

Enhancing Lightning Resistance Property of Polymeric Composite for Aerospace Applications

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ABSTRACT

Aircraft structures are being redesigned to use fibre-reinforced composites mainly due to their high specific stiffness and strength. One of the main drawbacks from changing from electrically conductive metals to insulating or semi-conducting composites is the higher vulnerability of the aircraft to lightning strike damage. The current protection approach consists of bonding a metal mesh to the surface of the composite structure, but this weight increases negatively impact the fuel efficiency. This paper presents an overview of the lightning strike problematic, the regulations, the lightning damage to composite, the current protection solutions and other material or technology alternatives. The physicothermal characteristics of the polymeric composite were characterized using field electron scanning electron microscopy (FESEM) and Fourier transform infrared spectroscopy (FTIR). Electrical conductivity of the basic uncoated composites was determined using the megger of resistivity measurement. It was observed that electrical conductivity of the composite is low and it can be achieved by increasing the conductivity of polymeric composites in order to provide better protection against lightning strikes. To increase the electrical conductivity on polymeric composite coatings have to be made on the surface of the epoxy laminate by deposition of copper, titanium nitride and nickel on a polymeric composite using physical vapour deposition (PVD) to increase the thermo-electrical properties.

KEYWORDS: *Polymer-matrix composites (PMCs), Electrical properties, lightning strike, conductive coating, Thermomechanical*

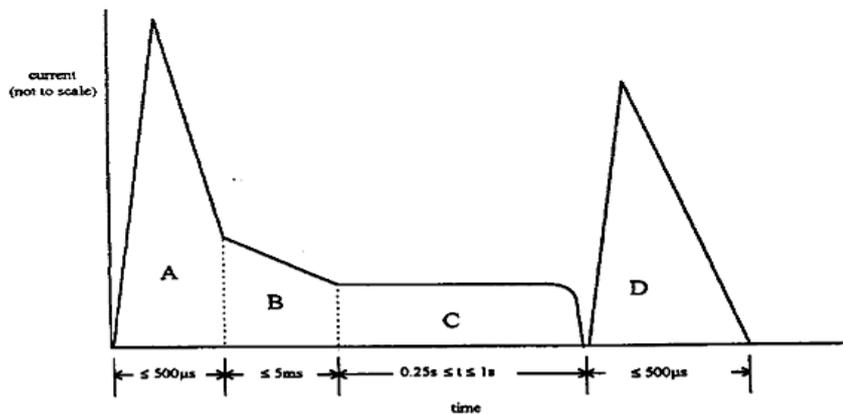
1. INTRODUCTION

With the on-going quest towards more lightweight aircraft and better fuel efficiency, the demand is greater from the aerospace industry to replace conventional materials with composite equivalents. Owing to their high strength to weight ratio, carbon-fibre-reinforced plastics (CFRPs) are already well established and the 20% increase in fuel efficiency that they offer has resulted in substantial fuel savings. The anisotropic electrical conductivity of CFRPs, which is high along the fibres but minimal across them, stems from the arrangement of the different components, with conducting carbon fibres in different orientations reinforced with epoxy to fulfill mechanical strength requirements. This leads to complex electrical phenomena under different external conditions. Anisotropic electrical conductivity also accounts for the unpredictable behavior of CFRPs under lightning strikes and the inevitable damage that arises. The resistivity of CFRP materials is 1000 times higher than that of aluminium, such that a CRFP sample will dissipate 1000 times more energy than an equivalent one made of aluminium for the same lighting current magnitude. The risk of lightning-induced damage is, therefore, much greater for CFRPs as the electrical charge is less readily dissipated. However, polymeric composites have been gaining importance in the aircraft industry for a decade now because of their high specific strength (i.e., low weight 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. However, the major problem with polymeric composites is that they are very poor conductors of electricity. Therefore, due to these poor conductors of electricity, the modern aircraft structure cannot withstand the effects of a lightning strike. An aircraft may get struck by lightning

once or twice a year. A lightning strike to an aircraft structure results in damage to the polymeric composites due to the poor conductive path for electricity to discharge off from the structure.

