Tensile Measurements of the Modulus of Elasticity of Nb_3Sn at Room Temperature and 4 K

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***Abstract*—The critical current of Nb_3Sn superconductors is highly sensitive to strain. Consequently, accurate mechanical modeling of these conductors is necessary to interpret experimental data and to predict conductor performance in applications such as large magnet systems. A key parameter in these models is the modulus of elasticity (E, Young's modulus); however, there are large discrepancies in the available data, and there are no published tensile-test data on E for Nb_3Sn. Tensile test specimens were prepared from a starting material of Nb tape with 1.4 wt.% ZrO_2 precipitates. Tensile measurements of unreacted Nb and partially reacted Nb-Nb_3Sn tapes were made at room temperature (293 K) and at 4 K. A modulus of elasticity of 65 ± 15 GPa was extrapolated from these measurements for polycrystalline Nb_3Sn at 4 K, and 150 ± 15 GPa at room temperature.**

I. INTRODUCTION

Nb_3Sn is presently the most common superconductor used in magnetic-field applications above 10 T; below 10 T, Nb-Ti dominates. Unlike Nb-Ti, however, which is ductile at room temperature and relatively insensitive to strain, Nb_3Sn is brittle and its critical current (I_c) at high magnetic fields is extremely sensitive to strain [1]. In magnet applications of composite Nb_3Sn conductors, sources of strain may include coil fabrication, differential thermal expansion between the superconductor and the conductor matrix as well as the magnet structure, and the magnetic forces generated within the energized coil.

The magnetic forces in a solenoid magnet produce orthogonal stress components in the conductor, axial tensile stress and transverse compressive stress. The effects of both stress components on the I_c of Nb_3Sn are well documented [1]-[4]. A difficulty arises, however, in comparing their relative effects on I_c. Due to experimental limitations, the independent variable in the axial test is strain, while in the transverse test it is stress [3]. To directly compare the two effects, the strain data must be converted to stress, or stress to strain, which requires the modulus of elasticity (E, Young's modulus) of Nb_3Sn at 4 K. Also, the modulus of elasticity is important to Nb_3Sn magnet designers for modeling the mechanical and electrical responses of the conductor to the various sources of stress.

Numerous data have been reported on E of Nb_3Sn at various temperatures including 4 K [5]-[13]. The majority of these data are based on ultrasonic measurement techniques applied to single-crystal and polycrystalline specimens. The results of vibrating-reed measurements and static beam deflection measurements of Nb-Nb_3Sn composites have also been reported. Unfortunately, the reported data for E of Nb_3Sn at 4 K ranges from 32 GPa to 165 GPa.

In the present study, tensile tests were performed at room temperature (293 K) and 4 K on Nb and Nb-Nb_3Sn tapes. The modulus of elasticity of the Nb_3Sn portion of the composite was then extrapolated from these data at each temperature.

II. EXPERIMENTAL DETAILS

A. Tensile-Test Specimens

Tensile-test specimens of Nb, Nb-1 wt.% Zr, low-carbon steel, and partially reacted Nb-Nb_3Sn (with ZrO_2 precipitates) composites were prepared for this study. In all cases the widths of the specimens are 3.18 ± 0.07 mm. The specimens were carefully cut to their nominal width by simply using a straight edge and razor blade. This technique resulted in a uniform specimen width, along its length, typically within ± 1% of the mean. The Nb_3Sn specimens were cut after the reaction heat treatment. The gage lengths of the specimens range from 237 mm to 266 mm. The thickness of the specimens differ for each material. The Nb specimens are approximately 0.075 mm thick, 0.050 mm for the steel, and 0.025 mm for the Nb-1 wt.% Zr as well as the Nb-Nb_3Sn composites.

The 0.025 mm specimens fall into two categories, knurled and smooth. The knurled materials have a mechanically textured surface to promote adhesion of the liquid Sn-10 wt.% Cu coating that is applied to the Nb tape prior to the Nb_3Sn reaction process [14]. The smooth specimens lack this surface texturing. Although the smooth specimens are inherently superior to the knurled specimens for tensile tests, because of their uniform cross sections, the knurled specimens were also tested because they were available in a variety of Nb-to-Nb_3Sn ratios, unlike the smooth specimens. The different composite ratios are achieved by varying the reaction time. Pure Nb_3Sn specimens could be prepared by increasing the reaction time; but, without the ductile Nb core, the specimens would be too brittle to handle. Initially, all of the 0.025 mm specimens had a Sn-10 wt.% Cu surface coating. The coating was removed with a dilute nitric acid solution prior to testing.

