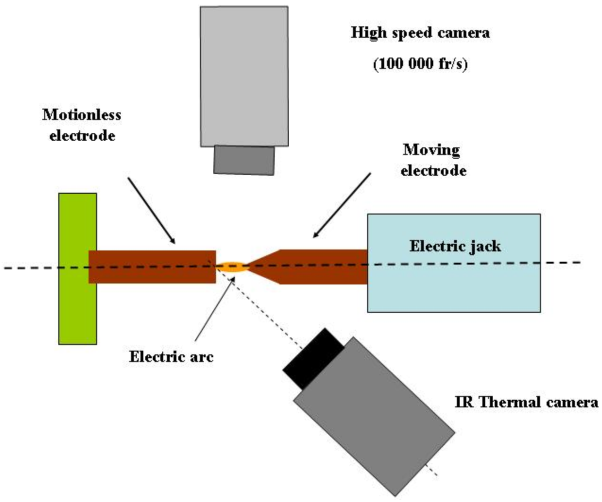

Figure 2. Schematic description of the experimental device.

2.1 The electrical device

The power supply is made up with a set of three 12V electric batteries. The internal resistance of this set is about 18 mΩ. An electronic device, made of IGBTs (Insulated Gate Bipolar Transistors) allows the control of the intensity pulse in the circuit and is also used to switch off the arc current. This static device may switch off a current intensity as high as 1500 A in less than a microsecond and may dissipate up to 275 J. The load in the circuit is made of an adjustable resistance (0 to 400 mΩ) and is supposedly no inductive.

2.2 The mechanical device

Two coaxial electrodes constitute the contact. A motionless one is a cylinder and has a flat surface. In order to increase the observable area on the flat electrode when the contact is open, a conical shape was chosen for the moving electrode.

A photograph presented in figure 3 and taken before the arc illustrates the position and the shapes of the two electrodes. The electric jack is used to open the contact with nearly constant velocity.

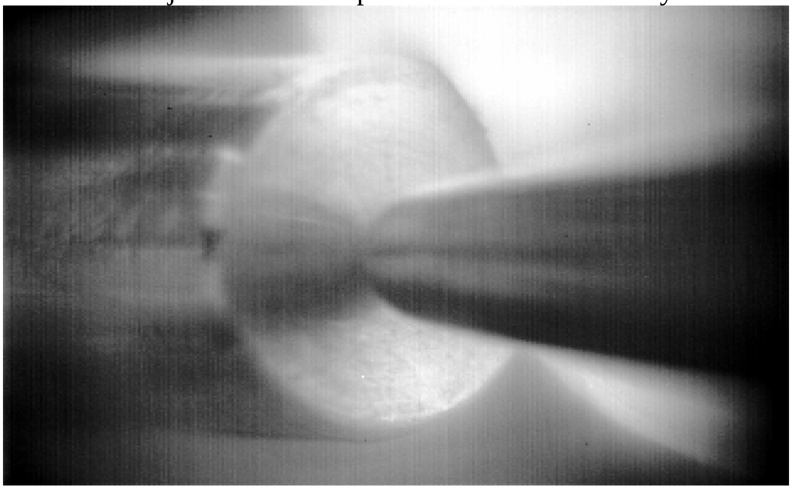

Figure 3. Photography of the electrodes before the arc: the contact is closed.

3. Measurements and description of the method

During the electric arc the following parameters were recorded:

- The current intensity.
- The arc voltage.
- The electrode gap.

Moreover, the electric arc was filmed with the help of a high speed camera (100 000 frames/s). To measure the temperature distribution on the flat motionless electrode surface, an infrared camera was used. The spectral response of the InSb camera detector is in the range 3.7 μm – 4.8 μm. The matrix detector is 320 pixels x 240 pixels. The optic used allows a spatial resolution of 40 μm to 60 μm by pixel. The first operation to achieve was to calibrate this camera for copper electrodes. It was realized with the help of a specific device described in [6] which allowed to calibrate precisely the camera until electrode fusion temperature.

Because of the intense light of the electric arc it was not possible to photograph the electrode surface and obtain the surface temperature distribution during the arc duration. The electronic system allowed to force the switching off of the electric arc in less than 1 μs (this duration is denoted τ_{elec}).

