THE EFFECT OF MAGNETIC IMPURITIES AND BARRIERS ON
THE MAGNETIZATION AND CRITICAL CURRENT OF FINE
FILAMENT NbTi COMPOSITES*

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A.K. Ghosh and W.B. Sampson
Brookhaven National Laboratory, Upton, NY 11973
E. Gregory, S. Kreilick and J. Wong
Supercon Inc., Shrewsbury, MA 01545

Abstract

It has been shown that the highest critical currents in fine filament NbTi conductors are obtained when the filaments are closely spaced.¹ However, the filaments in a composite with a high purity copper matrix tend to be coupled via the "proximity effect" as the filament spacing is reduced leading to large magnetization at low fields. To reduce the "proximity" coupling, trial billets of NbTi have been fabricated with Cu-30% Ni matrix, Cu-0.5% Mn matrix and one with a Ni barrier around the filaments. Wires drawn from these billets have shown that this interfilament coupling can be suppressed for very small filament separations. A full sized commercial billet with Cu-0.5% Mn matrix demonstrates that high J_c conductors with filament size $\sim 1.5 \mu\text{m}$ can be fabricated which show no interfilament coupling at low fields.

Introduction

The early conductors for SSC were designed to have a J_c in the superconductor exceeding 2400 A/mm^2 at 5 Tesla. These were fabricated using NbTi in a high purity copper matrix and with filament diameters, d , of the order of $20 \mu\text{m}$ in the final size wire. The normal metal separation of the filaments, d_n , in these conductors was greater than $2 \mu\text{m}$.

In order to reduce the error fields generated in the SSC dipoles by the superconductor magnetization, conductor R&D was directed towards producing high J_c wires with filament sizes $\sim 5 \mu\text{m}$. It was shown by Supercon that besides the use of the niobium barrier around the NbTi filaments, the filament spacing to filament diameter ratio, s/d , must be small to produce uniform filaments with high J_c .^{1,2}

In an earlier report³ was described the magnetization and J_c results on fine filament wires fabricated from a 4164 filament billet with an unconventionally low s/d ratio of ~ 0.12 . It was found that as the filament size decreased below a certain value the low field magnetization increased rapidly contrary to what is expected from the critical state model.

Based on the results of that study it was proposed that the anomalous magnetization was due to interfilament coupling by transverse persistent currents through the normal copper matrix via the "proximity effect".⁴ This supercurrent flow would couple all the filaments giving rise to an additional magnetization M_c which would be a strong function of field and d_n . Assuming this coupling mechanism, the magnetization of the conductor in a ramped transverse field is given by

$$M = M_f + M_e + M_c \quad (1)$$

where M_f is the normal hysteretic magnetization as given by the critical state model

$$M_f(H) = \frac{2}{3\pi} J_c(H) d \quad (2)$$

where $J_c(H)$ is the critical current density of NbTi at the field H . M_e is the contribution due to the eddy currents and is proportional to $\dot{B}$, and M_c is the coupling magnetization,

$$M_c = C_{cl} r \quad (3)$$

where J_{cl} is the transverse supercurrent density, r is the outer radius occupied by the filaments, and C is a constant.

At a given field, M_c was found to vary as $\exp(-K_n d_n)$ and as a function of field it was observed to have an exponential dependence, i.e., $\exp(-H/H_0)$. This field dependence is similar to that observed by Finnemore, et al.,⁵ for the critical currents in Pb-Cd-Pb SNS sandwiches. These observations are consistent with the interpretation of "proximity" induced J_{cl} which can be written as

$$J_{cl} = A J_c \exp(-K_n d_n) \quad (4)$$

The penetration length $K_n^{-1} = \ell(\ell_n, v_n, T, H)$, where ℓ_n and v_n are the electron mean free path and the Fermi velocity in the normal metal. Expressions for K_n can be found in Refs. 4 and 5.

In this paper we show further evidence that the enhanced magnetization must involve the normal matrix. We also show that the A.C. susceptibility measurement is a simple way of detecting the onset of filament coupling.

Initial Magnetization and A.C. Susceptibility

When a sample is cooled below T_c in zero applied field, the initial magnetization for fields less than the lower critical field H_{c1} , is usually written as

$$-M = D_m^{-1} \chi_0 H \quad (5)$$

where H is the external field, D_m is the demagnetization factor which is equal to $1/2$ for a cylinder in transverse field and 1 for longitudinal field, and χ_0 is the volume fraction of superconductor in the wire. For multifilamentary conductors with filament size d , Eq. 5 does not include the effect of the weak field penetration depth $\lambda(T)$.⁶ Ignoring the possibility of interfilament coupling and treating λ as isotropic, the magnetization is suppressed by a factor $P(d/2\lambda)$ where

$$P\left(\frac{d}{2\lambda}\right) = 1 - \left(\frac{6\lambda}{d}\right) \coth\left(\frac{d}{2\lambda}\right) + 3/(d/2\lambda)^2 \quad (6)$$

When $d \gg 2\lambda$, the suppression factor,

$$P = \left(1 - \frac{2\lambda^3}{d}\right)$$

Note that the suppression is considerable even for rather large values of $(d/2\lambda)$. The susceptibility $\chi = M/H$ can then be written as

$$\chi = \chi_0 D_m^{-1} P(d/2\lambda) \quad (7)$$

In the following sections we shall use Eq. 7 to analyze the zero field A.C. susceptibility of samples in longitudinal fields.

