Field and Angular Dependence of Critical Currents in Nb_3Sn II*

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INTRODUCTION

A field-dependent critical current density relation

$$J_c = \alpha/(H + B_0) \qquad (1)$$

has been deduced by Kim, Hemstead, and Strnad[1] from magnetization experiments on superconducting cylinders. In Eq. (1) α and B_0 are constants depending on the temperature and properties of the medium. In these experiments the induced cylinder current is perpendicular to the applied field.

We have recently[2] extended this relation to the nonperpendicular field-current case by examining the field and angular dependence of critical currents in thin strips of Nb_3Sn which may be rotated in a field. The current is externally applied. It was found[2] that the data are in excellent agreement with a simple modification of Eq. (1) to account for the angular position of the sample in the field:

$$J_c = \alpha/(H \sin\theta + B_0)\,, \qquad (2)$$

where θ is the angle between the current and the field. To further confirm the correspondence between the induced current experiments of Kim *et al.*[1] and our applied current measurements, the magnetization of a cylindrical Nb_3Sn deposit prepared in the same run as the strip sample was measured in the manner described by Kim *et al.*[1] The calculated critical current densities in the cylinder and the measured critical currents in the strip are in good agreement in fields greater than approximately 5 kG. We also observed a sharp increase in the critical current for longitudinal fields up to approximately 8 kG, and a subsequent field-independent current density up to 20 kG, which was the highest field applied. This field-independent behavior is predicted by Eq. (2) where $\theta = 0$ deg. The initial increase in the critical currents with an increase in the longitudinal field we associated with a transition from a superficial to a uniform current distribution, and the subsequent field independence we associated with current carried uniformly in the cross section of the sample with no resultant Lorentz force from the applied field.

The purpose of this paper is to further examine the relationships observed[2] and extend the measurements to a lower temperature and to single-crystal whisker Nb_3Sn samples.

EXPERIMENTAL

All the samples used in this investigation have been prepared by the simultaneous hydrogen reduction of niobium pentachloride and tin dichloride vapors.[3,4] The Nb_3Sn is deposited on ceramic flats and 0.25-in.-o.d. × 2-in.-long ceramic tubes. The whiskers are obtained as a side product in various areas of the deposition furnace. They grow in both polycrystalline and single-crystal form. Within the limits of optical microscopy, using the Picklesimer anodizing method,[5] and x-ray diffraction, the deposits appear to be single phase. The deposits characteristically grow with a columnar structure perpendicular to the substrate, but with no preferred orientation in the plane of the substrate. All the material of any one preparation run is of essentially the same stoichiometry and transition temperature.

The strips are cut from continuous deposits by sandblasting, and potential and current contacts are made with indium solder to nickel-plated areas. Critical currents are determined by the first sign of voltage on an amplifier whose noise level is 0.2 μV. Flux shielding measurements on the cylinder are made in the manner of Kim *et al.*[1]

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1 Y. B. Kim, C. F. Hemstead, and A. R. Strnad, Phys. Rev. **129**, 528 (1963).

2 G. W. Cullen, G. D. Cody, and J. P. McEvoy, Jr., Phys. Rev. **132**, 577 (1963).

3 J. J. Hanak, in *Metallurgy of Advanced Electronic Materials*, edited by G. E. Brock (Interscience Publishers, Inc., New York, 1963), p. 161.

4 G. W. Cullen (to be published).

5 W. L. Picklesimer, Oak Ridge National Laboratory Report 2296 (1957).

RESULTS AND DISCUSSION

Flat and cylindrical deposits from preparative run FS-20 were chosen for discussion because the cylindrical deposit from this run is one of a group that exhibits no flux jumping (at 4.2°K) up to 14 kG (the highest field currently used in the magnetization experiments). The current densities, however, are among the lowest observed for deposited samples.[2]

Figure 1 shows the critical current as a function of fields transverse and longitudinal to the strip axis at 4.2° and 2.1°K. The shape of the curve at the two temperatures is essentially the same, thus the quenching process in the strip sample is not strongly influenced by the temperature, within the range measured, in either the transverse or longitudinal case.

At both temperatures current stability was tested by applying the current before the field, and by increasing the field rapidly. The critical currents of the strips were found to be independent of these variables. The quenching currents in the longitudinal case are independent of the rate of application of the current, but in this orientation the current cannot be applied before the field since the current is field supported. The critical currents of the strip in both the longitudinal and transverse case is increased by approximately 11% with a 2.1°K decrease in temperature.