The control electronic developed with the infrared camera allowed to activate this one with a time delay of 15 μs (this duration is denoted $\tau_{activate}$) and has a precision less than 0.1 μs. The exposure time of the infrared camera is denoted $\tau_{exposure}$. According to the temperature range, $\tau_{exposure}$ takes values in the range [10 μs, 120 μs].

Then, the duration denoted τ_{image} will be considered as the instant for which the photography is taken and is such as:

$$\tau_{image} = \tau_{elec} + \tau_{activate} + \frac{1}{2}\tau_{exposure}$$

These different times are schematically presented in figure 4.

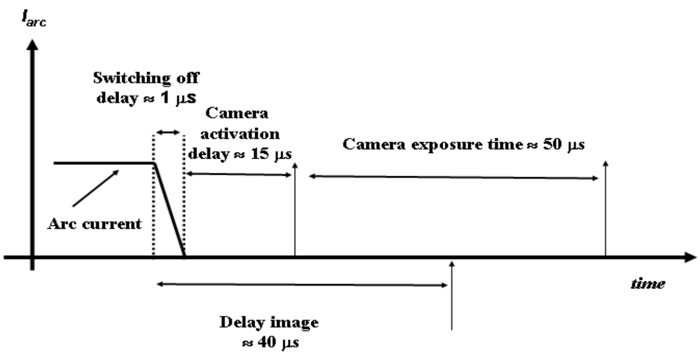

Figure 4. Description of the different delays - $\tau_{exposure}$ = 50 µs.

The electrode material was copper OFHC (Oxygen Free High Conductivity). The covering gas was air at atmospheric pressure. The diameter of the electrodes was 8 mm. The conical electrode has a half angle at the top equal to 30°. Moreover, an electric jack was chosen in order to allow a precise synchronization (<0.1 µs) between the motion and the IR camera. Consequently, this choice limited the opening velocity.

The process of opening operation is as follows:

When the IGBTs are closed, DC current in the electrical circuit is in the range 100 A – 150 A. When the contact opens the arc current drops rapidly and becomes stable around its mean value (≈ 60/70 A) and decreases slowly during the arc until the switching off. At this instant, its value is in the range 50 A – 60 A. The contact voltage increases at the contact opening to the arc voltage value and remains quite stable during the arc. The arc duration is controlled by the IGBTs triggering which depends on the software control for which exists an uncertainty of 2 ms. For each opening, the data are automatically recorded. Figure 5 presents typical evolution for contact voltage, current intensity and electrodes gap during the contact opening.

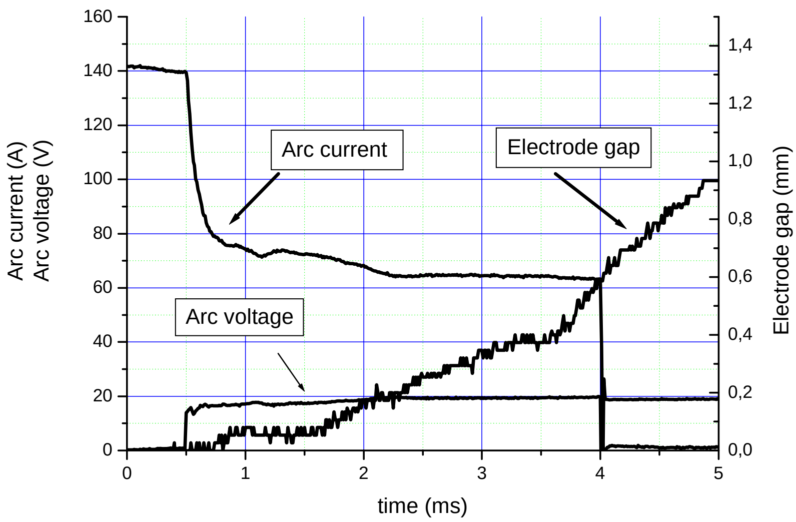

Figure 5. Typical time evolution of arc voltage, arc current and electrode gap.

4. Experimental results – Assessment of the surface temperature

The temperature profiles were investigated for:

- an average arc current $I_{arc} \approx 70$ A
- arc durations dt in the range 3 ms - 4 ms
- various values of τ_{image} (40 μs, 200 μs, 500 μs and 1 ms) in order to observe the temperature decrease after the arc extinction and then to propose an assessment of the surface temperature at the instant of the arc extinction.

For each τ_{image}value about ten measurements were made.

