Silver-based conductive materials for lightning strike protection of aircraft composite structures

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***Abstract*—Lightning strike protection of composite structures, is an increasingly studied subject in the aerospace industry. The important weight savings offered by composite structures are hindered by their lower electrical conductivity, as much as four orders of magnitude, compared to their aluminium alloy counterparts. Commercially available metallic expanded foils such as expanded copper foils (ECF) offer good protection at the cost of difficult reparability and significant weight penalty, thus negating the weight benefits that composites can bring. Here we study a wet-metallization process with Tollen's reagent to plate milled carbon fibres with silver. The silver coated carbon fibres (SCCF) are integrated to a carbon fibre reinforced polymer (CFRP) panel with different adhesives under three configurations, then the panels are sealed with aerospace grade paint for realistic finition and are subjected to high impulse strikes. The aim of the SCCF sacrificial coating, layered upon the CFRP panel, is to effectively mitigate damage due to lightning strike and to offer a scalable and viable LSP solution. Configuration DPE-SCCF (Painted Double stacked PEDOT:PSS and SCCF) had 54% retention of flexural strength in bending and an area of damage of 314 squared millimeters. Moreover, configuration PE-SCCF (Painted PEDOT:PSS and SCCF) being two times less areally dense than the former, had 42% retention of flexural strength in bending with an area of damage of 1550 squared millimeters, 5 times more then the DPE-SCCF configuration. Finally, configuration PR-SCCF (Painted Primer and SCCF) had an area of damage of 777 squared millimeters. All three configurations displayed delamination in the first two plies. Both configurations PE-SCCF and DPE-SCCF performed better than P-CFRP (Painted unprotected CFRP panels) in retained mechanical properties but displayed inferior retention of mechanical properties compared to P-ECF (Painted Expanded Copper Foil).**

***Index Terms*—composites, lightning strike protection, coating, conductivity, expanded copper foil, aircraft.**

I. Introduction

There is an increasing demand for composites in aircraft structures to meet the CO_2 emission targets of the aviation industry. Many countries are introducing strict legislations to curb the growth of greenhouse gas emissions. Both Canada and the United States of America have set their goal to reach carbon-neutral growth by 2020 and net reduction over the long term (2050) [1–2]. However, due to the global pandemic's complications, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) carbon-neutral growth deadline has been extended and reconfigured to three implementation phases that will last till 2035 [3]. Life cycle assessment demonstrated that the introduction of composite aircraft provides significant environmental benefits [4] and net negative emissions, even when taking into account the increased emissions from the manufacturing and decommissioning phases [5].

Composite structures have generally a much lower electrical conductivity than metallic structures, and unprotected elements are at risk of being significantly damagewhen exposed to lightning strikes [6]. The resistance to lightning is a crucial design factor for aircraft. On average, during commercial operation, an aircraft is subjected to approximately one lightning strike event per year [8].

A solution that is widely applied in the industry is the integration of a layer of expanded copper foil (ECF) on the outer surfaces of elements at risk of lightning strikes [9–10]. This solution offers a good protection against damage from direct lightning strike but is prone to galvanic corrosion [11] and adds a significant weight to composite structures [10]. In addition, repairs of the outer layer after lightning events are complicated by the need to correctly re-establish the conductive network [12]. Despite the good protection ECF offers, researchers are looking at new materials to overcome the downsides of ECF. Conductive resins and nanofillers [13–15] and buckypapers [17] are commonly studied solutions because of their high electrical conductivity, their high aspect ratio and their ability to be functionalized [16–17].

Cauchy *et al.* studied hybrid core-shell high aspect ratio carbon–silver nanofibres with a continuous silver coating, which effectively diverted the impulse strike [22]. However, the application of nano-scale solution is quite hazardous in industry, as nano-scale fibres represent a significant danger for workers, which need to be effectively monitored in terms of health and safety risks [23–24]. Diamanti *et al.* studied the synthesis of carbon nanotube (CNT) buckypapers (BP) for lightning strike protection by preparing hybrid buckypapers with silver nanoparticles and graphene nanosheets. The conductivity of the hybrid buckypaper reached $6.7 \times 10^4\ \mathrm{S/m}$

