Enhancing Lightning Resistance property of the Polymer Composites

M.K. MARICHELVAM* AND K. KANDAKODEESWARAN

Department of Mechanical Engineering, Mepco Schlenk Engineering College, Sivakasi, Tamilnadu, India – 626005.

ABSTRACT

Aircraft structures are redesigned by fibre-reinforced composites mainly due to their high specific stiffness and strength. However, while using the semi-conducting composites in an aircraft it may be failed due to lightning strike damage. The existing protection techniques will increase the weight and hence negatively impacts the fuel efficiency. This paper addresses an overview of the lightning damages that occur due to the usage of composites and existing protection techniques. The Plasma coating of copper and titanium nitride on the epoxy laminate was carried out to increase the electrical conductivity on polymeric composite coatings. The surface conductance of the coated and uncoated laminate was analytically determined. And the lightning strike test was experimentally carried out and finally the tensile strength of damaged and undamaged laminates were measured. Due to the titanium nitride coating, electrical conductance of epoxy laminates was increased. Further, it was observed that the weight can be reduced up to 85% with less damage on exposure to high current and temperature when compared to the uncoated laminate.

Key words: Composites, Plasma coating, Electrical conductivity, Lightning strike test.

1. INTRODUCTION

Polymeric composites have been widely used in the aircraft industry for the past several years due to their high specific strength and high stress-bearing capacity. Polymeric composites show superior performance in tensile, compressive and fatigue strength. They have good flexural properties and excellent inter-laminar and in-plane shear strengths. Weather condition in a flight route is essentials it is associated with passenger's safety. Composites are typically made up of fine fibers such as carbon or glass that are oriented at certain directions and surrounded in a supportive matrix material. Although a wide

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Correspondence author e-mail: mkmarichelvamme@gmail.com

variety of matrix materials are commercially available, elevated temperature cured epoxy resins are the most commonly used. In most component design, the plies of the composite material are arranged at a variety of angles depending on the direction of major loading. This manufacturing technique produces a stacked laminated structure which is highly an isotropic and structurally in homogeneous. It is well established that the composite structures in aircrafts are more susceptible to the lightning damage compared to metallic structures.

Researchers showed that a set of analytical design models to predict the electrical and mechanical properties of hybrid carbon nanotubes (CNT)/carbon-fibre (CF)/epoxy composites for potential use in fuselage and airframe constructions against lightning strike. The hybrid CFRP/CNT composite configuration yielded a weight-efficient design solution for representative fuselage structures. This reduced the use of traditional methods for composite lightning protection of aircraft [1]. The relatively low electrical conductivity leads to the vulnerability to lightning strike. Some specific features of lightning arcs observed in flight and the direct effects on the lightning skin are also investigated [2] .Researchers investigated the relationships in the important damage process including electrical, thermal and chemical phenomena. In order to examine the internal damage of the tested specimen, a non-destructive inspection namely ultrasonic testing was carried out [3].

Researchers sprayed the Silver Nano-particles on the surface of carbon fibers, which were then impregnated by epoxy resin to form a CFRP specimen. The electrical conductivity was increased by four times of the ordinary CFRP[4].

It has been reported that 90% of lightning strikes to aircraft are initiated by the aircraft. This indicates that the aircraft extremities provide the region of high electric field [5-8]. The carbon nanotube bucky paper-based coatings composed of conductive bucky paper and insulating adhesives were developed to protect the CFRP laminates [9]. Korenevhas investigated the widely used composite materialsbased on magnesium and aluminum oxides [10] and other alumina components that are similar in composition but have different reactivity with respect to water glass [11]. Rowan suggested that the metal is embedded in the matrix of the outer layer of the skin and positioned outwardly of reinforcing graphite fibers[12]. The method and structures for enhancing the conductivity of graphite composite materials for lightning protection and prevention of attachment of lightning to fasteners was explained by the researchers[13]. The interaction of lightning with aircraft and the challenges of lightning testing were discussed by the researchers[14]. A complete dielectric surface shield of appropriate dielectric strength and thickness which electrically isolated the protected component from the swept stroke and restrike lightning current channel was briefly explained in the literature [15-18].