Preliminary remarks:

- The choices of I_{arc} value and of the arc durations have been imposed by the present limitation in the camera calibration temperature range. For higher arc current intensity or for longer electric arcs, temperatures reached on the surface may be greater than the melting temperature.
- It should be emphasised that temperature distribution observed using thermal mapping can not show the heating resulting from the existence of microscopic structures such as fragments or microspots observed in [7] which have life durations equal respectively to 20 ns and 10 μs and a spatial size of some micrometers. Indeed, the exposure time of the infrared camera is quite greater than the life duration of these structures and the size of an observed pixel is quite greater than a microspot size.

In these conditions the temperature distributions obtained show only an average temperature distribution that may result from a multi spot intense heating that may be represented by the heating of a single macroscopic arc root [8].

In the first part temperature measurement for copper anodes are presented for different values of τ_{image} in the range 40 μs – 1000 μs.

The second part concerns results for copper cathodes and the third part concerns the assessment of the surface temperature at the extinction instant.

4.1 Results concerning copper anodes

4.1.1 Results for τ_{image} = 40 μs.

In this case $\tau_{exposure}$ = 50 μs (and $\tau_{activate}$ = 15 μs). In this case the mean arc duration was equal to 3.6 ms, the average arc current was equal to 68 A. The mean maximum temperature reached on the anode surface (T_{max}) was equal to 750 °C.

The values of arc durations and the average arc currents are quite close for all seven cases, however an important dispersion in the T_{max} values was observed. Different explanations may be proposed for that:

- images obtained with the high speed camera have shown that the arc mobility on the electrode surface (and the arc stagnation time) could be different from one electric arc to another one. Moreover, in two cases no stagnation time could be determined: the electric arc seems to move by jumps or continuously during all the arc duration.
- The arc current intensity at the switching off instant may vary from one arc to another between 48 and 62 A. This dispersion may also be due to the different arc behaviors.

Two surface temperature distributions are presented in figures 6(a) and 6(b). In figure 6(a) the electric arc was motionless some ms before the switching off. A single heated area is discernible. The temperature distribution is practically symmetric.

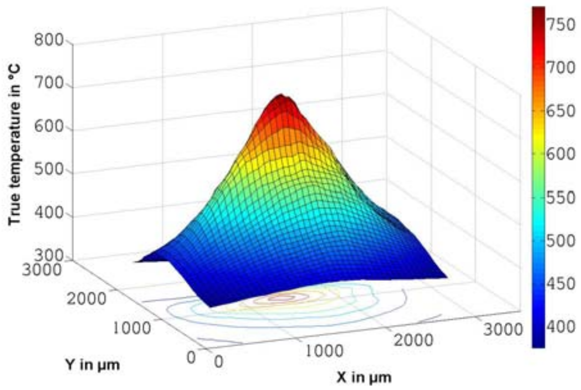

Figure 6(a). Example of surface temperature distribution (copper anode) in the case of a motionless electric arc.

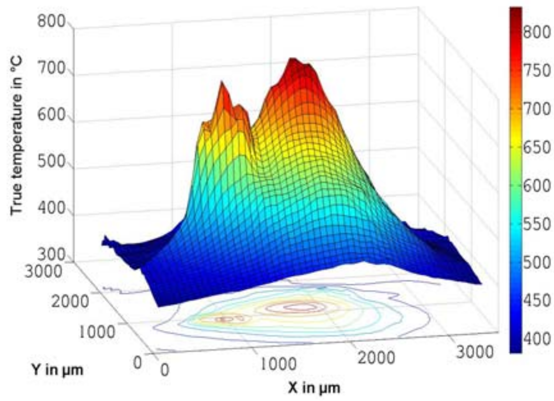

Figure 6(b). Example of surface temperature distribution (copper anode) in the case of a jumping arc root during the arc.

On the contrary in figure 6(b) the electric arc has moved just before switching off. Two heated zones are discernable. In the case of nearly motionless arcs (at the end of the arc), a typical profile of temperature taken along an arc root diameter is plotted in figure 7.
In all the observed cases, the temperature peak width for T = 500°C is less than 1.5 µm and for T = 600°C it is less than 900 µm. The maximum surface temperature gradient value obtained is around 440 °C/mm.

4.1.2 Results for τ_{image} = 200 µs
In this case $\tau_{exposure}$ = 50 µs (and $\tau_{activate}$ = 15 µs). In this case the mean arc duration was equal to 3.5 ms, the average arc current was equal to 72 A. The mean maximum temperature reached on the anode surface (T_{max}) was equal to 620 °C. In figure 8 a typical profile is plotted. The maximum surface temperature gradient value obtained is around 310 °C/mm.

