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# EXPERIMENTAL CHARACTERIZATION OF THE INTERACTION BETWEEN A HIGH CURRENT ARC AND AERONAUTICAL MATERIALS

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## ABSTRACT

In this paper, we present the work realized on an experimental setup which simulates in laboratory the transient phase of a lightning arc applied to aluminum samples with different thicknesses and surfaces coating. A high current pulsed arc is utilized in this study, which has a peak value of 100 kA and a peak time to around 12  $\mu$ s. This device is instrumented with high speed video cameras to assess the geometric characteristics of the arc attachment on the material. The shock wave generated by the arc expansion is analyzed near to the surface material, using the Background-Oriented Schlieren method. The position and velocity of the wave front and the arc root radius are determined up to 70  $\mu$ s, when the lightning arc is applied to aluminum samples with different paint thickness. Finally, we perform comparisons with previous results of the hydrodynamic properties of a free arc channel subjected to the same levels of current, but without the material's interaction.

## 1. INTRODUCTION

Laboratory experiments of lightning effects on aeronautical materials indicate that numerous physical mechanisms are involved in the damaging process. During the 100kA peak current arc, the material is exposed simultaneously to hydrodynamic and magnetic forces, to high thermal fluxes, to Joule heating and to high electric field [1-3]. The material and the surface coating interact with the arc plasma, and some technical solutions have been developed in the industry to moderate these damages with an empirical approach. The phenomenology remains not well understood, and advanced experiments are required to get accurate information on the different aspects of the lightning constraints. We have designed and built an experimental setup to produce in laboratory high current waveforms that makes

possible the study of the arc plasma and also the test of new materials employed in aeronautics. One of the main goals of these experiments is to evaluate the thermo-mechanical constraints subjected on aeronautical materials during a lightning strike to aircraft. The historical reference material in aeronautical construction is aluminum, but nowadays, carbon fiber reinforced plastic (CFRP) came to replace this former generations and is massively used on the modern aircraft.

First experimental investigations of a pulsed arc with a current waveform of 100 kA peak utilized in lightning certification and four lower peak current ranging from 10 kA to 75 kA were performed in Ref. [3]. In this previous work, the hydrodynamic and electrical properties of the free arc column, without the interaction with the material were determined. The aim of the present work is to investigate experimentally the electric arc during the transient component of the lightning current waveform, focusing on the arc attachment. In this point, the interaction between the plasma and the material is very important and may vary depending on the material composition and the surface coating. A high current peak, which reaches 100 kA at about 12  $\mu$ s, is studied. The measurements will supply necessary database for comparison and validation of numerical codes for this category of high current pulsed arcs. First we described the current generator and the optical diagnostics employed in this work. In section 3, the different measurements and results are presented, discussed and compared to previous studies of a free arc channel.

## 2. EXPERIMENTAL SETUP

The high current arc studied in the present work is produced in laboratory in accordance with the criteria imposed by aeronautics standards, as defined in the document SAE ARP 5416 [4]. The current generator

is described in more details in Ref. [3]. Concisely, it is formed by four capacitors of 50  $\mu\text{F}$  each, connected in parallel, which discharge through a series of ballast resistors. The switching is performed by a spark gap and the generator is designed in an approximated coaxial structure, having the current flow on the central axis of the structure and the current return realized by four symmetric aluminium bars. One electrode is formed by a tungsten rod on which a dielectric sphere is fixed at its tip. This is commonly called jet diverter electrode. The other one is formed by a square panel of 400 mm side and corresponds to the material under test. The air gap between the electrodes is 60 mm. In order to reduce the working voltage, the arc is ignited with a thin carbon wire with diameter of a few micrometers. The ignition wire is fixed at the center of the square panel and on the jet diverter electrode at the junction between the tungsten rod and the dielectric sphere. For every shot, the wire is carefully aligned and fixed at the same location, to ensure repeatability of the experiment.

Non-intrusive approaches, as optical diagnostics are commonly used for plasma characterization. We have chosen to employ high speed video cameras to analyze the arc attachment point shape and to characterize the shock wave propagation. Figure 1 present the schematic diagram of the arc attachment point and shows the viewed area by each camera. The cameras were placed in a perpendicular direction to the arc channel axis, having a grazing angle with the material surface. A patterned background is placed behind the channel to allow the background-oriented schlieren (BOS) measurements. A third camera is configured to a wide view and is used to observe both electrodes and the whole arc column. The three high speed cameras (HSC) employed in this work are Phantom V711 from Vision Research, which have a CMOS sensor of  $1280 \times 800$  pixels with a pixel size of 20  $\mu\text{m}$ . The HSC can work up to 1.0 Mfps at reduced resolution of  $128 \times 16$  pixels and allows us to set the exposure time to a minimum of 300 ns.