Previous researchers focused on development of a multifunctional material which allowed conducting of electrical current and simultaneously hold mechanical properties of a polymeric composite. Such material could be applied for exterior fuselage elements of an aircraft in order to minimize damage occurring during lightning strikes. In this paper the Plasma coating of copper and titanium nitride on the epoxy laminate was carried out.

For this purpose, carbon fiber plain weave ply reinforced with epoxy resin laminate is fabricated by using vacuum bag molding technique. Then, Plasma etching was carried out to remove the impurities on the surface of the laminate and to increase the surface energy of the laminate. The surface conductance of the coated and uncoated laminate was analytically carried out. And the lightning strike test was experimentally carried out and finally measures the tensile strength of damaged and undamaged laminates. The failure condition of aircraft due to lightning strike is given below in table 1.

TABLE 1. Failure condition of aircraft fails due to lightning strike

Failure Condition Definition	Failure Condition	System lightning Certification Level
Failure conditions that prevent continued safe flight and landing. The definition is: failure conditions that are expected to result in multiple fatalities of the occupants, or incapacitation or fatal injury to a flight crew member normally with the loss of the airplane.	Catastrophic	A
Failure conditions that reduce the aircraft's or the crew's ability to cope with adverse operating conditions that would: • Greatly reduce safety margins or functional abilities; • Cause physical distress or larger workload that could prevent flight crew members from performing their tasks accurately or completely; • Seriously injure a few occupants	Hazardous / Severe-Major	B
Failure conditions that reduce the aircraft's or the crew's ability to cope with adverse operating conditions, for example: • Significantly reduce safety margins or functional abilities; • Significantly increase crew workload or decrease crew efficiency.	Major	C

2. EXPERIMENTAL SETUP

The following section illustrates the experiments carried out in this research.

2.1 Sample Preparation of Composite

A carbon fiber plain weave ply and an epoxy resin film (SK Chemical) which will be used for the resin impregnation for the carbon fiber layers. The first step for making laminate is to cut the HCP200H into a piece and enforced with epoxy resin of dimensions 100 ×100 mm by using compression molding technique. The ratio for resin and hardener is about 4:1 is taken for laminate carbon fiber. The Uncoated Epoxy laminate is depicted in Figure 1.

Figure 1. Uncoated epoxy laminate

2.2 Plasma Coating on Epoxy Laminate

The plasma coating of copper and titanium nitride on epoxy laminate was carried out by using plasma spray process in this paper. The three layer of coating was done in epoxy laminate.

The plasma metalized coating was added in the following way:

- First layer of coating—titanium nitride (1 μ)
- Second layer of coating—copper (1 μ)
- Third layer of coating—titanium nitride (2 μ)

The titanium nitride and copper were chosen because titanium nitride is thermally stable and highly resistant in terms of formation of oxide layers and copper is electrically conductive. Therefore, layers of copper and titanium nitride were coated on epoxy laminate. This plasma spray coating on epoxy laminate is shown below in Figure 2

2.3 Functional Group of Uncoated and Coated Laminate

To find the functional groups present in uncoated laminate FTIR in attenuated total reflection (ATR) mode was carried out. The source used for conducting FTIR analysis was infrared spectrum. The FTIR used is MID FTIR, with a range of 4,000–400 cm^{-1} laminate. The functional group of uncoated epoxy laminate by FTIR spectrometer and the corresponding waveform is shown in table 2.