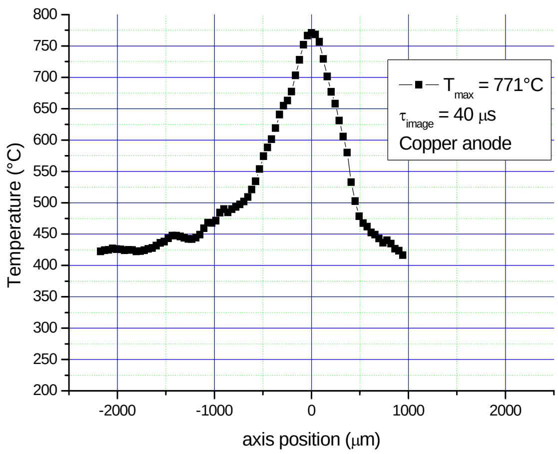

Figure 7. Typical surface temperature profile along the diameter of the arc root for τ_{image} = 40 µs. Case of copper anode.

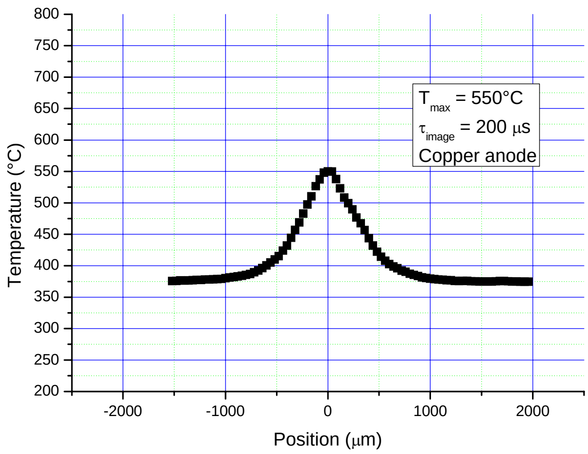

Figure 8. Typical surface temperature profile along the diameter of the arc root for τ_{image} = 200 µs. Case of copper anode.

4.1.3 Results for τ_{image} = 500 µs

In this case $\tau_{exposure}$ = 10 µs (and $\tau_{activate}$ = 15 µs). In this case the mean arc duration was equal to 3.5 ms, the average arc current was equal to 69 A. The mean maximum temperature reached on the anode surface (T_{max}) was equal to 398 °C. A typical value of the maximum surface temperature gradient value obtained is around 235 °C/mm.

4.1.4 Results for τ_{image} = 1000 µs.

In this case $\tau_{exposure}$ = 10 µs (and $\tau_{activate}$ = 15 µs). In this case the mean arc duration was equal to 3.7 ms, the average arc current was equal to 72 A. The mean maximum temperature reached on the anode surface (T_{max}) was equal to 322 °C. A typical value of the maximum surface temperature gradient value obtained is around 175 °C/mm.

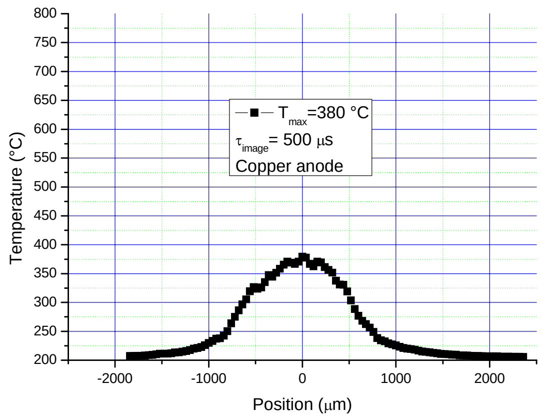

Figure 9. Typical surface temperature profile along the diameter of the arc root for τ_{image} = 500 µs. Case of copper anode.