The high current waveform utilized in this work are identical to this presented in [3]. It corresponds to the D-component of the lightning wave sequence. We show in figure 2 the average of the current waveforms created by the generator computed for 10 shots. A similar repeatability was found for over more than 50 tests and the standard deviation of the current remains always lower than 0.3 kA. On average, we obtained current peak of 100.2 kA, maximum growth rate of  $21.6 \text{ kA} \cdot \mu\text{s}^{-1}$  and action integral of  $0.28 \times 10^6 \text{ A}^2\text{s}$ .

The aeronautical material examined in this work is made of aluminum. Two different panel thicknesses are studied, with widths of 1.0 mm and 1.6 mm. Generally, for aeronautics purposes, the material has to be coated by paint or other kinds of protections

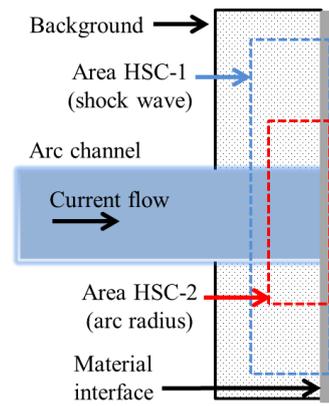


Fig. 1 Side view of the arc attachment point. Area of collection for the two high speed cameras (HSC).

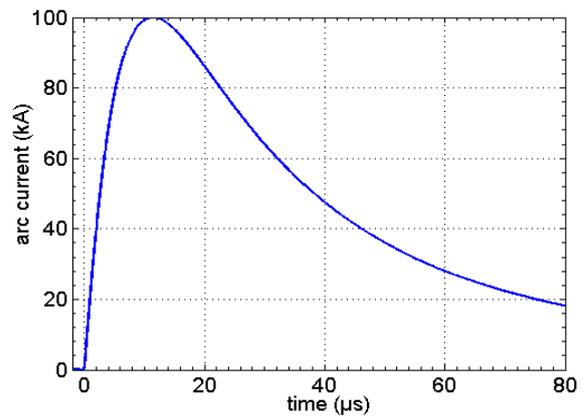


Fig. 2 Average of the measured current waveform produced with the current generator.

layers. In order to analyze the influence of the paint thickness, four category of surface coating are studied; unpainted aluminum panels and with 100  $\mu\text{m}$ , 300  $\mu\text{m}$  and 500  $\mu\text{m}$  of paint thickness. The paint corresponds to standard ones utilized in aeronautics and has an accuracy of 5  $\mu\text{m}$ .

### 3. RESULTS AND DISCUSSION

Arc plasmas in ambient air are generally highly luminous and suitable for observation and characterization by fast imaging. Both qualitative and quantitative information can be obtained from the analysis of images and intensities profiles [1, 3]. Working with a reduced pixel resolution of  $256 \times 32$  pixels, we are able to perform faster imaging up to a rate of 500 kfps. The exposure time was set to 300 ns, and neutral filters were also used to avoid saturation. We observed that the attachment point starts around the ignition wire and develops as a symmetrical form, which reaches a radial position of several centimeters. Figure 3 shows an example of a picture obtained working at a resolution of  $256 \times 96$  pixels, which allows us to observe the electrode's configuration and the homogenous column formed in the central region.

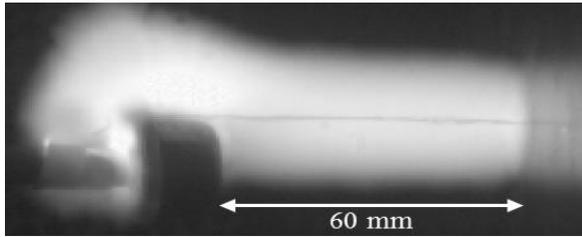


Fig. 3 Example of arc picture taken at 15  $\mu\text{s}$  after the current triggering. The jet diverter electrode is located on the left-hand side and the aluminum panel is on the right-hand side (resolution: 0.46 mm/pixel; exposure time: 0.3  $\mu\text{s}$ )

Close to the material surface an axisymmetric shape of the attachment point is also observed. Figure 4 shows examples of pictures of the arc close to the material surface (see figure 1), using a camera resolution of  $256 \times 32$  pixels. The symmetrical shape of the arc root is observed, but, the region near to the material surface seems to increase lower than the arc channel.