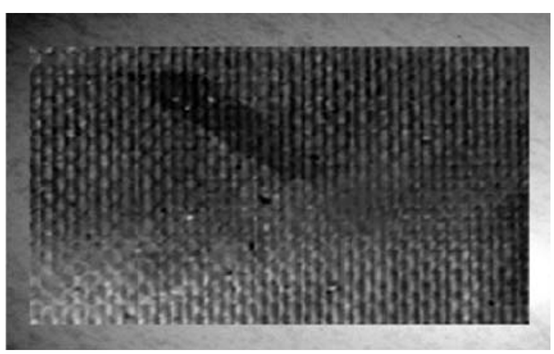


Fig. 2. Plasma spray coating of epoxy laminate

TABLE 2 Functional Group of uncoated epoxy laminates by FTIR spectrometer

Waveform	Bond	Functional group
3383.60	N-H stretch	Amines, amides
2934.07	C-H stretch	Alkanes
1576.57	-C=C- stretch	Alkenes
1287.92	C-O stretch	Alcohols carboxylic acid, esters, ethers
1037.66	C-N stretch	Amines
694.68	=C-H stretch	Alkenes

The wave number 3383.60 cm^{-1} shows N-H stretch peak. Hydrocarbons show IR absorption peaks between 2,800 and 3,300 cm^{-1} due to C-H stretching vibrations. The hybridization of the carbon affects the exact position of the absorption. Alkane C-H bonds are fairly abundant and therefore usually less useful in determining structure. Ethers have a C-O stretch that appears in the region at 1,050–1,260 cm^{-1}. This is generally a strong absorption, but can be difficult to detect if the region is complex. The many peaks seen between the wave numbers 500 and 1,500cm^{-1} represents carbon in bonded form, and hence prove non-conductivity.

The functional group of coated epoxy laminate by FTIR spectrometer and the corresponding waveform is shown in table 3.

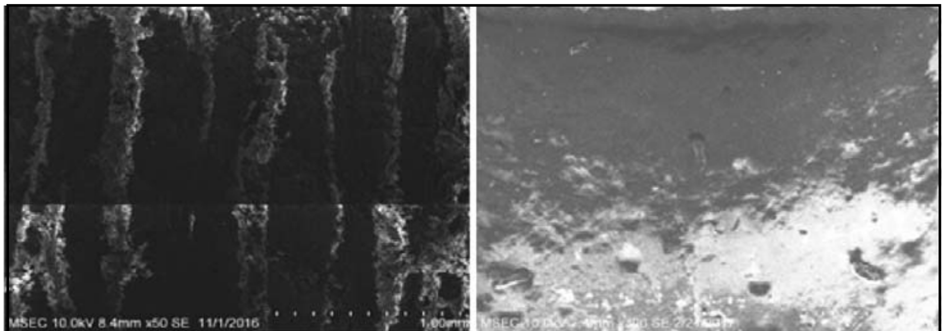
TABLE 3. Functional Group of uncoated epoxy laminates by FTIR spectrometer

Waveform	Bond	Functional group
3404.06	N-H stretch	Amines, amides
2921.80	C-H stretch	Alkanes
1718.78	-C=C- stretch	Alkenes
1459.02	C-O stretch	Alcohols carboxylic acid, esters, ethers
908.54	C-N stretch	Amines
722.37	=C-H stretch	Alkenes

The peak corresponding to 3,404.06 cm^{-1} wave number shows the reduction of the hydroxide bond. This proves that the titanium nitride coating is not vulnerable to corrosion and does not undergo oxidation. The peak corresponding to the wave number 1,459.02 cm^{-1} shows the presence of nitro compounds proving that titanium nitride is present on the laminate and also the nonconductive carbon functional group peaks have reduced significantly, proving the increase in conductivity of the laminate.

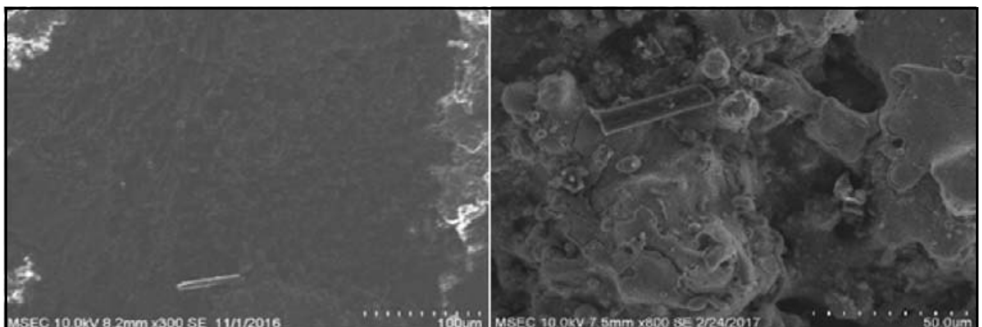
2.4 Surface Morphology of Uncoated and Coated Laminate