When there is "proximity" coupling between the filaments then the A.C. susceptibility will deviate from the predictions of Eq. 7 and approach the limiting value of $\chi_L > \chi_0$ given by

$$\chi_L = \left(\frac{D_f}{D}\right)^2$$

where D_f is the diameter of the filament boundary in the wire of diameter D .

Evidence for "Proximity" Coupling

To show that the enhanced magnetization involves the normal metal, we compare the magnetization⁷ of a conductor with and without the normal copper matrix. The data shown below is for an SSC outer cable consisting of 30 strands of 0.65 mm diameter. The filament diameter is 5 μm and the normal metal separation of the filaments $d_n \sim 0.75 \mu\text{m}$. The initial slope of the magnetization curve in the flux exclusion region below H_{c1} , indicated that the fractional volume of conductor excluding flux $\chi = 0.75$, whereas the actual NbTi volume $\chi_0 = 0.40$. This value of χ is consistent with χ_L so that the composite behaves as a solid superconductor with a diameter enclosed by the filament boundary. In the case of the etched cable, the value of χ normalized to the original volume of the cable, was equal to 0.34. This is consistent with Eq. 7 when field penetration effects are taken into account. This is discussed further in the following section.

Figure 1. Magnetization data of 5 μm filament cable. The solid line is for the etched conductor. The shaded area is the low field coupling magnetization.

To highlight the difference in magnetization of the conductor before and after the copper is etched away, the data are superimposed in Fig. 1 with the solid line showing the data for the etched conductor and the dashed line indicating the excess magnetization in the presence of the copper between the filaments. The shaded area represents the contribution of the coupling magnetization M_c which is seen to have a strong field dependence being fully suppressed by a field of -0.14 Tesla. In Fig. 2, the magnitude of M_c is plotted as a function of H , where H is now corrected for the demagnetization field of a cylinder in transverse applied field. The field dependence of M_c is seen to be exponential of the form $M_c = A \exp(-H/H_0)$. This is similar to that observed earlier.³ If we define H_n as the field at which the excess magnetization is < 1 mT, then the data on the 4164 billet wires shows that H_n has an exponential dependence on d (or d_n),⁴ and can be fitted to the expression $H_n = 10 \exp(-d_n/0.16)$. H_n is similar to the breakdown field in the normal metal discussed in Ref. 4.

Figure 2. Plot of M_c versus H showing an exponential field dependence.

In the following section some ways are discussed by which the "proximity" coupling can be suppressed and a simple test is described to detect the onset of such coupling as the filament size is reduced.

Reduction of "Proximity" Coupling

The interfilament coupling can be reduced by controlling $J_{c\perp}$. This can be achieved by changing K_n or d_n . For a given interfilament distance necessary to achieve high J_c , $J_{c\perp}$ can be reduced by decreasing K_n . This can be done by introducing impurities in the Cu which will reduce ℓ_n and thereby ξ_n . Replacing Cu by Cu-Ni in the interfilamentary region would significantly reduce the coupling. In this respect magnetic impurities will be more effective than non-magnetic impurities. Finnemore, et al.,⁸ have shown that in SNS sandwiches of Pb-Ag-Pb, the critical currents in Pb-(Ag₉₅Mn_{0.15})-Pb are orders of magnitude lower than in Pb-(Ag₉₃Al_{2.07})-Pb sandwiches. This shows that magnetic impurity scattering (which is a spin scattering) is more effective in destroying the supercurrent flow in the normal metal than merely increasing the matrix resistivity by using cupro-nickel. A third alternative is to put a magnetic barrier around the NbTi filaments. At the ferromagnetic interface, superconductivity is destroyed and this approach should work for a magnetic barrier thickness of ~ 100 Å.

At Supercon various trial billets were assembled with different matrix compositions and configurations, some of which have been reported elsewhere.⁹

For this study we examined wires drawn from three trial billets each with 1812 filaments. SCN3 billet was assembled with Cu-30% Ni, SCN12 had Cu-0.5% Mn matrix and SCN8 had a thick Nickel barrier around each subelement of NbTi/Cu. The resistivity of Cu-30% Ni at 10K is $\sim 30 \mu\Omega\text{-cm}$, whereas Cu-0.5% Mn has a resistivity of $\sim 1.5 \mu\Omega\text{-cm}$ at low temperatures. Additionally two commercial size 305 mm billets¹⁰ with ~ 11000 filaments were assembled, one with high purity copper, the other with Cu-0.5% Mn in the interfilamentary region. Wires from these billets were optimized to

produce $J_c > 2700 \text{ A/mm}^2$ at 5T, suitable to produce SSC inner cables.

