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Measurement and Tailoring of Composite Electrical Properties

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Deep dielectric charging and subsequent electrostatic discharge in composite materials are growing concerns as these materials are used ever more extensively in spacecraft. A previous study showed that electric properties are critical to this problem. The goals of the current investigation are 1) experimental measurements of the continuum electrical properties of a carbon fiber/epoxy composite and 2) the creation of a composite with electrical properties that can be tailored without affecting its mechanical properties. The measurement of the conductivity and dielectric strength of carbon fiber/epoxy composites showed that these properties are difficult to measure, are dominated by details of the composite microstructure, and should not be treated as continuum properties. Conversely, a tailorable glass fiber/epoxy system was created by adding conductive carbon black to the epoxy. This material has consistent and measurable properties. It has conductivity variable over three orders of magnitude, and dielectric constant variable by a factor of 16, with good dielectric strength and mechanical properties.

Nomenclature

A	=	cross-sectional area, m^2
C	=	capacitance, F
E_{max}	=	dielectric strength, V/m
E_{mech}	=	Young's modulus, MPa
h	=	thickness, m
h_{SL}	=	surface layer thickness, m
l	=	length, m
m	=	mass, kg
P	=	load, N
P_{fail}	=	failure load, N
R	=	resistance, Ω
t	=	time, s
V_{BD}	=	breakdown voltage, V
Vol	=	volume, m^3
$V(t)$	=	voltage, V
V_0	=	initial voltage, V
X_1, X_2, X_3	=	laminate coordinates
x', y', z'	=	ply coordinates
Δl	=	change in length, m
ε_{max}	=	failure strain, dimensionless
ε_{X1}, ε_{X2}	=	strain in X_1 and X_2 directions, dimensionless
ε_0	=	permittivity of free space, $C^2/N\text{-}m^2$
θ	=	ply angle, rad
κ	=	dielectric constant, dimensionless
ν	=	Poisson's ratio, dimensionless
ρ	=	density, kg/m^3
σ	=	conductivity, $1/\Omega \cdot m$
σ_{max}	=	failure stress, MPa
σ_{SL}	=	conductivity of surface layer, $1/\Omega \cdot m$
σ_{X1}	=	stress in X_1 direction, MPa
τ	=	time constant, s

Introduction

THE charging of spacecraft and its possible role in spacecraft anomalies due to electrostatic discharges are well-known problems. Charging is caused by energetic particles in the space environment: electrons, protons, and positively charged heavy ions. There are three types of charging: entire vehicle charging, surface charging, and internal charging, also known as deep dielectric charging. Entire vehicle charging is when the entire potential of the spacecraft is raised. Surface charging is when only the potential of the spacecraft surface is raised; however, this may also occur locally where only part of the surface has its potential raised due to geometric and material considerations. Deep dielectric charging is like surface charging, except that the potential increase is not on the surface of the spacecraft component but inside the material of the component. The last two types are a concern for composite material structures, and the last type, deep dielectric charging, is the focus of this research.

Composites are replacing metals, such as aluminum, as the structure of spacecraft, due primarily to their higher stiffness-to-weight ratios. Composite laminates are made up of multiple layers or plies, which are in turn made up of fibers and a matrix material that surrounds the fibers. Fiber and matrix materials can have drastically different properties. By varying fibers and matrices used and the stacking sequence of the plies (Fig. 1), one can change properties of the laminate. The ply angle is defined as the angle between the laminate coordinate system and the ply coordinate system. The laminate coordinate system is arbitrarily assigned to a structural direction, for example, the length of a solar panel array, and the ply coordinate system is aligned with the fiber direction (Fig. 2). A laminate is usually specified by listing the ply angles of each ply; a [0/±45/90] laminate is shown. The laminate properties can be calculated based on the ply properties and the ply angles using classical laminated plate theory (CLPT).[1,2]

Motivation

Analyses performed using CoDDCA, a code developed in-house to investigate deep dielectric charging of composite materials,[3] showed that the key material parameters in controlling deep dielectric charging are the through-thickness conductivity and dielectric strength of the material. A review of existing data on these properties shows a wide range of values[4] and no thorough investigation of the effects of layup, test sample geometry, etc., that might explain this variation.