The surface morphology of the uncoated and coated laminate was examined using SEM with a magnification of 100× and 300×. The lens mode used for magnification was in-lens and secondary electron (SE2). The acceleration voltage of electrons was set as 10 V. The material size used for this test was 1 × 1 mm.



(a) (b)

Fig. 3. SEM image of (a) uncoated and (b) coated laminate at lower magnification



(a) (b)

Fig. 4. SEM image of (a) uncoated and (b) coated laminate with copper and titanium nitride higher magnification

The FESEM of the uncoated and coated epoxy laminate at lower magnification is shown in Figure 4 and higher magnification is shown in Figure 4. From the FESEM studies, it is found that the coating given on epoxy laminate is uniform up to a certain extent. Spots of uncoated regions are found in the coated laminate for a magnification factor of 100×, as can be seen in Figure 3. Crests and troughs are visible on the surface of the coated laminate, which would lead to non-uniform conductivity. Therefore, it can be concluded that a conformal coating of epoxy before a metalized coating may attribute to a more uniform conductivity on the epoxy laminate. A similar observation is obtained with 500× magnification factor as seen in the figures, respectively, in terms of surface topography. The figure reveals that there is a molecular level interaction between the epoxy laminate with the corresponding coating.

2.5 Estimation of Surface Conductance of the Uncoated Laminate

The surface resistance of uncoated laminate was estimated by using megger. The resistance of uncoated epoxy laminate is observed to be 7.142× $10^6\Omega$.

Fig. 4. SEM image of (a) uncoated and (b) coated laminate with copper and titanium nitride higher magnification

In order to know the conductivity of a material, tests are carried out.

$$\rho = \frac{RA}{L} \tag{1}$$

Where:

R = resistance (Ω)

ρ = resistivity ($\Omega \cdot m^2/m$)

L = length (m)

A = area (m^2)

$$\rho = \frac{7.142 \times 10^6 \times 0.1}{0.01}$$

$$\rho = \frac{7.142 \times 10^7 \ \Omega m^2}{m}$$

$$\sigma = \frac{1}{\rho} \tag{2}$$

Where:

σ = conductivity and ρ = resistivity

$$\sigma = \frac{1}{7.142 \times 10^7}$$

$$\sigma = 1.4 \times 10^{-8}$$

The conductance of uncoated epoxy laminate is 1.4×10^{-8} $\Omega m^2/m$.

Previous researchers found the conductivity of IM7 carbon fibers was investigated using C-AFM. The resistivity measurement of IM7 fibers are of (3.2 ± 0.8) x 10-3 Ω-cm, but that result was higher than the expected manufacturer specification of 1.5 x 10-3 Ω-cm[14]. But in this paper, due to titanium nitride coating, electrical conductance of epoxy laminates increases considerably and consequently it may improve protection when subject to lightning strike.

2.6 Estimation of Surface Conductance of the Coated Laminate

The surface resistance of coated laminate was estimated using four probe collinear method. The current was varied from 0.01 to 0.1 A with a difference of 0.01 A. The average conductance of coated epoxy laminate is found to be 17.1745 $\Omega m^2/m$. The currents and corresponding voltages are listed in Table 4. The conductance of uncoated epoxy laminate is observed to be $1.4 \times 10^{-8} \Omega m^2/m$. The conductance of titanium nitride coated epoxy laminate increases up to 17.1745$\Omega m^2/m$. Therefore, due to titanium nitride coating, electrical conductance of epoxy laminates increases considerably and consequently it may improve protection when subject to lightning strike.

