Modeling of Lightning Direct Effects – Interaction of Continuing Current with Aluminum Skins

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Abstract: An interaction of aluminum aircraft skins with laboratory-simulated, low-level, long-duration, continuing current component C representative of a natural lightning flash (per ARP 5412) was modeled with COMSOL Multiphysics. The goal of this paper was to demonstrate the ability to model a melt-through or hot-spot formation caused by the continuing current and testify that such modeling can match the damage caused by high-current direct effects testing. For this paper the analysis was limited to six cases: 200 C of charge transfer at 50, 200, and 500 A of current average levels of amplitude in 0.028/0.050"-thick bare 7075 aluminum sheets. The melt-through areas were documented. Time-dependent, electrical current steady-state Joule heating analysis was conducted initialized by an ideal rectangular waveform. The model was solved for the final temperature distribution from which the melt-through areas were estimated. Experimentally obtained and simulated damage areas were comparatively analyzed.

Keywords: Aircraft, lightning, aluminum skin, direct effects, continuing current.

1. Introduction

Natural lightning is a probabilistic transient high-voltage, high-current phenomenon and may occur as a result of strong electric fields present in the atmosphere with the purpose to restore the atmospheric equilibrium via an electrical discharge.

An aircraft in flight is vulnerable to lightning strike and, if not properly protected, may result in a catastrophic event. However, if it is struck, the different surfaces of the aircraft will experience various levels of damage produced by lightning; therefore, in order to design a proper electrical protection and for certification purposes, the aircraft surface is conditionally subdivided into the lightning zones. Aircraft external environment is characterized by the idealized voltage waveforms and current waveform components which represent the important characteristics of natural lightning (1). Components are grouped into certain sequences to constitute zones and, thus, define different levels of severity produced by lightning.

The choice of protection against the direct effects of lightning is typically decided upon according to the physical testing of the aircraft skin materials. Particularly, the high-current testing based on the combination of current components A, B, C, and D is employed to predict materials response to different lightning zones.

This work focuses on the analysis of the severity of damage inflicted by the continuing current with the characteristics of Component C in bare aluminum skins. Component C represents the long duration currents and is typically expressed as a rectangular waveform of 200-800 A average current amplitude level with durations of 0.25-1 seconds to transfer 200 C (±20%) of charge (2). The typical damage may result in a melt-through or hot-spot formation that can manifest into fuel ignition in metal skins depending on material's thickness, electrical conductivity, and surface finish.

Previous work demonstrated that a linear relationship exists between the amount of charge transferred and the metal melted away, although, the melting effects are also dependent on current amplitudes, and the rate of charge transfer may be a decisive factor in determining the damage, however, the nature of this dependence is not intuitive. Moreover, due to insufficient experimental work large amount of data is extrapolated (3). It has been also emphasized that the peripheral damage and overheating around the damage area cannot be neglected; moreover, the electrode polarity during the high-current testing could be important (4). An analytical expression relating the constant coulomb amount to the melt-through area has been empirically derived (5), however, no attempts have been undertaken to model the physics of the process to develop a model capable to predict the damage.

The objective of this work was to develop an analytical model based on the physics simulation environment offered by COMSOL Multiphysics. Ideal rectangular waveform input parameters were employed to investigate whether a close match with the non-ideal test conditions is possible and damage is predictable. The present study was reduced to examination of six cases: 200 C of charge transferred at 50, 200, and 500 A amplitude levels for 0.028” and 0.050” bare aluminum sheets.

2. Methods

The high-current direct effects testing was conducted on 20”-square bare 7075 T6 and T7 aluminum sheets with nominal 30-40 % IACS conductivity range. The current to the test articles was supplied by a 1450-volt DC battery bank (LTI, Pittsfield, MA). The amount of charge transferred was controlled by a fuse link (Cooper Power Systems) and/or electronic timer; the amperage was adjusted with the circuit resistance and inductance. Test panels were sandwiched between thick aluminum frames held by the spring-clamps and grounded to the return path of the generator (Figure 1). A thin aluminum arc-initiating wire was attached to the electrode tip and positioned in the middle of the panel with a paper tape to minimize the arc wandering. Depending on the current amplitude, the length between the panel and electrode was varied within 3/8-2 inches; no jet diverting insulating sphere was used. Current was monitored with the T&M Research F-1000-4 current viewing resistor (shunt); the resistive voltage divider was used to collect the V-t characteristics.