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The steel specimens were included in the study as control specimens to confirm the accuracy of the measurement method.

B. Measurement Method

The ends of the test specimen are soldered to heavy brass grips, and the specimen is then installed in a rigid cryogenic tensile-test apparatus. The apparatus consists of two stainless steel tubes, an outer stationary tube for force reaction and an inner tube for applying tensile load to the specimen. The brass grips are attached to the load tube and the reaction tube with clevises that allow the grips to pivot in the plane of the specimen, which ensures self alignment and uniform loading. The probe is inserted in a liquid-helium dewar and it is externally connected to a servohydraulic actuator, which provides the tensile load. The actuator is equipped with a linear variable differential transformer (LVDT) for strain measurement and a 1300 N load cell for stress measurement.

The stress-strain characteristic of the specimen is first recorded at room temperature without exceeding its elastic limit. The specimen is then cooled to 4 K in liquid helium, and the stress-strain characteristic is measured again. The modulus of elasticity is calculated from the slope of the stress-strain characteristic. The slope is measured at low strain, typically 0.01% to 0.1%, to ensure pure elasticity.

To measure stress in the specimens, their cross-sectional areas must be determined. Moreover, the area of each component of the composite specimens must be measured to determine E of the Nb_3Sn. After the tensile tests are completed, three samples are cut from the specimen, one from the center and one from each end. The samples are then mounted in epoxy resin and polished for optical microscopic analysis.

The microscopic images are digitized and computer analyzed. The width of each of the three samples is measured, and an average width is calculated. Because many of the specimens are quite thin (0.025 mm), the surface roughness often limits the precision of the thickness measurements. This is particularly true for the composite specimens where the reaction process increases the roughness. To statistically reduce this problem, 90 width measurements of each specimen are made, 30 for each sample, and an average width is calculated. In the case of the composite specimens, both the total thickness and the Nb-core thickness must be measured to determine the component areas, doubling the number of required measurements. Finally, the average width of the specimen is multiplied by the average thickness to determine the cross-sectional area.

The overall uncertainty of the E measurements is dominated by the area measurements and estimated to be ± 10%. In addition to standard instrument calibrations, including the load cell and the LVDT, a control specimen was prepared from commercial low-carbon steel sheet (0.050 mm thick) and tested at room temperature. The value of E was determined to be 210 GPa, which is comparable to the published values for this material, 208 to 209 GPa.

III. RESULTS

The tensile-test results for the smooth specimens are shown in Fig. 1, which is a plot of E as a function of specimen composition at room temperature (293 K) and 4 K. The data located on the ordinate are from the unreacted Nb-1 wt.% Zr specimens. The remaining data, from the smooth composite specimens, are for a Nb_3Sn content of approximately 46%.

Focusing first on the unreacted Nb-1 wt.% Zr data, Fig. 1 shows a slight increase in E when the specimen is cooled from 293 K (93 GPa) to 4 K (97 GPa). These E values are approximately 11% and 13% lower, respectively, than previously published ultrasonic measurement results for Nb single crystals [15]. Texturing of the Nb grains is the probable source of the reduced E values. Fig. 2 is a photomicrograph of a typical cross section from the composite specimens, showing a central Nb core and Nb_3Sn layers on each side. The appearance of the core is consistent with texturing in the Nb grains. In the tensile tests, the orientation of the applied load is perpendicular to the plane of the figure.

The ultimate purpose of the Nb tensile tests is, of course, to isolate the elastic modulus of the Nb_3Sn portion of the composite specimens by subtracting the Nb-core contribution. The unreacted Nb-1 wt.% Zr specimens, however, are slightly different from the reacted composite's core, which contains ZrO_2 precipitates rather than Zr in solid solution. In either case the effect on E is undoubtedly slight, given the low concentration of additions.