TABLE 4. Values of Current and Voltages Used and the Corresponding Resistance Obtained

Points	Current (A)	Voltage(V)	Resistance (Ω)	Conductance (Ω m²/m)
0	0.01	5.26×10^{-4}	5.26×10^{-2}	17.30
1	0.02	1.17×10^{-3}	5.80×10^{-2}	17.24
2	0.03	1.74×10^{-3}	5.80×10^{-2}	17.24
3	0.04	2.34×10^{-3}	5.85×10^{-2}	17.09
4	0.05	2.91×10^{-3}	5.82×10^{-2}	17.18
5	0.06	3.50×10^{-3}	5.83×10^{-2}	17.15
6	0.07	4.09×10^{-3}	5.84×10^{-2}	17.17
7	0.08	4.69×10^{-3}	5.84×10^{-2}	17.17
8	0.09	5.28×10^{-3}	5.86×10^{-2}	17.06
9	0.1	5.84×10^{-3}	5.84×10^{-2}	17.12

2.7 Thermal Insulation Coefficient of Coating Measurement

In this coated carbon fiber-reinforced composite, the exposed surface of the coating layer consists of silicon carbide (SiC) having good oxidation resistance, and the part of the coating layer contacting to the substrate consists of titanium carbide (TiC), zirconium carbide (ZrC) or hafnium carbide (HfC), and the composition of the intermediate layer continuously changes from titanium carbide, zirconium carbide or hafnium carbide of the part contacting to the substrate to silicon carbide of the surface. Accordingly, the coefficient of thermal expansion of the coating layer is larger at the part contacting to the substrate than at the surface. For example, titanium carbide has the coefficient of thermal expansion of 7.6 x 10^{-6} κ, and silicon carbide has the thermal expansion of 4.6 x 10^{-6} κ. In addition, the composition has a gradient and then the coefficient of thermal expansion continuously decreases from the substrate side to the surface in the coating layer. Therefore, not only the surface layer consisting of silicon carbide is not cracked, so that the oxidation resistance and the thermal shock resistance are simultaneously improved.

To impart the oxidation resistance to the composite, it is proposed to apply an oxidation resistant ceramic coating on the surface of composite. However, since a difference between a coefficient of thermal expansion of the composite and that of the ceramic coating is very large, the coating layer tends to be cracked due to thermal stress so that the ceramic coating is peeled off or the strength is greatly decreased. Here in this Lanthanum hafnate ceramic coating is used.

2.8 Lightning Strike Test

A lightning strike test was carried out for exposure times of 0.5 s and 1 s with current and temperature equal to 150 A and 2,500°C on (1) uncoated laminate and (2) laminate coated with titanium nitride as the top layer.

Lightning strike was simulated by exposing the laminate to current of 150A and a temperature of 2,500°C, as listed in Table 5. The time of exposure was chosen such that the overall energy level is as close as possible to an actual lightning strike, in this case, up to 660 kJ. It was not possible to conduct an experiment with higher energy level than 660 kJ due to limitation in the facilities. Therefore, it is recommended to perform this test with a higher energy level up to 2,800 kJ. Damage to the uncoated and coated laminates was visually inspected. It is clearly evident from the figures 5 and 6, that damage created on the coated laminate is much less severe than the damage created on the uncoated laminate. The damage due to exposure time of 10 s is seen on the left of the image and the damage due to exposure time of 1 s is seen on the right of the image. In coated laminate, the damage is not visible on the backside of the laminate. However, in the case of the uncoated laminate, the damage is visible on the back, as seen in figure 6. There sult shows that the coating has improved the thermal stability and electrical conductivity of the epoxy laminate.

