REPLACING METAL-BASED LIGHTNING STRIKE PROTECTION LAYER OF CFRPS BY 3D PRINTED ELECTRICALLY CONDUCTIVE POLYMER LAYER

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ABSTRACT

Electrically conductive adhesive layers were deposited on top of aerospace grade carbon fiber reinforced plastic (CFRP) panels using a small-scale 3D printer. Polylactic acid (PLA) filaments with copper filler (CU-PLA) and graphene filler (GO-PLA) were used to print around 0.7 mm thick electrically conductive layer on top of CFRP panels. 3D printed polymeric layers were tested for their effectiveness as a lightning strike protection (LSP) material by subjecting them to a simulated lightning strike. A painted, electrically non-conductive unprotected panel was also tested for comparison. In the case of the CU-PLA protected sample, a high electrical conductivity proved to be useful in fast dissipation of the lightning current. Fast current dissipation helped to reduce the resistive heating after a lightning strike. Thermography, high-speed camera and ultrasonic analysis were employed to study the heat generation, current dissipation and direct damages during the lightning strike. These results established that a useful Faraday Cage was applied via additive manufacturing successfully. This work shows the successful application of 3D printing for producing LSP technologies, with future work aimed at investigating optimal printable electrically conductive thermoset material candidates.

1. INTRODUCTION

In recent years, metal-based primary structural parts of aircraft are being replaced by carbon fiber reinforced plastic (CFRP) parts, but replacement of current lightning strike protection (LSP) technologies with non-metal based material has yet to be realized successfully in practical applications [1,2]. Discovery of new conductive structural materials and improvement in the processing of polymer composites using additive manufacturing has led to many research opportunities. Researchers have challenged the conventional metal-based lightning strike

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protection system with new ideas and concepts [3]. Among them, carbon-based nanomaterials and intrinsically conductive polymers based LSP are leading the way [4,5]. In literature, it has already been established that electrically conductive polymers including carbon nanotube (CNT), graphene oxide (GO) and polyaniline (PANI) can be a part of the next-generation polymeric-based lightning strike protection systems which may replace the current metal-based LSP in future [6]. However, practical use of polymer based LSP is currently in a development phase along with additive manufacturing technology for CFRP structures. In this work, we have combined both techniques to show that additive manufacturing can be applied to LSP systems, where electrically conductive polymers can be deposited on CFRP structures.

Lightning strike damage studies are essential for composite materials, as they possess a very low electrical conductivity compared to metallic structures [7,8]. Many industries such as aerospace, energy, and athletics are heavily dependent on CFRP structures. CFRP materials have already been implemented in aircrafts, wind turbine blades, storage tanks, poles, and other such application where they are often exposed to lightning strikes. Therefore, low electrically-conductive CFRP structures are needed to protect from lightning strike damages. At present, the most commonly employed method is to place metal-based mesh or foil on the top surface of CFRPs, but this solution defeats the purpose of implementing lightweight CFRPs. In addition, installing these meshes significantly increases the cost, further reinforcing the desire for new LSP technologies. Therefore, research on non-metallic LSP is gaining attention. Among all the potential candidates, carbon-based nanofillers and intrinsic conductive polymers are better options.

In the present work, the AM method is combined with electrically conductive polymer composites to apply LSP on top of CFRP structure. Fused filament fabrication is one of the most common methods used to prepare 3D printed parts [9,10]. Printed parts are built by depositing material layer-by-layer in a pre-defined tool path until the final structure is obtained. Considerable research has already been done to show the application of 3D printed polymers in prosthetics, sensor, structural components, etc. Work has also been done to show that printed electrically conductive polymers have applications in electromagnetic interference shielding (EMI SE) and structural health monitoring (SHM) making these materials potential lightning strike protection candidates [11].

2. EXPERIMENTATION

2.1 Materials and methods

CFRP panels were prepared using prepreg from Raptor Resin (USA). Carbon Fiber T300-12 K (2×22 twill weave) and BMI-1-OOA resin were utilized to prepare the prepreg. The prepreg was cut into 20 cm × 20 cm sheets, and 8-layer laminates were prepared using a hot-press. The thickness of the obtained panels was around 2.35 (0.07) mm. The unprotected painted panel was tested as a base case. The thickness of the paint was in the range of 76 to 127 µm.

