Effect of transverse stress on the critical current of bronze-process and internal-tin Nb_3Sn

J. W. Ekin, S. L. Bray, and W. L. Bahn
Electromagnetic Technology Division, National Institute of Standards and Technology, Boulder, Colorado 80303

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The effect of transverse stress on the critical current of two substantially different Nb_3Sn superconductors, a bronze-process conductor and an internal-tin conductor, has been measured. Photomicrographs of the two conductors reveal a basic difference in their microstructure. The bronze-process conductor exhibits columnar grains that are radially oriented within the Nb_3Sn filaments, while the grains of the internal-tin conductor are more equiaxed and randomly oriented. The radial orientation of the bronze-process grains defines an anisotropy between the axial and transverse directions that might account for the greater sensitivity of the critical current to transverse stress reported previously. The effect of transverse stress measured on the internal-tin conductor, however, is comparable to that of the bronze-process conductor. Thus, these data indicate that the transverse stress effect is not highly dependent on either grain morphology or fabrication process. From an engineering standpoint the similarity of the transverse stress effect for these two types of Nb_3Sn superconductors represents an important simplification for setting first-order quantitative limits on the mechanical design of large superconducting magnets.

Internally generated stresses within the windings of a superconducting magnet can adversely affect its performance through a reduction in the superconductor's critical current (I_c). The superconducting wire is subjected to two dominant stress components, a tensile stress that is aligned with the wire's longitudinal axis (axial stress) and a compressive stress that is perpendicular to its axis (transverse stress). The effect of *axial* stress on the I_c of A15 superconductors has been the subject of extensive research.[1] More recently, the first measurement of the effect of *transverse* stress was made,[2] and it was significant in bronze-process Nb_3Sn, with the onset of degradation occurring at about 50 MPa. In an applied field of 10 *T*, the effect of transverse stress is about seven times the effect of axial tensile stress. Subsequently, the results of these measurements were substantiated at several other laboratories.[3–5] A bronze-process Nb_3Sn conductor was used for the initial transverse stress measurements and for several later measurements. The bronze process results in a characteristic grain morphology[6] that might explain the greater sensitivity of these conductors to transverse stress. Because of its dissimilarity to bronze-process conductors, an internal-tin Nb_3Sn conductor was selected for this study to directly address the effect of grain morphology on the transverse stress effect.

The apparatus allows measurement of the superconducting sample's I_c as a function of magnetic field and transverse stress at 4 K. Figure 1 shows the mutually perpendicular orientation of the current, magnetic field, and force. Force is applied to the sample through a pivoting self-aligning anvil that ensures uniform force application along the sample's compressed length. The voltage leads are soldered to the sample within this region so that the electric field is measured only over the uniformly stressed portion of the sample. The force is supplied by a servohydraulic test system, the current by a 900 A battery-powered supply, and the magnetic field by a 10 *T* split-pair magnet.

The characteristics of the two conductors that were tested are given in Table I. The cross section of each sample is shown in Fig. 2. The bronze-process conductor is stabilized with an external 64 vol% copper ring which surrounds the Nb_3Sn filament-bronze core and is separated from it by a tantalum diffusion barrier. The tin core modified jelly roll internal-tin conductor is stabilized with 65 vol% copper. The copper is separated from each of the conductor's 42 Nb_3Sn and bronze subelements by diffusion barriers consisting of a ring of niobium surrounded by a ring of vanadium.

Figures 3(a) and 3(b) show the shape and orientation of grains within the Nb_3Sn filaments for the bronze-process and internal-tin samples, respectively. The photographs show fractured transverse cross sections of the filaments. In the case of the bronze-process conductor, the grains have a columnar shape with their longitudinal axes oriented approximately radially within the filament. This microstructural anisotropy is a possible source of the conductor's greater sensitivity to transverse stress than to axial

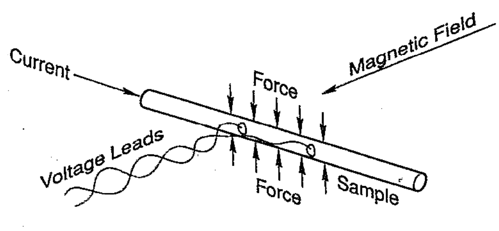

FIG. 1. Relative orientation of test sample, current, magnetic field, applied transverse force, and voltage sensing leads.

TABLE I. Sample characteristics.