TABLE 5. Parameters of Lightning Strike Simulation Test

Value	Parameters of lightning strike simulation
Voltage (V)	440
Current (A)	150
Temperature (K)	2773.5
Time (s)	1 & 10
Energy (V × I × t) (kJ)	660

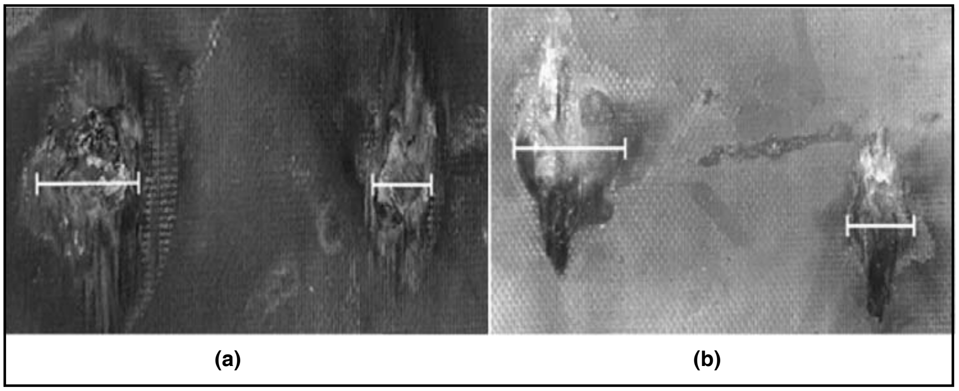


Fig. 5. Damage after lightning test on the front side of (a) uncoated laminate; (b) coated laminate

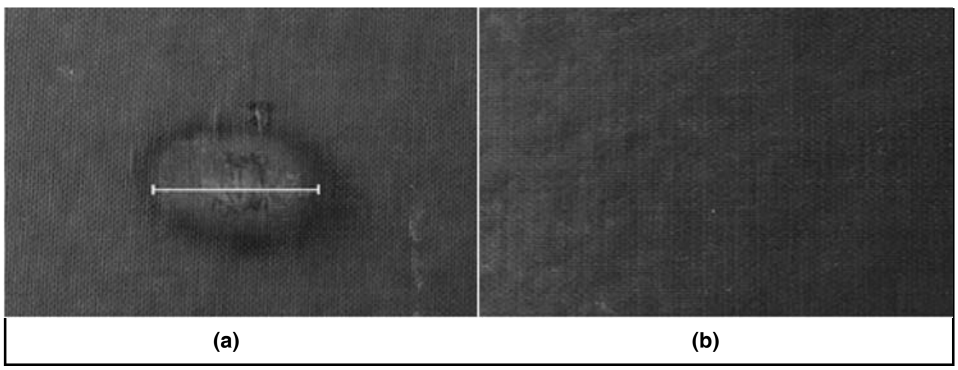


Fig. 6. Damage after lightning test on the back side of (a) uncoated laminate; (b) Coated laminate

3. RESULT AND DISCUSSION

The following section illustrates the results and discussions.

3.1 Measuring the Tensile Strength of Damaged and Undamaged Laminates

Tensile tests were conducted with rectangular specimens with dimension 120 × 25 × 2 mm according to ASTM D638-14. After the lightning test, the damaged specimens were cut according to these dimensions. Tensile testing was carried out using a computer-controlled universal testing machine under a load cell of 50kN. The specimens were loaded in tension at a test speed of 10 mm/min. At each condition five samples were tested, and mean value with standard deviation are reported in the result. The tensile strength of basic and damaged epoxy laminate is shown in Figure 7. The figure reveals that the basic epoxy laminate demonstrates tensile strength of 980 MPa and coated epoxy laminate by copper and titanium nitride possess tensile strength of 1,000 MPa. However, it reduces significantly to 620 MPa when a tensile test is performed after exposure to lighting energy. When the same epoxy laminate is coated by copper and titanium nitride, the damage is not as severe and shows tensile strength of 760 MPa. Therefore, it can be concluded that due to increases in the thermo electrical properties of epoxy laminate under plasma coating of copper and subsequently titanium nitride, the damage to the polymeric composite is marginalized.

