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Analysis of Dielectric Properties of Carbon-Epoxy Composite Laminates

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Abstract

This study highlights the investigation of different dielectric properties of non-interleaved carbon-epoxy and interleaved carbon-epoxy-nylon 66 nanofiber composite laminates. Carbon-epoxy quasi-isotropic composite laminates were developed in an autoclave using A 24-ply AS4/3501-6. Nylon-66 solution of 12 wt.% was prepared in dissolving crystals of Nylon-66 in the 90% formic acid and chloroform mixture with the weight ratio of 75/25, respectively. The nano fabric was developed by electro-spinning technique using prepared Nylon-66 solution. The fabric of 0.7g/m^2 average aerial density and composite ply (AS4/3501-6) of 260 g/m^2 average aerial density were observed. The interleaved laminates were developed using a nylon-66 nanofiber layer between the adjacent laminate flies. Measurement of some of the dielectric properties like dielectric constant, tan δ, and ac conductivity of the interleaved composite laminates was done at the frequency of range from 20 Hz to 10 MHz. Improvement in the different dielectric properties of the interleaved composite laminates was observed with the addition of a small wt.% of Nylon-66 nano fabric between the alternate layers of carbon-epoxy composite. A possible mechanism involved in the improvement of dielectric properties in the nanocomposites was reported in this paper.

Keywords: Carbon Fiber, Composite Laminates, Electro-Spinning, Interleaving

1.0 Introduction

Advanced polymer composites made from carbon fibers and epoxy resins are used in emerging engineering applications like Electromagnetic Interference (EMI) shielding, static dissipation of electricity, capacitive reactance components, and electric heaters. There is a great demand for laminated composites made by bonding of micro-structured lamina and nano-structured laminates in fiber-reinforced polymers to modify the electrical properties of conductive composites. This has led to widespread applications, especially in the electronic industries and space instrumentation.

The anisotropic behavior in the electrical properties of continuous fiber composites was observed by several researchers[1-3]. It is observed that the ply stacking sequence and fabrication techniques used play a major role in Carbon Fiber-Reinforced Polymer (CFRP) electrical

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characteristics. Ply stacking sequences of Quasi-Isotropic (QI) normally consisting of a combination of three different ply angles (0°, ±45°, and 90°) are typically used for aerospace applications, wherein the angles formed are relative to the applied load direction. The unidirectional (UD) conductivity of the CFRP panels was discussed in the papers[4-9]. The high and low conductivity of UD CFRP panels were observed in the direction of the fiber orientation and in the fiber transverse direction respectively indicating low-loss dielectric characteristics. The impact of epoxy used and fiber dimensions on these dielectric characteristics was observed. In contrast to this, high conductivity in all directions was observed in QI panels[8]. To overcome the above drawbacks, the current study is focused more on the frequency and temperature effect on different dielectric properties of the base, non-interleaved, and interleaved type carbon-epoxy composite laminates. The results of all three laminates are compared in this paper.

2.0 Experimental

2.1 Materials

To analyze the interleaving effect of Nylon-66 nanofiber on different dielectric properties, Hexcel Composites manufactured AS4/3501-6 prepreg was used as the base material. DuPont Company manufactured Nylon-66 of Zytel101 and MW of 20,000 g/mol was used to fabricate the non-woven nano fabric by electro-spinning technique[10,11]. Nylon-66 is known to be highly elongated to fracture and has better adhesion to the matrix. Also, has a melting temperature of about 250°C which is normally more than AS4/3501-6 (base laminates) curing temperature of about 177°C. The Nylon-66-based fibers will not be affected by composite laminate curing processing time because of their excellent properties.

2.2 Preparation of Panels and Test Specimens

The 24-ply laminates were made using a stacking sequence [-45/90/45/0] of quasi-isotropic laminate. One layer of the nano fabric was placed between the two continuous layers of prepreg and nano fabric layers were also placed at the laminate top and bottom surfaces to prepare the interleaved laminates. These laminates were prepared based on the procedure suggested by the prepreg supplier using an autoclave. The interleaved laminates of average thickness of about 4.15 mm and base laminate (AS4/3501-6) of average thickness of about 4.14 mm were observed. The difference of 0.2% in average thickness was also observed between the interleaved AS4/3501-6 laminates and the base matrix. The sample notations used to represent interleaved composite laminates (P2-11) and base laminates (PP-1) of carbon-epoxy composite laminates will be recalled in the results and discussion part.

2.3 Measurements

A high-frequency LCR meter (6500P, Wayne Kerr model) was used to measure the values of capacitance, tan δ, and conductance at the frequency range of 20Hz to 10MHz. The ε' (Dielectric constant) and the σ_{ac} (AC conductivity) were calculated by using the measured specimen thickness and the specimen electrode contact area.

3.0 Results and Discussions

The effect of a frequency on ε', tan δ, and σ_{ac} of base and interleaved composite laminates at different temperatures are discussed.