Sensitivity studies[3] showed that the deep dielectric charging problem is particularly sensitive to the exact value of conductivity in insulating materials. Ultralow conductivity materials such as some fiberglass/epoxy composites are most likely to be involved in a discharge event, and increasing their conductivity even slightly can reduce the likelihood of an electrostatic discharge. Therefore, a composite system is desired with through-thickness electrical properties that can be tailored without greatly affecting the composite's mechanical properties. Such material could, for example, have a low level of conductivity tailored to be sufficient to bleed off deep dielectric charging without compromising its role as an electrical insulator.

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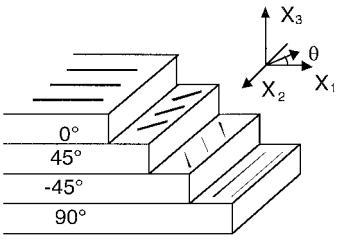

Fig. 1 Laminate and its coordinate system.

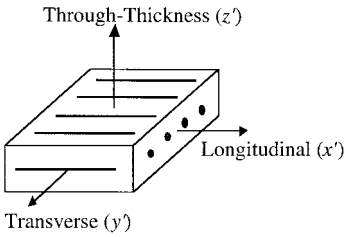

Fig. 2 Ply and its coordinate system.

Experiments

This section will present the geometry of the tests performed and the equations used to reduce the data. The detailed test procedures are presented in the next section.

The geometry of the electrical test samples, used to measure conductivity, dielectric constant, and dielectric strength, is shown in Fig. 3. The sample may be made from a number of plies, but the microstructural details are ignored and the sample is treated as a continuous material of thickness h. As will be seen later, one detail could not be ignored, the presence of a surface layer of pure epoxy left by manufacturing of thickness h_{SL}. The conductivity and dielectric constant samples are clad in a very highly conductive coating prior to testing.

The geometry of the mechanical test samples, used to measure Young's modulus, Poisson's ratio, ultimate stress, and failure strain, is shown in Fig. 4. The through-thickness conductivity of the sample is calculated as

$$\sigma = h/RA \tag{1}$$

where R is the measured resistance across the sample.

The resistance of some samples could not be directly measured. Instead, they were treated as resistance–capacitance (RC) circuit. The voltage across the sample as it discharges is given by

$$V(t) = V_0\, e^{-(t/\tau)} \tag{2}$$

where τ is the RC circuit time constant defined as

$$\tau = \mathrm{RC} \tag{3}$$

In some cases, it was postulated that the resistance due to the surface layer was much greater than that due to the rest of the composite. In these cases, Eq. (1) is modified, replacing the sample thickness h with the total thickness of surface layers:

$$\sigma_{\mathrm{SL}} = 2h_{\mathrm{SL}}/RA \tag{4}$$

The dielectric constant of the sample is defined as

$$\kappa = Ch/\varepsilon_0 A \tag{5}$$

The dielectric strength of the sample is defined as

$$E_{\max} = V_{\mathrm{BD}}/h \tag{6}$$

where V_{BD} is the voltage applied to breakdown the material. To calculate the dielectric strength of the surface layer, we use Eq. (6), replacing the sample thickness h with the total thickness of surface layers:

$$E_{\max} = V_{\mathrm{BD}}/2h_{\mathrm{SL}} \tag{7}$$

The density is defined as

$$\rho = m/\mathrm{Vol} \tag{8}$$

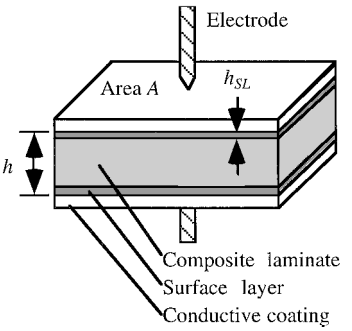

Fig. 3 Electrical test specimen.

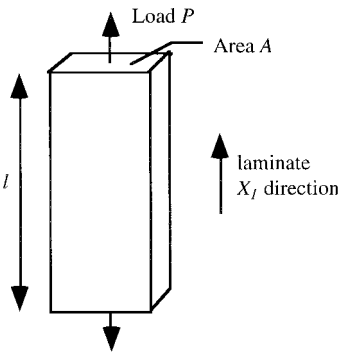

Fig. 4 Mechanical test specimen.