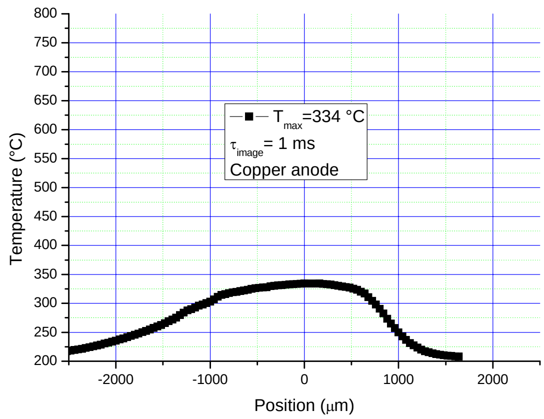

Figure 10. Typical surface temperature profile along the diameter of the arc root for τ_{image} = 1000 µs. Case of copper anode.

4.2. Results concerning copper cathodes

4.2.1 Results for τ_{image} = 40 µs

In this case $\tau_{exposure}$ = 50 µs (and $\tau_{activate}$ = 15 µs). In this case the mean arc duration was equal to 3.5 ms, the average arc current was equal to 63 A. The mean maximum temperature reached on the anode surface (T_{max}) was equal to 710 °C.

- Two examples of surface temperature distribution are proposed in figures 11(a) and 11(b) and two different typical temperature profiles along the arc root diameter are presented in figure 12. Two kinds of profile appear in the case of cathode: one is quite similar to the temperature profiles observed for anodes. In these cases, the maximum surface temperature gradients that have been observed may reach 580°C/mm.
- Another type of profile does not show a significant temperature peak, it is wider and has a “flat” top. That may be due to a continuous motion of the arc root on the cathode just at the end of the electric arc.

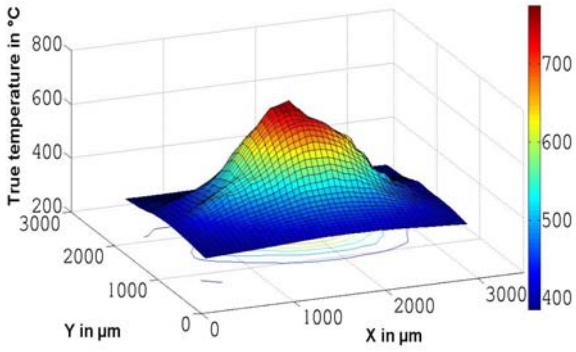

Figure 11(a). Example of surface temperature distribution (copper cathode) in the case of a motionless electric arc.

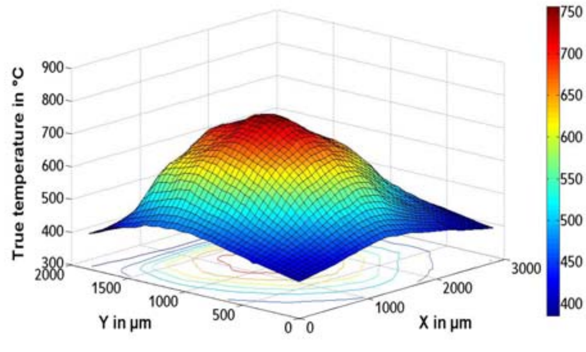

Figure 11(b). Example of surface temperature distribution (copper cathode) with flat top.

4.2.2 Results for τ_{image} = 200 µs

In this case $\tau_{exposure}$ = 50 µs (and $\tau_{activate}$ = 15 µs). In this case the mean arc duration was equal to 3.5 ms, the average arc current was equal to 71 A. The mean maximum temperature reached on the anode surface (T_{max}) was equal to 600 °C. In figure 13 a typical profile is plotted. The maximum surface temperature gradient value obtained is around 300 °C/mm.

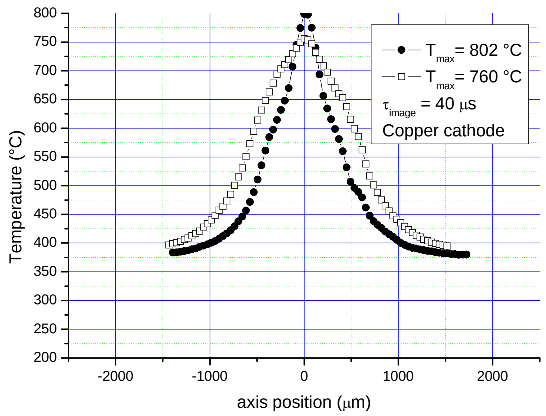

Figure 12. Typical surface temperature profiles along the diameter of the arc root for τ_{image} = 40 µs. Case of copper cathodes.

