**MECHANICAL AND ELECTRICAL PROPERTIES OF GLASS AND
CARBON FIBER REINFORCED COMPOSITES**

G. R. Headifen
Center for Electromechanics

E. P. Fahrenthold
Department of Mechanical Engineering

University of Texas
Austin, TX 78712

Presented at ASME Energy-Sources
Technology Conference
New Orleans
September 15, 1989

Publication No. PN-164
Center for Electromechanics
The University of Texas at Austin
Bureau of Engineering Research
Balcones Research Center
10100 Burnet Road
Austin, TX 78758-4497
(512)471-4496

MECHANICAL AND ELECTRICAL PROPERTIES OF GLASS AND CARBON FIBER REINFORCED COMPOSITES

G.R. Headifen
Center for Electromechanics

E.P. Fahrenthold
Department of Mechanical Engineering

University of Texas
Austin, TX 78712

The material properties of S-2 glass-epoxy, IM6 graphite-epoxy, and hybrid glass-carbon epoxy composites have been studied to determine their suitability for composite rotor fabrication. For both the S-2 and IM6 materials, tension specimens in the form of longitudinal and transverse coupons and torsion specimens in the form of hoop wrapped and axial wrapped tubes were fabricated and tested to determine mechanical and electrical properties. Volume fractions for the samples were analyzed using electron microscopy and analysis by digestion. The results of the mechanical experiments were compared to rule of mixtures and Halpin-Tsai correlations for composite material properties as well as to torsion test results for a hybrid glass-carbon fiber reinforced tube.

INTRODUCTION

The materials industry has widely accepted the use of composite materials that can provide structures stronger and lighter than those composed of traditional materials. Advances in understanding fiber reinforced composites allow components to be designed specifically for each application, giving high strength where required but with minimum weight. Manufacturing of composite materials is not an easy task since procedures must be established and perfected before composite materials can be used reliably. Understanding the variables involved in the development and manufacturing of composite materials is difficult and is most effectively gained by experience combined with theoretical study.

Current electromechanical systems research focuses in part on the conversion of rotational kinetic energy stored in high speed rotors into electrical energy in the form of transient current pulses. Since stored energy requirements for certain applications can be as high as one gigajoule, the subject rotors must spin at very high speeds to remain within practical size limits. Fiber composites of S-2 glass and IM6 graphite are therefore under

study for use in pulsed power supply rotors. The purpose of this study was to investigate the mechanical and electrical properties of hybrid S-2 glass and IM6 graphite composites under consideration for use in such applications.

Manufacture of the fiber composites was performed using a multi-axis winding machine. Two configurations of composite specimens were required: (1) flat coupons which were used as tensile specimens for mechanical characterization tests and electrical specimens for conductivity tests, and (2) thin walled tubes incorporating fibers either aligned with the axis (axially wrapped) or wrapped around the axis (hoop wrapped). One problem associated with the use of graphite fibers in electrical machines is that they conduct electricity. Since conduction of eddy currents through composite rotors will decrease the efficiency of the pulsed power supplies, this work included the investigation of the electrical conductivity of the composites studied in the mechanical experiments. In particular an investigation to determine the electrical conductivity of an axially wound hybrid tube composed of graphite fiber and incorporating thin glass strips used to insulate sections of the tube was performed in order to determine whether or not eddy current losses could be reduced while maintaining the strength properties of the rotor.

In order to aid in understanding the structure of the composite specimens, the test samples were cut, polished and inspected using a Scanning Electron Microscope, with photographs made at magnifications between 100 and 1000 times. To provide further analysis of the manufacturing process, small specimens of the composite were submerged in a solvent in order to remove the binding matrix (epoxy) and establish the volume fraction of the fiber in the composite. Rule of mixtures and Halpin-Tsai (1969) expressions were used to predict the mechanical properties of the composite material, normalized with respect to fiber volume fraction.

The sections which follow discuss results of all of the material property tests and resulting conclusions for rotor fabrication.

TENSILE TESTING

Tensile testing of the composite and pure epoxy coupons was performed using an MTS tensile testing machine. Test specimens of S-2 glass-epoxy and IM6 graphite-epoxy were manufactured using a McClean Anderson Four Axis Numerically Controlled Filament Winding Machine. The epoxy used in all the composite specimens was Epon 9405 resin with Epon 9470 curing agent, manufactured by Shell Chemicals U.S.A. An air release additive BYK 501 manufactured BYK Chemie U.S.A. was also used.