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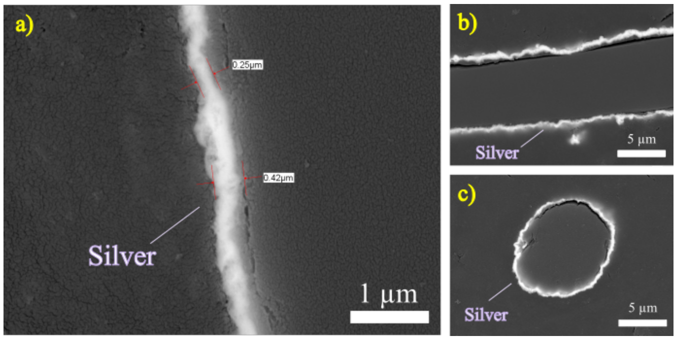

Fig. 1. Silver coated carbon fibres (SCCF) under Scanning Electron Microscopy a) Coating thickness measurement (x20 000), b) Long cross section (x5000) c) Circular cross-section (x5000).

but was dependent on areal mass [25].

Here we present a silver-based solution consisting of wet metallized milled carbon fibres, that act as a topmost sacrificial ply of CFRP composite panel. Through electroless deposition with the Tollen's reagent, we successfully coated milled carbon fibres, exploiting the advantageous properties of both carbonaceous substrate and metallic reactants to provide near metallic conductivity to the SCCF. The silver coated carbon fibres (SCCF) were thereafter integrated to large carbon fibre reinforced polymer (CFRP) panels with different integration methods and were then painted with aerospace grade paint. The different integration methods were then subjected to emulated lightning strike. The circuit is able to subject the samples to modified a A-component impulse waveform defined in the SAE ARP 5412 standard [18].

II. Experimental

A. Silver deposition process

The silver deposition was performed on milled carbon fibres (mCF) PX-30 from Zoltek. The processed fibres had an average length of $150\,\mu\mathrm{m}$. The silvering process was based on the Tollen's reaction, with an initial sensitization step. The sensitization process was performed with stannous chloride dihydrate and hydrochloric acid. The silvering process was performed with anhydrous glucose, potassium hydroxide, nitric acid, denatured reagent alcohol, silver nitrate and ammonium hydroxide. The metallized fibres have been observed under a scanning electron microscope (SEM) for the quality of silver coverage on the milled carbon fibres as shown in Fig. 1 and Fig. 2.The silver coverage was predominantly uniform and represented a 20% volumetric ratio to the carbon fibre.

B. Integration to CFRP panels

Prior to the deposition on the panels, the SCCF were filtered and then completely dried in a vacuum oven to remove residual water. The surface preparation CFRP consisted of manually sanding the panels with 240 grit paper to remove the resin layer and cleaning the residual particles with Acetone.

Furthermore, two methods of integration were used to help the binding of the SCCF on the CFRP panel. The use of a primer and the use of a conductive ink was studied to replace the typical surfacing film used for the analog solution, expanded copper foil. With the two methods of adhesion, three configuration of panels were made as per Fig. 3.

1) Integration with primer: To improve the adhesion of the SCCF, a thin mist of epoxy primer from Hentzen was deposited on the surfaced-prepared panels with a 3M Accuspray spray gun with a nozzle diameter of 1.4 mm. Dried SCCF were then evenly distributed on top of the panel with a 30 cm #100 sieve (opening size $150\,\mu\mathrm{m}$). The surface density of SCCF was $150\,\mathrm{g\,m^{-2}}$ compared to expanded copper foil of $141\,\mathrm{g\,m^{-2}}$ of mesh and $191\,\mathrm{g\,m^{-2}}$ of adhesive.
A coat of paint was applied to seal the surface and prevent migration of the SCCF. The panels were cured in an oven according to the specifications of the epoxy primer before being weighted and further tested.

2) Integration with conductive ink: The second method consisted of coating the surface-prepared panels with PEDOT:PSS (1.5% wt in aqueous solution) denominated as conductive ink. This ink presents a conductivity of 200 S/cm and was considered to help the conductive network between the SCCF to be established, contrary to the resistive nature of the primer. After the PEDOT:PSS coating, the same sieving and sealing process was used as the integration with the primer. However, two surface densities of protective coatings were tested (not including the paint's areal density) : $70\,\mathrm{g\,m^{-2}}$ with the [PEDOT:PSS/SCCF] configuration and $150\,\mathrm{g\,m^{-2}}$ with the [PEDOT:PSS/SCCF/PEDOT:PSS/SCCF] configuration.