The test articles were subjected to 50, 200, and 500-ampere current amplitudes to deliver 200-coulomb charge at each level of amplitude. Two panel thicknesses, 0.028” and 0.050” were studied. The surface of panels was specially prepared via scuffing and solvent cleaning to insure the elimination of any insulating contamination. The choice of panel thickness was dictated by the typical aircraft skin thicknesses comprising 0.020-0.060” and 0.050-0.080” ranges. The diameters of the melt-through were measured and areas calculated.

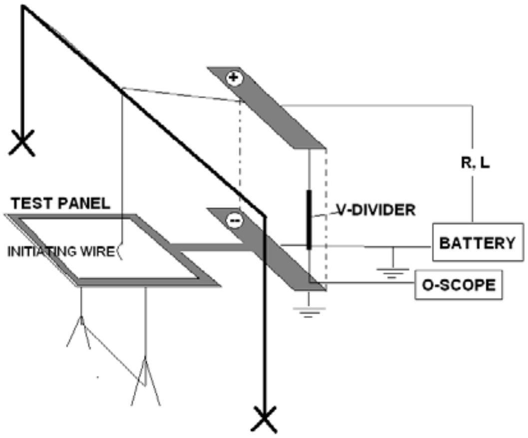

Figure 1. Schematic of the high-current test set up.

3. Experimental Results

The experimental waveforms and damage areas are summarized in Table I. Examples of damage resulted from the high-current test on aluminum panels are shown in Figure 2.

Table 1: Characteristics of the current waveforms due to 200 C charge transfer at 50, 200, and 500 A current amplitudes.

Panel	Charge, C	Time, s	I_{avg}, A	Damage Area, inch^2
0.028”				
500 A	232	0.46	508	1.8
200 A	232	1.1	214	1.2
50 A	206	3.6	56	0.7
0.050”				
500 A	234	0.45	515	0.4
200 A	232	1.1	216	0.6
50 A	206	3.6	56	No melt-through, traces of re-solidification

4. Use of COMSOL Multiphysics

A 3D steady-state Joule heating analysis was used to compute the coupled electrical-thermal interaction and obtain a solution for the final time temperature distribution. The system of governing equations is described by:

$$-\nabla \cdot \left(\sigma \nabla V - \vec{J}^{\,e}\right) = Q_j$$

$$\nabla \cdot \left(-k \nabla T\right) = Q + q_s T$$, where

σ - electrical conductivity,

V - electrical potential,

$\vec{J}^{e}$ - externally generated current density,

Q_j - current source,

k - thermal conductivity,

Q - heat source,

q_s - production/absorption coefficient,

T - temperature.

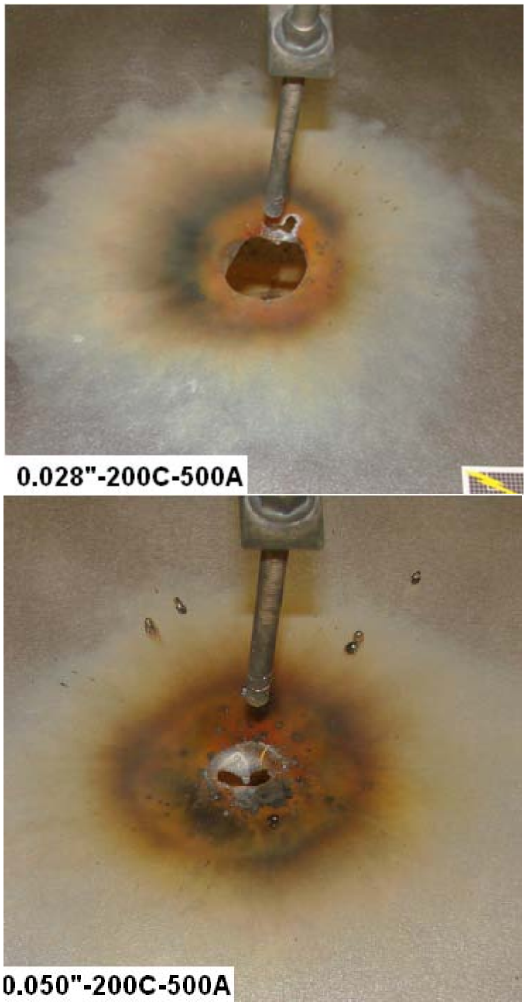

Figure 2. Photographs of the damage areas caused by continuing current in thin (top) and thick (bottom) aluminum sheets: 200 C charge at 500 A average level of amplitude.