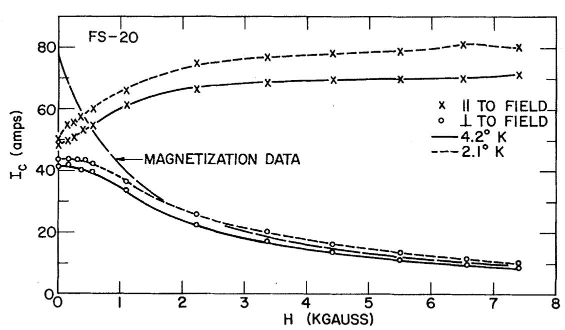

Fig. 1. Critical currents in an Nb_3Sn strip as a function of fields transverse and longitudinal to the strip axis, at 4.2° and 2.1°K. Also included is a field-dependent critical current curve calculated from cylinder magnetization data.

Also shown in Fig. 1 is a field-dependent critical current curve calculated from magnetization data on the cylindrical deposit. It is seen that the magnetization data (taken at 4.2°K) are in good agreement with the strip sample data above 2 kG. The magnetic behavior of the cylinder, however, is influenced by the temperature. Flux jumps are observed at 2.5°K, but not at 4.2°K. One might anticipate that since movement of flux through a sample is thermally activated,[6] the flux pinning points are more effective at the lower temperature, and a greater flux builds up at any one point. When the flux reaches some critical value, breakdown occurs. The lack of instability in the strip sample at the lower temperature must be associated directly with the difference in sample geometry, since the current density is the same for the strip and cylinder.

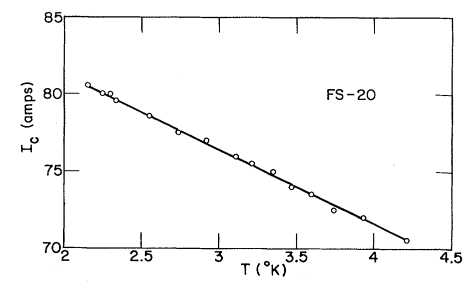

Fig. 2. Critical current of a strip sample in a 7.4-kG longitudinal field as a function of temperature.

The critical current of the strip sample in a longitudinal field of 7.4 kG is a linear function of temperature over the range investigated. This is shown in Fig. 2.

The angular dependence of the critical current in a strip at 7.4 kG is presented in the form $1/I_c$ vs $\sin\theta$ in Fig. 3. Straight lines are obtained which show the agreement of the data with Eq. (2) and yield α and B_0 values in good agreement with those obtained from the cylinder magnetization experiment (see Table I).

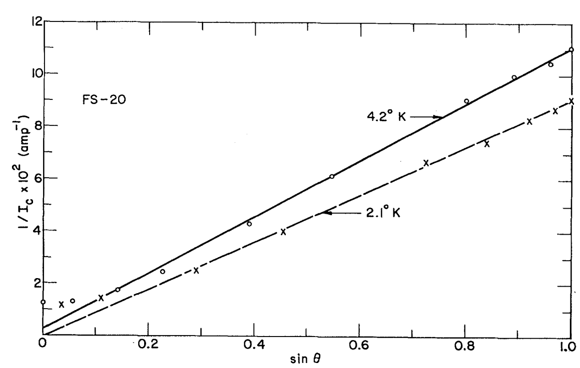

Fig. 3. The reciprocal of the critical current of a strip sample as a function of the angle between the strip axis and the field at 4.2° and 2.1°K.

[6] P. W. Anderson, Phys. Rev. Letters 9, 309 (1962).

The temperature variation of α and B_0 derived from these curves is given in Table I. One notes that α changes by about 24% and B_0 by about 26% in the 2.1°K temperature interval from 4.2° to 2.1°K. The temperature variation of α is to be expected from theory[6]; the temperature variation of B_0 is somewhat obscure as is the nature of this constant itself.

TABLE I. Summation of data for Nb_3Sn samples.