C. Emulated lightning strikes

Emulated lightning strikes with a current of up to 40 kA were produced by the discharge of a bank of capacitors into a modified RLC circuit. The circuit is equipped with a column of diodes in parallel with the sample, which help convert the circuit's behavior from RLC to RL during the current decay phase of the current. The current was injected at the centre

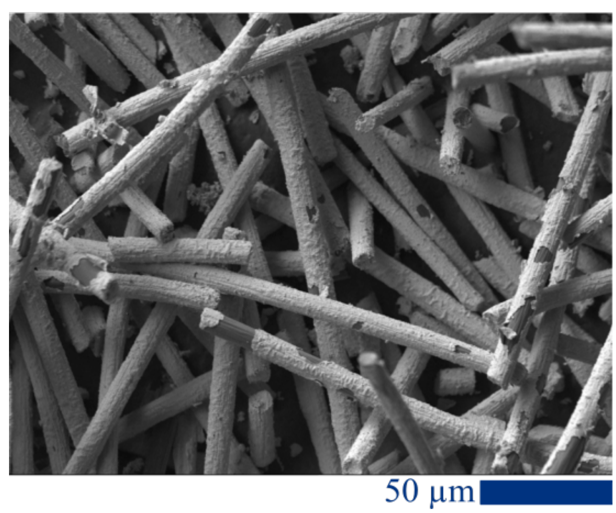

Fig. 2. Silver coated carbon fibres (SCCF) under Scanning Electron Microscopy (x500)

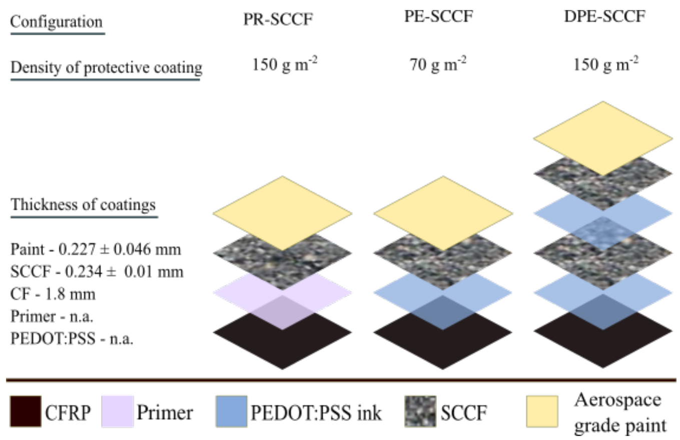

Fig. 3. Panel LSP stacking configurations from left to right : Primer and SCCF, PEDOT:PSS and SCCF and Double stacked PEDOT:PSS and SCCF.

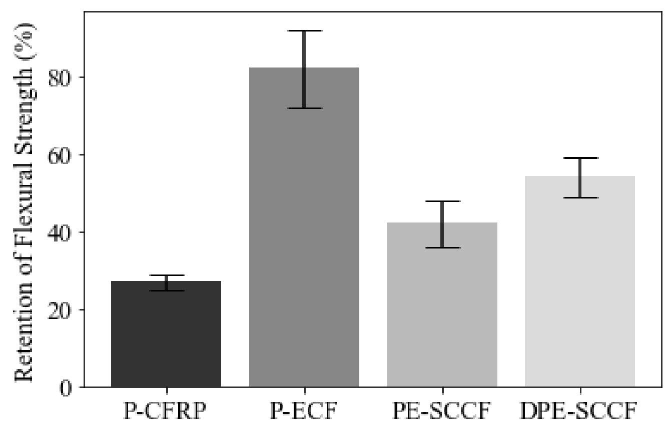

Fig. 4. Flexural strength in bending retention after lightning damage on different protection configurations.

of the 30.5 cm by 30.5 cm composite samples by a 12.7 mm copper electrode with a tapered conical tip. For recording the test data and waveforms, we used a 200 MHz oscilloscope (LeCroy WaveSurfer 422).