PROTECTION DESIGN AND VERIFICATION ENVIRONMENT

The lightning environment for aircraft protection design and certification testing has been synthesized from negative and positive natural lightning flash characteristics and includes components designated A, B, C and D. These components are illustrated in Figure and are from the document "Aircraft Lightning Environment and Related Test Waveforms Standard," Committee Report: AE4L-97-4," July 1997.



COMPONENT A (First Return Stroke)	
Peak Amplitude	: 200kA (± 10%)
Action Integral	: $2 \times 10^6 \text{A}^2\text{s}$ (± 20%) (in 500μs)
Time Duration	: ≤ 500μs
COMPONENT B (Intermediate Current)	
Max. Charge Transfer	: 10 Coulombs (± 10%)
Average Amplitude	: 2kA (± 20%)
Time Duration	: ≤ 5ms
COMPONENT C (Continuing Current)	
Amplitude	: 200 - 800A
Charge Transfer	: 200 Coulombs (± 20%)
Time Duration	: 0.25 to 1 s
COMPONENT D (Subsequent Return Stroke)	
Peak Amplitude	: 100kA (± 10%)
Action Integral	: $0.25 \times 10^6 \text{A}^2\text{s}$ (± 20%) (in 500μs)
Time Duration	: ≤ 500μs

Standardized Aircraft Lightning Environment

AIRCRAFT LIGHTNING ATTACHMENT POINTS

A lightning flash initially attaches to, or enters, an aircraft at one spot and exits from another. Usually these are extremities of the aircraft such as the nose or a wing tip. For convenience, these are called initial entry and initial exit points. At any one time, current is flowing into one point and out of another. The "entry" point may be either an anode or a cathode; that is, a spot where electrons are either entering or exiting the aircraft. The visual evidence after the strike does not allow one to resolve the issue and usually no attempt is made. Instead, by convention, attachment spots at forward or upper locations have usually been called entry spots and those at aft or lower locations on the aircraft have been termed exit points. Since the aircraft flies more than its own length within the lifetime of most flashes, the entry point will change as the flash reattaches to other spots aft of the initial entry point. The exit point may do the same if the initial exit spot is at a forward portion of the aircraft. Thus, for any one flash, there may be many "entry" or "exit" spots and the following definitions are used:

- Lightning attachment point: The place where the lightning flash touches (attaches to) the aircraft.
- Initial entry point: The place where the lightning flash channel first "enters" the aircraft (usually an extremity).
- Final entry point: The place where the lightning flash channel last "enters" the aircraft (typically a trailing edge).
- Initial exit point: The place where the lightning flash channel first "exits" from the aircraft (usually an extremity).
- Final exit point: The last place where the lightning flash "exits" from the aircraft (usually a trailing edge).
- Swept "flash"(or "stroke") points: Spots where the flash channel reattaches between the initial and final points, usually associated with the entry part of the flash channel.

