

CRITICAL-CURRENT DEGRADATION IN MULTIFILAMENTARY Nb₃Al WIRES FROM TRANSVERSE COMPRESSIVE AND AXIAL TENSILE STRESS

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Abstract--The effect of transverse compressive stress and axial tensile stress on the critical current of multifilamentary Nb₃Al superconducting wires has been measured. Compared with commercial Nb₃Sn, Nb₃Al exhibits a relatively small sensitivity to both axial and transverse stress. For a given degradation of critical current at 9 T, Nb₃Al will tolerate about twice as much axial stress as Nb₃Sn and about five times the transverse stress. The elastic modulus of Nb₃Al, 169 ± 20 GPa, was measured for the first time at cryogenic temperatures and found comparable to that of Nb₃Sn. A comparison between the effect of axial and transverse stress showed that Nb₃Al, like Nb₃Sn, is more sensitive to transverse stress than axial stress. For a given level of critical-current degradation, the transverse stress tolerance of Nb₃Al is about half the axial stress tolerance. The favorable electromechanical characteristics of Nb₃Al, compared with Nb₃Sn, may allow increased operating limits for the next generation of large high-field superconducting magnets.

I. INTRODUCTION

Presently, the most common conductor material used in high-field (>10 T) superconducting magnet designs is Nb₃Sn. Commercially available multifilamentary Nb₃Sn conductors typically have noncopper critical-current densities (J_c) exceeding 10^5 A/cm² at a magnetic field of 10 T. High current densities and high fields interact within magnet windings to produce large Lorentz forces supported by the conductor and the magnet structure. The two dominant components of stress in the windings are a tensile stress aligned with the conductor's longitudinal axis (axial stress) and a compressive stress that is perpendicular to its axis (transverse stress). The J_c of Nb₃Sn is highly sensitive to its stress state. Consequently, it is the internal stress state of the magnet windings, rather than the J_c of the unstressed superconductor, that determines the design limits for large high-field magnets.

As new magnet designs call for larger coils and higher fields, stresses must be limited by structural reinforcement of the windings. Control of the stress, which accumulates radially within the windings, requires distributed internal reinforcement. Aside from complicating the design and increasing the cost of the magnet, additional internal

reinforcement limits the superconductor packing fraction and, thus, reduces the magnetic field. Also, internal stresses within cable-in-conduit conductors can be difficult to control; thus, a superconducting material that is less sensitive to stress but comparable to Nb₃Sn in J_c has significant design advantages. A promising candidate material for this application is the A-15 superconductor Nb₃Al.

Early measurements of Nb₃Al wires demonstrated their relative insensitivity to axial stress [1], but these experimental conductors were only available in short test sample lengths, unsuitable for magnet applications. More recently, technologies have been developed that allow fabrication of multifilamentary Nb₃Al wires of practical lengths [2]. In this paper, both the axial and transverse stress effects for these conductors are investigated, and their performance is compared with that of a commercial binary Nb₃Sn conductor. Also, results from the first elastic-modulus measurements of Nb₃Al at cryogenic temperatures, which were required to compare the axial and transverse stress effect in Nb₃Al, are presented.

II. EXPERIMENTAL DETAILS

The critical-current (I_c) degradation of round multifilamentary Nb₃Al composite wires, caused by both axial and transverse stress, was measured at a temperature of 4 K and as a function of magnetic field. An electric-field criterion of $2 \mu\text{V}/\text{cm}$ was used for determining the I_c . The overall precision of the I_c data is about $\pm 0.5\%$. In the case of the transverse tests, a servohydraulic actuator and load cell are used to apply a compressive transverse load to the sample. The apparatus design allows mutually perpendicular application of current, field, and load [3] to simulate the conditions within the windings of a magnet. The transverse stress is calculated by dividing the load by the projected area of the compressed region of the sample. This technique is justified by previous comparative transverse stress measurements between round and rectangular Nb₃Sn samples [3].