Tensile testing was performed at a strain rate of 0.043 inches/minute. Each specimen type was cycled up to varying levels of strain in order to observe hysteresis. Slight hysteresis effects in longitudinal, transverse, and epoxy specimens were observed for some of the specimens. Table 1 provides results of the uniaxial tension tests performed on S-2 glass-epoxy and IM6 graphite-epoxy composite coupons, with the subscript T denoting transversely oriented fibers, R denoting 2-3 direction oriented fibers, and C denoting calculated values. Ultimate strengths for the longitudinal coupons are not shown, since failure occurred at the glue attached tabs located between the clamping jaws. It was observed that in all the composite tensile tests, graphs of load versus longitudinal and transverse strain were linear to failure. Hysteresis effects were barely noticeable in the longitudinal fiber direction specimens. They were slightly more noticeable, but still small, in the transverse and 2-3 direction specimens.

Results of tensile tests conducted on 9405 pure epoxy specimens cured under atmospheric conditions showed a slight curvature of both the longitudinal and transverse stress-strain curves. However the failure mechanism was a brittle fracture. A Young's modulus of 435 kpsi and Poisson's ratio of 0.375 were determined based on the average of the measured values at initial loading and at failure. The chosen epoxy was selected due to its long pot life of approximately 30 hours. This property is important when large rotors are fabricated.

TORSION TESTING

The MTS Axial-Torsional testing machine used in the torsion tests was capable of applying 50,000 pounds force in tension and 20,000 inch pounds of torque. Special clamping rings were manufactured in order to properly position the composite tubes between the two clamp stocks. A tube mandrel was designed in order to fabricate test specimens with an inside diameter of 2.3 inches. It was required that this mandrel be capable of making tubes with fibers aligned either along the tube axis or hoop wrapped around the mandrel, as shown in Figure 1. Three tubes of each material type were constructed along with two hybrid glass-carbon tubes of the type shown in Figure 2.

The shear modulus and shear strength results for the homogeneous tubes are shown in Table 2. The failure mechanism for the axial tube was different than that of the hoop wrapped tube. The hoop wrapped tubes failed after plastic deformation. The stress strain curves were initially straight, then curved gradually until catastrophic failure, at which the wrap unpeeled at one position, usually near the top or bottom of the tube. The axially wrapped tubes failed in their linear stress-strain range due to several cracks which formed along the fiber direction and ran the length of the tubes.

The properties of the fiber-epoxy specimens showed good repeatability over the range of tests performed. The measured shear moduli for the axial and hoop configurations were similar for each material. However the failure strengths were significantly different. This was due to the fact that the tubes exhibited different failure mechanisms. The propagation of cracks along the tube in the axially wound case could possibly be reduced by winding the layers at opposing angles close to zero (e.g. $\pm 2^\circ$) rather than at exactly zero degrees.

An additional experimental investigation was performed to determine the properties of an axially wound graphite fiber-epoxy tube with impregnated strips of glass fiber. As previously mentioned, it is desirable to achieve low electrical conductivity in composite

rotor shafts so that eddy currents are kept to an acceptable level. Hence glass strips serve to insulate sectors of the tube from one another. Figure 2 is a schematic of the tube design.

Two tubes were manufactured from graphite fiber using a technique similar to that used for the homogeneous tubes, except that a numerical control program was written to skip winding of an area every 90 degrees. Glass fiber was laid down in these areas after the graphite was wound. Both tubes were tested in the Axial - Torsion MTS machine to determine whether or not the presence of impregnated glass was detrimental to the shear properties of the tube. Table 7 shows the shear modulus and the shear stress at failure for the tubes, determined from torsion tests. The tube fracture mechanism was similar to that of the axially wound tubes, where several cracks propagated along the fiber direction. The cracks developed in the graphite sections, not at the glass interface as one might expect.

The results indicate that the shear modulus and the failure shear stress for the hybrid graphite-glass-epoxy tube are higher than those of the graphite-epoxy tube.

The following two sections consider the microstructure and fiber volume fraction properties of the composites.

