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ABSTRACT

The critical current density of commercial multifilamentary Nb_3Sn conductor has been measured during the application of uniaxial tension at 4.2 K and after bending at room temperature. Significant reductions in the critical current density J_c occurred under uniaxial loading. Results are presented for a monolithic conductor manufactured by the bronze diffusion technique and for cable conductors formed by the tin-dip technique.

The construction of large, stable superconducting magnets operating at fields of 11 T or higher presently requires the use of multifilament (MF) Nb_3Sn.[1] Of great concern, however, is the ability of the inherently brittle Nb_3Sn to operate successfully under the mechanical loads which will be encountered in the construction and operation of large devices. These loads are of two types. The first occurs during winding as the conductor is subjected to twists and bends; the room temperature bend test simulates this type of stress.[2] The second type of loading occurs as the device is cooled and energized. The conductor then experiences both the forces due to differential thermal contraction and the Lorentz forces of the magnetic field. Magnetic and thermal stresses are in part simulated by the tensile test at 4.2 K in the magnetic field.

Reported here are the results of tensile tests at 4.2 K with current and field simultaneously applied, and the effects of room temperature bending tests on cabled and monolithic conductors obtained from commercial sources.

The conductors are typical of available commercial material (Fig. 1). The first five are cables manufactured via the tin-dip process.[3] The basic 0.060-cm-diam strand contains 230 filaments (6 μm diam). Various

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*Fusion Energy Division.

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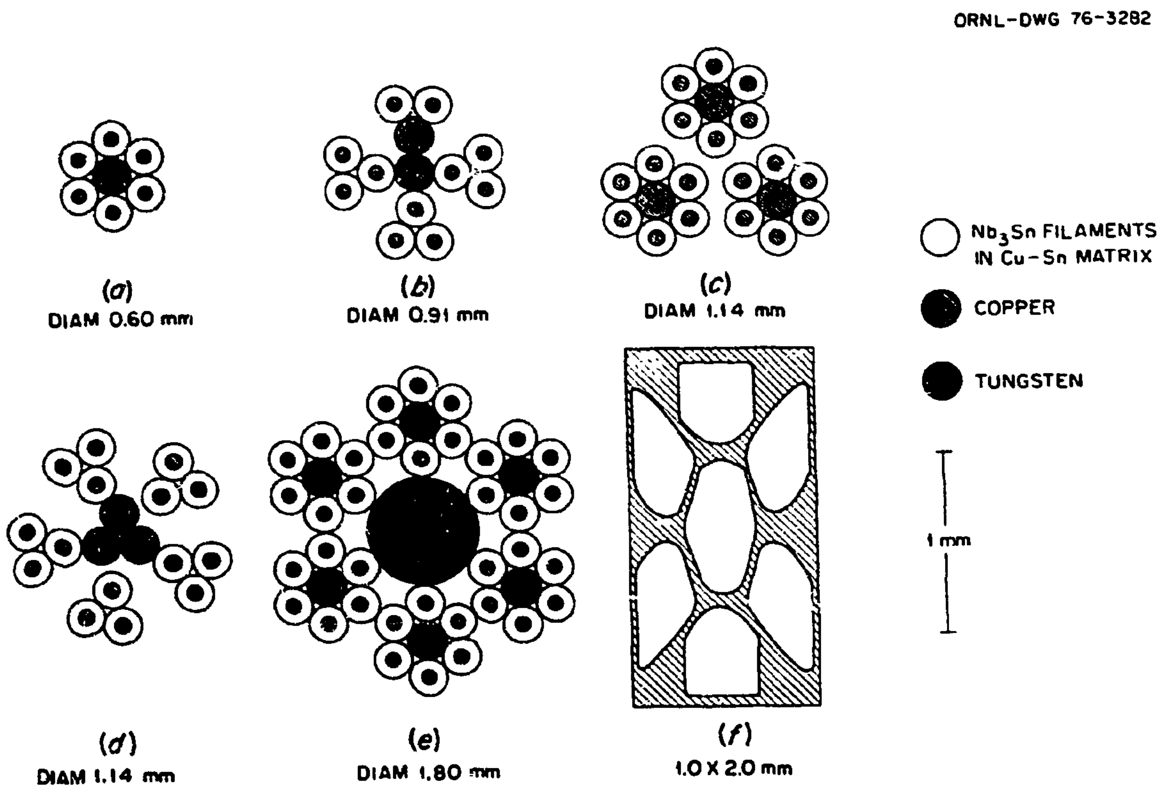

Fig. 1. Multifilamentary Nb_3Sn Conductors.

cable configurations with copper and tungsten cores were tested. The sixth conductor is a 0.1 cm × 0.2 cm monolithic conductor containing 24781 filaments (4 μm diam) produced by the bronze diffusion technique.[4]

The bend test consists of forming a short sample of the conductor about a cylindrical mandrel of the desired diameter, then straightening the sample at room temperature. Bends of smaller diameter than the mandrel are carefully avoided. The sample is then soldered into a groove in a large diameter copper mandrel that provides mechanical support and electrical stabilization. The short sample critical current density was measured as a function of bend diameter (Fig. 2).