3.1 Dielectric Constant

Dielectric constant variation with frequency at different ranges of temperatures such as 30°C, 60°C, and 90°C respectively is shown in Figures 1 (a) and (b). The plot indicates a decrease of ε' up to 1 MHz for base laminates, and up to 3 MHz for interleaved composite laminates, thereafter increasing up to the measured frequency. The changes in the electric field due to polarization, minimum loss, and maximum ε' are observed at 20 Hz frequency[12]. Space charge polarization occurs at the interfaces in conducting polymer composites as the conducting fibers are covered with the insulating matrix. This is supported by the Maxwell-Wagner model and also by the space charge polarization concept. Due to the charge accumulation at the interfaces, the interfacial polarization may also occur at the interfaces at a lower frequency[13]. When voltage is applied to the polymer composites made of fillers and polymer matrix having different conductivity leads to the formation of layers of electric charges at the interfaces at low frequency. The interfacial polarization occurs due to this increase in the dielectric constant. The change in the electric field is very quick for the polarization effects appeared at high frequency (1 MHz and 3 MHz). However, the exchange of electrons

will not take place at the conditional frequency of the applied electric field[14], and therefore dielectric constant decreases due to decrement in the polarization.

The ε′ increases with an increase in temperature in the base laminate. But in the interleaved composite laminates, ε′ decreases with an increase in temperature (30-90 °C). A gradual increase in ε′ as the temperature increases is mainly because of the increment of polarization and ionic conductivity at the interface. Also, an increase in polymer chain segmental mobility resulted in changes in the conductive network motion, and this in turn resulted in changes in the dielectric properties. Further, dielectric properties are adversely affected due to the thermal expansion difference in the polymer matrix, which is normally higher than the conductive filler. Furthermore, the net effect will contribute to both positive and negative contributions especially when temperature increases[15]. A decrease in ε′ for interleaved composite laminates was observed. This is due to the dipoles present in the composite which normally cannot reorient themselves in higher speed and hence decrease in the dielectric constant.

3.2 Dissipation Factor

A slight decrease in tan δ values is observed in the frequency range from 20 Hz to 10 KHz and a slight increase is observed after 10 KHz for base laminate. However, a decrease in tan δ values was observed as the frequency increased from 20 Hz to 1 KHz, beyond that, the tan δ value increased for the interleaved composite laminates. This is due to the gradual failure of induced charges in following the reversed field. This in turn reduces the electronic oscillations as the frequency increases[16]. The anomalous behavior of composites can be observed based on the increase of tan δ values as the frequency increases.

Figures 2 (a) and (b) show the frequency dependence of tan δ at different temperatures. It is observed that in Figure 2(a) with an increase in temperature, tan δ increases in base laminates whereas, in the case of interleaved composite laminates tan δ values decrease with an increase in the frequency range 20 Hz - 10 MHz as shown in Figure 2(b). The increase in tan δ as temperature increases because of the increase in the relaxation rate resulted from thermally activated charge carriers. The local motion for polar

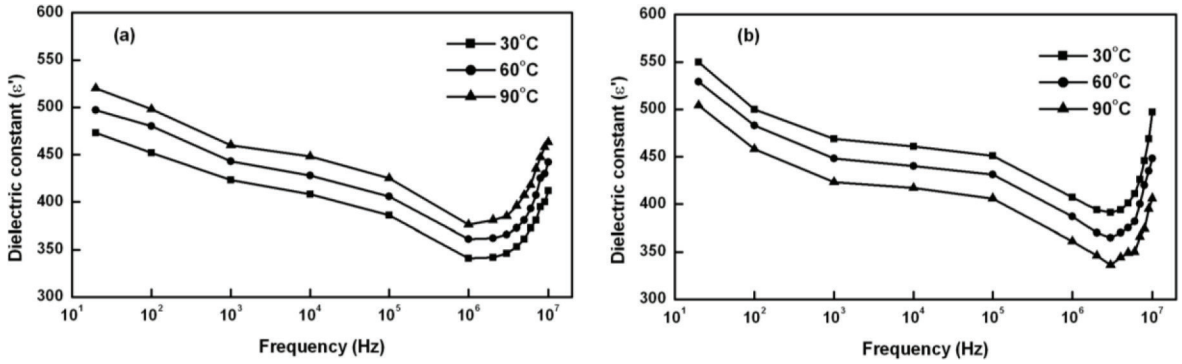


Figure 1. Dielectric constant variation with frequency and temperature of (a) base laminate and (b) interleaved composite laminate.