For the current study, polylactic acid (PLA)-based filaments with copper (CU-PLA) and graphene (GO-PLA) filled electrically conductive fillers were procured from MULTI3D and BLACKMAGIC3D companies, respectively. According to the suppliers, the electrical resistivity of GO-PLA and CU-PLA were 0.88 Ωcm and 0.006 Ωcm respectively. A small-scale printer (M2 Rev. E) with a build size of 929 cm^2 from MakerGear company was used to print the electrically conductive layers on CFRP substrate. Printing paths were optimized to print a continuous layer in an alternating [0°/90°] direction as shown in Figure 1. Three samples were prepared with details shown in Table 1.

Table 1. Parameter of prepared samples.

Sample Name	Surface Coating	Print Orientation	Layer Thickness (mm)	Layer conductivity (S/cm)
CF/BMI-Paint	Paint	-	-	-
CF/BMI-CU-01	CU-PLA	[0°/90°]	0.72	13.33
CF/BMI-GO-01	GO-PLA	[0°/90°]	0.68	1.66

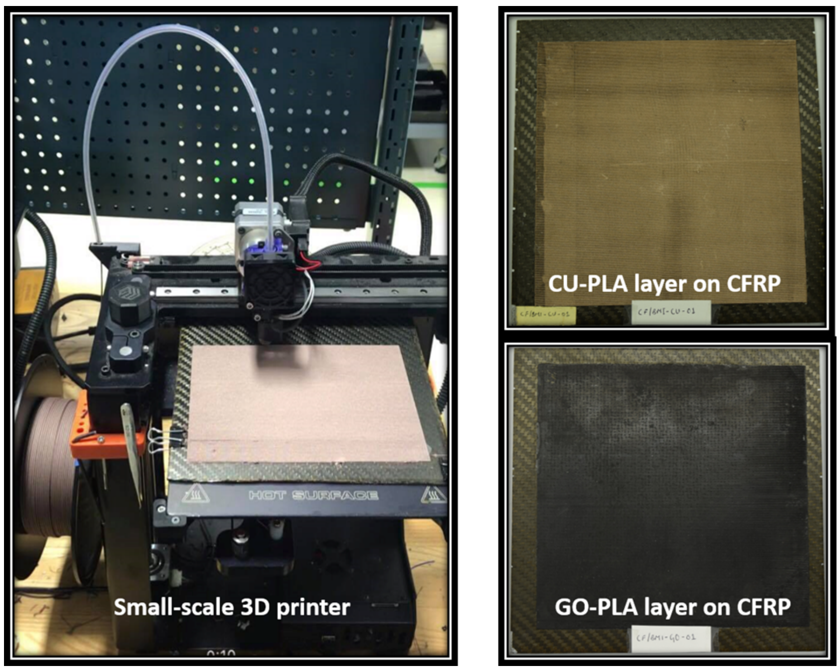

Figure 1. 3D printing of conductive polymers on top of the CFRP structure as lightning strike protection material.

To measure the electrical conductivity of the deposited material, 3 bars (50mm×12.5mm×2mmcm) with different layer orientations (0°, 45°, and 90°) were also printed and tested. The electrical conductivity (DC measurement) of the polymer composite bar was measured using a multi-meter (HEWLETT PACKARD (HP), USA). DOTITE conductive adhesive paste (SPI supplies, USA) was applied at the ends along with aluminum tape (electrode). DOTITE was entirely dried before measuring the resistance.

Nondestructive Evaluation (NDE) inspection was performed utilizing ultrasound technique to qualitatively visualize the damaged locations on the composites surface after lightning strike test. An Olympus OmniScan SX phased array system was used to capture inspection data. The inspection setup was a pulse-echo scan, normal to the damaged surface, within an immersion tank giving a 1.0-mm scan resolution. The two specimens were inspected using a 64 element, linear phase array transducer (5L64-NW1) with 5 MHz frequencies. The scan parameters had an overall gain of 8 dB and a band-pass filter was applied with center frequency of 2.3 MHz and 1.0 – 3.5 MHz bandwidth. This allowed surface and sub-surface analysis of the damaged caused by the lightning strike.