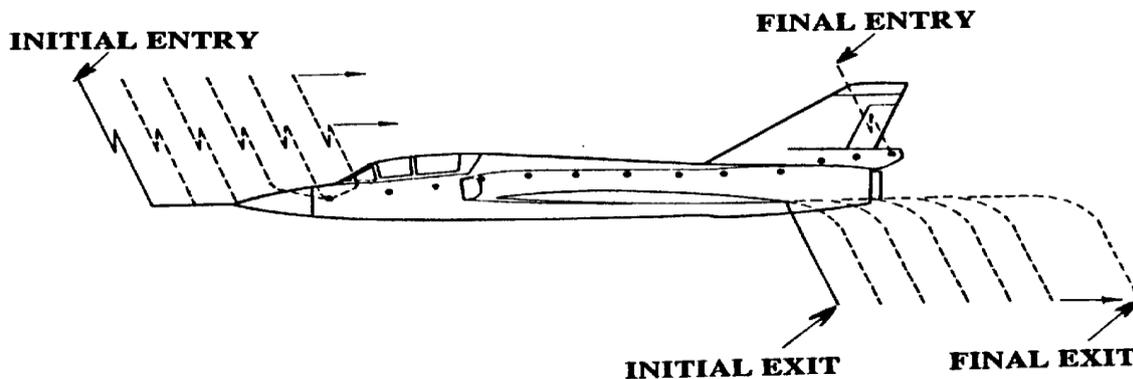
AIRCRAFT LIGHTNING EXPERIENCE

The altitudes at which the reporting projects discussed above show aircraft are being struck shows in figure. This data indicates that there are more lightning strikes begin experienced at intermediate altitudes than at cruise altitudes for transport airplanes. This fact indicates (1) that there are more lightning flashes to be intercepted below about 20,000 ft. than above this altitude, and (2) that jet aircraft are being struck at lower than cruise altitudes: that is, during climb, descent, or hold operations.

It is generally thought that strikes which occur above about 10,000 ft. result from intra-cloud flashes between positive and negative charge centers in the cloud (or between adjacent clouds), whereas strikes below this level are more likely to result from cloud-to ground flashes. Strike incidents occurring above 20,000 ft. occur less frequently because aircraft at these altitudes can more easily divert around areas of precipitation than can aircraft at lower altitudes and most pilots make an effort to avoid regions of convective activity where cumulus tops are greater than 20,000 or 25,000 thousand feet.

SWEPT FLASH PHENOMENA

After the aircraft has become part of a completed flash channel, the ensuing stroke and continuing currents which flow through the channel may persist for up to a second or more. Essentially, the channel remains in its original location, but the aircraft will move forward a significant distance during the life of the flash. Thus, whereas the initial entry and exit points are determined by the mechanisms previously described, there may be other lightning attachment points on the airframe that are determined by the motion of the aircraft through the relatively stationary flash channel. In the case of an aircraft, for example, when a forward extremity such as the nose becomes an initial attachment point, its surface moves through the lightning channel, and thus the channel appears to sweep back over the surface, as illustrated in Fig.

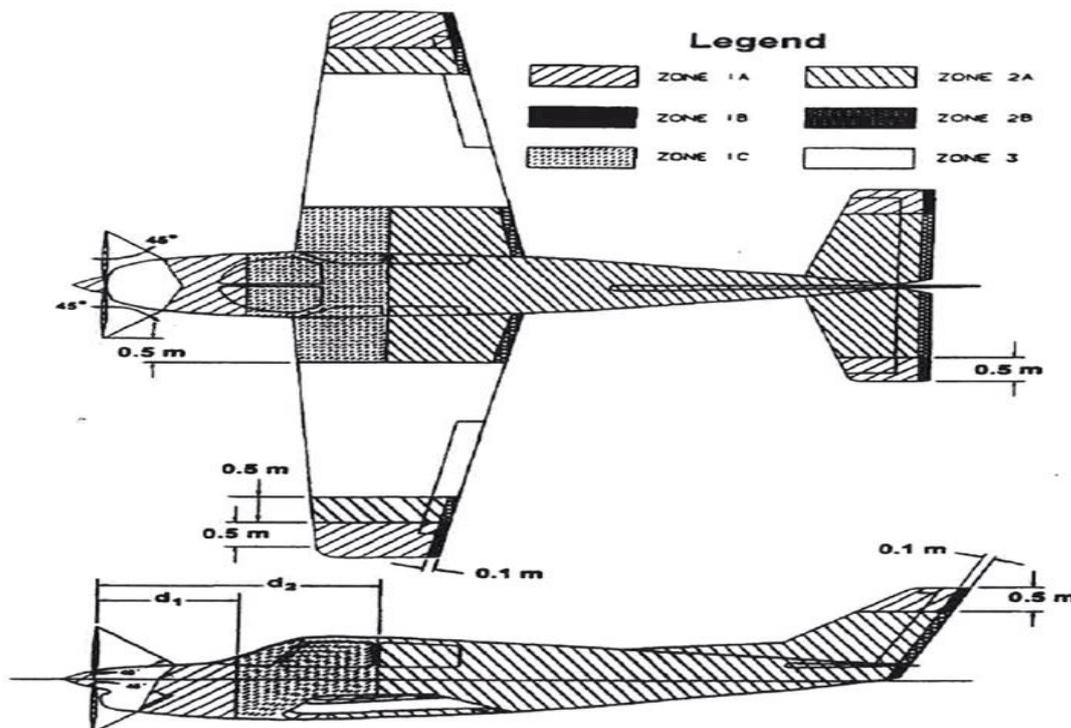


Typical path of swept flash attachment points.