The Young's modulus is defined as

$$E_{\mathrm{mech}} = \sigma_{X1}/\varepsilon_{X1} = P/A\,\varepsilon_{X1} \tag{9}$$

where σ_{X1} is the stress due to the applied load, ε_{X1} is the strain due to the applied stress, and P is the load applied to the material. The Poisson's ratio is defined as

$$\nu = -\varepsilon_{X2}/\varepsilon_{X1} \tag{10}$$

where ε_{X2} is the strain perpendicular to the direction of the applied load and ε_{X1} is the strain in the direction of the applied load. The failure stress is the maximum stress in the material before failure:

$$\sigma_{\max} = P_{\mathrm{fail}}/A \tag{11}$$

where P_{fail} is the load applied to the sample at failure. The failure strain is

$$\varepsilon_{\max} = \Delta l/l \tag{12}$$

Procedures

There are two separate experimental efforts described in this paper. The first is the investigation of the conductivity and the dielectric strength of a carbon fiber/epoxy composite. The second is the creation of a conductivity tailorable composite material using a fiberglass/epoxy composite. The two material systems used in this investigation are a Hercules AS4/3501-6 tape prepreg and a woven fabric wet layup fiberglass/epoxy. The first material system, AS4/3501-6, is a unidirectional prepreg and has a first-generation brittle (low strain-to-failure) 3501-6 matrix, which has been widely used in the aerospace industry. The second system comprises a unidirectional woven fiberglass cloth type 1543-38 prepared in a wet layup with Rutapox L20/SL resin. This system is being used in the aircraft industry by Grob Aerospace of Germany in their general aviation aircraft. Neither of these systems is extensively used in satellites. They were selected based on availability and processability in the available facility. They are representative of two broad classes of materials of interest: generally conductive (carbon fiber/epoxy) and generally insulating (fiberglass/epoxy) composites.

The through-thickness electrical properties of composites made of carbon fiber/epoxy prepreg were investigated. The composite parameters that were investigated were the laminate thickness, the laminate stacking sequence, and the sample cross-sectional area. Three different thicknesses were used, 4, 8, and 32 plies, corresponding to

approximately 0.5, 1.0, and 3.8 mm thick, respectively. Two different stacking sequences were used, $[0_n]$ unidirectional and $[0/\pm 45/90]_{ns}$ quasi isotropic. Here, n indicates repeating the ply angle sequence as many times as necessary to get the required thickness, and s indicates that the laminate is made symmetric about its midplane by repeating the ply angle sequence in reverse order. With four plies, a symmetric quasi-isotropic laminate cannot be produced, and so $[\pm 45]_s$ was used. The cross-sectional areas used for the conductivity samples are 25.4 × 25.4 mm (1 × 1 in.), 25.4 × 50.8 mm (1 × 2 in.), and 50.8 × 50.8 mm (2 × 2 in.), corresponding to approximately 645, 1290, and 2580 mm^2. All of the dielectric strength samples were 25.4 × 25.4 mm.

One 152.4 × 177.8 mm (6 × 7 in.) laminate of each layup was manufactured, and samples were cut from each panel. Three replicate samples were used for each test. The conductivity investigation required 6 laminates and 3 sample areas, resulting in 18 sample types and a total of 54 samples. For the dielectric strength investigation, 6 laminates but only 1 area were required, resulting in 6 sample types and a total of 18 samples. The thickness was measured in five different locations, and the area was calculated by measuring the length and width in three different places. Each sample was measured three times for electrical properties.

To investigate the development of a conductivity-tailorable composite, a glass fiber/epoxy wet layup procedure was used. Carbon black was added to the epoxy in five different percentages by mass: 0, 5, 10, 15, and 20%. The electrical properties measured included the conductivity, dielectric constant, and dielectric strength, and the mechanical properties measured included the density, Young's modulus, Poisson's ratio, failure stress, and failure strain. Three 304.8 × 355.6 mm (12 × 14 in.) $[\pm 45]_s$ laminates of each percentage were manufactured, and two replicate samples were cut from each panel. Thus, a total of 6 replicates for each of 5 percentages of carbon black were made for a total of 30 samples for each test. The size of the samples used for the electrical properties are 25.4 × 25.4 mm (1 × 1 in.). The density was measured using the conductivity samples. The size of the tensile test specimen used were 50.8 × 355.6 mm (2 × 14 in.) with 50.8 × 76.2 mm (2 × 3 in.) tapered glass loading tabs at each end on both sides. For the tensile specimen the thickness was measured nine times, the width three times, and the length between tabs twice. Each sample was tested once.