2.2 Lightning strike test setup

According to SAE ARP-5412B standard of lightning strike waveform and environment, the lightning test is comprised of 4 main current waveform components, namely A, B, C, and D as shown in Figure 2. Simulated lightning strike test were conducted at the NTS facility situated in Pittsfield, MA. This facility can generate all forms of a lightning strike. However, the current generator for component A and component D was the same; therefore, either A, B and C or B, C and D could be applied continuously; the remaining component (either A or D) can be applied separately. The current generator works on RLC circuits, whose values were adjusted to obtained desired waveforms of a lightning strike. A spherical jet diverter electrode was held 25 mm above the specimen (Figure 3). A small electrically conductive thread was attached to the jet diverter and positioned towards the specimen. The specimen was placed on a wooden structure and clamped with braided aluminum bars for grounding purposes. High-speed camera, thermal camera, and still camera was used to capture the transient lightning test. Three Tektronix oscilloscopes were employed to measure each lightning waveform component. Parameters of incident lightning strike for each sample are shown in table 2.

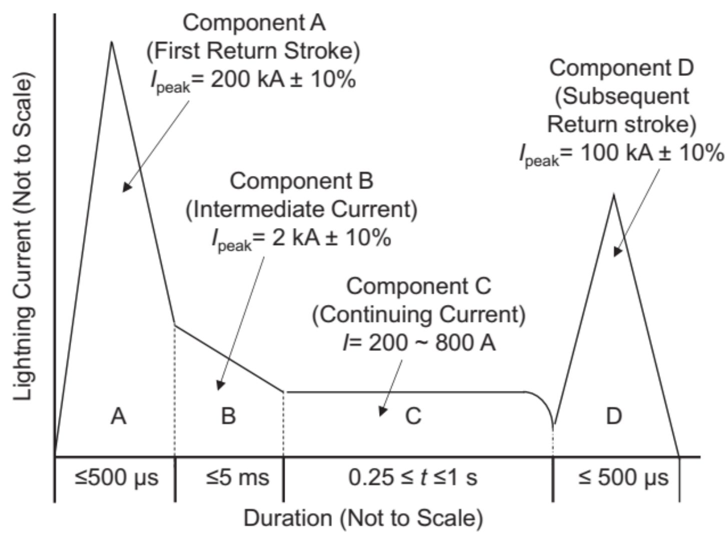

Figure 1. Lightning current waveform [12].

Figure 3. Simulated lightning strike testing setup.

Table 2. Parameters of lightning waveform.

	Component A		Component B		Component C		
Sample Name	I_{peak} (-kA)	Action Integral ($x10^6 A^2 s$)	I_{avg} (-kA)	Charge (-C)	I_{avg} (-A)	Charge (-C)	Time (ms)
CF/BMI-Paint	105.1	0.622	2.01	10	481	13.7	28.42
CF/BMI-CU-01	103.4	0.61	2.01	10	435	15.3	35.13
CF/BMI-GO-01	105.4	0.58	2.02	10.1	470	13.7	29.12

3. RESULTS

3.1 High Speed Imaging and Videography

The event of the lightning strike was captured using a high-speed camera at a frame rate of 5100 fps. Although this frame rate is not adequate to capture the highly transient lighting strike event lasting only for a few microseconds in case of component A and a few milliseconds in case of component C as shown in table 2. The damaging behavior of CFRP due to lightning strike was captured successfully using the employed video camera. Figure 4. shows the lightning event on (a) unprotected CFRP (b) CU-PLA protected CFRP (c) GO-PLA protected CFRP. The unprotected CFRP suffered fiber puncture and resin evaporation at multiple places.

Figure 4. Lightning strike on composite panels with (a) Paint (b) CU-PLA layer (C) GO-PLA layer.

It should be noted that the unprotected CFRP was a painted panel without any electrically conductive layer protection on top of it. Paint behaved as the dielectric material and reduced the fast dissipation of the lightning current. Resistance to the current flow created heat, known as “Joule's heat”, on the surface of the CFRP structure. Low thermal diffusion due to paint application led to thermal damage of the CFRP panel [13]. On the other hand, the CU-PLA based layer had much higher surface electrical conductivity than the painted CFRP panel. The high electrical conductivity of CU-PLA dissipated the lightning current faster without damaging the CFRP panel significantly. However, as the PLA has a low thermal degradation point, during the event of a lightning strike, some part of CU-PLA layer melted and stripped away from the surface of the panel. This allowed for contact of lightning current to the exposed area resulting in significant damage in that area. Damage to the CU-PLA protected CFRP was found to be lower than the unprotected CFRP. On the other hand, the electrical conductivity of GO-PLA was not as high as the CU-PLA layer, hence the lightning strike damaged the GO-PLA layer on the CFRP surface. GO-PLA may not have provided enough protection to the panel, but it was successful in constraining the damage to a limited area.