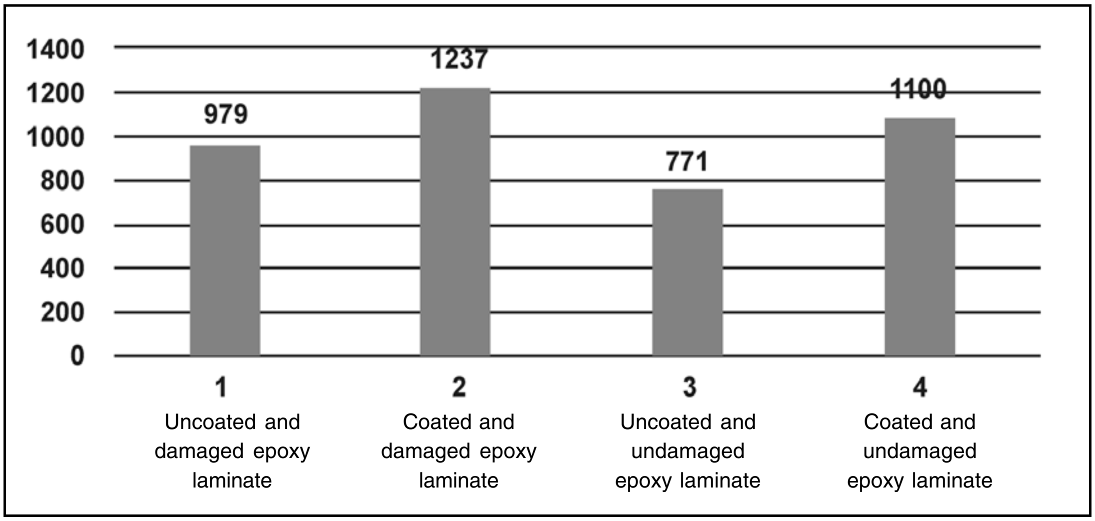


Fig. 7. Tensile strength of basic and damaged without coated, and damaged with coated epoxy laminate

3.2 Non-Destructive Evaluation of Lightning Strike Induced Damages

Non-destructive evaluation of the panels were carried out before and after the simulated lightning strikes by visual inspection and Air-Coupled Ultrasonic C-scanning Testing (AC-UT), with an objective to assess the extent of external/internal damages. AC-UT, a relatively newer and emerging NDT technique, uses ambient air itself as the coolant between probe and the sample. Further, the lower frequencies employed in this new air scan method ensures improved transmission characteristics of the ultrasound through all the materials in general, foams and sandwich composites in particular. The material configuration for the lightning test panels are listed in Table 6.

Table 6 Material configurations for the lightning test panels

Sample No.	Skin material	Protective layer	Lay-up sequence	
			Material	orientation
1	Carbon fabric epoxy (C)	NIL	C	+ (0/90)
2	Carbon fabric epoxy (C)	Copper (Cu) and titanium nitride(TiN)	Cu and TiN	+ (0/90)

The test samples were subjected to air-coupled ultrasonic C scanning both before and after the simulated lightning strikes. The unit consists of SONDA 007CX ultrasonic module with transducers of 120 kHz frequencies. The C-scanning helped to assess the quality of the composite panels before the lightning testing as well as for assessing the damages in the panels after lightning strikes. The gain and attenuation settings used were 60 dB & 71 dB for 120 KHz and 40 dB &77 dB for 225 KHz respectively. The NDT C-scan images of uncoated test panels before and after lightning tests at 120 KHZ are depicted in Figure 8.

The NDT C-scan images of coated test panels before and after lightning tests at 120 KHZ are depicted in Figure 9.

