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CRITICAL CURRENT STUDIES ON FINE FILAMENTARY NbTi ACCELERATOR WIRES*

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ABSTRACT

The magnets for the Superconducting Super Collider, a high energy proton colliding beam accelerator, require a superconductor with very high current density ($>2400 \text{ A/mm}^2$ at 5 T) and very small filaments ($< 2 \mu\text{m}$ in diameter). Previous work has shown that by controlling the formation of Cu_4Ti compound particles on the filament surfaces it is possible to make fine filamentary NbTi wire with high critical current density. The performance of multi-filamentary wire is characterized by the current density and the quantity "n" which describes the superconducting-normal transition. Micrographs of wires having high J_c and high n show smooth, uniform filaments. Recently wires of very high critical current and high n have been produced in experimental quantities by commercial manufacturers.

MASTER

INTRODUCTION

Magnet design requirements of the Superconducting Super Collider Project (SSC)¹ have recently stimulated two impressive improvements in NbTi multifilamentary wire. Larbalestier and coworkers have shown that critical current densities in the vicinity of 3000 A/mm^2 (at 5 Tesla and 4.2 K) can be attained by means of a series of anneal-strain cycles during the reduction of starting billet to final wire.² This is more than 50% greater than the mean current density of the wire used in the Fermilab Tevatron.³ It is also well in excess of the original SSC specification of 2400 A/mm^2 . A more appropriate specification might now be 1800 A/mm^2 at 6.5T.

A second requirement of the SSC design is that the diameter of the NbTi filaments be in the range $2-3 \mu\text{m}$, considerably smaller than was common previously; the filaments in Tevatron wire are $9 \mu\text{m}$. It has been pointed out that uniform small diameter filaments can be produced only if care is taken to control the formation of intermetallic compound (Cu_4Ti) particles on the filament surface during processing.⁴ Magnetization measurements have shown that the transport current in wires having non-uniform filaments may be drastically reduced without altering the intrinsic current density.⁵

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In this paper, further electrical and metallurgical characterizations of this problem are presented. Wire manufacturers have recently succeeded in making developmental wire having uniform filaments of small diameter and high critical current density. Examples of these are given.

CRITICAL CURRENT AND FILAMENT UNIFORMITY

In order to compare results for different wires it is usual to quote a critical current density, $J_c \equiv I_c/A_s$, where I_c is the measured critical current and A_s is the total superconductor cross section. In wires having large filament diameters, $d \gtrsim 20\mu\text{m}$, say, the filament cross section is usually constant enough as a function of length that J_c is equal to the microscopic or intrinsic critical current density. However, variations in filament cross section, such as sausageing, pinching, breaks, etc., cause I_c to be reduced.

The reduction in I_c due to filament non-uniformity is accompanied by a broadening of the superconducting-normal state transition. This transition is frequently represented by the equation

$$\rho = VA/I = \text{const} \cdot I^n$$

where V is the voltage per unit length, A is the total wire cross section area, and I is the measuring current in the sample.⁶ The critical current is defined as the current at which $\rho = 10^{-12}$ ohm cm. This definition is based on the practical fact that for this value of the resistivity the dissipation in large scale devices is acceptably small or negligible.⁷ The n -value is inversely related to the width of the V - I transition.

Figure 1 illustrates these comments by showing results for a series of wires which are drawn to successively smaller diameters. The starting wire was a BNL CBA Project (CBA) wire in which the n -value was relatively large and in which the $9\mu\text{m}$ filaments were seen to be smooth and uniform as observed using scanning electron microscopy, Fig. 2A. As the wire is drawn down, surface imperfections, which are not important at large filament size, gradually produce significant variations in filament cross section, as illustrated in Fig. 2B. Correlated with this are decreases in I_c and n .

Fig. 1 Superconducting-normal transitions for a series of drawn wires. Mean filament diameters are, right to left, 9.0, 4.6, 2.3, and 1.3 μm , respectively. CBA starting wire, Cu/SC ratio = 1.7, $T = 4.23\text{K}$, $B = 5\text{T}$.

Fig. 2A SEM Micrograph of 9 μm filaments in CBA wire used in the draw down experiment. $J_c = 2000$ A/ mm^2 , $n = 40$ at $T = 4.23\text{K}$, $B = 5\text{T}$.

Fig. 2B SEM Micrograph of filaments after reduction to mean diameter 1.3 μm (wire diameter = .004").

The same effect is observed within a group of wires which are nominally the same in composition and metallurgical treatment but in which the prevention of Cu_3Ti particle formation is inconsistent. A statistical distribution of I_c 's and n -values results, and these are correlated as shown in Fig. 3. This figure gives data for CBA wires obtained from one particular manufacturer. In this graph J_c is plotted as a function of n ; the latter is an index of filament quality.

Photomicrographs of filaments of high n , high I_c and of low n , low I_c wires are shown in Figs. 4A and 4B, respectively. Examination of the necked regions at higher magnification indicates that these result from the presence of compound particles.⁴ Similar results have been observed in the newer, very high J_c wire produced by multiple anneal-strain cycles, and in monolithic conductors produced for NMR medical apparatus. The filaments in the latter conductors are generally large, typically 30-50 μm , and n -values between 50 and 100, at 5T, are commonly observed.

