OPTIMIZATION OF THE HIGH FIELD CRITICAL CURRENT DENSITY IN MF Nb_3Sn FOR MAGNET USE+

S.O. Hong, D.C. Larbalestier*

ABSTRACT

We here report new high field critical current measurements on FM Nb_3Sn conductors together with some bend test data on a conductor to be used for a 15 tesla magnet system. The results show that zero stress J_c values of 280 A/mm^2 (measured over the bronze + Nb cross section) at 15 tesla are obtained. These high values have now been obtained for 3 different composites from 3 different sources, suggesting that it should now be possible to specify high J_c from filamentary Nb_3Sn with some confidence. We have also made measurements of J_c under tensile stress in the field range 13-16 tesla, obtaining values of over 500 A/mm^2 at 15 tesla, approximately twice as large as those obtained in zero stress measurements. We also report on some room temperature bend test measurements for which no degradation in J_c was observed until outer filament strains of at least 0.5% were reached.

I. INTRODUCTION

In recent papers[1,2] we have considered some of the design questions which need to be faced when selecting a properly optimized filamentary (FM) Nb_3Sn conductor for magnet use. At present we are designing and constructing a 15 tesla solenoid magnet system (though construction has been delayed due to slow delivery of conductor) and there is an important need to maximize J_c in the 12-15 tesla range if such a magnet is to be made economically. From this practical and also from the viewpoint of intrinsic interest we have extended our investigations of the J_c attainable from FM Nb_3Sn to include measurements of J_c under tensile stress at fields between 13 and 16 tesla. We have also made some measurements of the effect of bending on pre-reacted wires in order to assess the possibilities of the wind after reaction route rather than the reverse procedure that we have followed until now.[1,3]

II. EXPERIMENTAL PROCEDURE

Conductors

In this paper we report on measurements made with 3 conductors from 3 separate commercial sources. Details of the 3 conductors are given in Table I from which it can be seen that the conductors are somewhat different. Conductor 1 has a much higher bronze to Nb ratio than conductors 2 and 3 and there is also a range of filament sizes.

Critical Current Measurements

High field critical current measurements were made in Bitter solenoids at the National Magnet Laboratory MIT in fields up to 18 tesla. For the zero external stress measurements hairpin samples reacted on stainless steel forms with a hairpin radius of 17.5 mm are used. The legs of the hairpin are $\sim$100 mm long and the wire is everywhere soldered to a brass and Cu support to protect it from damage due to the Lorentz forces. A voltage criterion of 3 μV over 50 mm defines I_c. I_c measurements are converted to J_c by dividing the original bronze and Nb cross-section. This definition of J_c will be used throughout this paper.

Measurements of critical current under stress were made with 4 or 5 turns of wire wound (and reacted) on the Cu and stainless steel barrels shown in Fig. 1. Since the barrel is in effect a small solenoid, it produces a net self field which can interact with that of an external solenoid such that the force on the wire (equal to IBr, where r is the radius of the barrel) can be either tensile (barrel and external field adding) or compressive (the two fields opposing). If the wire is wound tightly on the barrel or soldered only at the copper current junctions at either end, the wire is free to expand under tensile stresses. While in compression the wire is supported by the stainless steel mandrel. We have previously used this arrangement as a simple, cheap fatigue test,[2] obtaining stresses of up to 250 PMa ($\sim$36 ksi) from 50 mm dia. barrels.

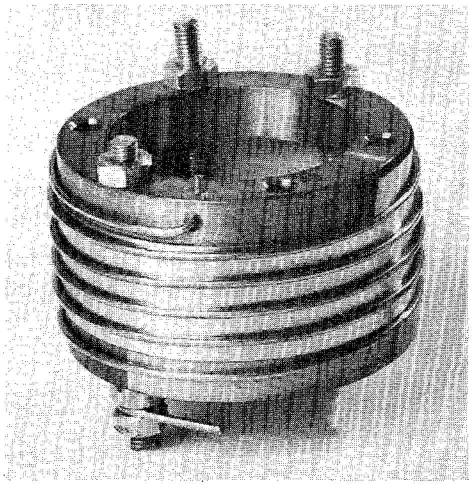

Fig. 1. Barrel sample holder.

Barrel sample holders were also used to measure the bend sensitivity of the J_c. Samples of conductors 1 and 3 were reacted on various diameter mandrels. After reaction the helical coils were carefully wound on to our standard 35 mm diameter barrel and the I_c measured in a field of 5 tesla in Madison. In this test the sample field is arranged opposite to the external field so that the conductor is supported by the barrel. Figure 2 shows an actual trace obtained from this test, indicating the good sensitivity possible from the $\sim$0.5 m long wire on the barrel. The voltage spikes are inductive in origin, probably due to small wire movements.

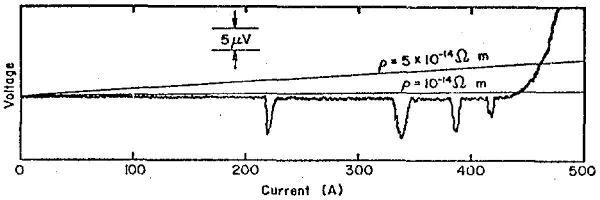

Fig. 2. I-V Characteristic.