Several specimens of pure Nb were also measured. The pure Nb specimens are approximately three times the

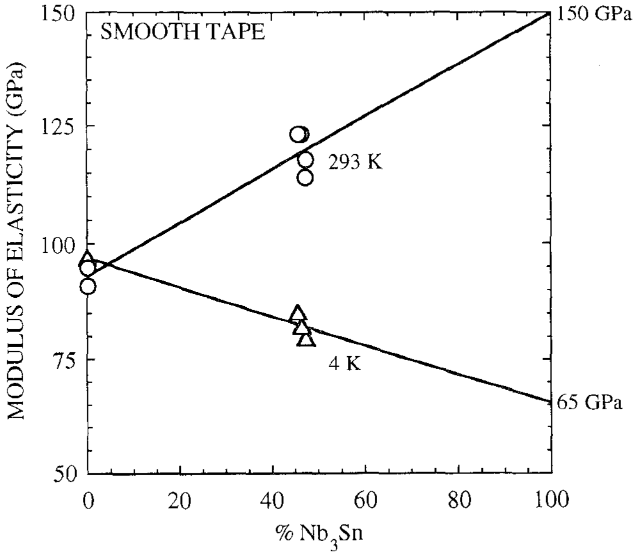

Fig. 1. Modulus of elasticity of smooth specimens at 293 K and 4 K as a function of Nb_3Sn content. Extrapolated values for 100% Nb_3Sn are also shown. The polycrystalline Nb_3Sn contains 1.4 wt.% ZrO_2 precipitates (to limit grain growth and enhance flux pinning).

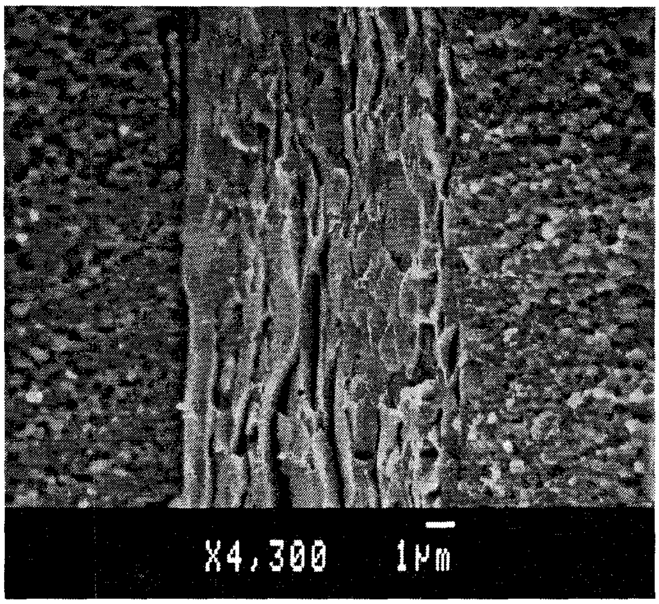

Fig. 2. Cross-sectional photomicrograph of composite specimen, showing central Nb core and Nb_3Sn outer layers. In the tensile tests, the orientation of the applied load is perpendicular to the plane of the figure.

thickness of the Nb-1 wt.% Zr specimens, which increases the precision of the cross-sectional area measurements. Consistent with the Zr-alloyed specimens, the measurements of pure Nb tape produced relatively low E values, 87 GPa at 293 K and 94 GPa at 4 K, approximately 15% below previously published values [15]. Again, texturing is the likely source of the reduced modulus values, and differences in texturing probably account for the relatively small variation in E between pure Nb and the Nb-1 wt.% Zr. The E values for these textured materials are not indicative of the elastic modulus of nontextured polycrystalline Nb; however, the Nb-1 wt.% Zr data are the required values for solving the problem at hand— isolating E for Nb_3Sn from the composite data.

Turning to the 46% Nb_3Sn composite data, Fig. 1 shows that E is greater for Nb_3Sn than for Nb at room temperature (293 K). At 4 K the opposite occurs; E is lower for the composite, which demonstrates the dramatic softening of Nb_3Sn at 4 K [16]. A linear least-squares fit of the data yields extrapolated Nb_3Sn E values of 150 ± 15 GPa at 293 K and 65 ± 15 GPa at 4 K. The microstructure of these tapes have been studied in detail [17] using transmission electron microscopy (TEM). TEM analysis of the Nb_3Sn layers shows that the fine, equiaxed crystals shown in Fig. 2 are randomly oriented. Consequently, the elastic-modulus values for these tapes are indicative of macroscopically isotropic, polycrystalline Nb_3Sn (with 1.4 wt.% ZrO_2 precipitates).