More elaborate equipment is required for the uniaxial tensile test.[5] The sample is mounted in a tensile testing machine so that a tensile load can be applied while the sample is submerged in liquid helium. Current leads are attached, and the sample is placed under load in a magnetic

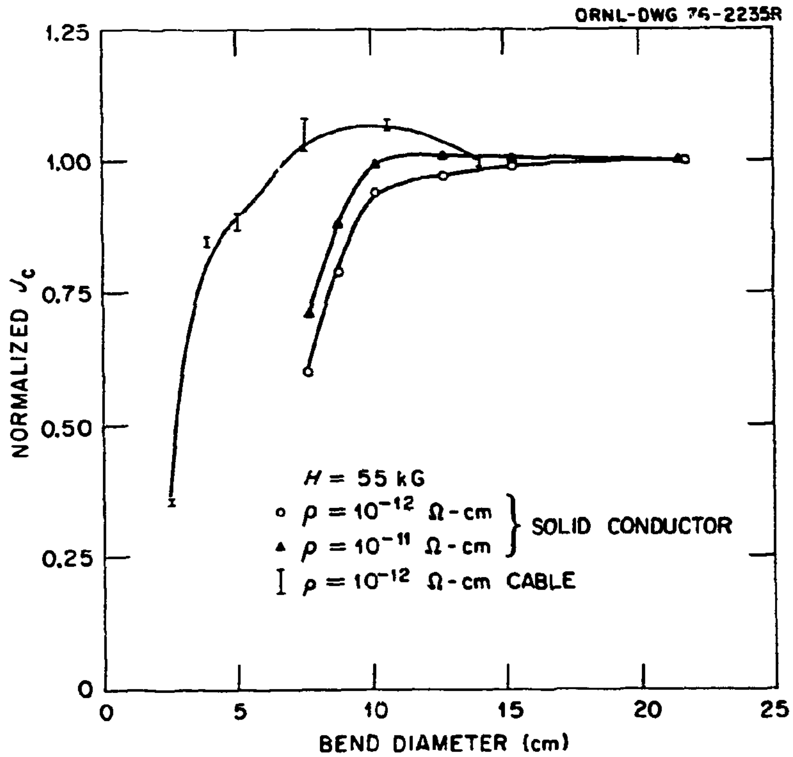

Fig. 2. Critical Current Density Normalized to Unbent Sample Value Versus Bend Diameter. (a) 1- × 2-mm monolithic sample. (b) 36 strand cable with tungsten cores.

field. Strain is measured using a clip-on extensometer previously calibrated at 4.2 K, and Lorentz forces in the sample are supported by a Micarta backing block. For comparison purposes, J_c in the tensile tests is defined as the current density at an equivalent sample resistivity of 5×10^{-12} Ω-cm. Values of J_c are referred to the entire conductor cross sectional area which, in the case of the cables, was taken as the area of the circumscribed circle.

Typical J_c vs strain plots are presented for all the conductors tested (Fig. 3). The strain values are apparent strain obtained from the extensometer and do not represent the actual strain in the Nb_3Sn filaments. Evaluating the stress state of a composite is difficult, and even accounting for the effects of cabling is no simple matter. A theoretical investigation of this last problem is presently under way.

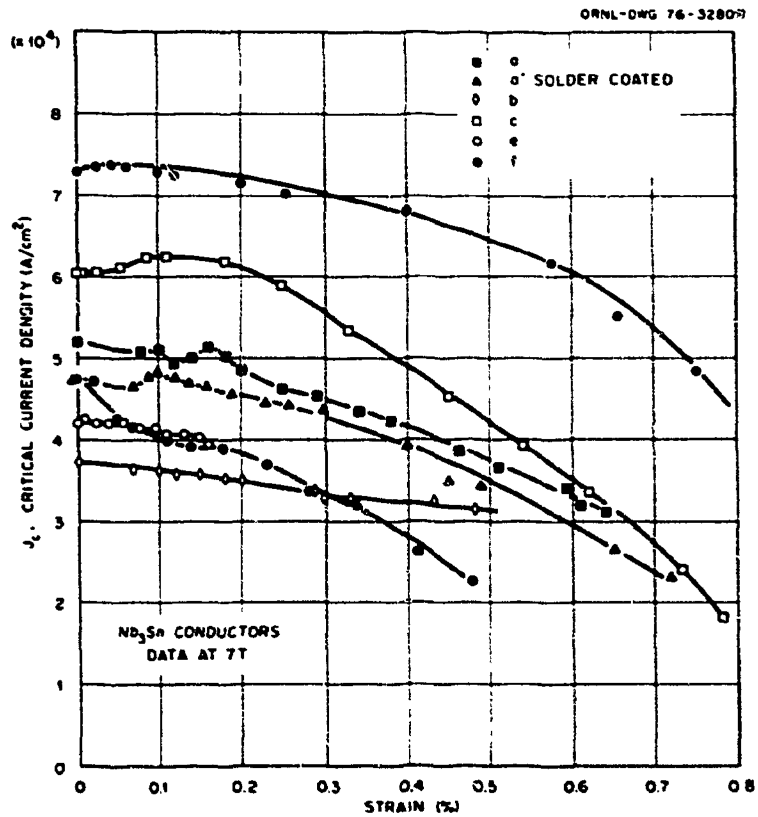

Fig. 3. Critical Current Density as a Function of Apparent Strain. (Legend letters refer to Fig. 1).