Conductivity Measurement

American Society for Testing and Materials (ASTM) Standard D257-93 summarizes the issues related to measurement of dc resistivity in insulating materials.[5] To measure the conductivity of the samples, the current had to be uniformly distributed across the surface of the samples. Therefore, the application of a conductive coating was required. After experimenting with various coatings, including gold sputtering, vapor-deposited silver, and conductive epoxy with various curing processes, it was decided to use conductive epoxy with an aluminum foil surface. To prevent moisture from penetrating the samples, they were stored in an air-tight jar with desiccant.

The conductivity of the carbon fiber/epoxy samples was determined by measuring the resistance across the sample and calculating the conductivity using Eq. (1). The resistance was measured using the direct method of measurement. The direct method is the application of a known voltage and measurement of the resulting current. A high-resistance electrometer with an applied voltage of 0.05 V was used. The sample was placed between two electrodes in a sample holder made of Lexan, a highly resistive material. The sample holder was placed in a shielded enclosure, and a two probe technique specified by the manufacturer was used to reduce signal noise.

To determine the effect of the matrix-rich surface layer on the conductivity measurements, measurements were repeated with these layers removed. The samples were sanded, removing both the conductive coating and the surface layer (see Fig. 3), and then the samples were recoated with conductive material and retested.

The glass fiber/epoxy samples required a different procedure because of their high resistance. When direct measurements were tried with these samples, the conductive coatings on the surfaces made the sample act like a capacitor, the resistance reading kept increasing as the current able to flow decreased. To get the resistance of the sample, the sample was assumed to be modelable as a resistor and capacitor in parallel, and the RC circuit discharge constant was measured. By using two 6-V batteries in series, 12 V was applied across the sample. The voltage source was removed, and 500 voltage and time data points were recorded an electrometer. Once the data were collected, a curve was fit to the data, thus giving the time constant from which the conductivity was calculated using Eqs. (2) and (3).

Dielectric Constant Measurement

The dielectric constant was calculated by measuring the capacitance of the sample. The conductivity samples were used because they were already coated with conductive epoxy and they were not damaged by the conductivity measurements. The samples were placed in the aforementioned Lexan sample holder, and the capacitance was measured using a capacitance meter. The dielectric constant was calculated using Eq. (5).

Dielectric Strength Measurement

ASTM Standard D149-94 summarizes the issues related to measurement of the dielectric strength of insulating materials.[5] The testing procedure described here was developed by Aaron Bent of the Active Materials and Structures Laboratory at the Massachusetts Institute of Technology.[6] The testing was performed using a function generator that can output a dc source voltage from 0 to 1.0 in 0.01-V increments. The two voltage amplifiers used were a high-voltage (±10,000 V) amplifier and a lower voltage one, which supplied 1000 V. When using the lower-voltage amplifier, the voltage increment was 10 V, whereas when using the higher-voltage amplifier, the voltage increment was 100 V. The samples were placed in a silicone oil test fixture. Silicone oil surrounded the specimen to prevent flashover and partial discharges, as per ASTM D149-94. The oil was kept at room temperature. The sample was held between two 0.25-in.-diam hemispherical electrodes (electrode type 5 in ASTM D149-94), which were connected to the voltage amplifier. Hemispherical electrodes make contact with a discrete point of the sample, in contrast to the coated samples, which would give a measurement of the weakest link dielectric strength of the entire sample. To prevent moisture absorption, the samples were stored in an air-tight jar with desiccant before testing.

The method B step-by-step testing method of ASTM D149-94 was used in the application of voltage. A dc voltage was applied to the specimen in single increments of the voltage generator. At each time step, the voltage was held for 5-s soak time and then immediately dialed to the next voltage. The starting voltage for each sample was approximately 50% of the breakdown voltage. For a test to be valid at least five increments need to be made before breakdown. The recorded breakdown voltage is the highest level reached where the sample survived for the entire 5-s duration. Breakdown occurs when the voltage is sufficiently high to allow a current path through the sample material. The test was first done using the lower-voltage amplifier. If breakdown did not occur by the 1000-V maximum of the amplifier, the higher-voltage amplifier was then used. The dielectric strength was calculated from Eq. (6).

Density Measurement

The density measurement was performed on the conductivity samples before the conductive epoxy coating was applied because the area and thickness of the samples was already measured. The sample mass was measured using a precision digital balance, and the density was calculated using Eq. (8).