In the case of the axial tests, an axial tensile load is applied to the sample and the resulting axial strain is measured with an extensometer [4]. The magnetic field is perpendicular to the strain and current, which are coaxial, again simulating the conditions within a magnet. The characteristics of the Nb₃Al samples, which were prepared by the Nb-tube process [2], are given in Table 1.

Table 1. Nb₃Al Sample Characteristics

Wire diameter	0.5-0.57 mm
Matrix material	Nb
Filament composition	Al-1 at% Cu, 1 at% Ge (prior to heat treatment)
Matrix-to-filament volume ratio	31:1
No. filaments	1,728,000
Filament size	~80 nm
Heat treatment	3 hours at 800 °C
Overall J_c at 12 T	8,600 A/cm ²
Filament J_c at 12 T	274,000 A/cm ²

III. RESULTS

The results of the Nb₃Al axial strain measurements are shown in Fig. 1 where I_c is plotted as a function of axial strain for several magnetic fields. The ordinate is the measured I_c normalized to the starting (zero-strain) value (I_{c0}). For comparison, previously acquired data for a commercial bronze-process Nb₃Sn conductor [3] are also presented. The available data do not allow direct comparison of the Nb₃Al and Nb₃Sn conductors at a common field; however, interpolation of the Nb₃Sn data allows comparison at 9 T. For I_c degradations greater than 10%, the Nb₃Al will tolerate approximately twice the strain of the Nb₃Sn while undergoing the same degradation in I_c .

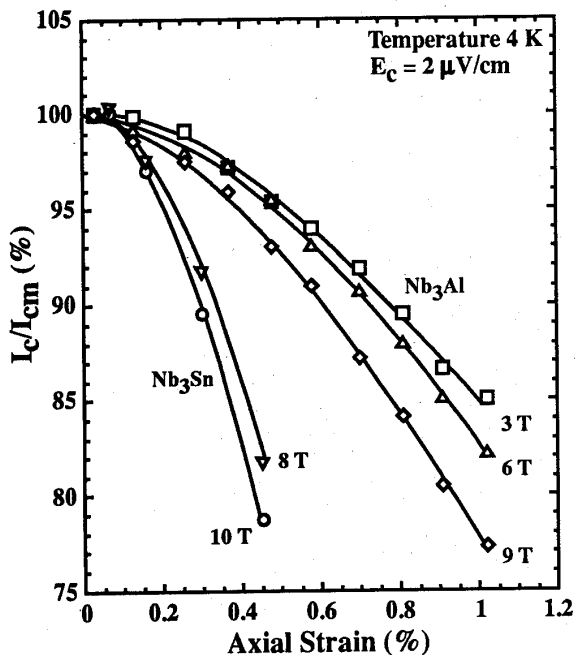


Fig. 1. Critical-current degradation caused by axial tensile strain.

Figure 2 shows a similar comparison between Nb₃Al and Nb₃Sn subjected to transverse stress. By convention, the stress is negative to indicate compression. The difference between Nb₃Al and Nb₃Sn is even greater in the case of transverse stress. For I_c degradations greater than 10% at 9 T,

the Nb₃Al will tolerate approximately five times the stress of the Nb₃Sn while undergoing equal I_c degradation.

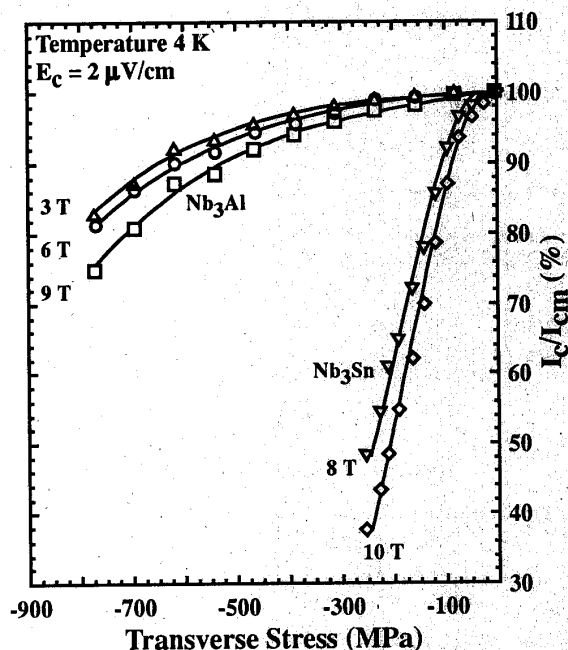


Fig. 2. Critical-current degradation caused by transverse compressive stress.