III. EXPERIMENTAL RESULTS

Hairpin Samples

Although a number of samples of conductors 1 and 2 were tested we were unable to improve on the best

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* University of Wisconsin, Madison, WI 53706

TABLE I

Characteristics of FM Nb_3Sn Composites

	Composite Source	Dia. (mm)	Filament No.	Filament Size (μm)	Bronze to Nb Ratio	Bronze Composition w/o Sn	v/o Cu + Barrier
Conductor	AERE	1.02	5143	7-8 ∿4	4.62:1	13	11.7
Conductor 2	IMI	0.5	1500	7-8	2.68:1	11.1	none
Conductor 3	AIRCO	0.6	8965	∿3	2.9:1	13.5	16

values previously obtained and take this to mean that we have established the limits to the zero external stress state J_c for these 2 conductors. Substantially reacted (> 85%) samples of conductor 3 gave J_c values essentially identical with the best of conductors 1 and 2 with 3 to 4 μm diameter filaments. Conductors 2 and 3 have very similar bronze to Nb ratios (2.7 and 2.9:1) while conductor 1 is much larger (4.6:1). The effect that this has on the precompression stress is, however, much less important for 3-4 μm rather than 7-8 μm diameter filaments as we have previously discussed.[1] Further evaluation of conductor 3 is in progress. At present, we regard it as encouraging that 3 rather different conductors, produced by different manufacturers have similar good values of J_c. The values attained are shown in Figure 3 and are 1000 A/mm^2 at 10 tesla, 650 A/mm^2 at 12 T, 380 A/mm^2 at 14 T and 240 A/mm^2 at 16 T.

Measurements of the J_c under stress were made for 0.6 mm dia. samples of conductor #1 reacted for 1 week at 750°C, a heat treatment which produces virtually complete (> 90%) reaction. The values of J_c from the barrel tests are given by the upper two curves of Figure 3 and the values of I_c, J_c and tensile stress are presented in Table II. Since the forces are considerable and the wires contain very little copper stabilizer, some training was observed and we were in fact unable to observe resistive transitions below 13 tesla. Generally training was worse when the fields opposed, perhaps due to frictional heating caused by sliding of the conductor on the mandrel.

A number of things are noteworthy about the results of this test. The first is that the J_c values obtained are remarkably high (e.g. 660 A/mm^2 at 15 T under a tensile stress of 160 MPa (23.2 ksi)) compared to 280-300 A/mm^2 for the well soldered hairpin samples where the externally applied stress was zero. Second, the slope of the 2 curves obtained from the barrel test is opposite to that obtained from the conventional zero external stress test. The third feature of interest is that the curve obtained with the fields opposing is still superior to the zero stress sample.

Enhancements of J_c on the application of a tensile stress have been observed by a number of workers both for short samples[4,5] and coils.[1,3] Deis, et al.[5] found enhancements of ∿25% in I_c at a strain of 0.4% in a field of 12 tesla and also found that the magnitude of the enhancement increased with field over the range 8-12 tesla. We had found essentially similar behavior in solenoid magnets producing fields up to 12 tesla with hoop tensile stresses up to 150 MPa: the maximum enhancement of I_c reached 40% and increased with field.[1,3] The present measurements, made in fields up to 16 tesla, show a more than 100% enhancement and suggest that the high field solenoid designer will be favorably assisted by the tensile hoop stresses his magnet develops. From a fundamental point of view it appears that the increase in J_c is a consequence of the increase in Hc_2 produced as the compressive stress on the Nb_3Sn is relieved.

At present we have no complete understanding of the fact that the sample compressed on to the mandrel still shows considerable critical current enhancement over the zero external stress samples. In a test of a second sample of this conductor, we again obtained an enhancement of I_c due to the tensile stress but were unable to measure it with fields reversed since the sample burnt out during a trip circuit malfunction. Further tests are currently in preparation.

The bend test results made in a field of 5 tesla are shown in Figures 4 and 5. The strain figures quoted are the maximum strains at the outer filament radius (not the wire surface) produced by bending the wire from the larger reaction radius to the smaller barrel test radius. An important feature of the results is that no degradation was obtained until strains exceeded at least 0.5% in both cases. The current densities in both cases were quite high, exceeding 1400 A/mm^2, about 70% of the value to be obtained from these composites at 5 tesla.[6] Composite 1, showing an enhancement of I_c with strain, had the higher bronze:Nb ratio and was also reacted to a lesser extent, indicating that there was a greater precompression existing in comparison with the sample of conductor #3. We defer any detailed comparison of the behavior of the 2 composites until further reactions have been carried out. Both samples were twisted, conductor #1 having a twist pitch of 12.5 mm, #2 7 mm. In both cases the voltage taps were 110 mm apart so that measurement is made over

TABLE II

Results of the Barrel Test on 0.6 mm dia. Conductor #1 Reacted 168 hr/780°C

Field	Fields Additive (Tension)			Fields Oppose
	$I_c(10^{-13}) \Omega m)$	$J_c(Br + Nb)$	$\sigma = JBr$	$I_c(10^{-13}) \Omega m)$
13 tesla	205 A	798 A/mm^2	167 MPa	169
14	188	732	165	
15	170	661	160	135
16	143	556	143	
17				87

