CARBON FIBER POLYMER-MATRIX COMPOSITES AS CAPACITORS

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Introduction

Capacitors are important elements in electrical circuits, although they tend to be more bulky than other elements, such as resistors, diodes and transistors, and their high frequency performance remains an issue. The bulkiness is of particular concern when a large capacitance is required. Capacitors based on electric double layers cannot operate at a high frequency, so capacitors based on dielectrics are most common for electronics. This paper is focused on capacitors based on dielectrics.

Capacitors based on dielectrics are conventionally parallel-plate capacitors in which a dielectric is sandwiched by electrically conducting plates. The dielectric material can be paper [1], polymer [1], a high dielectric constant ceramic such as barium titanate in thin film or thick film forms [2], or other electrically insulating materials. The conducting plates are commonly metals in foil, thick film or thin film forms [1,2]. To achieve a high capacitance, the conducting plates are large in area, the dielectric is low in thickness, and numerous layers of dielectric and conducting plates are alternatively stacked (and usually wound to save space).

This paper provides a new type of parallel-plate capacitor, namely carbon fiber polymer-matrix composites in which continuous carbon fiber layers serve as the conducting plates and paper (placed between the fiber layers), together with the polymer matrix, serves as the dielectric. Carbon fiber polymer-matrix composites are structural materials that are important for lightweight structures, such as aircrafts, automobiles, sporting goods, wheel chairs, etc. The ability of these composites to serve as capacitors and other circuit elements means that the structure is itself the electronics, so that the electronics "vanish" into the structure. Electronics made from structural materials such as carbon fiber polymer-matrix composites and concrete constitute a new field of electronics called structural electronics [3]. In the case of continuous carbon fiber polymer-matrix composites, the carbon fibers are the conductors (resistors) and they can be intercalated to become electron metals or hole metals [3]. By having the electronics vanish into the structure, space is saved. The space saving is particularly valuable for capacitors of large capacitance. Due to the large area of a structure and the numerous fiber layers in a composite laminate, the capacitance in a composite structure can be very large. In addition to space saving, structural electronics have the advantage of being mechanically rugged and inexpensive, since structural materials are necessarily rugged and inexpensive. The use of a structure as a capacitor is particularly valuable in conjunction with structures that are powered by solar cells, as the structure (capacitor) can be used to store the electrical energy generated by the solar cells.

Experimental methods

Epoxy-matrix composites comprising four continuous unidirectional carbon fiber layers were constructed from individual layers cut from a 12 inch wide unidirectional carbon fiber prepreg tape manufactured by ICI Fiberite (Tempe, AZ). The product was Hy-E 1076E, which consisted of 976 epoxy matrix and 10E carbon fibers. The matrix was electrically insulating, whereas the fibers were electrically conducting, with a resistivity of 2.2×10^{-3} Ω.cm.

The composite laminates were laid up in a 0.5 inch (13 mm) diameter steel compression mold with laminate configuration $[0/90]_2$ (i.e., four unidirectional fiber layers stacked in the sequence [0/90/0/90]). The individual fiber layers were cut from the prepreg tape. A liquid mold release was used. The laminates were cured using a cycle based on the ICI Fiberite C-5 cure cycle. Curing occurred at 355 ± 10°F (179 ± 6°C) and 89 psi (0.61 MPa) for 120 min. Then the samples were sanded to a rectangular shape (about 8 x 8 mm; the exact dimensions were measured for each sample in order to calculate the area of the rectangle) for capacitance measurement.

Composites without interlayer (additive between the fiber layers) and with various types of dielectric interlayers were fabricated. In a composite with an interlayer, the interlayer was placed between the second and third fiber layers in the stack of four fiber layers. The interlayers were paper and barium titanate thick film. The interlayer thickness after composite fabrication was determined by cross-sectional optical microscopy. The barium titanate thick film was applied as a paste, which was made by mixing barium titanate powder (1 μm size, from TAM Ceramics Inc., Niagara Falls, NY) and epoxy (Epon Resin 862 and EPI-Cure 3274 Curing Agent from Shell Chemical Co., Houston, TX). The barium titanate powder was in amounts ranging from 17 to 80 vol.% of the paste. The epoxy from the prepreg layers penetrated the paper (tissue, bond or writing) interlayer, which was porous, during the composite fabrication.

Capacitance (for the sample capacitance and sample resistance in parallel) measurement was made using a precision RLC capacitance meter (Model 7600, QuadTech, Inc., Marlborough, MA) at frequencies ranging from 10 Hz to 2 MHz. During the measurement, the rectangular sample (mechanically polished on the rectangular faces) was sandwiched by two copper disks (mechanically polished on the circular faces) of diameter 0.5 inch (13 mm). The sandwich was held together by pressure provided by a clip.

Results and Discussion

Due to the touching of the fibers of the two fiber layers, the through-thickness conductivity was too high for meaningful capacitance measurement for the composite without interlayer, the composite with tissue paper interlayer and the composite with barium titanate thick film (without paper) interlayer. The use of a writing paper or bond paper interlayer was sufficient for avoiding the fibers of one layer to touch those of the other layer, but the use of tissue paper or barium titanate thick film interlayer was not. The fibers were not able to go through the writing paper or bond paper, even though the epoxy matrix was able to penetrate the paper. (The penetration of epoxy is desirable for the mechanical integrity of the composite.) As a result, only composites with a writing paper or bond paper interlayer could serve as capacitors.

The highest capacitance per unit area (1.2 $\mu F/m^2$) was attained by using writing paper alone as the interlayer. The use of bond paper as the interlayer gave lower capacitance per unit area (0.5 $\mu F/m^2$) due to the larger interlayer thickness. The combined use of writing paper and barium titanate as the interlayer also gave lower values of the capacitance per unit area (up to 0.9 $\mu F/m^2$ at 2 MHz) than the use of writing paper alone. By using a paste with 80 vol.% barium titanate, the relative dielectric constant attained the highest value of 19.8, but the large thickness of the interlayer (resulting from the low workability of this paste) caused the capacitance per unit area to be low (0.7 $\mu F/m^2$). Therefore, the use of a barium titanate interlayer is not attractive, whatever is the volume fraction of $BaTiO_3$ in the paste.

Conclusion

Carbon fiber epoxy-matrix composite was found to be a parallel-plate capacitor with capacitance 1.2 $\mu F/m^2$ at 2 MHz, if the composite contained a writing paper interlayer of thickness 0.04 mm. The further addition of a $BaTiO_3$ thick film to the interlayer decreased the capacitance due to the increase in interlayer thickness. Without an interlayer or with a more porous paper interlayer, the composite was conducting in the through-thickness direction. The capacitance of the epoxy impregnated paper (0.10 mm thick) was 0.21 $\mu F/m^2$. The high capacitance for the composite with paper interlayer is partly due to the large area of the surface of a fiber layer; this area is two times that of the flat area. The high capacitance is partly due to the reduction in the paper thickness during composite fabrication.

References

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