Mechanical Properties of Epoxy Impregnated Superconducting Solenoids

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Abstract—**The mechanical properties of epoxy impregnated coils are critical to proper stress analysis of high field superconducting magnets. In order to identify the engineering properties of coil composites, mechanical test specimens of epoxy impregnated coil windings are prepared. The samples consist of multiple layers of superconductor separated with interlayer insulation and are epoxy impregnated. Mechanical tests are performed at liquid nitrogen and liquid helium temperature. Orthotropic elastic properties are measured for the composite and used for mechanical analyses. Properties in a direction longitudinal to the conductor (hoop direction) are measured in tension. The compression modulus is measured for properties transverse to the conductor, representing radial and axial directions.**

I. Introduction

A large bore 900 MHz NMR magnet is currently under development at the National High Magnetic Field Laboratory. Primary aspects of the design are the epoxy impregnated, high current density Nb_3Sn and NbTi superconducting coils. The final magnet configuration greatly depends on the mechanical analysis and thus accurate representation of the elastic constants is essential. Mechanical measurements on samples consistent with the coils of the 900 MHz magnet have not been conducted previously. Therefore, material property measurements are presently initiated on test samples representing a NbTi coil and its main constituents.

The NbTi coils are wound with interlayer cloth and vacuum impregnated with epoxy. Young's modulus of the constituent materials, bare conductor and epoxy, are measured at room temperature and at cryogenic temperatures. Straight samples of a superconducting coil composite are manufactured. Young's modulus in the direction longitudinal to the conductor is measured through tensile tests. During operation of the magnet, the coil windings are placed in compression in the radial and axial directions; thus the Young's modulus transverse to the conductor is measured through compressive tests. Measurements are made at 77 K and 4.2 K to determine the property difference between the two temperatures. If small differences exist, then future test may be made at 77 K, thus reducing the cost of each test.

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II. Mechanical Test Sample Description

The test samples consist of four layers of five NbTi conductors. A layer of E-glass is contained between each conductor layer and on the outer conductor surfaces. The assembly is impregnated with epoxy. The final configuration of the test samples is shown in Figure 1. Fabrication of the test samples is performed by winding the superconductor around a racetrack shaped form. The racetrack shape provides two straight winding surfaces from which test samples can be manufactured. The winding form width is defined by the number of turns in the sample. After vacuum impregnation with epoxy, the test samples are cut from the straight regions of the racetrack mandrel and machined to a desired length.

The cross-section dimensions of the composite are nominally 5.7 mm x 11.55 mm. The lengths of the samples for tensile tests are 190 mm long and samples for compressive tests are 12.7 mm long.

The construction of the test samples produces a cross-sectional geometry which may be defined by an array of unit cells. The properties of the coils are based on the average material constants of all constituents within the unit cell. The unit cells each contain three primary regions; a conductor, an interturn, and an interlayer region. The packing factor of the bare conductor to the unit cell is approximately 0.80 for all test samples. The packing factor of the interturn and interlayer regions are 0.06 and 0.14

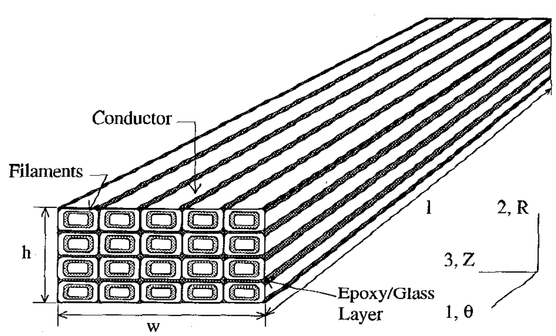

Fig. 1. Schematic of NbTi winding composite configuration

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TABLE I
AVERAGE ELASTIC MODULUS OF NbTi SUPERCONDUCTOR AT VARIOUS TEMPERATURES

Temperature (K)	Number of Samples	Average Modulus (GPa)
295	6	97.9
77	4	112.8
4.2	2	118.3

respectively. The axial direction (Z or 3) is normal to the interturn region and contains epoxy (0.02 mm thick) and Formvar insulation. The radial direction (R or 2) is normal to the interlayer region. The contents of which are insulation, epoxy, and E-glass. The thickness of the epoxy-glass subregion is 0.127 mm.