	Bronze-process	Internal-tin	
Diameter	0.70 mm	0.60 mm	
No. filaments	2869	$\simeq$15 800	
Filament size	3.8 μm	$\simeq$1.1 μm$\times$(1.1–2.2)μm	
Filament twist pitch	25 mm	12.1 mm	
Composition (vol%)	64% Cu	65% Cu	
	25% bronze	12.0% Nb	
	2.4% Ta	11.8% Cu	
	8.6% Nb_3Sn and Nb	6.3% Sn	Noncopper
		2.45% Nb	
		2.45% V	
Noncopper area	1.35×10^{-7} m^2	9.90×10^{-8} m^2	
Reaction	96 h at 700 °C	220 h at 220 °C	
	48 h at 730 °C	16 h at 340 °C	
		110h at 650 °C	

stress. In contrast, the internal-tin grains are more equiaxed, as described in Ref. 6. If the source of the transverse stress sensitivity of bronze-process Nb_3Sn is in fact the anisotropy, then the internal-tin conductor would be expected to show a smaller sensitivity to transverse stress.

The critical current of the test sample was measured at zero applied force and 4 K as a function of magnetic field. Force was then applied to the sample at 4 K and again the I_c was measured as a function of field. This process was continued while incrementally increasing the applied force to generate the data shown in Fig. 4.

The effective overall transverse stress is calculated by dividing the applied force by the compressed area of the sample. A projected area equal to the sample diameter multiplied by the length of the compressed region is used for this calculation. This simple technique is justified by the results of previous comparative measurements between otherwise identical round and rectangular Nb_3Sn samples.[2]

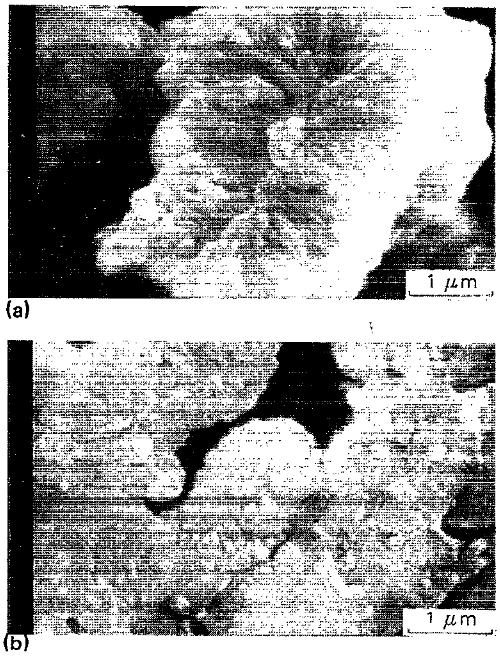

FIG. 3. Micrographs of bronze-process conductor (a) showing columnar radially oriented grains, and internal-tin conductor (b) showing more equiaxed and randomly oriented grains.

An electric-field criterion of 2 μV/cm was used to determine the I_c. The overall precision of the I_c data is about $\pm3\%$.

Figure 4(a) shows the critical current of the internal-tin conductor as a function of transverse compressive stress for several applied magnetic fields. The ordinate is the measured critical current normalized to the starting (zero-stress) value, and the abscissa is the effective overall transverse stress. Figure 4(b) shows the 8 and 10 T internal-tin data compared with the bronze-process data.

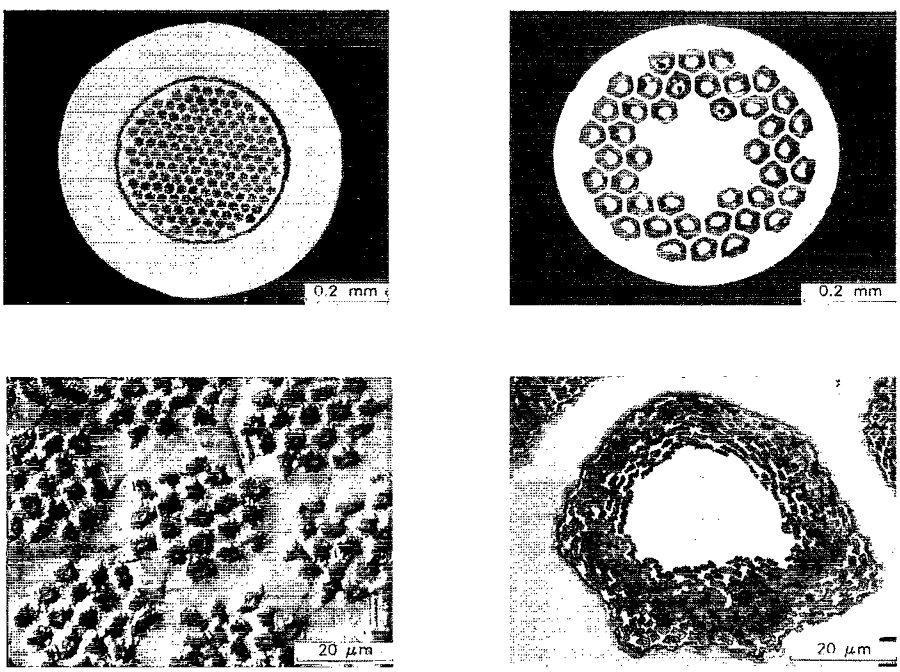

FIG. 2. Cross-sectional view of bronze-process sample (top) and internal-tin sample (bottom).