Fig. 3 is a plot of E as a function of specimen composition at 293 K and 4 K for the knurled specimens. Again, E for the unreacted Nb is slightly higher at 4 K than at 293 K, and for the reacted composites it is significantly lower at 4 K, indicating significant low-temperature softening of the Nb_3Sn.

The data in Fig. 3 are plotted on the same scales as the data in Fig. 1 for comparison. The knurling reduces the measured values of E at both temperatures. This compliance of the knurled specimens is undoubtedly a geometric effect rather than a material property. The knurling creates an undulation along the length of the specimen, which apparently acts like a spring, artificially reducing the measured E value. Consequently, knurled-specimen data are not indicative of intrinsic material properties. The relatively linear relationship between E and Nb_3Sn content for the knurled specimens, however, supports the linear extrapolation applied to the smooth-specimen data in Fig. 1.

IV. DISCUSSION

Ternary additions of Ta, Ti, and Zr to Nb_3Sn have been shown to suppress the martensitic transformation and increase E at 4 K, in comparison with binary Nb_3Sn [10]. The specimens tested in the present study contain 1 wt.% Zr, which is oxidized prior to Nb_3Sn reaction to form ZrO_2 precipitates. These precipitates may suppress the martensitic transformation and, thus, they may have a significant effect on E.

Ternary additions and precipitates are commonly used in Nb_3Sn multifilamentary and tape conductors to improve critical-current density and Nb_3Sn growth kinetics [18]-[20]. Consequently, tensile-test data on these materials are, from an engineering standpoint, as important as data on basic binary Nb_3Sn.

Additional tensile measurements are needed to accurately determine E for pure Nb_3Sn. Ideally, a series of smooth composite specimens of Nb_3Sn and Nb, with different Nb-to-Nb_3Sn ratios like the knurled specimens in the present study, need to be tested to determine a more definitive value of E for pure Nb_3Sn.

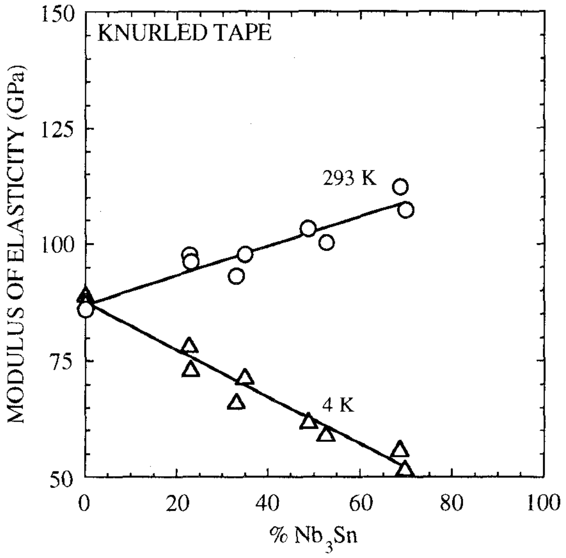

Fig. 3. Modulus of elasticity of knurled specimens at 293 K and 4 K as a function of Nb_3Sn content.

V. CONCLUSIONS

There is a broad range of reported values for the elastic modulus of Nb_3Sn at 4 K using various measurement techniques, 32 GPa to 165 GPa. The present data are the first published results on the elastic modulus of Nb_3Sn from tensile tests. These results are qualitatively consistent with most earlier data from ultrasonic, vibrating reed, and static beam deflection measurements, which usually show a low-temperature softening of the elastic modulus. The results of the present study are summarized in Table I.

TABLE I
ELASTIC-MODULUS VALUES FROM TENSILE TESTS OF POLYCRYSTALLINE Nb_3Sn^a SPECIMENS

Temperature	Elastic Modulus
293 K	150 ± 15 GPa
4 K	65 ± 15 GPa

[a] The Nb_3Sn specimens contain 1.4 wt.% ZrO_2 precipitates and are macroscopically isotropic.

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