A rectangularized, monolithic superconductor with multi-filamentary NbTi is used. The bare dimensions of the conductor are 1.18 mm x 2.19 mm and the Formvar insulation thickness is approximately 0.038 mm. The rectangularization process creates a corner radius of 0.254 mm. The copper to superconductor ratio is 3.6:1. The elastic modulus of the conductor has been measured at room temperature, 77 K, and 4.2 K. The average modulus values as well as the number of samples tested to obtain the results are listed in Table 1 for each temperature. Figure 2 is the corresponding stress-strain curve for the first load cycle of the NbTi conductor at 77 K and 4.2 K. It is evident that a slight temperature dependence exist in the superconductor. For comparison, the difference in modulus of copper between 77 K and 4.2 K is about 1% [1].

The epoxy, developed in house and designated as NHMFL 61, is a standard DGEBA resin with amine curing agents, including a toughening agent (Jeffamine[1] D2000) [2]. The cure schedule was 24 hours at 60 C with an additional 48 hours at 80 C. Low temperature tensile tests have also been performed on molded dogbone shaped epoxy using extensometers for instrumentation. The average measured elastic modulus at 4.2 K is 7.5 GPa.

The interlayer E-glass cloth is a standard 2116 style with a plain weave and a 60 x 58 fiber count. The cloth is oriented in the composite such tat the warp direction is parallel to the conductors. The nominal thickness is 0.097 mm and the weight is 10.9 g/m^2. The cloth was treated with a Volan-A finish; however, a silane type finish may be better suited for bonding purposes.

III. MECHANICAL TEST CONFIGURATION

Tensile and compressive modulus measurements are made by loading the sample in its longitudinal and transverse directions respectively. The tests were performed on a materials test machine configured for testing samples in

[1]Identification does not imply recommendation or endorsement by NHMFL.

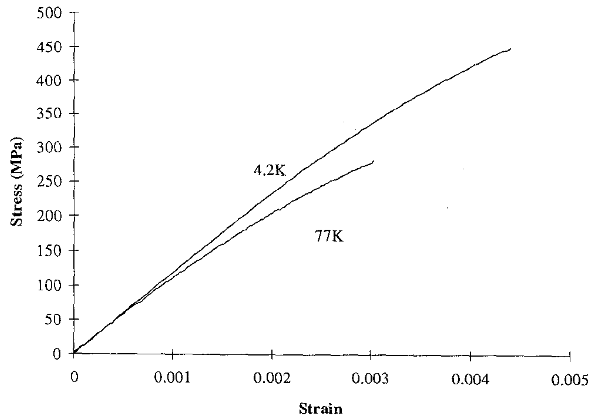

Fig. 2. Stress-strain curve of NbTi conductor at 77 K and 4.2 K

cryogens. The machine's actuator is located above the load frame to allow for the immersion of a sample into an open cryostat.

The overall mechanical properties are dominated by the superconductor, because of its packing factor. This relatively large component of the composite is a source of problems for strain readings of the composite. Strain in a direction transverse to the composite (2, 3 direction) is dependent on the modulus of the local components. The overall strain is a summation of the strain through each component. To determine average properties, measurement of the strain through an integer of *n* unit cells is desired. However the sizes of strain gages available do not exactly match a fixed number of unit cells. Thus an attempt is made to appropriately size gages to cover a set number of cells. Strain longitudinal to the composite is equal through each component and thus size and placement of gages is not as critical.

Strain readings were taken through strain gages suitable for cryogenic application. They were place longitudinal to the load direction for modulus measurements and transverse to the load direction for Poisson's ratio measurements. Whenever possible, two strain gages were used to measure and average the strains in each direction. The active gage length of strain gages placed longitudinal to the conductor was 3.175 mm. Gages on the radial surface were 3.175 mm and covered slightly more than two unit cells. Gages on the axial surface were 1.575 mm which covered one unit cell. The gages were applied to the surface with a two component epoxy suitable for cryogenic use and cured at 30 C. The tests were run in displacement control at 0.5 mm/min.

IV. RESULTS OF ELASTIC PROPERTY MEASUREMENTS

A tensile test is performed to measure the longitudinal modulus (E_{11}). Grips attach on opposing ends of the long composite samples (190 mm) such that a distance of 115 mm exists between the grips. Two identical samples were used for the tensile tests at temperatures of 77 K and 4.2 K. The stress-strain curves for each temperature is plotted in Figures 3 and 4. The samples were loaded up to approximately 120 MPa, which is near the operating stress in the NbTi coils of the 900 MHz magnet. The initial loading of the first specimen was done at 77 K with secondary measurements taken at 4.2 K. The second specimen was initially loaded at 4.2 K with subsequent measurements made at 77 K. The specimens were cycled three times at each temperature while acquiring stress and strain data.