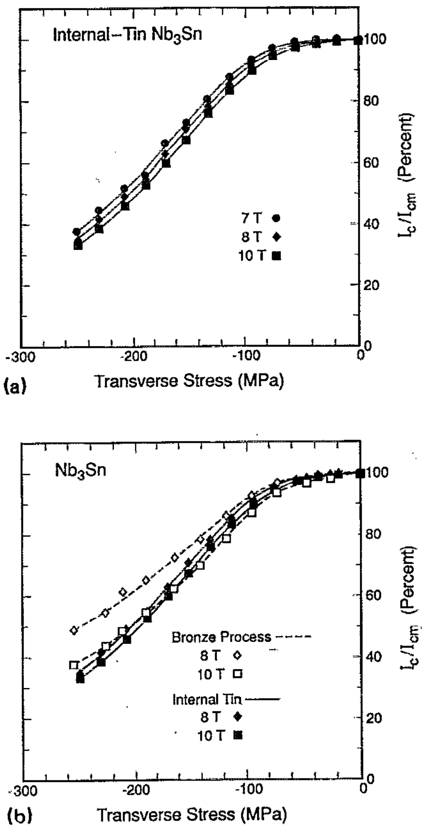

FIG. 4. Critical-current degradation as a function of transverse stress and magnetic field for the internal-tin conductor (a) and (b) a comparison of the effect in internal-tin and bronze-process conductors. By convention, the negative values of stress indicate compression.

Comparing the 8 T internal-tin and bronze-process data of Fig. 4(b), a 10% reduction in the I_c occurs at a transverse stress of approximately 100 MPa for both samples. Moreover, the two sets of results show nearly the same transverse stress effect, within the limits of error, over the entire measured range of transverse stress. If anything, the internal-tin sample has a slightly greater I_c degradation than the bronze-process sample, which is opposite to what would be expected if the columnar grain morphology was the source of the transverse stress sensitivity. At a stress of 200 MPa, the internal-tin sample shows a degradation of approximately 50%, whereas the bronze-process sample is degraded slightly less than 40%. Considering that the two test conductors were fabricated by different manufacturers using fundamentally different processes, the two data sets are in surprisingly close agreement.

The difference between the magnitude of the effect of axial and transverse stress on the I_c of Nb_3Sn is presently the source of speculation. Based on these data, however, the difference would not appear to be due to microstructural anisotropy. Moreover, recent measurements of the transverse stress effect in Nb_3Al (Ref. 7) and $PbMo_6S_8$ (Ref. 8) demonstrate that the large difference between the two effects is not limited to Nb_3Sn or even to A15 superconductors. If, in general, this is a common characteristic of superconductors, the transverse stress effect may be important for developing a fundamental understanding of stress effects in superconductors. From a practical point of view, the relatively large magnitude of the transverse stress effect makes it a significant factor in the designing of large magnets where the large radial thickness of the conductor can lead to accumulation of high internal transverse stress loading of the strands within cabled conductors.[2] Although the effect of transverse stress on the I_c of Nb_3Sn is considerably greater than that of axial stress, their relative importance in magnet design may be comparable because the axial stress imposed on typical magnet conductors is usually greater than transverse stress. The main effect of transverse stress will be to place limits on the conductor thickness in the direction of the Lorentz force. This can be particularly significant in cabled conductors where stress concentrations can occur at strand crossover points.

The effect of transverse stress on the critical current of *internal-tin* Nb_3Sn superconductors was nearly identical to that measured for *bronze-process* Nb_3Sn. The magnitude of the effect was nearly the same even though photomicroscopic analysis revealed significant difference in grain morphology and orientation for the two conductor types; the bronze-process conductor grains had a columnar shape and were oriented in a radial pattern within each Nb_3Sn filament, while the internal-tin conductor grains were more equiaxed. These data also indicate that the transverse stress effect is not highly sensitive to the Nb_3Sn fabrication procedure. The data shown in Fig. 4, thus, should serve as a general starting point for determining the effect of transverse stress and setting engineering design limits for the conductor windings in Nb_3Sn magnets.

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