Tensile Tests

The tensile test was performed to determine the Young's modulus, Poisson's ratio, failure stress, and failure stain. The testing apparatus used was a 110,000-lb testing machine with an automatic controller and a separate computer data acquisition system. The tests were performed using stroke control with a rate of 0.02 in./s and a gripping pressure of 500 psi. The load range used was ±10,000 lb, and the stroke range used was ±1 in. The data acquisition was done using a simple data acquisition program with a sampling frequency of 2 Hz. The procedure followed is documented in Ref. 7.

Before testing, the samples were prepared by bonding tapered glass loading tabs to each end of the samples on both sides. The tabs were bonded using a two-part epoxy that cures at room temperature in 48 h, with steel weights placed on the tabs to hold them in place. Following the tab application, two strain gauges were adhesively bonded to the tensile specimen. The gauges were placed near the center of the sample, one in the load X_1 direction and the other in the transverse X_2 direction.

The Young's modulus was calculated by plotting the applied stress vs the longitudinal strain and graphically measuring the slope of the linear portion of the curve [Eq. (9)]. Poisson's ratio was calculated by plotting the transverse strain vs the longitudinal strain and graphically measuring the slope of the linear portion of the curve [Eq. (10)]. The failure stress was calculated from the maximum load applied to the sample. The load can be converted into stress using Eq. (11). The failure strain is the strain in the material at the maximum load. Unfortunately, by the time the sample failed, the strain gauges had stopped functioning. Therefore, the strain was calculated from the stroke using Eq. (12). This value can be inaccurate because using stroke as a measurement of strain ignores the possibilities of grip slippage and load train flexibility.

Results and Discussion

Carbon Fiber/Epoxy Electrical Properties

The data are shown in Figs. 5–7. The same formatting is used on all three figures. The sample electrical resistances are plotted vs sample area, and the sample breakdown voltages are plotted vs sample thickness. The mean of each group of data (with each thickness and layup) is shown. The error bars represent ±1 standard deviation. The unidirectional samples are displayed with open symbols, and the quasi-isotropic samples are displayed with filled-in symbols. The thickness of the samples is represented by increasing size of the symbol: a triangle for the 4-ply samples, a circle for the 8-ply samples, and a square for the 32-ply samples. For clarity, the horizontal placement of the data has been shifted slightly, and so the x-axis variation within each area or thickness group is not meaningful.

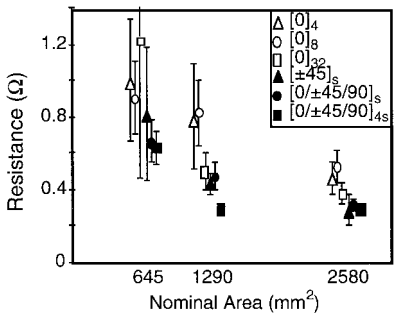

Fig. 5 Carbon fiber/epoxy resistance data.

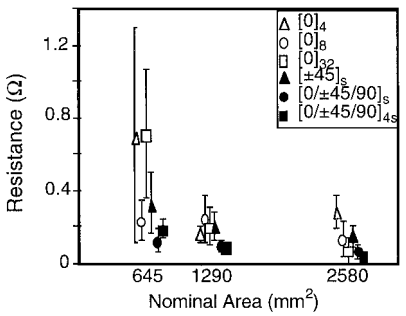

Fig. 6 Carbon fiber/epoxy resistance data from sanded samples.

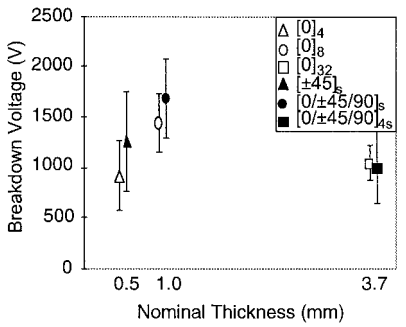

Fig. 7 Carbon fiber/epoxy breakdown voltage data.

Resistance and Conductivity

The raw resistance data are shown in Fig. 5. The resistance values are all very low and have high scatter. There is no observable trend with thickness; the resistance should increase with increasing sample thickness. The resistance decreases with increasing area, as it should, but it is unclear if the relation is the expected inverse one due to the high scatter. Also, there seems to be a stacking sequence trend; the resistances of the quasi-isotropic samples are lower than those of the unidirectional samples.