We can assume that the luminous radius is a good approximation of the conductive radius of the arc. In order to define the arc radius root based on the intensity profile measurements, two criteria were tested. The first one was to find the position of maximum rate of change of the intensity for each profile side. The second was to use a threshold of 20% of the maximum intensity of all images from a shot. Both criteria lead to approximately the same results, with a maximum variance of 0.6 mm. Analyzing the radial profiles for each image at 1 mm from the material surface, we can deduce the evolution of the arc root radius versus time as presented in figure 5. Generally, for the different panels and paint thickness, the arc root radius has a similar shape during the first 18  $\mu\text{s}$ , following the evolution of the free arc column. From this time, the

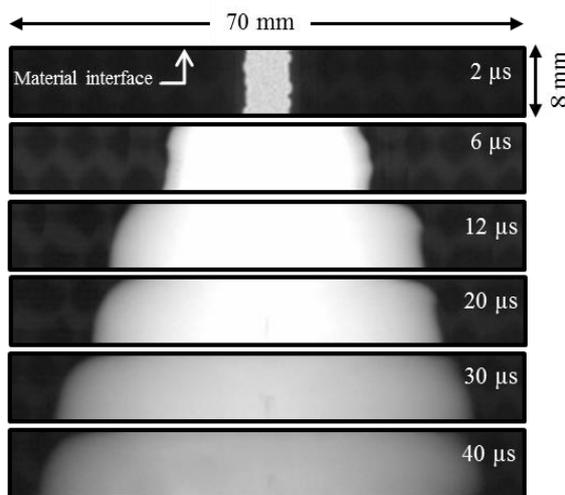


Fig. 4 Pictures of the arc attachment point evolution over time applied to an unpainted aluminum panel (the material surface is located on the top of each picture).

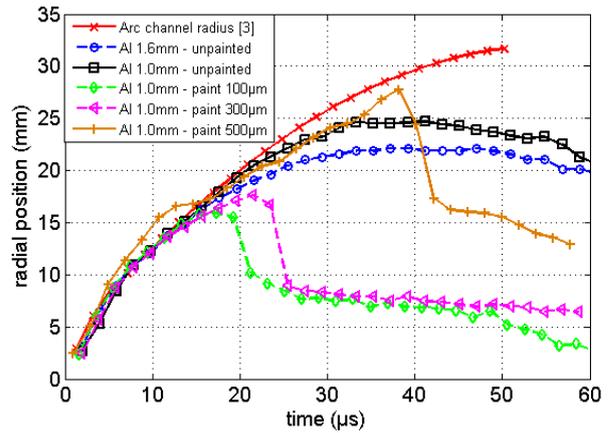


Fig. 5 Evolution of the arc root radius and the radius of a free arc.

arc roots increases slower than the arc column, and is also reduced as the aluminum thickness changes from 1.0 mm to 1.6 mm for the unpainted panels. For the panel with paint, there is abrupt reduction of the arc root radius during the expansion phase of the arc column. This is probably related to the constriction of the current streamlines in the small surface where the paint is vaporized. As the paint thickness increases, the maximum radius reached by the arc root also increases. The time for this rapid decreasing also changes, changing from 20  $\mu\text{s}$  for the 100  $\mu\text{m}$  paint to 38  $\mu\text{s}$  for the 500  $\mu\text{m}$  paint.

The fast increase of the temperature in the channel arc leads to the propagation of a strong shock wave in the radial direction of the arc. This shock wave exhibits a strong discontinuity of the mass density which makes possible the use of schlieren techniques. This technique is a well-known method to visualize density gradients in compressible media. It is based on the refraction of light crossing a media with variable refractive index. Among different schlieren methods, the background-oriented schlieren (BOS) was selected due to the high luminous intensity of the arc plasma. This method allows refractive matters to be visualized by their distortion of a patterned background [5].

The BOS camera was placed in a perpendicular direction to the discharge axis, at the same point of view of the light intensity measurements camera (see figure 1). Figure 6 shows some pictures of the shock wave propagation when the arc is applied to a painted aluminum panel. The images are purposely saturated in the arc channel to allow the collection of enough light from the background. We can identify the position of wave front by the detection of the changing patterns of the background squares. For the detection purposes, we used the difference between the image to be analyzed and a reference image, taken without arc. Starting from the farthest position from the center, for each side of the axis, the position of the first high gradient in the intensity variation is defined as the wave front.