	Cylinder FS20	Strip FS20	Whisker #2	Whisker #4
T_c(°K) midpoint	18.3	[b]	17.7	[c]
ΔT_c(°K)	0.04	[b]	0.8	[c]
Composition(wt%Nb)	70.5 ± .3	[b]	. . .	. . .
Thickness (10^{-3} cm)	5	3.6	10.1	9.4
Width (10^{-2} cm)	. . .	1.5	. . .	. . .
J 7.4 kG ‖ (10^5 A/cm²)	. . .	15	8.2	7.4
J 0 Field (10^5 A/cm²)	16[a]	9.6	5.6	4.6
J 7.4 kG ⊥ (10^5 A/cm²)	1.9	1.9	1.5	1.6
α (10^6 kG-A/cm²)	1.54(4.2°K)	1.28(4.2°K)	. . .	. . .
	2.10(2.5°K)	1.58(2.1°K)		
B_0 kG	0.78(4.2°K)	0.87(4.2°K)	. . .	. . .
	1.20(2.5°K)	1.10(2.1°K)		

[a] Extrapolated.
[b] Material of any one run is of essentially the same composition and T_c.
[c] Measured on a bundle of whiskers from the same run.

The critical currents of two single-crystal Nb_3Sn whiskers, as a function of fields transverse and longitudinal to the whisker axis, are shown in Fig. 4. The form of the curves is similar to that observed with strip samples, and indicates that the behavior previously discussed is not unique to material deposited on ceramics. Additional whisker data are presented in Table I.

It is noted that after a high longitudinal field current quench, the first zero-field quenching current is similar to the maximum current measured. As is shown in the upper portion of Fig. 4, this is seen to a lesser extent in the strip samples. It appears that a trapped field allows the current to be carried homogeneously in the absence of an applied field. If the $1/H$ portion of the transverse curve is extrapolated to zero field, the current intercept agrees with the maximum longitudinal field value. It is also noted that the zero-field extrapolation of the magnetization data is in agreement with the maximum longitudinal field current measured in the strip sample. (See Fig. 1 and Table I.) This suggests that ideal behavior according to Eq. (2) is possible only if the current can remain uniformly distributed in the sample at low fields, and that the uniform distribution for this sample sets in at about 2 kG.

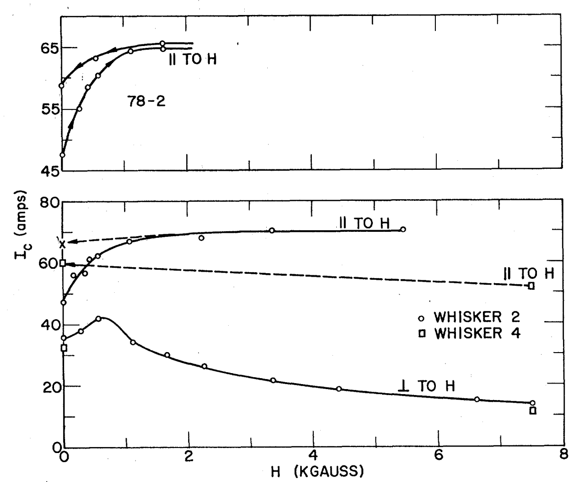

FIG. 4. Critical currents of Nb_3Sn single-crystal whiskers as a function of fields transverse and longitudinal to the whisker axis. Also included is a detail of the behavior of a strip sample in low longitudinal fields. The onset of hysteresis at fields less than 1000 G should be noted.

The study is currently being extended to higher fields, and the influence of the metallurgy of the deposits on the current-carrying behavior is being studied in detail.

Discussion 12

CHANDRASEKHAR: What was the diameter of your whiskers?

G. CULLEN, *R.C.A. Laboratories:* 70 to 100 μ.

MENDELSSOHN: Can you compare maximum current density of your sample with that obtained on cold-worked Nb_3Sn?

CULLEN: Cold work is thought of in terms of NbZr where you have flow properties. Cold working on Nb_3Sn is a different situation. It is an extremely brittle material and cannot be cold-worked in the same sense as NbZr. One can, however, ask if such behavior is a function of strain in the sample and this is something we haven't done yet but is, of course, of great interest.

M. A. R. LE BLANC, *Aero Space Corporation:* I have measured a sample of Nb in a longitudinal field where the critical current in one direction is higher throughout most of the curve than in the other direction. Upon reversing the direction of the field, the critical-current curves exchange position. I believe this phenomenon arose from twisting the wire in one direction while mounting the sample. I have also measured the magnetization produced in zero field by these currents. The current that has the higher values in the presence of a field is that current which produces a moment which enhances the field in the interior of the material, whereas the current which is the low one is the current which lowers the field inside. My present hypothesis is that part of the current flows helically in filaments at the surface. When this current opposes the superficial shield currents, it can go to a higher value than when it flows with the latter.