VOLUME FRACTION ANALYSIS

The strength and electrical conductivity of a composite material depends on its constituent properties as well as the volume fractions of constituents present in the composite. Hence volume fraction analysis of the samples was performed using both scanning electron microscopy and digestion techniques.

Optical magnification of a composite can provide useful information concerning the structure and volume fraction composition of the material. Optical micrographs were made of the composites manufactured for this study, to aid in the interpretation of the results of the mechanical and electrical property tests. Several specimens of graphite/epoxy and glass/epoxy were taken from the test tubes and coupons previously described for viewing under a Joel JSM 35C Scanning Electron Microscope. The specimens were approximately

0.5 inches in thickness in the cross fiber direction and were laid in a 1 inch diameter pot of Armstrong epoxy for viewing. The specimens were allowed to set for twenty-four hours before viewing. Upon cure the specimens were smoothed with sand paper using a succession of 180, 320, 400, and 600 grit treatments. They were then polished until shiny with POL polishing compound manufactured by Hohn and Hohn of Germany.

ASTM (1986) has devised a method by which the volume fraction of a composite material may be determined. This method involves digesting the composite in a solvent and measuring the composite mass before and after digestion. The volume of the composite before digestion is also measured, using a water displacement method, so that the void volume fraction of the composite can be determined (ASTM, 1976).

Small pieces of composite, approximately 0.3 grams in weight, were prepared for study by first measuring their mass and volume. Glass-epoxy specimens were digested in Nitric acid for 5 hours at 75° C. ASTM (1976) recommended that graphite-epoxy specimens be digested in a boiling solution of 10% sodium hydroxide in ethylene glycol for one hour, since nitric acid attacks the graphite. However the 9405 epoxy was insoluble in this mixture and therefore volume fraction analysis by digestion was not performed on the graphite samples. The fiber volume fraction measured for the glass samples was compared to the fiber area fraction determined from the micrographs of the glass samples in order to determine if the results were similar. If so, the fiber volume fraction of the graphite specimens could be inferred from their micrographs. The densities of the graphite specimens were measured to determine the volume fractions of the epoxy and void once the fiber volume fraction was known. It was found that this was not an exact method for determining the volume fraction because the examined area was small compared to that of the entire specimen. However the results obtained from this method are within ten percent of the exact values.

Table 3 shows fiber, epoxy, and void volume fractions determined from micrographs and digestion test results. From the glass specimens it was determined that the

fiber volume fraction could be approximately determined by observation of micrographs. Therefore in Table 3 is the volume fraction of graphite fibers determined from micrographs of longitudinal, transverse, hoop, and axially wound graphite specimens.

The digestion volume fraction analysis method gave repeatable results for the specimens tested. The fiber volume fraction of the plate wrapped coupon specimens was low, about 55% for glass and 60% for graphite. A high void volume fraction was also present in some of these specimens. The latter effects were inherent in the coupon mandrel design, since the down force applied to the fiber strands during the wrap was low and thus voids and excess epoxy were trapped in the composite. The volume fraction analysis of the tube specimens was consistent with the corresponding microscopic analysis in that the fiber volume fraction of the tube specimens was determined to be higher than that of the coupon specimens. This result is due to the fact that in the tube specimens individual fibers are pulled down upon one another as they are wrapped around the mandrel, since high tension is applied to the strands as they are laid down. It is therefore expected that, in general, higher strand tension leads to higher fiber volume fractions in the composite.

MECHANICAL PROPERTY ANALYSIS

This section considers the application of rule of mixtures and Halpin-Tsai theory in predicting the properties of composite materials.

Using the rule of mixtures one may calculate E_1 , E_2 , ν_{12} , and G_{12} for a composite material if the constituent volume fractions and mechanical properties are known (Jones, 1975). Alternately Halpin and Tsai (Jones, 1975) developed an interpolation procedure that provides an approximate representation of other more complicated micromechanical constitutive equations for mixtures. The referenced equations take the form:

$$E_1 = E_f V_f + E_m V_m \quad (1)$$

$$\nu_{12} = V_m \nu_m + V_f \nu_f \quad (2)$$

$$\frac{M}{M_m} = \frac{1 + \xi \eta v_f}{1 - \eta v_f} \quad (3)$$

where

$$\eta = \frac{(M_f/M_m) - 1}{(M_f/M_m) + \xi} \quad (4)$$

with ξ a measure of fiber reinforcement of the composite, and

$$M = E_2, G_{12} \text{ or } v_{23}$$

$$M_f = E_f, G_f \text{ or } v_f$$

$$M_m = E_m, G_m \text{ or } v_m$$

Solving for ξ yields

$$\xi = \frac{M v_f + \frac{M M_f (1 - v_f)}{M_m} - M_f}{M_f v_f + M_m v_m - M} \quad (5)$$