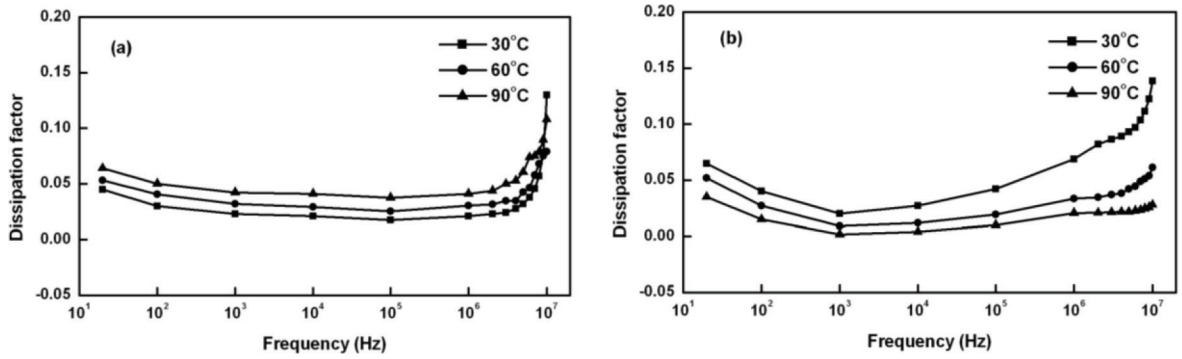


Figure 2. Variations of dissipation factor with frequency and temperature of (a) base laminate and (b) interleaved composite laminate.

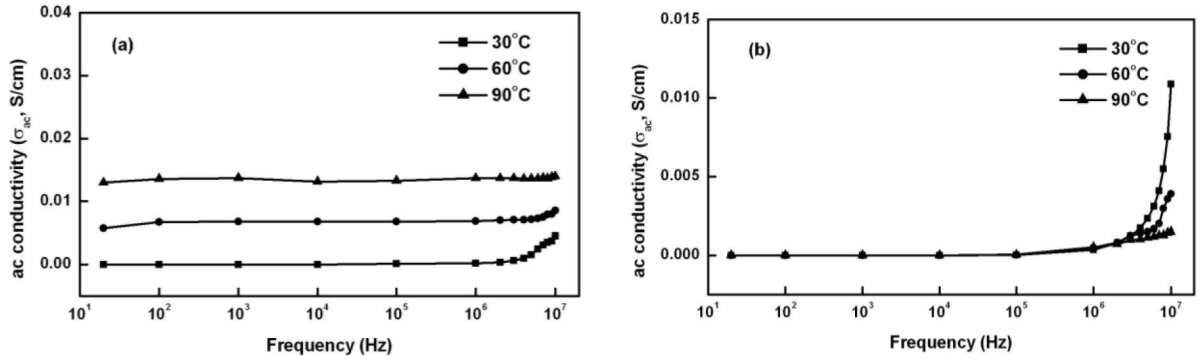


Figure 3. AC electrical conductivity variation with frequency and temperature of (a) base laminate and (b) interleaved composite laminate.

groups increases the relaxation process which in turn varies the tan δ with frequency. Higher dielectric loss at higher frequencies is observed at lower frequencies due to the synchronization of dipole orientation with the field. Also, molecular inertia and binding forces become more effective as the frequency is increased and this will increase the dielectric loss at higher frequency[17]. For both base and interleaved composite laminates, the dissipation factor shows an increasing trend at higher frequencies due to the enhanced molecular mobility, dipolar rotation, interfacial polarization, and space charge polarization produced from the sample electrode interface.

3.3 AC Conductivity

Figure 3 (a) and (b) indicate the variation of σ_{ac} of base and interleaved laminated composites with frequency and temperature.

Conductivity remains almost constant up to 2 MHz, thereafter a considerable increase in conductivity is observed. This result clearly indicates that conductivity depends largely on high frequency and shows limited variation at lower frequencies. This mechanism may be due to the resistive conduction occurring in the bulk composite tunneling between carbon and epoxy. Further, conductivity is proportional to frequency due to the carbon, epoxy matrix, and that between the conducting fibers capacitance at higher frequencies. Furthermore, a continuous conductive network is formed due to more number of closed conductive fibers in these composites. This resulted significant increase in conductivity which in turn increases the conductivity of the composite after a critical frequency.

The conductivity increases as the temperature increases. This may be due to an increase in the charge carrier mobility in the base composite laminate. However, no significant effect of temperature on conductivity is observed for the interleaved composite laminates.

4.0 Conclusions

The conclusions drawn based on the observations made in the present investigation as follows.

- The dielectric constant increases by 14 % with carbon-epoxy interleaved composite laminates as compared to carbon-epoxy composite (base) laminates.
- High dielectric constant and low dissipation factor were observed for carbon-epoxy composite (base) laminates and carbon-epoxy interleaved composite laminates.
- There is a significant effect of temperature and the least effect of frequency on AC conductivity was observed in the case of carbon-epoxy composite (base) laminates.
- However, there is no significant variation of ac conductivity was observed for carbon-epoxy interleaved composite laminates due to variations in frequency and temperature.
- Finally, the dielectric properties of carbon-epoxy base and interleaved composite laminates are dependent on measured frequency and temperature range.

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