Figure 6 shows the resistance of the samples after the epoxy-rich surface layer has been removed. Comparison of Figs. 5 and 6 shows that the resistance of the samples decreased after sanding, as would be expected because the bulk composite conductivity is much greater than the pure epoxy conductivity. There is still a fair amount of scatter in the data. The sanded resistances are for the most part in or near the 0.1-Ω noise floor of the electrometer. The data seem to have no apparent thickness trend. There seems to be the expected trend of decreasing resistance with increasing area. Also, the stacking sequence trend observed in the unsanded samples is less clear.

When the resistance data are interpreted as conductivity [Eq. (1)], there are nonclassical thickness and surface area dependencies. If conductivity is a true material property, all data from the various samples with different thicknesses, areas, and stacking sequences would reduce to the same value of conductivity. Instead, there appears to be some decrease in conductivity with area and a distinct increase in conductivity with thickness. The range of values of conductivity measured here, 0.8–7.0 $1/\Omega \cdot$ m, fit within the low end of the range of through-thickness conductivities for carbon fiber/epoxy composites previously reported (0.1–106 $1/\Omega \cdot$ m) (Refs. 8 and 9). When the resistance of the sanded samples is interpreted as conductivity, there seems to be no area dependency, but there is still a nonclassical thickness dependency. Higher values, 1.5–35 $1/\Omega \cdot$ m, are measured.

The change in the resistance when the surface layers were removed indicated the importance of these layers. The apparent epoxy surface layer thickness was measured microscopically. For the unidirectional laminates it was approximately 9.0 μm, and for the quasi-isotropic laminates it was approximately 10.0 μm. The unsanded resistance data was then interpreted as the conductivity of the surface layer using Eq. (4). A reasonably consistent set of conductivities, 0.01–0.02 $1/\Omega \cdot$ m, results. There is a slight nonclassical area dependency, but no thickness dependency. The values of the conductivity computed in this way are above the range of reasonable values for the conductivity of epoxy by approximately one order of magnitude, indicating that the surface layer is not a uniform insulator.

Dielectric Strength

There was no observable trend with thickness in the breakdown voltage. The data seemed to be scattered around the overall mean value of approximately 1220 V, as shown in Fig. 7. It was postulated that the epoxy surface layer might again be dominating the data, and so the surface layers were sanded off as done with the conductivity samples. When the sanded samples were tested, no breakdown voltage could be measured because there was a current flow at the lowest possible voltage increment.

When the breakdown voltage data are interpreted as a material property (dielectric strength), there is a nonclassical thickness dependency. Instead of being a constant value with some scatter, there seems to be a decrease in dielectric strength with thickness. When the breakdown voltage data are interpreted as the dielectric strength of the epoxy surface layer [using Eq. (7)], more consistent results are obtained. The dielectric strength of the surface layer measured

in this way shows a fair amount of scatter around a constant value of approximately 150 MV/m, which is within the range of previously reported values for organic polymers.[8,9]

Conductivity-Tailorable Glass Fiber/Epoxy

The results of tests on the conductivity-tailorable glass fiber/epoxy composites were as desired, the electrical properties were increased significantly whereas the mechanical properties displayed minimal change.

Some manufacturing difficulties were encountered during the cure process. The main reason for these was that the higher percentages of carbon black made the epoxy very viscous. This resulted in the epoxy not flowing well during the cure process, which resulted in thicker laminates. This increase in thickness was created when the extra epoxy on the top surface of the laminate did not flow out around the top cure plate during the curing process. The surface layer was measured using a microscope. The total surface layer thickness of the carbon black filled laminates was greater than that of the control laminate. In particular, the surface layer thickness for the 15 and 20% carbon black laminates increased significantly.

Conductivity

The conductivity, as shown in Fig. 8, increased with the addition of carbon black to the epoxy resin. It increased by up to three orders of magnitude with the 20% carbon black samples. The conductivity seems to be constant until approximately 10% carbon black, at which point there is a rapid increase. This trend is consistent with percolation theory, where there is no significant increase in properties until there are sufficient particles to create percolation paths from one edge of the sample to the other. Therefore, it would appear that the percolation limit for this carbon black system is around 10% carbon black by mass of epoxy resin.