VARIATION OF n -VALUE WITH APPLIED FIELD

The shape of the superconducting-normal state transition varies with the external field. In high quality multifilamentary wire n varies over the entire range of applied field, going to zero at the critical field. In low n -value material on the other hand n is relatively independent of field. This is illustrated in Fig. 5, which shows n -values for three CBA wires as a function of field. As before, SEM photomicrographs show a correlation between smooth, uniform filaments and high n -values, and moderate to strong filament non-uniformity in the low n wire.

Fig. 3 J_c vs n for CBA wires of one manufacturer. Cu/SC ratio = 1.7. $T = 4.23K$, $B = 5T$.

Fig. 4A SEM Micrograph of filaments of low quality wire. $n = 14$, $J_c = 1400 A/mm^2$.

Fig. 4B SEM Micrograph of high quality CBA wire. $n = 40$, $J_c = 2000 A/mm^2$.

Fig. 5 n vs B with B for CBA wires of varying filament uniformity.

In studying multifilamentary Nb_3Sn wire, Suenaga et al have observed that in wires in which n is low the n vs B curve is flat over most of the field range and joins the curve for high n wire near the critical field.⁸ Furthermore, when the temperature was lowered from 4.2K to 1.8K, the critical currents of both types increased by the same percentage. The value of n stayed constant for the low n wire but increased for the high n wire (50% at $B = 16T$, e.g.). These observations in Nb_3Sn and the present data suggest that J_c is limited in low n wire by geometrical factors, such as filament non-uniformity, while in high n -wire it is determined by superconducting properties, such as flux pinning strength.

EFFECT OF MECHANICAL DAMAGE

Flat cables of multifilamentary wire usually have lower I_c 's and n -values than those of the pre-cabled wire.⁹ In keystone cables, the packing factor of the wire in the thin edge region is frequently around 100%, so the possibility of mechanical damage is not small. Wires tested before cabling and after removal from a damaged cable show a pattern of behavior similar to that described above. This is illustrated in Fig. 6. The $NbTi$ in this example is of the newer high J_c , high homogeneity type; the pattern of behavior is the same as for the older material. In this case, the filament degradation is localized to the regions of the wire which pass around the cable edge. The appearance of the filament distortion is also different, as shown in Fig. 7. Scanlan and co workers observed the formation of slip lines on the 200 μm filaments of a large, square cross section, monolithic conductor due to the final sizing steps.¹¹

Although the example cited above is a drastic case of mechanical damage on the filaments influencing the n -value, less drastic deformation such as light rolling of a wire can also reduce n . In general, when a wire is deformed to make an aspected conductor, the value of its J_c becomes anisotropic; i.e., J_c for B parallel is greater than that for B perpendicular to the flat face. Correspondingly, if the original wire n -value is large, in the flattened wire the parallel n -value is larger than the perpendicular.

Fig. 6 n vs B in a high homogeneity wire before and after cabling. Wire diameter = .65 mm, filament diameter = 20 μ m, Cu/SC ratio = 1.8, $T = 4.23K$, $B = 5T$.

Fig. 7 SEM Micrograph showing filament damage in thin edge region.

ORIGIN OF THE n -VALUE

The inverse correlation between n -value and filament non-uniformity indicates that some form of current sharing is responsible for the observed behavior. Suenaga¹² has suggested that a model similar to that used to describe resistivity of in situ superconductors¹³ may be appropriate. However, a detailed theory of the n -value is lacking, nor is it clear that the correct functional dependence is $\rho \propto I^n$.¹⁴

In an example of very fine filament wire in which the matrix is cupronickel, the n - B curve is as shown in Fig. 8. The data in this figure are for wire having 0.6 μ m filaments.¹⁵ Photomicrographs show

them to be smooth and clean. J_c is low, ~ 900 A/mm² at 5T, and the n -values are low. In this case the curve is not flat even though n is low. It is suspected that filament breakage arising from sources other than compound particles is responsible for this behavior.

It is possible to have a wire in which n is high and I_c is low: we have measured a conductor with 3.5 μ m filaments which had an n -value in excess of 100 at 5T but current density of 500 A/mm². However, it is not possible to have a high I_c , low n wire because of the large cross section area variations associated with low n .

RECENT DEVELOPMENTS

Using the newly devised methods of improving J_c , and proprietary techniques for suppressing compound formation, a number of manufacturers have produced high J_c wires with filament diameters below 5 μ m. Some of these have been made available to us in connection with the SSC R and D program and are listed in the following table.

Recent Developmental Fine Filament NbTi Wire

Wire Size mm	No. of Filaments	Cu/SC Ratio	Filament Size μ m	J_c^* A/mm ²	n	Manufacturer
.23	3000	1.1	2.9	2400	25	Furukawa
.29	1950	1.4	4.3	2800	32	I.G.C.
.11	367	1.1	4.0	2500	31	M.C.A.
.04	127	0.75	2.7	2950	45	Supercon
.33	4164	1.2	3.5	2950	45	Supercon

*Determined from transport current

Fig. 8 n vs B for a 0.12 mm wire containing 15000 0.6 μ m filaments. The filaments are in a cupronickel matrix which has a stabilizing copper core.¹⁵ $T = 4.23$ K $B = 5$ T.

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