3.2 Thermography

Thermal camera (FLIR) imaging was utilized to study the temperature rise on the surface of the CFRP panel after the lightning strike as well as to study the path taken by the current from the panel to the ground wire. The drawback of the FLIR camera being used in this study was its ability to capture a maximum temperature of only 160°C. Therefore, in most of the test, it reached its maximum value and could not be used to demonstrate which panel produced the least resistive heat. However, thermal images also helped to understand the extent of damage due to thermal diffusion of the lightning current. As can be seen from Figure 5. thermal patches were scattered all over the panel in each direction. There is no sign of continuous current flow from the point of lightning attachment to the grounding set up. On the other hand, CU-PLA protected samples showed the concentrated thermal zone and a path of current from the center to ground via the unprinted CFRP surface. Similarly, the GO-PLA sample showed the concentrated thermal shock and burning of resin at the center of the panel. Some amount of current also escaped through the unprinted portion of the CFRP panel. It was observed that thermal dissipation was quickest in the CU-PLA protected sample, which could be assigned to the high electrical conductivity of the CU-layer and reduced Joule's heat. The GO-PLA layer showed the slowest thermal dissipation compared to the painted panel. This could be due to the damaged layer around the attachment point which caused penetration of the current into the structure leading to significant thermal damage.

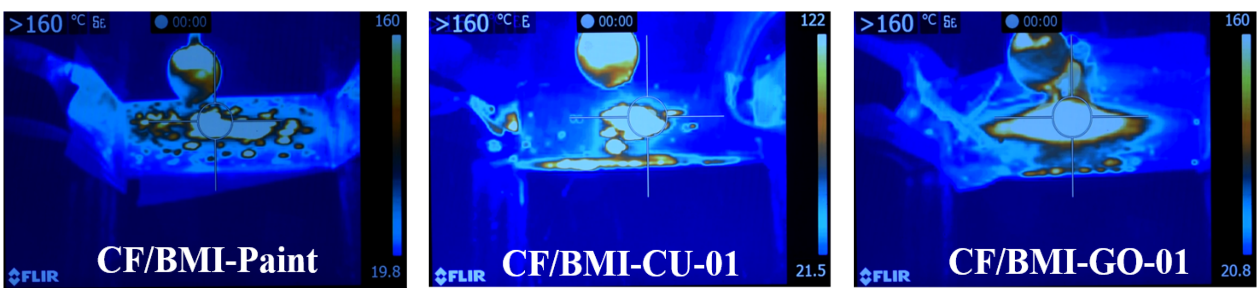

Figure 5. Thermography during lightning strike test on CFRP with (a) Paint (b) CU-PLA layer (C) GO-PLA layer.

3.3 Non-Destructive Evaluation

The ultrasonic results were able to depict the damaged areas on the composite samples after lightning strike tests. The gate was placed at the front wall echo with the band-pass filter applied to inspect damage at the surface and sub-surface. A typical signal response of the undamaged areas on the CFRP composite produces a 60% signal amplitude (yellow) in the ultrasound C-Scan. The CF/BMI-CU-01 sample has a more complicated acoustic response for the ultrasound inspection. The AM printed CU-layers were intact to the CFRP composite during inspection and

caused another level of complexity for evaluation. It can be seen on the outer edges that the exposed, undamaged CFRP has a 60% signal amplitude (yellow) in the ultrasound C-Scan. Undamaged AM printed locations have a low amplitude response of 30%-40% (blue and green) due to the scattering off the round 3D printed surface as shown in figure 6.
There is obvious erosion of the AM printed material at the strike entry location leaving exposed, damaged CFRP. Out-of-plane damage of the CFRP with fiber breakage and exposure has a low amplitude response below 30% (blue) due to scattering and absorption. These responses are in multiple locations, but mainly in the center at strike entry and at the right of the sample at strike exit where the ground clamp was located. This shows the complexity of this inspection due to the similar acoustic responses for both the out-of-plane damage (30%) and the undamaged AM printed surface (30%-40%). There are also other surrounding locations where AM printed material was removed, but exposed CFRP shows undamaged surface resulting in a mixed signal of mostly high amplitude (70%-90%). Another response shown is the large amplitude response (80%-100%) on the left side of the panel which correlates to the AM printed surface. It is not well known why this response was captured but a quick hypothesis is the AM printed CU-PLA surface smoothed out due to high thermal exposure and causing reheating and cooling after the strike. The smoothed AM surface causes a normal incidence for the ultrasound waveform to reflect most of the acoustic energy back to the sensor. Further investigation is needed.