Dielectric Constant

The dielectric constant, as shown in Fig. 9, also displayed the same trend as the conductivity, remaining fairly constant up to 10% carbon black, then increasing rapidly. This trend is consistent with the exponential increases that were observed by Bent,[10] who examined up to 5% carbon black samples, and by Yacubowicz and Narkis,[11] who observed dielectric constants in the hundreds with a lower percolation limit. Both the large variation in the dielectric constant at 20% carbon black and the very high values may be due to the complex internal geometry of percolation paths.[4]

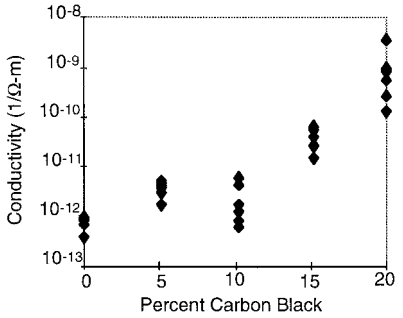

Fig. 8 Carbon black filled fiberglass/epoxy conductivity data.

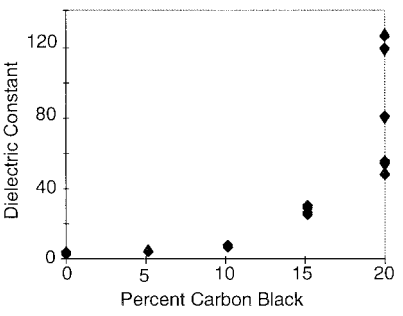

Fig. 9 Carbon black filled fiberglass/epoxy dielectric constant data.

Dielectric Strength

None of the samples broke down when the maximum voltage, 10,000 V, was applied across the samples. Therefore, the dielectric strength of all samples was greater than 10.5 MV/m. The published values for the dielectric strength of glass fiber/epoxy composites is between 17.7 and 21.7 MV/m (Refs. 8 and 9).

Density

The measured density of 1600 kg/m^3 was the expected value. Theoretically, the density should increase modestly and linearly with increasing percentage of carbon black. This trend was not seen; the density of the samples was not a function of the percentage of carbon black. It is speculated that, due to the high viscosity of the epoxy, increased voids canceled out the extra mass of the carbon black.

Mechanical Properties

Young's modulus, Poisson's ratio, failure stress, and failure strain data were taken. Values were nominal, in good agreement with MCLAM predictions for the $[\pm 45]_s$ layup used. MCLAM is an in-house CLPT code using a Tsai–Wu failure criterion (see Ref. 2). Note that the $[\pm 45]_s$ layup was used because it exaggerates the importance of the matrix (which is modified with carbon black) to the mechanical properties.

The laminate Young's modulus decreases from just under 12.0 GPa to around 10.5 GPa when carbon black is added to the matrix. The drop is not linear, all percentages of carbon black except zero gave the lower result. The drop is probably associated with the manufacturing difficulties mentioned earlier. Poisson's ratio remains fairly constant around the expected value of 0.56 with a little scatter above and below this value. The failure stress of just over 100 MPa remains fairly constant, slightly increasing with increasing percentage of carbon black, then slightly decreasing. The mean failure strain decreases linearly with increasing percentage of carbon black, from just over 6% strain to 5% strain. Scatter in the failure strain data is very high, and so the significance of the trend in the mean values is questionable. All values are well above any acceptable amount of strain that should be seen in an actual aerospace structure. Also note that the high values of failure strain were calculated from stroke data. They should, therefore, be treated only as comparative values.

Tailorable Composite Summary

With the addition of conductive carbon black into the insulating matrix of a composite, the conductivity can be increased significantly, as was desired. The dielectric constant can also be increased. The dielectric strength is greater than 10.5 MV/m in all cases. The increase in electrical properties had little effect on the mechanical properties of the composite. They remained fairly constant across all values of carbon black added. The only problem with the addition of carbon black to the matrix of the composite was the manufacturing difficulties caused by the increase in the epoxy viscosity. This problem could be overcome by using a less viscous epoxy, or by developing a manufacturing technique that would allow the epoxy to flow out of the composite during the curing process. Possible manufacturing technique variations include heating the epoxy before mixing so that it is less viscous; using pressure during the cure to press the top cure plate down into the laminate and, thus, force the extra epoxy out; or modifying the cure cycle to include a hold time at the flow temperature of the epoxy instead of ramping straight up to the cure temperature.