AIRCRAFT ZONING

The aircraft can be divided into three lightning zones as shown below Figure. These zones are defined as follow

- Zone 1: Surface of the vehicle for which there is a high probability of direct lightning flash attachment or exit
 - Zone 1A: Initial attachment point with low probability of flash hang-on, such as nose
 - Zone 1B: Initial attachment point with high probability of flash hang-on, such as tail cone.
- Zone 2: Surface of the vehicle across which there is a high probability of a lightning flash being swept by the airflow from Zone 1 point of direct flash attachments
 - Zone 2A: A swept-stroke zone with low probability of flash hang-on, such as a wing mid-span
 - Zone 2B: A swept-stroke zone with high probability of flash hang-on, such as a wing trailing edges
- Zone 3: Zone 3 includes all of the vehicle areas other than those covered by Zone 1 and Zone 2 regions. In Zone 3 there is a low probability of any direct attachment of the lightning flash arc, but Zone 3 areas may carry substantial amounts of electrical current by direct conduction between some pairs of direct or swept-stroke attachments points in other zones.



Aircraft Zoning

EFFECTS ON AIRCRAFT DUE TO LIGHTNING

The effects caused in the aircraft due to lightning are divided into direct and indirect effects:

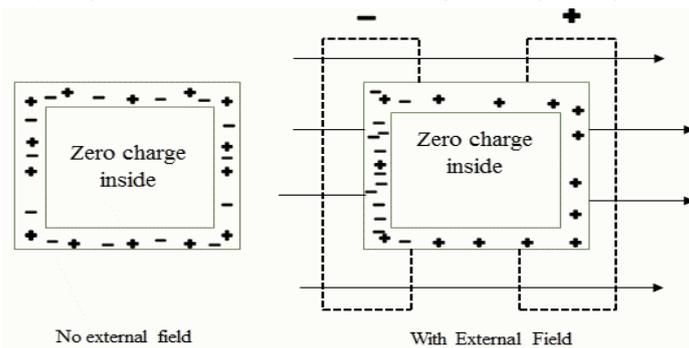
Direct effects: Any physical damage to the aircraft and/or electrical/electronic systems due to the direct attachment of the lightning channel. This includes tearing, bending, burning, vaporization or blasting of aircraft surfaces/structures and damage to electrical/electronic systems.

Indirect effects: Voltage and/or current transients induced by lightning in aircraft electrical wiring which can produce upset and/or damage to component within electrical/electronic systems. Problems caused by indirect effects in cables and equipment are averted by carefully shielding, grounding and the application of surge suppression devices when necessary.

AIRCRAFT - LIGHTNING PROTECTION

FARADAY CAGE

A Faraday Cage is a shell made of an electrical conducting material. If there is a large electric field outside the conducting shell, the electric charges on the shell will move around and redistribute themselves until the electrical field inside the shell is zero. Therefore, a Faraday Cage acts as a shield for large electric fields or for electromagnetic waves. It is an application of Gauss's law, one of Maxwell's equations. Gauss's law describes the distribution of electrical charge on a conducting form, such as a sphere, a plane, a torus, etc. Even if a Faraday cage experiences the large electric field of a lightning strike, the electric field inside the Faraday cage will be zero. Hence a Faraday cage makes an effective shield against lightning strikes.



Principles of Faraday cages

The protection can be divided into three different parts:

- Skin and surface protection
- Protection of radomes and antenna fairings
 - Solid bar diverters
 - Segmented diverters
- Protection of composites with conductive applications
 - Thermal sprayed metals
 - Woven wire fabrics
 - Solid metal foils
 - Expanded metal foils
 - Aluminized fibreglass
 - Conductive paints
 - Metalized fabrics
 - Interwoven wires.