This equation predicts ξ and hence E_2 , v_{23} and G_{12} when the constituent properties are known. Note that equations (1) and (2) represent the generally accepted rule of mixtures for E_1 and v_{12} (Halpin and Tsai, 1969) while for $\xi = 0$ equation (5) is the rule of mixtures for E_2 and G_{12} . There is no rule of mixtures for v_{23} .

The rule of mixtures was used in conjunction with the volume fraction results from the preceding section and known fiber and epoxy matrix properties in order to determine E_1 , E_2 , v_{12} , and G_{12} for the composites of interest here. The results may be compared with the experimental values presented in Tables 4 and 5, which show comparisons for the glass and graphite composites respectively. The tables also show calculated values of ξ based on the experimental results, volume fraction measurement results, and fiber and epoxy property data. Table 6 provides Young's modulus, Poisson's ratio, and shear modulus values assumed to apply to the epoxy, glass, and graphite fibers. The results allow the compliance matrix for the glass or carbon epoxy composite to be estimated.

ELECTRICAL CONDUCTIVITY MEASUREMENTS

This section describes the results of electrical conductivity measurements on the composites considered for rotor fabrication.

The electrical conductivity of graphite-epoxy and S-2 glass-epoxy composites plays a significant role in determining their suitability for use in pulsed power supply applications. Since the proposed composite rotors will spin in a magnetic field, eddy currents will develop in a conducting rotor. The induced eddy currents must be kept to a minimum in order to avoid reducing the efficiency of compulsators and similar devices. One way of reducing undesirable eddy currents is to reduce the electrical conductivity of any composite rotor used in the machine.

The electrical conductivity of a composite depends upon the electrical conductivity of its constituents as well as the volume fractions of the constituents. It is therefore important to combine the results of these tests with the results of the volume fraction analysis so that composite properties at various fiber volume fractions may be predicted.

The conductivity of graphite epoxy composite was determined using an ASTM standard test (ASTM, 1974). For the two probe method current was passed through ohmic contacts at the ends of a bar specimen of the composite and the potential difference was determined between two probes located on the specimen surface. The conductivity was calculated from the measured current, measured potential values at the probes, and the test geometry. Current was applied to the circuit and the potential difference across the known resistor was measured. Potential difference across the two probes was then measured. The preceding measurements were performed at various excitation frequencies. Twelve specimens were prepared for testing by abrading the surface with sand blasting. The ends of each specimen were coated with silvermet type 170 (manufactured by Transene Company, Rowley, Massachusetts) and placed in a vacuum for 5 minutes in order to force conducting material in amongst the fibers.

The two probe method failed to provide measurable conductivity estimates for the glass-epoxy composite and for the pure epoxy specimens. It was decided to use an Amprobe insulation testing meter (model AMC 4) to determine the resistance of these specimens. Testing produced a resistance greater than 500 megaohms for the glass/epoxy specimens in both the longitudinal and transverse directions. The pure epoxy specimens also produced a resistance of greater than 500 megaohms. The cross sectional areas of the 1 cm long glass-epoxy and pure epoxy specimens were approximately 0.4 cm^2 and 1.3 cm^2 respectively. For the purpose of this investigation, S-2 glass and 9405 epoxy were therefore considered to be very good insulators.

Table 8 summarizes the results of electrical conductivity measurements made on the IM6 graphite-epoxy. Figures 3 and 4 show example electrical conductivity measurement results, including dependence on frequency, for graphite-epoxy specimens.

It was mentioned previously that the graphite fiber volume fraction in the tube samples was much higher than that in the coupon specimens. The micrographs showed that the hoop wrapped specimens had randomly placed fibers with no regular epoxy rich zones. This leads to a higher electrical conductivity, the effect of which is seen in Table 8, which shows a much higher transverse conductivity in the hoop wound specimens than that measured for the transverse direction in the coupon specimens.