Model description: the geometry constituted a 0.028”/0.050”-thick 20”-square panel placed in between two ground frames of identical size with an 18”-square cut out. A 0.002” radius arc current attachment point was created in the middle of the panel. Aluminum material properties were used for all pieces with 30 % IACS for the thin and 40 % IACS for the thick panels (due to the difference in temper). The dependence of material conductivity on temperature was not taken into account. Heat transfer, Joule heating application mode was used for analysis. The frames were set at a ground potential and a high potential was assigned to the attachment point. The high potential was set to inject the current waveform based on V=IR. An ideal rectangular, time-dependent current waveform (created in the study section) was characterized by the average current amplitude (50, 200, and 500 A) and time to transfer 200 C of charge. Resistance of the object under the initial conditions was required to determine the voltage potential: the values of 2 mΩ for the thin and 1.5 mΩ for thick panels were used. The heat transfer coefficient of 25 W/m^2K was used for the aluminum-air heat transfer. Extremely coarse free tetrahedral meshing was applied to solve the finite element model. The model was solved for temperature at the final time.

5. Discussion

Examples of the final temperature distributions simulated in COMSOL are shown in Figure 3. The darkest red areas in the middle correspond to 660 deg C which is the melting point of aluminum, thus, based on the magnitude of these areas, the melt-through dimensions were determined for all specimens. The simulated areas in Figure 3 can be directly compared to the areas in Figure 2 from the high-current testing. It should be noted that in the 0.050”-200 C-50 A specimen no melt-through was produced by the arc, however, the traces of re-solidification were noticeable – the event was substantiated by COMSOL results where the final temperature at the attachment reached only 300 deg C.

The damage areas in thick and thin aluminum sheets as a result of high-current testing and COMSOL simulations are compared in Figure 4. A logarithmic dependence between the melt-through area and the rate of charge transfer at constant 200 coulomb contents was predicted by simulations. However, a perfect match based on the currently proposed model was not obtained due to a number of reasons.

First, formation of the imperfect ellipse-shaped damaged areas with irregular boundaries was observed which caused difficulty in measurement of exact dimensions resulting in approximate values of experimental damage areas – a more exact method is required. It is unclear at this point whether the rough periphery can also be simulated with COMSOL.

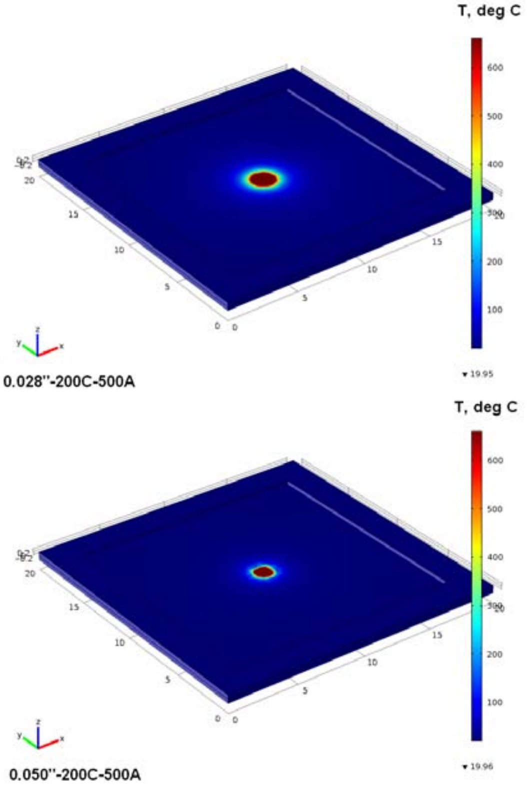

Figure 3. Final temperature distribution simulated in COMSOL (the axes units are in inches). The red areas represent the areas of the damage.