Longitudinal modulus measurements between each sample agreed very well. The average Young's modulus for the tests at 77 K and 4.2 K are 95.0 GPa and 99.5 GPa respectively. Agreement between Poisson's ratio measurements was more difficult to achieve because the strain gages were attached transverse to the conductors. The average value of ν_{12} is 0.33 at 77 K and 0.39 at 4.2 K. The average value of ν_{13} is 0.40 at 77 K and 0.42 at 4.2 K. Results of the tensile tests are included in Table 2.

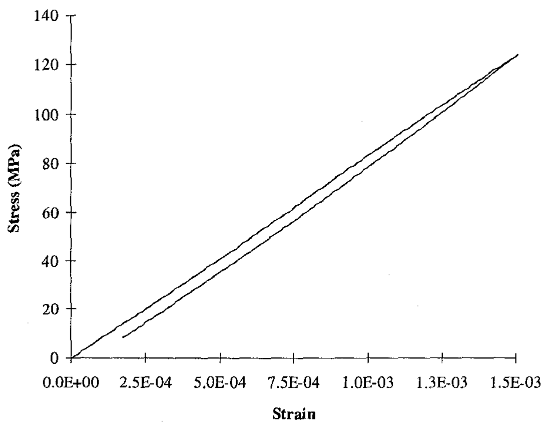

Fig. 3. Stress-strain curve of NbTi composite sample # 1, longitudinal (1) direction at 77 K

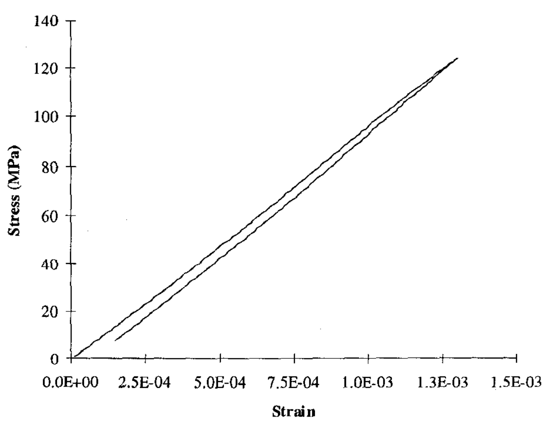

Fig. 4. Stress-strain curve of NbTi composite sample # 2, longitudinal (1) direction at 4.2 K

Transverse compressive measurements are performed to determine the axial and radial moduli. Square G-10 shims were placed between the load platens and the test sample to reduce end effects. The determination of properties in the transverse directions proved to be challenging. The macroscopic nature of the composite, coupled with the relatively small dimensions of the strain gages, lead to deviations in the measured data. The placement of strain gages is important in compressive tests since the strain is not constant through each constituent. The load path is transmitted in a series manner through the conductor and epoxy. The strain through each section is dependent on the corresponding modulus.

Typical stress levels in the NbTi coils of the 900 MHz magnet reach 20 MPa in the radial direction and 70 MPa in the axial direction. The load required to obtain modulus measurements was higher for each case because of seating of the specimen. At low loads, an arc exists in the stress-strain curves prior to the linear region. The arc probably does not represent a property of the material, but an irregularity of the test sample's surface.

Three specimens were tested in each of the two transverse directions with a single ramp to a high stress, past the onset of plastic deformation. Only one test was conducted at 77 K; all others were tested at 4.2 K. The results for all compressive tests are listed in Table 3.

Figures 5 and 6 show the stress-strain curves for the NbTi composite in the radial direction at 77 K and 4.2 K respectively. The average linear modulus is 41.0 GPa at 4.2 K and 40.0 GPa at 77 K.

TABLE II
TENSILE PROPERTIES OF NbTi COIL COMPOSITES AT 77 K AND 4.2 K

Specimen	Temp. (K)	Load Direction	Young's Modulus (GPa)	ν_{12}	ν_{13}
1	77	1	96	0.345	0.428
1	4.2	1	99	0.402	0.445
2	77	1	94	0.316	0.377
2	4.2	1	100	0.379	0.403
Average	77	1	95.0	0.331	0.403
Average	4.2	1	99.5	0.391	0.424

TABLE III
COMPRESSIVE PROPERTIES OF NbTi COIL COMPOSITES AT 77 K AND 4.2 K

Specimen	Temp. (K)	Load Direction	Young's Modulus (GPa)	ν_{23}	ν_{32}
3	77	2	40	0.149	
4	4.2	2	34	0.141	
5	4.2	2	48	0.343	
6	4.2	3	56		0.260
7	4.2	3	67		0.339
8	4.2	3	55		0.196
Average	4.2	2	41.0	0.246	
Average	4.2	3	59.3		0.265