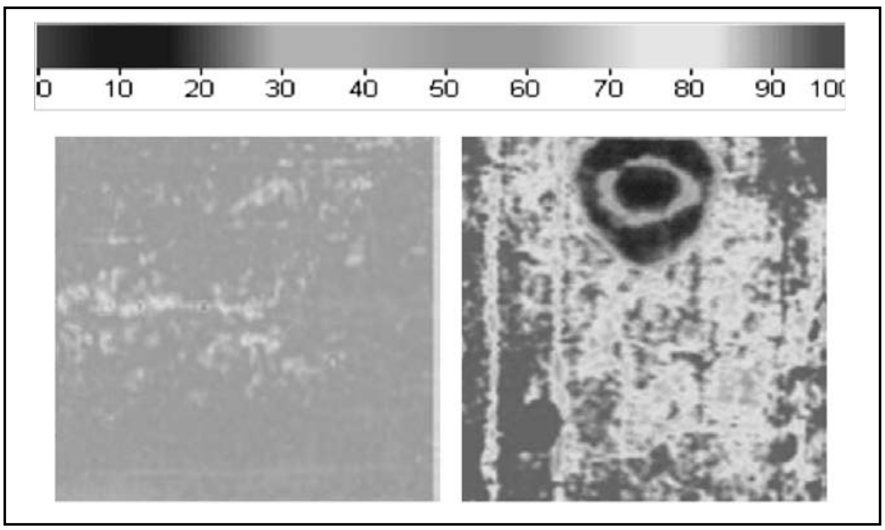


Fig. 8. NDT C-scan images of uncoated test panels before and after lightning tests at 120 KHZ

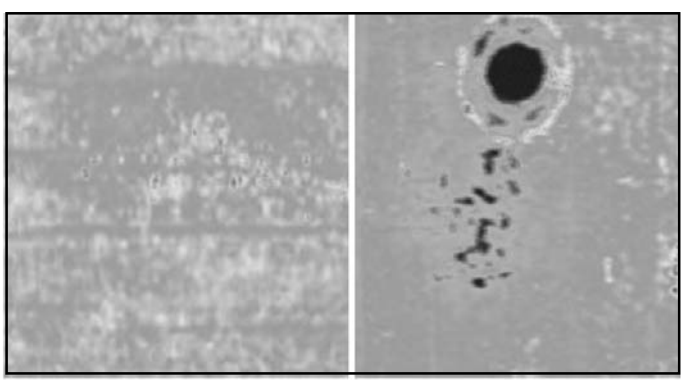


Fig. 9. NDT C-scan images of coated test panels before and after lightning tests at 120 KHZ

As can be seen from the figures, the upper and middle portions of all the panels were the locations of lightning current injections, revealed zones of lower transmissions (i.e. darker patches) after the lightning tests. The distinct patches in the lower middle extremities of some of the panels may be ignored as those were the signatures of the test fixture used during scanning. When compared with the corresponding NDT images of the panels before lightning strikes, the damages induced by the lightning current seem to be localized in nature, being mostly around the area of strike and do not look to have spread to other areas of the panels. As expected, the damages occurred after Zone 1 strikes (A, B and C waveforms in series) were found to be more severe compared to the Zone 3 strikes (only C waveform). Sample without any protection layer, was severely damaged by lightning strike of A, B and C waveforms. NDT of all sample 2 configurations after Zone 1 tests revealed only minimal extents of damages which were of repairable nature and did not pose any threat of catastrophic failure to the structures. For Zone 3 lightning tests, all the configurations, including the unprotected one were found to be acceptable, with very minimal localized damages which are recorded by AC-UT.

4. CONCLUSION

Normally the aircraft industries are mission oriented and continuously striving for better performance of polymeric composites. Therefore, the aim of this project is to increase the conductivity of polymeric composites in order to provide better protection against lightning strikes. Increase in the electrical conductivity depends on the concentration of conductive coating, which has very little risk to increase the weight of aircraft structures. This means that the coating process gives more benefits than the existing aluminums mesh foil method currently used for aircraft with composite fuselage structures. When coated as the top layer, titanium nitride provides better protection against heat and electricity than copper. Use of a coating to provide lighting strike protection will result in increased weight savings, up to 85%, as the coating is lighter than the copper and aluminum meshes currently used. The laminate that is coated undergoes less damage on exposure to high current and temperature when compared to the uncoated laminate. The damaged coated laminate can withstand a higher tensile load than the damaged uncoated laminate.

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