Previous studies comparing the axial and transverse stress effects in Nb₃Sn [3], [5], [6], [7] have all shown a much greater sensitivity to transverse stress than axial stress. This type of comparison requires a conversion of the axial strain data, the measured quantity, to axial stress. The relationship between stress and strain (elastic modulus) has previously been measured at cryogenic temperature for Nb₃Sn (165 GPa) [8] but not for Nb₃Al. Consequently, to allow comparison of axial and transverse stress effects, elastic-modulus measurements of Nb₃Al at cryogenic temperatures were made.

The Nb₃Al samples used in the I_c tests are not well suited for modulus measurements because of their ultra-fine filaments and small superconductor-to-matrix ratio. Consequently, a group of three different large monofilament Nb₃Al conductors were used for the modulus measurements. These are powder-process wires that vary in Nb₃Al content ($45 \pm 15\%$, $60 \pm 10\%$, and $81 \pm 2\%$ Nb₃Al). A detailed description of the wires is contained in [9]. All of the samples were 5 cm long. The results of these measurements are shown in Fig. 3 where the elastic moduli of the three different conductors are plotted as a function of their Nb₃Al content. Since the sample with the highest Nb₃Al content is $81 \pm 2\%$ Nb₃Al, the elastic modulus of pure Nb₃Al was extrapolated from the measured data.

Two samples of the 60%-Nb₃Al conductor were measured at both 76 K and 4 K. For both samples, the difference between measurements at 4 K and 76 K was less than 5%.

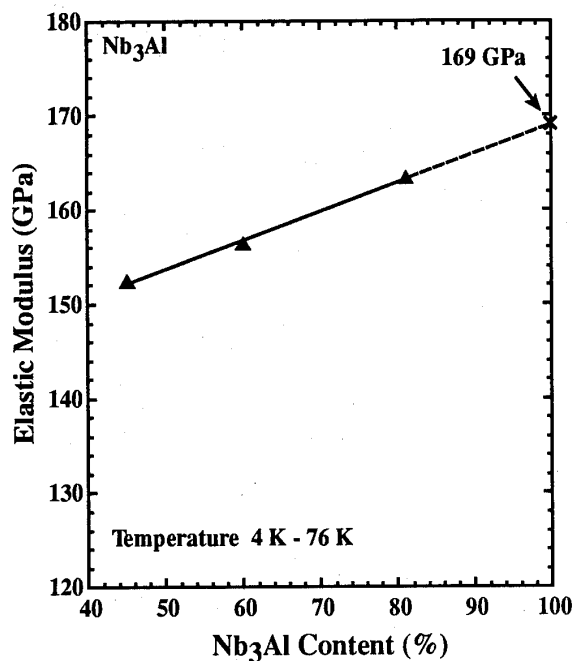


Fig. 3. Elastic modulus of three Nb₃Al wires, each with a different Nb₃Al content.

Given an overall experimental error of about 5% for the modulus measurements, the difference in the 4 K and 76 K measurements can reasonably be neglected.

Two 45%-Nb₃Al wires were measured, and the average of these measurements is plotted in the figure. The two measurements varied $\pm 1.6\%$ from the mean. Seven total measurements of four different 60%-Nb₃Al wires were made with a maximum variation of $\pm 9.2\%$ from the plotted mean value. For the 81%-Nb₃Al wire, two measurements were made, and the variation was $\pm 4.0\%$. The mean values are plotted for each type of conductor in Fig. 3; a linear extrapolation of the data yields an elastic modulus of approximately 169 ± 20 GPa.