The two curves shown for the monolithic conductor represent the limits of the behavior observed. Although the sample-to-sample repeatability for the cable conductor and for previously tested NbTi conductors has been about 5%, five of the adjacent lengths of the monolithic Nb_3Sn displayed widely varying characteristics. At the present time the source of the scatter is not known, and we can only set limits on J_c.

When normalized to zero stress J_c deviates as a function of apparent strain (Fig. 4). Most conductors show an initial increase in J_c when stress is applied and then a steady decrease. The approximate recovery of J_c when stress is released is indicated by the dashed line (Fig. 4). With the exception of the low J_c monolithic material, all conductors show a substantial recovery of J_c when stress is released. The mechanism responsible for these strain induced changes is still not understood although similar

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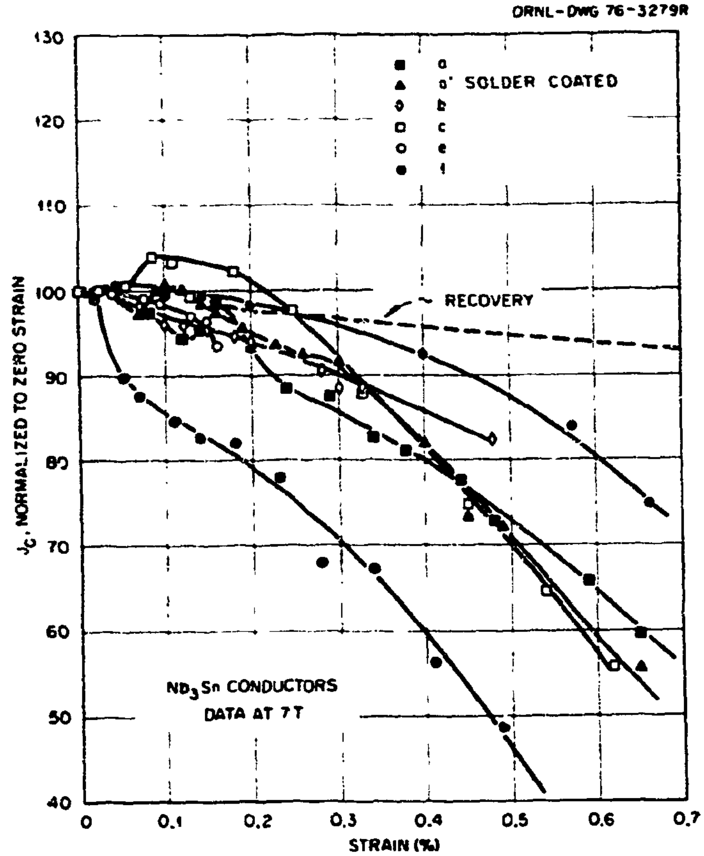

Fig. 4. Critical Current Density Normalized to Zero Strain Versus Apparent Strain. Dashed line indicates approximate values obtained upon release of load.

results were obtained as early as 1965 by Buehler and Levinstein.[6] Their work indicates that J_c is highest in unstrained Nb_3Sn and decreases under both tension and compression. Hence the initial increase of J_c with applied stress is attributed to relieving the compressive stresses due to differential thermal contraction of the surrounding bronze. Recently, Luhman and Suenaga[7] have suggested that stress related changes in T_c (critical temperature) and J_c in bronze-clad Nb_3Sn wires were possibly due to a martensitic phase transformation in the Nb_3Sn. Sweedler et al.,[8] have seen an increase in J_c following neutron irradiation of MF Nb_3Sn. These authors attributed the increase to an enhanced H_{c2} (critical magnetic field) resulting from an in the normal state resistivity. A similar resistivity increase could result from strain. In any case the behavior of J_c under strain is likely to depend not only on the geometry of the conductor but also on the stress state of the surrounding matrix and on the strength of the bond between Nb_3Sn and the matrix.

However, perhaps the most important result of these measurements is the rapid decrease in J_c with tensile strain and the fact that this behavior is not predictable from room temperature bend tests. In the monolithic conductor, for example, bending around a 15 cm mandrel which corresponds to approximately 0.6% strain in the outermost filament causes almost no reduction of J_c even at 10^{-12} Ω-cm resolution. However, a uniform tensile strain (ε) of only 0.3% can cause as much as a 12 to 30% decrease. This would indicate that for reliable design of MF Nb_3Sn magnets the conventional *H-I* plot must be superseded by a *H-I*-ε characteristic.

Since this work was completed, Ekin[9] has reported a somewhat similar study on Nb_3Sn multifilamentary composites. Differences in the results include: (1) our data for a monolithic conductor shows less degradation in J_c with strain and a much wider range of values, and (2) the increase in J_c we noted for small strains was not found, possibly due to his preloading of the sample.

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