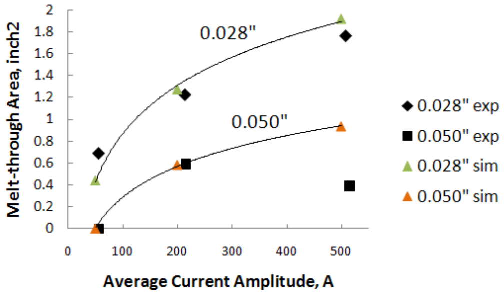

Figure 4. Dependence of the experimental and simulated melt-through areas on the average current amplitude for the 0.028” and 0.050” aluminum.

Second, there is an obvious deviation of the 0.050”-200 C-500 A experimental point from the logarithmic dependence (Figure 4). The discrepancy is possibly due to the atypical evolution of the arc development with respect to the process of material’s damage (compare Figure 5 to Figure 6). Examination of the arc-damaged area in the specimen revealed an unevenly-oval burned out area consisting of two partially-connected adjacent circles (Figure 2). Referring to the voltage waveform (Figure 5), the initiation of the arc formation process is due to the voltage breakdown which corresponds to the first spike in V-t; subsequent fluctuations of voltage are caused by the changing conditions at the cathode: heating, melting, and burning away the material’s surface and lengthening of the arc. In the middle of the waveform, however, additional spikes are present due to a possible arc reattachment to a new location followed by the moderately steady voltage while melting more material. A gradual current decrease in I-t oscillograms is also caused by the changing arc length and its increasing inductance.

Third, no dependence of electrical resistivity of aluminum on temperature was considered in the model. It also appears (Figure 4) that a thinner material is more susceptible to the inflicted damage and will require consideration of the additional minute nuances in modeling to generate a better correlation. Additional experimental data is required to gain statistical significance and establish reliable standard deviation and error margins.

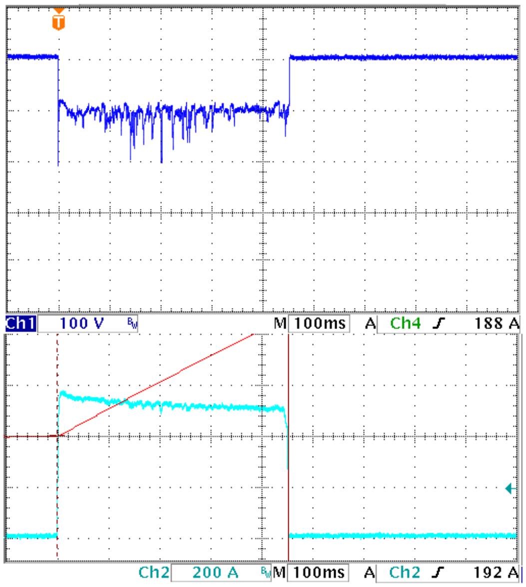

Figure 5. Voltage (100 V per division) and current (200 A per division) experimental waveforms for 0.050”-200 C-500 A panel.

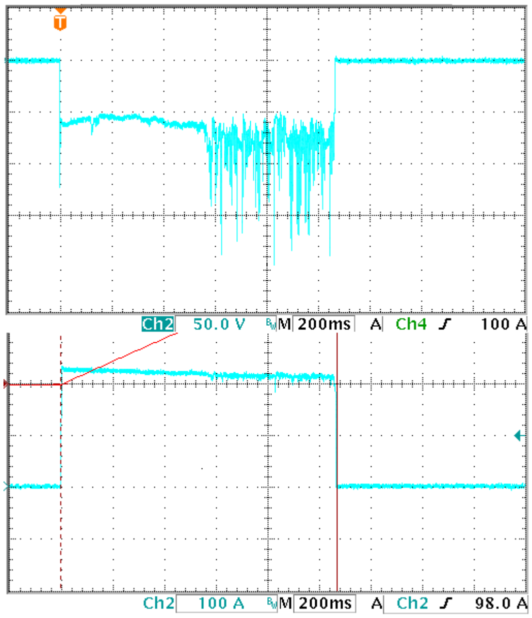

Figure 6. Experimental voltage waveform (50 V per division) and current (100 A per division)for 0.050”-200 C-200 A panel.

6. Conclusions

A successful effort on modeling of lightning direct effects continuing current has been demonstrated in bare aluminum sheets with two thicknesses and the simulated data was compared to the experimental damage areas. Exact match among the modeled and simulated values was not achieved, but is required to carry out reliable predictions of the melt-through areas in aluminum aircraft-graded skins. Discrepancies and further model development and improvement were discussed.

8. References

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