An axially wound graphite-epoxy layup may be used at the inner radius of a rotor to provide a high section modulus in bending. Since graphite fibers conduct electricity in the transverse as well as the longitudinal direction, a design goal is in this case to decrease cross-fiber conductivity, leading to an acceptable level of eddy current losses in the machine. Hence the electrical conductivity of the hybrid tube was tested between two adjacent areas of graphite using the amprobe insulation meter employed in the glass and epoxy conductivity tests. The interface between the glass and the graphite was 1 inch wide and 0.05 inches thick. It was found that the resistance separating the two graphite areas

was greater than 500 megaohms. It was therefore concluded that this method of reducing the tube conductivity was effective.

CONCLUSION

The tensile and torsion mechanical property tests gave good repeatability, with shear strengths of the axially wrapped tubes lower than that of the hoop wrapped tubes due to the development of axial cracks between the fibers in the axially wrapped tubes. It is suggested that the fibers should be wound a few degrees off zero and in opposing directions on adjacent layers in order to reduce the problem of crack propagation.

Volume fractions of fiber, epoxy, and voids in the glass specimens were determined by measuring the mass and volume of the composite before digestion and the mass of the fiber after digestion. This experiment provided valuable information concerning proposed manufacturing techniques and expected mechanical material properties. When measured fiber volume fractions were compared to the fiber area fractions determined from photographs of the microstructure it was found that fiber area fractions were within ten percent of the volume fractions measured using digestion tests. Volume fraction of fiber for the graphite-epoxy composite was determined by inspecting microstructure photographs. Epoxy and void volume fractions were then determined from density measurements. This technique was considered to estimate the true fiber volume fraction within ten percent.

The Halpin-Tsai expressions maybe used to provide a correction factor for mechanical property calculations based on the rule of mixtures. This allows five mechanical properties and thus the complete compliance matrix for S-2 glass-epoxy and IM6 graphite-epoxy composites to be determined at normalized fiber volume fractions.

The electrical conductivity of glass and epoxy was found to be negligible. The measured conductivity of graphite-epoxy composite varied with fiber volume fraction, manufacturing technique, and the direction of current flow with respect to the fiber direction. Coupon specimens demonstrated low conductivity due to low fiber content while

hoop wrapped tubes demonstrated high conductivity due to high fiber content. Axially wrapped tubes also demonstrated high fiber content, however measured cross fiber conductivity was in this case low, due to axially oriented epoxy rich zones created by radial pins at the ends of the winding mandrel.

An axially wound hybrid tube of graphite-epoxy inlaid with axial glass strips was manufactured to test shear properties and circumferential electrical conductivity of such a composite. It was found that the shear modulus and shear strength of the hybrid tube was higher than that of a pure graphite tube. The observed failure mechanism for the hybrid axially wound tubes was similar to that observed for pure graphite tubes. However axial cracks did not appear at the interface of the glass and graphite. The electrical resistance between two adjacent graphite tube sections was found to be greatly increased by the presence of insulating glass strips.

ACKNOWLEDGEMENTS

This research was supported by the U.S. Army Armament Research, Development and Engineering Center and the Defense Advanced Research Projects Agency.

REFERENCES

- Annual Book of ASTM Standards, 1986, Designation Number D 792-86.
- Annual Book of ASTM Standards, 1976, Designation Number D 3171-76.
- Annual Book of ASTM standards, 1974, Designation Number F 43-74.
- Halpin, J. C., and Tsai, S. W., 1969, "Effects of Environmental Factors on Composite Materials," AFML-TR 67-423, Air Force Materials Laboratory
- Jones, R. M., 1975, Mechanics of Composite Materials, Scripta Book Co., New York, New York, p. 114.
- Pagano, N. J., and Whitney, J. M., 1968, "Geometric Design of Composite Cylindrical Characterization Specimens," Journal of Composite Materials, Vol. 4, pp. 287-293.
- Tsai, S. W., and Pagano, N. J., 1968, "Invariant Properties of Composite Materials," Composite Materials Workshop, S. W. Tsai, J.C. Halpin, and N. J. Pagano (eds.), Technomic Publishing Co., Westport, Conn., pp. 233-253.
- Whitney, J. M., and Halpin, J. C., 1968, "Analysis of Laminated Anisotropic Tubes Under Combined Loading," Journal of Composite Materials, Vol. 2, No. 3, p. 363.