III. Results and discussion

After painting the CFRP panels on which the SCCF were integrated, the resistivity could not be measured due to high resistivity of the paint. However, the fibres were well dispersed, which suggests that multiple percolation paths were created.

The conductivity of the SCCF coatings alone could be measured with a 4-point probe test with a Keithley 2182A Nanovoltmeter and a Keithley 6221 current source. The measured conductivity of the SCCF coating was $5.85 \times 10^5\,\mathrm{S/m}$ and the conducitivity of the SCCF coating integrated with the PEDOT:PSS ink was SCCF coating was $7.2 \times 10^5\,\mathrm{S/m}$. This is a promising conductivity when compared to copper's conductivity of $8.08\times10^6\,\mathrm{S/m}$ [21]. However, the conductivity in S/m of expanded copper foils is hard to measure with the four point probe method as the mesh is embedded in the resin and the measurement would not be accurate as it is not a continuous sheet.

Following the impulse strike test of 40 kA on the 30.5 cm by 30.5 cm panels, configuration PR-SCCF had a $777\,\mathrm{mm}^2$ area of fibre damage with the delamination of the two first plies, configuration PE-SCCF had a $1550\,\mathrm{mm}^2$ area of fibre damage with delamination of the two first plies and configuration DPE-SCCF had a $334\,\mathrm{mm}^2$ area of fibre damage with a delamination of the two first plies. The visual damage was observed on the front side and on the cross section of the damage as seen in Fig. 5. in the Appendix. Configuration PR-SCCF and DPE-SCCF could be compared on the basis of areal density of protective coating, and configuration PE-SCCF and DPE-SCCF could be compared on the basis of method of integration, with varying areal density of protective coating.

After visual observation of damage, the panels were tested in compliance to ASTM D6272 - Flexural Test Composites Four-Point Bending [29]. The retention of flexural strength was calculated with respect to undamaged coupons from the panels. Fig. 4. shows the retention of flexural strength in configuration PE-SCCF and DPE-SCCF compared to Painted unprotected CFRP panel (P-CFRP) and Painted Expanded Copper Foil (P-ECF), that are respectively established as our worst case and best case references. P-CFRP shows the worst retention of flexural strength at 27% retention, while P-ECF with $141\,\mathrm{g\,m^{-2}}$ of foil and $191\,\mathrm{g\,m^{-2}}$ of adhesive shows the best retention at 82%. Configuration PE-SCCF with $70\,\mathrm{g\,m^{-2}}$ of protective coating retained 42% of its flexural strength, while configuration DPE-SCCF with $150\,\mathrm{g\,m^{-2}}$ of protective coating retained 54% of its flexural strength.

Lightning damage is mainly due to the degradation and evaporation of the resin of the CFRP structure, as well as rapid heat generation caused by 1) the Joule heating created when the current goes through the matrix and 2) concentration of the electric arc through dielectric materials such as resin and paint. The rapid surge of temperature during a lightning strike gives rise to pyrolysis of the matrix of the CFRP structure. Under rapid sublimation, the epoxy matrix expands as hot gas that creates mechanical loads caused by this sudden thermal expansion. Sudden thermal expansion gives rise to delamination and fibre breakage, as well as puncture through the CFRP laminate [27]. The return stroke in typical lightning occurences during flight can produce a rapid increase of plasma pressure, which induces a fast expansion of the plasma channel. This expansion leads to the initiation of a shockwave causing significant damage to the CFRP laminate. Furthermore, the damage always occurs at a greater degree when paint entraps the current and magnifies the shockwave [28].

This screening test was made with lifelike parameters such as high amperage and the integration of aerospace grade paint to emulate realistic operating conditions.