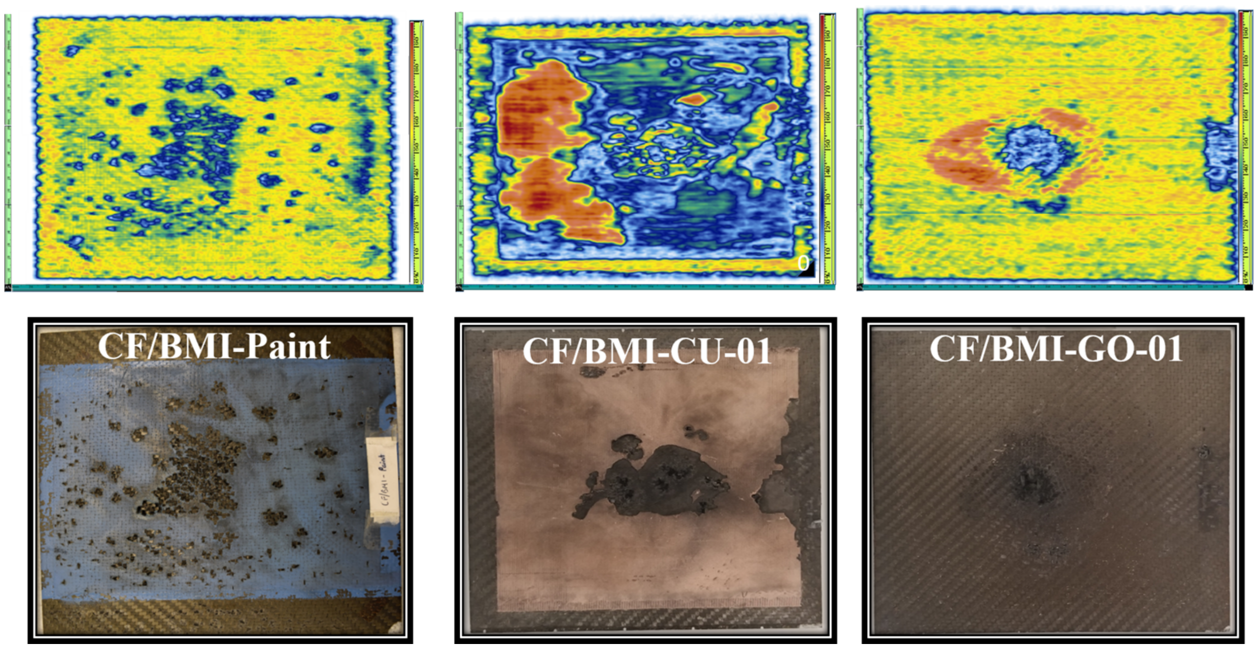

Figure 6. Ultrasonic inspection of the CFRP panels after lightning strikes.

For the CF/BMI-GO-01 sample, signatures caused by the lightning strike damage appear on the ultrasound C-Scan as low amplitudes below 30% (blue) due to the scattering and absorption caused by the out-of-plane damage. This occurred in three locations: the entry point of the lightning current at the center of the sample, two circular damages at the outer radial limits below the center damage region with large fiber breakage and the exit point on the right of the sample where the ground connector was clamped down. Around the center damage location are slightly higher amplitude responses ~70%-80% (red) which correlates to visual inspection. This is caused by matrix material being eroded/burned away exposing bare fibers with some fiber breakage. It can be concluded that ultrasound NDE inspection is a useful tool to qualitatively identify surface and subsurface damage of the CFRP composite after lightning strike.

4. CONCLUSIONS

3D printed electrically conductive layers were deposited on top of CFRP panels. They were subjected to a lightning strike of combined waveform component of A, B and C. Component A of around 100 kA intensity, component B of around 2 kA and component C of around 450 A was applied. It was observed that highly electrically conductive CU-PLA based LSP performed better than the unprotected painted panel. This behavior was captured using videography and thermography. Thermal images showed the decreased thermal diffusion and high Joule's heat in case of painted CFRP panel compared to protected panels. However, the high electrical conductivity of CU-LSP was not enough to protect the panel entirely due to the use of low-temperature thermoplastic as a binder, i.e. PLA. However, the concept of 3D printed LSP was laid in this work for the first time. To overcome the limitations of present work, the adhesion strength between printed layers and substrate structure needs to be improved in the future.

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