Using this modulus value, axial stress values were calculated from the axial strain data and plotted in Fig. 4 for comparison with the transverse data. Like Nb₃Sn, Nb₃Al is more sensitive to transverse stress than to axial stress; however, the difference in sensitivity is much greater for Nb₃Sn than for Nb₃Al. From Fig. 4, the stress that causes a given amount of I_c degradation at 9 T is almost two times smaller for transverse stress than for axial stress. In contrast, this ratio for Nb₃Sn at 10 T is approximately five [3].

As indicated in Fig. 4, transverse *compressive* stress is being compared with axial *tensile* stress. There are two practical reasons for this. First, these are the conditions that actually exist in the windings of an energized magnet, thus these data are useful from an engineering design standpoint for estimating magnet performance. Also, it is difficult to apply axial compressive stress to a superconducting wire. The

effect of axial compressive stress has been measured in Nb₃Sn by taking advantage of the compressive prestrain of the superconductor [4]. The Nb₃Al samples did not exhibit this prestrain, so the effect of axial compressive stress could not conveniently be measured. However, assuming that Nb₃Al behaves similarly to Nb₃Sn, in which the effects of tensile and compressive axial stress are approximately equal, the sense of the axial stress does not affect these results.

IV. CONCLUSIONS

For a given degradation of I_c at 9 T, Nb₃Al will tolerate about twice as much axial stress as Nb₃Sn and about five times the transverse stress. The elastic modulus of Nb₃Al, 169 ± 20 GPa, was measured for the first time at cryogenic temperatures and found comparable to that of Nb₃Sn, 165 GPa. The elastic modulus of Nb₃Al was needed in this study for comparing the axial and transverse stress effects, but, in a more general sense, it will ultimately be important for Nb₃Al magnet design.

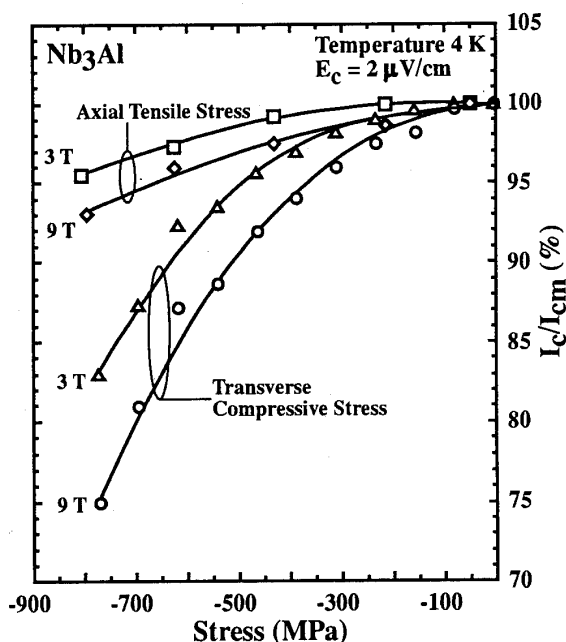


Fig. 4. Comparison between axial and transverse stress effects.

Nb₃Al conductors are more sensitive to transverse stress than axial stress. This suggests that the anisotropy in stress degradation, which was first observed in Nb₃Sn conductors, is not associated with a particular processing method or even a particular material. However, the difference between axial and transverse sensitivity is less for Nb₃Al than Nb₃Sn. A given level of I_c degradation at 10 T in Nb₃Sn requires about five times less transverse stress than axial stress; for Nb₃Al at 9 T, the ratio is only about two.

There are many factors that determine the suitability of a superconducting material for a particular application. Critical-

current density, critical magnetic field, cost, available conductor length, and handling properties are important considerations for most applications. For the large high-field magnets needed in fusion applications, stress effects often dictate the design operating limits of the magnet. The present interest in Nb₃Al superconductors is partially due to its relative insensitivity to stress. Ultimately, if Nb₃Al conductors can be developed that are otherwise comparable to the existing high-field commercial superconductors, their favorable electromechanical properties may extend the operating limits for future magnet designs.

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