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Study of the interaction of a free burning arc and an aluminium panel

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ABSTRACT

We developed at ONERA a 400 A dc current generator at a voltage of 1600 V to analyse the free burning arc interaction with a material for lightning applications. This voltage allows the generation of a long arc with a channel length ranging from 10 to more than 40 cm in some cases. With this experiment we studied the interaction of a generated arc root and a material under test; aluminium in this study. In particular, we focused on a regime exhibiting a stable plasma jet ejected from the panel. The aim is to gather experimental data to perform a comparison with previously published numerical results showing a similar behaviour [1]. In a first part, we present the experimental set-up namely the generator, the ignition method of the arc and the experimental set-up. In a second part we describe the results obtained on the plasma using fast imaging (100 kHz) and fast emission spectroscopy (10 kHz). In a third part we use fitting methods on the emission spectra and deduced electronic temperature. Finally, the presence of some magnesium metallic lines due to the vaporisation of the panel is discussed.

1. INTRODUCTION

Lightning induced heat and erosion to the material it strikes. Those damages are called lightning direct effects since the cause is directly the lightning current and not the induced current. Direct effects are especially an issue in the case of composite materials. Despite protection and studies, lightning is still a threat to aircraft and its effects need to be modelled and eventually predicted. SAE International Recommendations [2] advises several current waveforms: A, B, C and D, and a configuration to certify structures against the different phase of a lightning strike. The configuration is composed of two electrodes, one being a sample of aircraft fuselage, in our case a 40 cm large square piece. The other electrode is a tungsten rod with a dielectric piece placed on the tip. This piece is called the ‘jet diverter’ and is used to avoid influence of the electrode’s shape.

In order to understand this type of discharge, test different materials and validate our MHD code [1, 3], we designed and built a setup and a generator to produce a 100 kA pulse current waveform (D), a 4 kA pulse current waveform (B) and a 400 A DC current waveform lasting 0.5 s (C). This setup is used on aeronautic materials, and results on a 100 kA arc have already been published [4].

Among the different diagnostics used to study electrical arc and lightning in particular, optical emission spectroscopy (OES) allow to measure electronic temperature and density. For the study of welding arcs, we can mention the works of Ma et al. [5], and, for the investigation of circuit breaker, we can refer to Ratovoson et al. [6]. These works employed the Boltzmann plot method as well as other technics based on similar equations. Measurement of the Stark broadening of different line is also used to determine the electronic density. But all these methods require an optically thin plasma hypothesis and, for reliable results, well isolated and resolved lines, which is a difficult task when working in hot air plasmas. Moreover, in the case of not reproducible pulsed arc, a maximum of data need to be gather in a single shot. In a recent paper, Uhrlandt et al. [7] used high speed camera to gather spectroscopic data on their discharge and compare those results with fitted spectra obtained using an ICCD camera. High speed camera (HSC) are not as sensitive as ICCD camera and their spectral response is not as flat but since arc discharge emits so strongly, HSC is an excellent tool for arc applications. This is the reason why we use multiple HSC in this study focusing on an arc interacting with an aluminium panel. First, pictures of the arc gathered by an HSC are study and the arc radius is deduced. Second, OES measurements are used to measure the arc temperature along a line of sight using a fitting method.

2. EXPERIMENTAL SETUP

The test stand designed is presented in figure 1 and can be divided in three parts. A first part is the test area with two electrodes as described in figure 2.
Fig. 1 Pictures of the test stand, generator on the left and firing area on the right.

Fig. 2 Schematic of the electrodes and the diagnostics.

Fig. 3 Pictures of an arc for several moments with an exposure time of 10 µs.

The arc is produced between a jet diverter and the grounded sample under test. In this study, a panel of aluminium 1.6 mm thick is used. It is composed of 95% Al, 4% Cu and 1% Mg. The distance between the jet diverter and the sample is 8 cm. The second part is an RLC discharge generating a 4 kA pulse current waveform. The final part is a buck converter generating 400 A during 0.5 s but for this study and to avoid unnecessary damage to the sample, we purposely limit the duration to 50 ms. Both generated current waveform (Impulse and DC) are defined in SAE specifications [2]. The charging voltage for both generators is 800 V. To ignite this 8 cm electrical arc with only 800 V, a small carbon fibre is used to short-circuit the gap. This fibre is vaporised at the beginning of the test and do not interfere with it.

A Pearson current transformer (1330) is used to measure the current of both pulse and DC current waveform. Since the DC component last too long and a drift is observed on the current transformer after 10 ms, a shunt resistor is used to measure the DC component during the full 50 ms of the shot. For the OES measurements, we use an Acton SP-2750 spectrometer with 750 mm focal length, mounted with a grating of 300 grooves/mm, blazed at 500 nm. The entrance slit aperture is 50 µm yielding to an FWHM slit function of 0.2 nm. The HSC used to acquire the spectra is a Phantom V711 from Vision Research, which has a CMOS sensor (1280 × 800 pixels of 20 µm²). The HSC is set to work at 10 kfps with an exposure time of 100 µs. An optical system composed of two achromatic lenses is coupled to a fused silica optical fibre connected to the spectrometer.