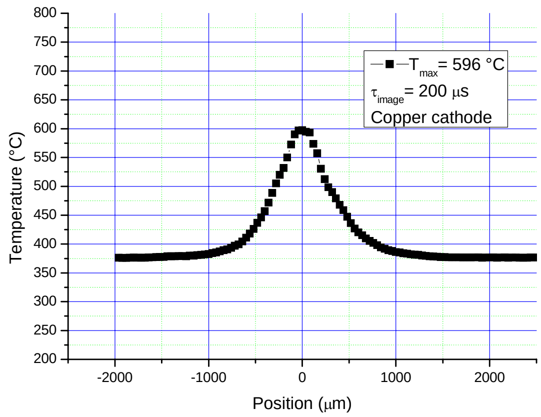

Figure 13. Typical surface temperature profiles along the diameter of the arc root for τ_{image} = 200 µs. Case of copper cathodes.

4.2.3 Results for τ_{image} = 500 µs.

In this case $\tau_{exposure}$ = 10 µs (and $\tau_{activate}$ = 15 µs). In this case the mean arc duration was equal to 3.5 ms, the average arc current was equal to 72 A. The mean maximum temperature reached on the anode surface (T_{max}) was equal to 375 °C. In figure 14 a typical profile is plotted. The maximum surface temperature gradient value obtained is around 180 °C/mm.

4.2.4 Results for τ_{image} = 1000 µs

In this case $\tau_{exposure}$ = 10 µs (and $\tau_{activate}$ = 15 µs). In this case the mean arc duration was equal to 3.6 ms, the average arc current was equal to 73 A. The mean maximum temperature reached on the anode surface (T_{max}) was equal to 330 °C. In figure 15 a typical profile is plotted. The maximum surface temperature gradient value obtained is around 130 °C/mm.

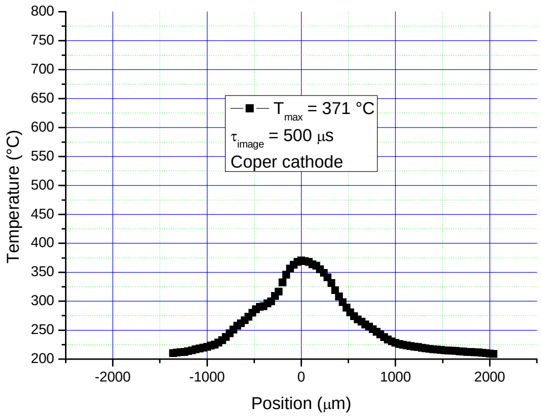

Figure 14. Typical surface temperature profiles along the diameter of the arc root for τ_{image} = 500 μs. Case of copper cathodes.

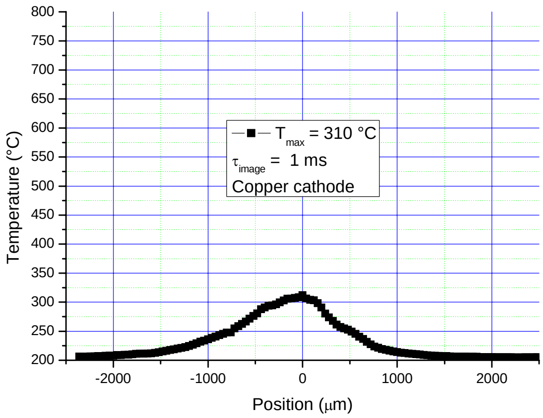

Figure 15. Typical surface temperature profiles along the diameter of the arc root for τ_{image} = 1000 μs. Case of copper cathodes.

4.3 Assessment of the surface temperature at the time of the arc extinction

Measurements made give the surface temperature 40 μs after the time of the arc extinction. With the help of the temperature evolution with τ_{image} it is possible to propose an extrapolation of the surface temperature and then obtain the surface temperature at the extinction time of the electric arc.

In figures 16 and 17 the evolution of the maximum temperature versus τ_{image} is plotted for anode and cathodes respectively. The dispersion is also presented. In [9] it has been shown that for a 1D problem and for very similar thermal conditions the temperature decrease with time was exponential. Two exponential fits have then also been plotted in these figures. They allow to reach an assessment of the surface temperature at the time of the arc extinction. A mean value of 815°C was obtained for copper anodes and 778°C for copper cathodes.