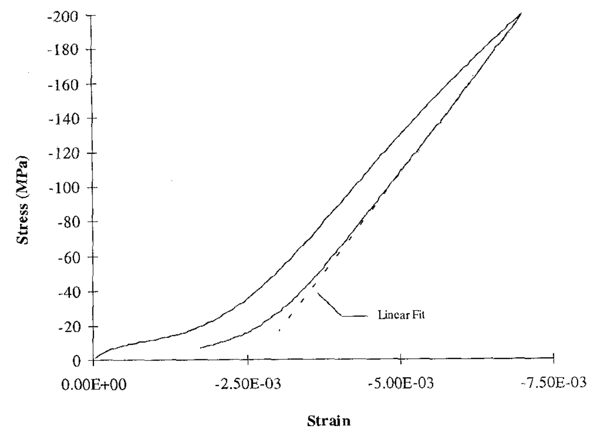

Fig. 5. Stress-strain curve of NbTi composite sample # 3, radial (2) direction at 77 K

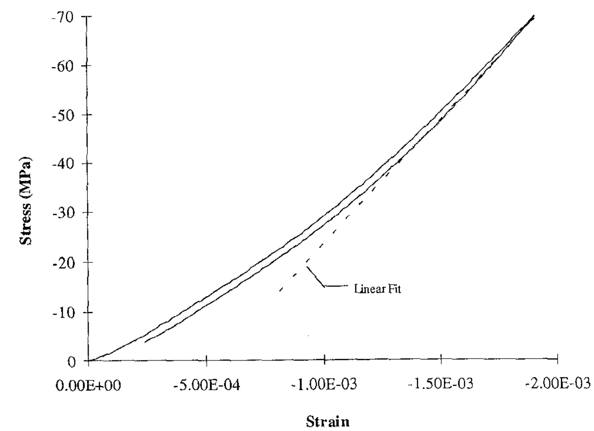

Fig. 6. Stress-strain curve of NbTi composite sample # 5, radial (2) direction at 4.2 K

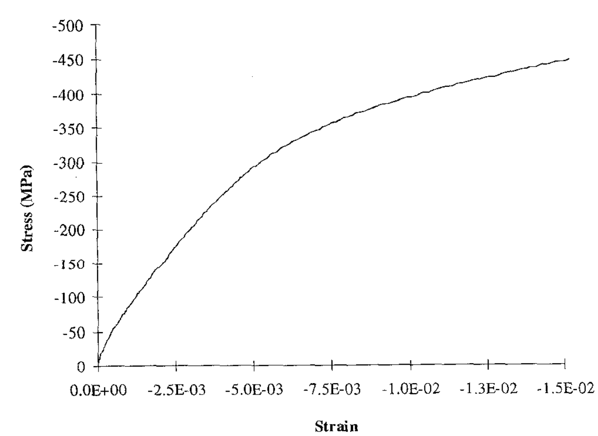

Fig. 7. Stress-strain curve of NbTi composite sample # 7, axial (3) direction at 4.2 K

The stress-strain curve for the NbTi composite in the axial direction at 4.2 K is shown in Figure 7. The average axial modulus at 4.2 K is 59.3 GPa. Two of the three samples were loaded to high stress, well past the point where yielding was observed. In both cases, the axial stress at yield was near 300 MPa. Compressive failure occurred in one sample at 475 MPa.

Differences between Young's modulus measurements at 77 K and 4.2 K are found to approximately 5% in the longitudinal direction. This corresponds to the temperature dependence seen in the superconductor.

V. Conclusions

A method is developed to manufacture mechanical test specimens that represent epoxy impregnated superconducting coils containing glass cloth between winding layers. Samples consisting of NbTi conductor, DGEBA resin with amine hardeners, and E-glass cloth are fabricated. Elastic property measurements are performed at low temperatures on the primary constituents and on the composite in all orthotropic directions.

The average elastic modulus of the epoxy at 4.2 K is 7.5 GPa. The average modulus of the conductor at 4.2 K is 118.3 GPa. The composite samples are loaded in tension for longitudinal modulus and in compression for radial and axial modulus. The longitudinal modulus results agreed between each sample. The average longitudinal modulus is 99.5 GPa. Agreement was more difficult to obtain with the compressive samples due to variations of strain in each constituent. Any scatter in the data is caused by the size of the gages in comparison to the size of the conductor. More consistent results may be attained using larger gages. The average radial and axial modulus measured at 4.2 K are 41.0 GPa and 59.3 GPa respectively.

Larger samples will be manufactured in the future to incorporate longer strain gages for improved averaging. In addition, measurements will be made on composite samples constructed of Nb_3Sn wires.

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