IV. Conclusion

The study of silver-based conductive coatings as a solution for lightning strike protection was investigated with realistic parameters such as finishing the panels with aerospace grade paint and modified A-waveform conform to SAE ARP5412. The performance of the coating was less than expected in terms of damage mitigation. However, the coating offers a promising conductivity of $5.85 \times 10^5\ \mathrm{S/m}$. Residual mechanical properties allowed a quantitave assessement of the impact of damage on the structural integrity of the panels, where the denser integration of the protective coating with conductive ink (configuration DPE-SCCF) retains 12% more of its flexural strength than configuration PE-SCCF and 27% more than configuration P-CFRP. Tests of residual mechanical properties on P-CFRP and P-ECF served as lower and upper references, respectively representing the worst case (27%) and the best case (82%). The silver-based configurations tested do not reach the mechanical properties retention of P-ECF (Painted Expanded Copper Foil). Visual observations also showed that configuration DPE-SCCF had a smaller area of damage than the configuration PR-SCCF with similar areal density of protective coating. Moreover, configuration DPE-SCCF also had a smaller area of damage than configuration PE-SCCF, both being compared on the basis of method of integration, with the latter having a lower areal density of protective coating. The availability of a high impulse strike setup provided us with a strong base of instrumentation and gave good insight on hybrid carbon-metal solutions. Further silver based solutions will be tested to compare their performance with the SCCF-based protective coatings. This research has been done in collaboration with our industrial partner Bell Textron.

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V. Appendix

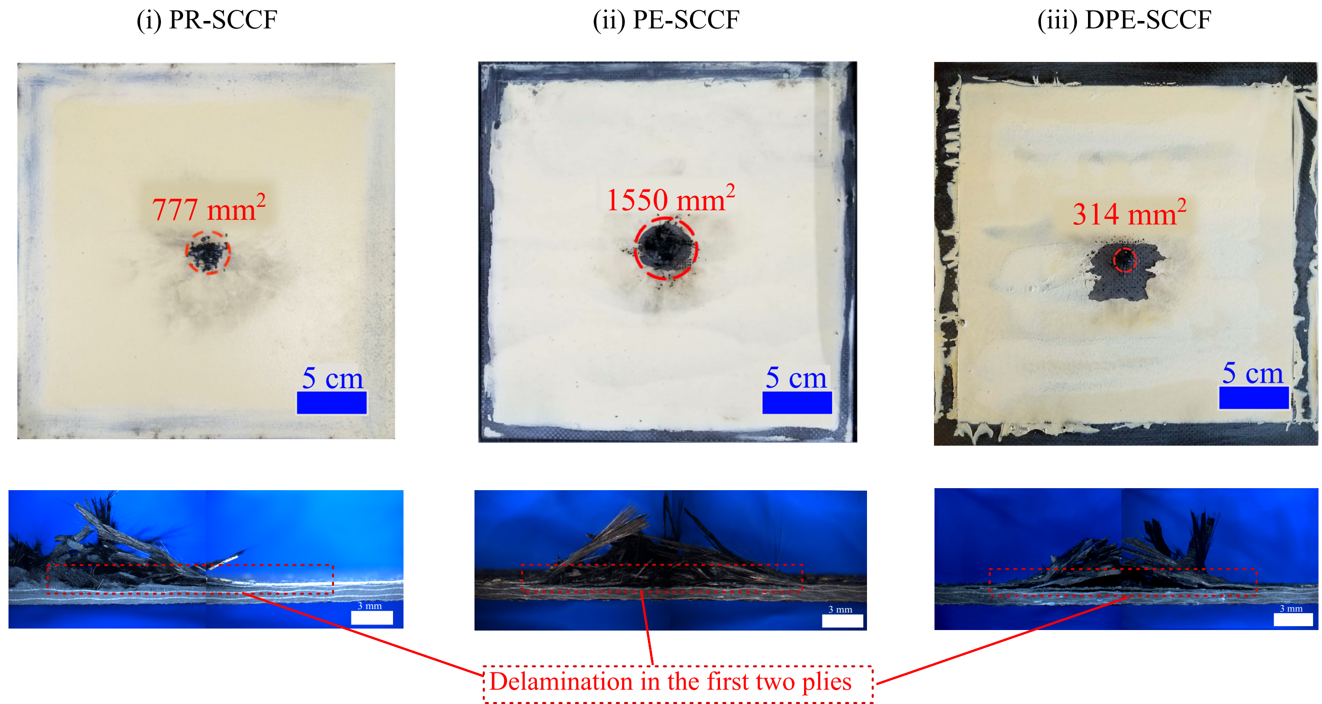

Fig. 5. Damage analysis of the three integration configurations post lightning impulse