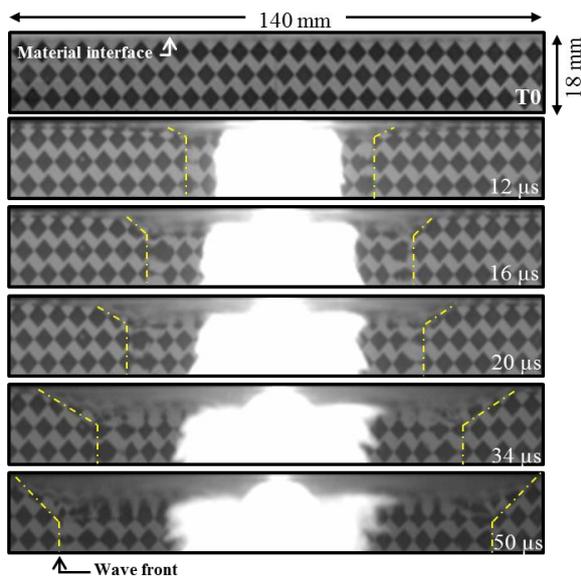


Fig. 6 Pictures of the shock wave propagation for the case of painted panels.

For the cases of the unpainted panels, the shock wave is transverse to the arc channel and has a cylindrical shape, which is very similar to those induced by a free arc column. Nevertheless, for painted panels, an additional shock wave superimposed to the main shock appears from the arc attachment point, which seems to propagate in the oblique direction, starting from the material surface as can be seen in figure 6. Due to the quasi-spherical shape of the wave front, this second shock wave could be interpreted as the result of a punctual energy deposition on the arc root, which seems to be more significant for the case of painted surfaces than compared to unpainted ones.

Figure 7 shows the average measurement of the wave front position of the cylindrical shock wave, for the different material and paint thicknesses. The measurements over different shots give a very good repeatability. The maximum deviation found was 1.3 mm, by using three shots for each type of panel. Comparing the results obtained from the curves shown in figure 7 to the arc root radius of figure 5, we can see that the time of detachment between the

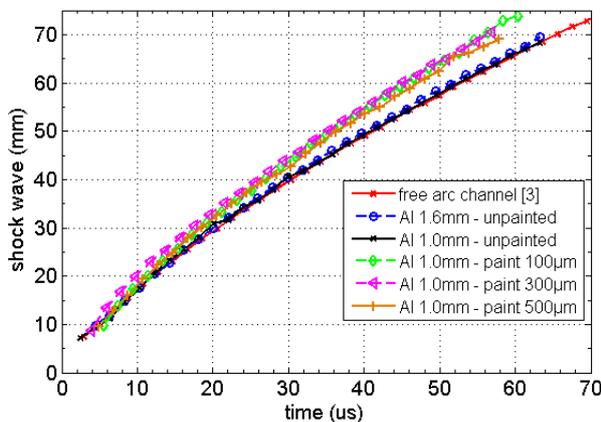


Fig. 7 Shock wave position for different paint thickness.

plasma and the shock wave is near  $6 \mu\text{s}$  for all tested material and for the free arc channel. While the arc channel radius increases approximately as square root function of time, the shock wave propagates faster in an almost linear shape. The results of the wave front position for unpainted panels have a very good agreement with those of shock waves generated by a free arc channel. However, the cylindrical component of shock waves induced using painted panels propagates faster, and reaches 70 mm at  $56 \mu\text{s}$ , while for the free arc column this radius is reached at  $65 \mu\text{s}$ .

#### 4. CONCLUSION

An experimental investigation of a high current pulsed arc applied to different aeronautical materials was performed. A configuration allowing the study of the effects of different materials thicknesses and surfaces coating in the arc attachment point was implemented. High speed imaging has allowed us to assess the temporal dynamics and the spatial form of the arc roots. The measurements of the characteristic lengths, as the shock wave and the arc root radius, have been made over time up to  $70 \mu\text{s}$ . The presence of the material reduces the arc root radius, when compared to the evolution of a free arc column. The paint impacts the arc root evolution, causing an abrupt reduction in the radius, after a few tens of microseconds. The maximum root radius is also influenced by the paint thickness. For unpainted panels, the shock wave close to the surface materials is cylindrical and its evolution is identical to those induced by a free arc channel. For painted panels, the shock wave spreads faster and gives rises to an additional quasi-spherical wave front, which is centered at the arc root.

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