2. PROBLEM IDENTIFICATION

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 variety of matrix materials are commercially available, elevated temperature cured epoxy resins are by far 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 anisotropic and structurally inhomogeneous. It is well established that the composite structures in aircrafts are more susceptible to the lightning damage compared to metallic structures.

- The major problem with polymeric composites is that they are very poor conductors of electricity.
- Due to the poor conductor of electricity, the aircraft structure cannot withstand the effect of a lightning strike.
- All the equipment directly connected with the aerospace structure, which sometimes may result in catastrophic failure.

- If the lightning occurs near the composite fuel tank since the fastener arcing may occur, creating a ignition sources for the fueled volume.
- Lightning current that flows along the body of the struck fastener could be high enough to generate hot particles or gases that may be ejected from the struck fastener into the fuel tank thereby creating a hazard.
- Lightning strikes have great effects on the composite structures including resistive heating at the center of the lightning strike, strong shockwaves and magnetic force effects on electronic systems
- Copper mesh results in a substantial increase in weight, increasing the fuel consumption and decreasing the specific strength.
- Carbon nanotubes are perhaps an alternative but they need to be incorporated during the manufacture of the material, and this method is expensive and inhomogeneous

3. METHODOLOGY

- To identify the problem based on literature survey.
- Based on the problem, identify the conductive coating on the carbon epoxy laminate, which is used as the base material.
- Characteristic of composite material and coated material of copper and titanium nitrate.
- Sample preparation of polymeric composite with sixteen layer of carbon fiberplain weave ply enforced with epoxy resin. Fabrication done by vacuum bag moulding
- Surface Preparation
- Plasma etching was carried out to remove the impurities on the surface of the laminate and to increase the surface energy of the laminate. Argon, which is an inert gas, was used to remove the impurities on the surface under the following operating conditions.
- Physical vapor deposition of copper and titanium nitride on the epoxy laminate was carried out.
- To find the melting and transition temperature of the uncoated laminate, TGA was carried out.
- Study of Functional Groups on Uncoated and Coated Laminates.
- Study of Surface Morphology of Uncoated and Coated Laminates.
- Estimation of Surface Conductance of the Uncoated and Coated Laminate.
- Fabrication of lighting strike test.
- Lightning Strike Test.
- Measuring the Tensile Strength of Damaged and Undamaged Laminates.

SAMPLE PREPARATION OF POLYMERIC COMPOSITE

A carbonfiber plain weave ply, HinFab™ HCP200H (hindoostan composite solution), and a 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 resinof dimensions 100 ×100 mm using a compression moulding. The ratio for resin and hardener is about 4:1 is taken for laminate carbon fiber.