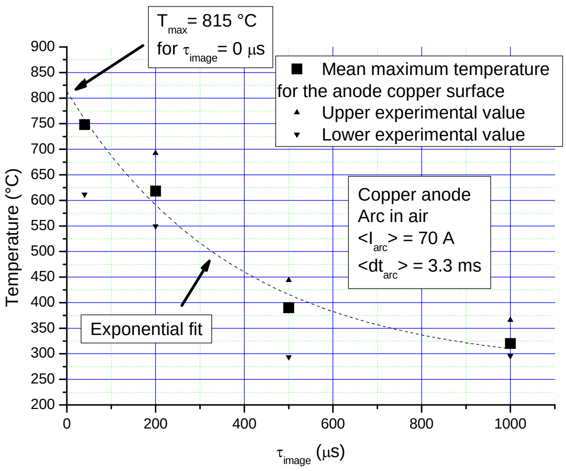

Figure 16. Evolution of the maximum surface temperature versus τ_{image} for a copper anode. Exponential fit of the curve and assessment of the surface temperature at the time of the arc extinction.

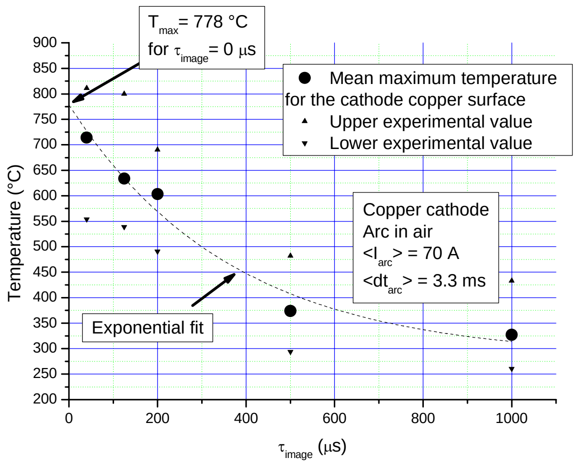

Figure 17. Evolution of the maximum surface temperature versus τ_{image} for a copper cathode. Exponential fit of the curve and assessment of the surface temperature at the time of the arc extinction.

It should be emphasized that the difference between the surface temperature at τ_{image} = 40 μs and τ_{image} = 0 μs may reach more than 50 °C.

5. Conclusions.

The aim of this paper was to obtain information concerning the surface temperature of copper anodes and cathodes submitted to a non stationary (average duration of 3.5 ms) electric arc burning in air at atmospheric pressure. For that the temperature distribution on the electrode surface was measured with a short delay of 40 μs after the arc extinction. The experimental method brought into operation presents several advantages:

- The IR camera may be used with short exposure times (between 10 and 120 μs)
- The duration of the switching off of the electric arc is forced and brutal (more than 200 A/μs).
- The IR camera may be precisely synchronized.

For such experimental conditions (non stationary arc in air, copper electrodes, …) it was then possible to obtain for the first time a temperature map of the electrode surface 40 μs after the arc extinction.
For copper anodes, only one sort of temperature distribution was observed and different types of temperature profiles appeared for copper cathodes. The observation made with the help of a high speed camera allowed to think that it was due to various arc behaviors (stagnation, jumps or continuous motions).
The measurement of the temperature distribution for different delays allowed also to propose by extrapolation an assessment of the temperature at the arc extinction instant. Maximum average temperatures of 815°C for the copper anode and 780°C for the cathode seem to be good assessments.

6. References

[1] J. Haidar and J D Farmer 1993 *J. Phys. D: Appl. Phys*. **26** 1224-1229
[2] J. Haidar and J D Farmer 1995 *J. Phys. D: Appl. Phys.* **28**, 2089-2094
[3] X Zhou, B. Ding and J. Heberlein, 1995 *Proc. Holm Conference* 219-231
[4] L. Dabringhausen, D. Nandelstädt, J. Luhmann and J. Mentel 2002 *J. Phys. D: Appl. Phys.* **35** 1621-1630
[5] J. Peters, F. Yin, C. F M Borges, J. Heberlein and C. Hackett 2005 *J. Phys. D: Appl. Phys.* **38** 1781-1794
[6] T. Klonowski 2007 PhD Thesis University Paris Sud 11
[7] B. Jüttner 2001 *J. Phys. D: Appl. Phys.* **34** R103-R123
[8] Ph. Teste, J. Rossignol, 2008 *J. of High Temperature Material Processes* **12** Issue 1 43-58
[9] Carslaw and Jaeger 1959 Conduction of heat in solids, Oxford University Press