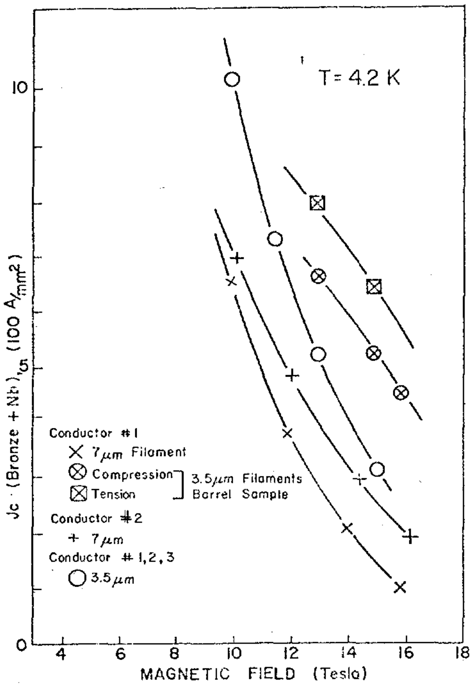

Fig. 3. Critical current vs. field.

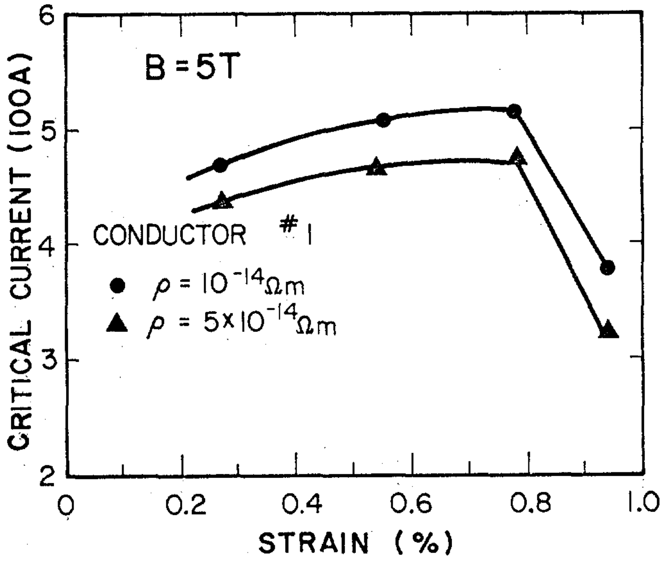

Fig. 4. Critical current vs. strain (conductor #1, 740°/108 hrs).

at least 9 twist pitches. It is perhaps surprising, therefore, that an enhancement of J_c is seen since each filament is both in tension and compression during each twist pitch. However, this same behavior, though smaller in magnitude, has previously been noted by Randall and co-workers.[7]

IV. CONCLUSIONS

The extreme stress sensitivity of the critical current of Nb_3Sn is now well documented. A pleasant feature of the effect for designers of FM Nb_3Sn magnets is that FM Nb_3Sn continues to demonstrate remarkably ductile properties for an intrinsically very brittle inter-metallic compound. An important feature of the two mechanical tests made here is that they refer to high current density conductors of immediate interest to magnet builders. The high values of J_c obtained in

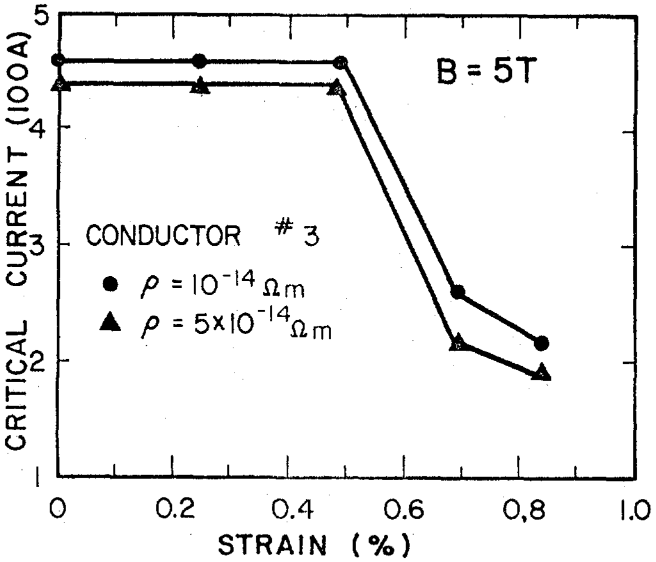

Fig. 5. Critical current vs. strain (conductor #3, 760°/84 hrs)

the barrel samples, though larger in magnitude, follow well those demonstrated in high current density coils produced by the wind and react route.[1,3,8] The bend tests also show good resistance to degradation by bending after reaction. Finally, the fact that 3 different conductors from 3 different sources can be made to yield the same high current density by appropriate heat treatment is another important sign that FM Nb_3Sn is a reliable and useful magnet conductor.

ACKNOWLEDGMENTS

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