Uncoated epoxy laminate

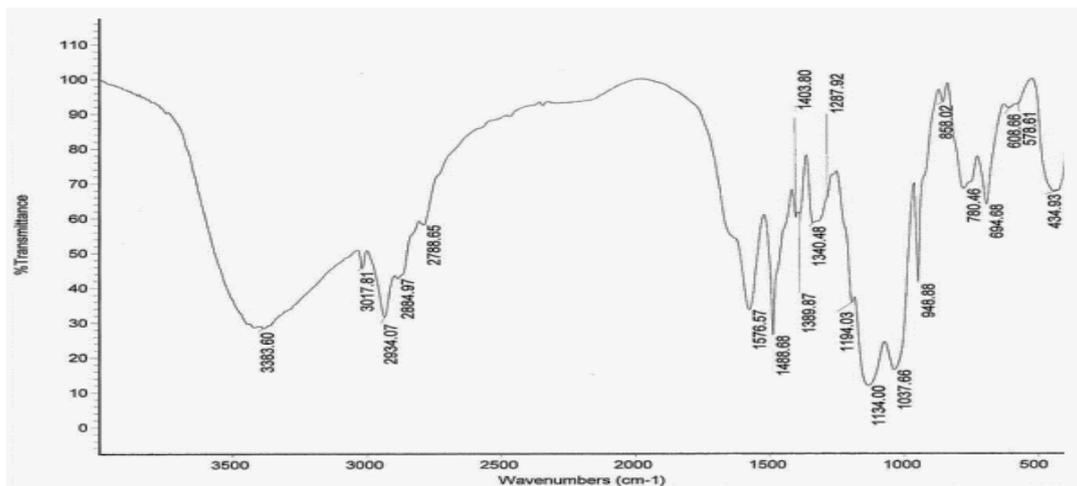
4. RESULT AND DISCUSSION

FUNCTIONAL GROUP OF UNCOATED 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 bonding group of various elements are listed below.

Function Group of uncoated epoxy laminate 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 carboylic acid, esters, ethers
1037.66	C-N stretch	amines
694.68	=C-H stretch	alkenes

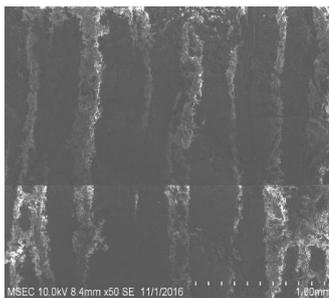


FTIR Spectrum of uncoated laminate

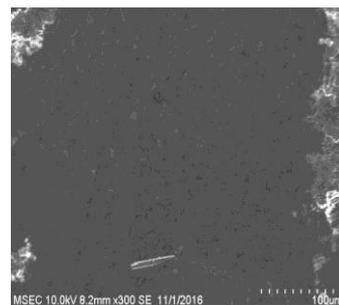
The many peaks seen between the wave numbers 500 and 1,500 cm^{-1} in Fig represent carbon in bonded form, and hence prove non-conductivity.

SURFACE MORPHOLOGY OF UNCOATED LAMINATE

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



SEM image of uncoated laminate 50SE



SEM image of uncoated laminate 300SE



The FESEM of the uncoated epoxy laminate at lower magnification is shown in Fig. and higher magnification is shown in Figure. From the FESEM studies, it is found that the epoxy laminate is uniform up to a certain extent. Crests and troughs are visible on the surface of the coated laminate, which would lead to non-uniform conductivity.

8.3 ESTIMATION OF SURFACE CONDUCTANCE OF THE UNCOATED LAMINATE

The surface resistance of uncoated laminate was estimated using megger. The device enables us to measure electrical leakage in wire, results are very reliable as we shall be passing electric current through device while we are testing. The equipment basically used for verifying the electrical insulation level of any device such as motor, cable, generator winding, etc. This is a very popular test being carried out since very long back.

The resistance of uncoated epoxy laminate is observed to be $7.142 \times 10^6 \Omega$.

Resistivity of an object is a measure of its opposition to the passage of a steady electric current.

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

Where:

R = resistance (Ω)

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

L = length (m)

A = area (m^2)

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

$$\rho = 7.142 \times 10^7 \Omega m^2/m$$

Resistivity is a constant that depends on the materials and the temperature. Inverse of resistivity is called conductivity.

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

Where:

σ = conductivity

ρ = resistivity

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

$$\sigma = 1.4 \times 10^{-8} (\Omega m)^{-1}$$

The materials offer a resistance to the flow of charges, governed by Ohm's Law

The conductance of uncoated epoxy laminate is $1.4 \times 10^{-8} (\Omega m)^{-1}$

5. CONCLUSION

In this work, conclude that the polymeric composite laminate with epoxy having less conductivity and the charge accumulation over the surface is high and this will lead to initiate the lightning strike in aircraft. The aim of this project is to increase the conductivity of polymeric composites in order to provide better protection against lightning strikes. In Phase-II two coatings have to be made on the surface of the epoxy laminate. The epoxy laminate is placed in a vacuum chamber and the surface is treated by plasma etching, after which a copper coating of $1 \mu m$ is deposited on the surface. This is followed by another deposition of titanium nitride and nickel over the copper layer to improve the conductivity on the surface of a polymeric composite.



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