Conclusions

A complete set of tests was done on the through-thickness electrical properties of a carbon fiber/epoxy composite. The results were incompatible with the idea that the through-thickness electrical properties are continuum material properties on the scale of the specimen. The actual numerical values were within the range of previously measured values, but the thickness, area, and stacking sequence dependencies were either nonclassical or indiscernible. The through-thickness electrical properties appear to be determined by the details of the microstructure (Fig. 10). Clearly, the presence of a resistive epoxy-rich surface layer affected the data. Even when

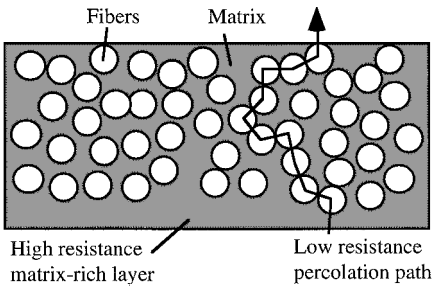

Fig. 10 Complex internal geometry complicates behavior of carbon/fiber epoxy composites.

the surface layer was removed, the data were not consistent with continuum material behavior. It is likely that percolation phenomena is occurring in which low conductivity paths through groups of conductive carbon fibers dominate the measurements.

The lessons of these data are to be wary of published electrical properties for composites; careful attention must be paid to surface and geometry effects. However, in spite of these difficulties, carbon fiber/epoxy materials appear to have sufficient conductivity to avoid serious deep dielectric charging problems.

The aforementioned difficulties do not apply to fiberglass/epoxy materials because the fiber is not a conductor. However, they are very low-conductivity materials, at risk for deep dielectric charging problems. Therefore, a conductivity-tailorable composite system was developed using a glass fiber/epoxy composite with conductive carbon black added to the epoxy resin. The conductivity was increased by three orders of magnitude and the dielectric constant was increased by a factor of 16 with minimal changes in the mechanical properties. The only drawback to using high percentages of carbon black in the epoxy resin is the increased manufacturing difficulties due to the high viscosity of the epoxy. This tailorable system will be very useful if a material used in the space environment needs to be an insulator, but deep dielectric charging also needs to be minimized.

References

[1]Jones, R. M., *Mechanics of Composite Materials*, Taylor and Francis, New York, 1975.

[2]Tsai, S. W., *Theory of Composite Design*, Think Composites, Dayton, OH, 1992.

[3]Czepiela, S. A., McManus, H., and Hastings, D., "Charging of Composites in the Space Environment," *Journal of Spacecraft and Rockets*, Vol. 37, No. 5, 2000, pp. 556–560.

[4]Czepiela, S. A., "The Charging of Composites in the Space Environment," M.S. Thesis, Dept. of Aeronautics and Astronautics, Massachusetts Inst. of Technology, Cambridge, MA, Aug. 1997.

[5]"ASTM D149-94 Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies," ASTM Standards Vol. 10.01, American Society for Testing and Materials, Philadelphia, 1994, pp. 19–30.

[6]Bent, A., "Active Fiber Composites for Structural Actuation," Ph.D. Dissertation, Dept. of Aeronautics and Astronautics, Massachusetts Inst. of Technology, Cambridge, MA, Jan. 1997, pp. 74–76.

[7]Lagace, P. A., Beaumont, M., Brewer, J. C., and Varnerin, C. F., "TELAC Manufacturing Course Notes," Technology Lab. for Advanced Composites, TELAC Rept. 88-4b, Massachusetts Inst. of Technology, Cambridge, MA, Sept. 1991.

[8]Frederickson, A. R., "Radiation Induced Currents and Conductivity in Dielectrics," *IEEE Transactions on Nuclear Science*, Vol. NS-24, No. 6, 1977, pp. 2532–2539.

[9]Kaddour, A. S., Al-Salehi, F. A. R., Al-Hassani, S. T. S., and Hinton, M. J., "Electrical Resistance Measurement Technique for Detecting Failures in CFRP Materials at High Strain Rates," *Composites Science and Technology*, Vol. 51, No. 3, 1994, pp. 377–385.

[10]Bent, A., "Active Fiber Composites for Structural Actuation," Ph.D. Dissertation, Dept. of Aeronautics and Astronautics, Massachusetts Inst. of Technology, Cambridge, MA, Jan. 1997, pp. 70, 71.

[11]Yacubowicz, J., and Narkis, M., "Dielectric Behavior of Carbon Black Filled Polymer Composites," *Polymer Engineering and Science*, Vol. 26, No. 22, 1986, pp. 1568–1573.

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