3. RESULTS

Using the HSC, we obtained the pictures presented in figure 3. At 0 µs, the fibre is vaporised and an electrical arc is generated between both electrodes. At 500 µs, we observed an explosion; the arc channel and the arc root reach their maximum radius as shown in figure 4. The remaining pictures at 5 and 30 ms demonstrate that after a few ms and during the DC component, a stable plasma jet occurs perpendicular to the aluminium panel. This hot jet plasma was simulated by Chemartin et al. [1] and their obtained arc diameter was 1 cm, which is similar to our 7-8 mm.
For the OES, we choose a spectral range according to the relative line intensity as a function of temperature available on NIST [10]. From these data we performed a study of the lines with high intensity variation with temperature which led us to the nitrogen ionic lines around 567 nm. Using the grating of 300 grooves.nm$^{-1}$ we were able to record a spectral window of 100 nm as seen in figure 5. Since copper and magnesium are also present in our sample, we also focused with the same spectral range on the Cu I and Mg I lines around 520 nm. N II immediately appear after the ignition and quickly disappear whereas Mg I only appear after several ms. Cu I was not observed even if its lines have similar transition strength as for Mg I lines. Concerning the damage taken by the panel, it was punctured during the shot but the melting pool close the hole when it solidified. Moreover, strong Mg I lines at 517 nm appear after a few milliseconds (figure 6) and for some reason the strong Cu I lines at 515 nm are not present even if the proportion of copper is more important compared to magnesium. One possible reason is a lower boiling point for magnesium (1090°C) compared to copper (2562°C).

4. DISCUSSION

In order to fit the spectra with N II lines and to deduce an electronic temperature, we calculate the absorption coefficient of each line and solve the radiation transfer equation along our line of sight. We assume that the arc column is homogenous, cylindrical and at local thermodynamic equilibrium (LTE). This is often the case for electrical arcs, which are dense and highly collisional plasma. Under the LTE assumption and using the Kirchhoff’s law, the absorption coefficient, can be written as:

$$\kappa(\lambda, T, N_e) = \frac{1}{\sigma^2} \sum_{\text{line}} \frac{h c}{\lambda_{\text{line}}} \frac{A_{ul}^{*}}{Q(\lambda)} e^{-\frac{E_u}{k T}} \int \lambda (\lambda - \lambda_{\text{line}}, T, N_e)$$

where $\sigma$ is the Planck function, $h$ and $k$ are respectively Planck and Boltzmann constants, $c$ is the speed of light, $E_u$ and $g_u$ are respectively the energy and the degeneracy of upper transition level, $A_{ul}^{*}$ is the Einstein emission coefficient for the transition from upper to lower level, $N_e$ is the total population of the radiating species, $Q$ is the partition function, $\lambda_{\text{line}}$ is the central wavelength of the transition and $f$ is the spectral line shape of the transition. With the approximation that the electronic density is high in an electrical arc, the broadening of the lines is assumed to be mainly due to Stark effect thus the line profile is Lorentzian. For the considered N II lines, the spectroscopic constants in equation (1) were taken from the NIST database [10]. The internal partition functions are calculated using the energy levels and the degeneracies from the NIST energy levels. The FWHM Stark as a function of the electron density and the temperature is obtained from linear extrapolation in the tables compiled by Konjevic et al. [11]. To obtain the population of each studied species we used the LTE air plasma composition, calculated by Chauveau et al. [8-9] under chemical equilibrium.

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**Fig. 4** Current and radius measurement for the pulse and DC component.

**Fig. 5** Spectra at 1 ms and 30 ms after the trigger.

**Fig. 6** Maximum intensity of the N II line and Mg I line as a function of time.
The radiative transfer equation is only a function of the absorption coefficient and the length of the line of sight. For each instant considered, this length is obtained from the arc channel radius (figure 3). The total absorption coefficient is calculated from equation (1) added to a linear term, $AA + B$, to model the continuum contribution. A calculated spectrum is obtained by a convolution of the radiative intensity (obtained from the radiative transfer equation) and the spectrometer slit function.

Figure 7 presents a fit using our method. Even if some carbon lines from the ignition wire are present, the residue of each fit was reasonable. A comparison between the current and the calculated temperature is presented figure 8. This temperature measurement is an average over a line of sight and thus is not really accurate, it is comparable to a temperature of 20 kK for a 400 A dc arc as given by Chemartin et al. [1]. After 5 ms, the signal to noise of the N II lines was too small for our method to be accurate.

5. CONCLUSION

In this study, we used a new generator to produce a 10 cm arc of 4 kA peak followed by a continuous current of 400 A during 50 ms. We performed high speed imaging and high speed spectroscopy on N II lines from 540 nm to 600 nm. Regarding the use of high speed camera compare to ICCD camera, the later one is more sensitive and allows much shorter integration time. Despite this, the HSC can be used with success in many electrical arc applications even coupled to a spectrometer that will drastically reduce the light intensity received by the camera. Using a fitting method on N II lines based on the calculation of the absorption coefficient and the solution of the radiative transfer equation, we obtained the plasma temperature during the first milliseconds. After this initial period, metallic lines appear and a plasma composition of air including metallic species is necessary to apply our method. This will be the subject of future studies.

REFERENCES