Table 1. Summary of composite tensile testing results

Property	S-2 Glass	IM6 Graphite
E_1 (Mpsi)	6.9	20.42
E_{2T} (Mpsi)	1.31	0.885
E_{2R} (Mpsi)	1.028	0.916
E_{2C} (Mpsi)	0.905	0.939
ν_{12}	0.303	0.359
ν_{21}	0.0450	0.0165
ν_{23}	0.422	0.513
σ_{fT} (psi)	1759.9	4885.7
σ_{fR} (psi)	1857.8	2344.9

Table 2. Results of torsion tests

Specimen	G_{12} (Mpsi)	$\tau_{failure}$ (psi)	Specimen	G_{12} (Mpsi)	$\tau_{failure}$ (psi)
Glass Hoop 1	0.932	8695	Graphite Hoop 1	0.679	8144
Glass Hoop 2	0.912	6085	Graphite Hoop 2	0.738	8091
Glass Hoop 3	0.954	8619	Graphite Hoop 3	0.728	1677
Glass Axial 1	1.174	1895	Graphite Axial 1	0.759	1135
Glass Axial 2	1.190	2242	Graphite Axial 2	0.660	944
Glass Axial 3	1.152	1673	Graphite Axial 3	0.596	730

Table 3. Volume fractions of graphite specimens

Specimen	$v_f\%$	$v_e\%$	$v_v\%$
Longitudinal	60	37	3
Transverse	61.5	32	5.5
Hoop Tube	75	18	7
Axial Tube	78	17	5

Table 4. Glass composite properties

v_f %	v_e %	v_v %	Property	Experimental	Rule of Mixtures	Halpin Tsai ξ
56.8	34.3	8.9	E_1 (Mpsi)	6.9	7.30	N/A
56.8	34.3	8.9	ν_{12}	0.303	0.257	N/A
54.4	32.8	12.9	E_2	1.31	1.19	1.105
55.0	33.0	10.0	ν_{23}	0.422	N/A	-0.945
64.7	29.2	6.0	G_{12} (Mpsi) Hoop	0.933	0.479	2.827
70.6	27.2	2.1	G_{12} (Mpsi) Axial	1.172	0.508	3.077

Table 5. Graphite composite properties

v_f %	v_e %	v_v %	Property	Experimental	Rule of Mixtures	Halpin Tsai ξ
60.0	37.0	3.0	E_1 (Mpsi)	20.42	24.15	N/A
60.0	37.0	3.0	ν_{12}	0.359	0.275	N/A
61.5	32.0	5.5	E_2 (Mpsi)	0.885	1.26	- 0.2704
61.0	34.5	4.2	ν_{23}	0.513	N/A	- 0.9007
75.0	18.0	7.0	G_{12} (Mpsi) Hoop	0.715	1.60	0.5748
78.0	17.0	5.0	G_{12} (Mpsi) Axial	0.672	1.64	0.1987

Table 6. Values of Young's modulus, Poisson's ratio, and shear modulus for epoxy, glass fiber, and graphite fiber

Property	S-2 glass fiber	IM6 graphite fiber	Epon 9405 epoxy
E (Mpsi)	12.6	40	0.413
ν	0.22	0.20	0.386
G (Mpsi)	5.0	4.0	0.149

Table 7. Hybrid tube shear properties

Specimen	G_{12} (Mpsi)	τ_{failure} (Psi)
Hybrid Tube 1	0.817	1749
Hybrid Tube 2	0.901	1449

Table 8. Resistivity measurements ($1/\Omega\text{m}$, DC)

Hoop Tube	Transverse to Fiber	70
Hoop Tube	Aligned with Fiber	47,500
Axial Tube	Transverse to Fiber	5
Axial Tube	Aligned with Fiber	34,000
Flat Coupon	Transverse to Fiber	1.5
Flat Coupon	Aligned with Fiber	6500

Fig. 1 Split tapered mandrel with connector rod

Fig. 2 Schematic of the hybrid tube

Fig. 3 Electrical conductivity versus frequency for three longitudinal graphite-epoxy specimens from a hoop wound tube

Fig. 4 Electrical conductivity versus frequency for three transverse graphite-epoxy specimens from a hoop wound tube