A.C. susceptibility of the wires were measured at 4.2K and zero external field with an A.C. field amplitude of 1 mT and at 11 Hz. Wires with high purity copper matrix showed that as d_n decreased below $1.5 \mu\text{m}$, the susceptibility ratio χ/χ_0 exceeded one indicating the onset of coupling. Appreciable magnetization shows up in the hysteresis loop for $d_n < 1 \mu\text{m}$.

Figure 3. Plot of $(\chi/\chi_0)^{1/2}$ versus $(1/d)$. The dashed line is the theoretical curve (Eq. 7) using $\lambda = 270 \text{ nm}$.

In Fig. 3 the susceptibility data are shown for a whole range of filaments sizes, plotted as $(\chi/\chi_0)^{1/2}$ versus $(1/d)$. In this plot the initial slope of the curve (from Eq. 7) is equal to 3λ . The dashed line is the theoretical curve drawn for $\lambda(4.2\text{K}) = 270 \text{ nm}$. d_n for these wires is $\sim 0.15 \text{ d}$. The solid lines show the region in which the filament coupling occurs as evidenced by the departure from the theoretical curve. The data points refer to wires drawn down from the 305 mm billet. The data indicate that this billet had a slightly smaller s/d ratio than the trial billet SCN12.

The figure shows the following: 1) before the onset of coupling the theoretical curve fits the data very well, 2) coupling onset is not observed in Cu-30% Ni matrix wires down to $d_n \sim 140 \text{ nm}$; 3) for Cu-0.5% Mn matrix coupling sets in at $d_n \sim 150 \text{ nm}$. However, in magnetization hysteresis data coupling is only evident at $d_n \sim 75 \text{ nm}$. Preliminary data on the Ni barrier material showed no coupling at $d_n \sim 400 \text{ nm}$. However, since this billet had a large fraction of nickel, the ferromagnetic signal from the Ni dominated the low field susceptibility. Future billets of this type will have Ni barrier amounting to $\sim 1\text{-}2\%$ of the matrix.

High J_c Wires With No "Proximity" Coupling

Wires from the two 305 mm billets 355E-1 and 355E-2 were optimized for critical current at the SSC inner cable wire size of 0.81 mm .¹⁰ At this size the filament diameter is $5 \mu\text{m}$ and $d_n \sim 0.75 \mu\text{m}$. The fraction of superconductor in these wires is 0.41, and the J_c of the wires exceeded 2200 A/mm^2 at 6T. SSC inner type cables were made at LBL with 23 strands, with a net twist in the wires of ~ 0.6 twist per cm.¹⁰ The magnetization data of the finished cables are shown in Fig. 4. As expected, the cable with the Cu-0.5% Mn matrix did not show the enhanced low field

magnetization. The higher resistivity of the interfilament matrix is seen in the reduced eddy current magnetization of the Cu-0.5Mn cable at fields exceeding H_n .

Critical current measurements¹¹ of the cables at 5.9 Tesla applied field transverse to the wide face of the cables can be summarized as follows:

1. Both cables exhibited 2-3 training quenches to reach the quench current plateau. This is typical of conductors with Cu/Sc ratio of ~ 1.4 .
2. The I_c defined for $10^{-14} \Omega\text{-m}$ was almost identical for the two conductors. Peak field corrected I_c of the conductors at 6T was $\sim 9400 \text{ A}$, indicating a nominal standard cabling degradation¹¹ of $\sim 12\%$.
3. The quench current plateau was higher in the Cu-matrix cable, reflecting the lower resistivity of Cu relative to Cu-0.5% Mn.
4. The low temperature resistance, of the cables were very nearly the same $\sim 0.16 \mu\Omega/\text{cm}$ at zero external field.

The results of these tests show that cables suitable for SSC can be made from Cu-0.5%Mn matrix which exhibit high J_c at high fields and no coupling magnetization at low fields. A dipole made from such cables will demonstrate whether the doped matrix has any effect on magnet performance. Susceptibility data show that high J_c conductors can be made with Cu-0.5% Mn matrix with filament diameter as small as $\sim 1 \mu\text{m}$ with no "proximity" coupling.

Figure 4. Magnetization data of SSC inner cables: — has Cu Matrix and -- has Cu-0.5% Mn between the filaments.

Summary

Fine filament closely spaced NbTi conductors with copper matrix exhibit the onset of "proximity" coupling as d_n is reduced below $1.5 \mu\text{m}$. Several ways to eliminate this has been explored. Although Cu-30% Ni can suppress this coupling, the high resistivity of the matrix has adverse effects on conductor J_c and stability. However magnetic impurities in the Cu effectively eliminate interfilament coupling at very low doping levels, and a comparison of the cables fabricated from pure Cu and Cu-0.5% Mn matrices show that the low field magnetization is suppressed for the $5 \mu\text{m}$

conductor without having any adverse effect on critical current or stability. The susceptibility data indicate that with 0.5% Mn doped matrix high J_c conductors can be fabricated at filament sizes down to $\sim 1 \mu\text{m}$.

Future work will deal with other levels of Mn doping and also will evaluate the use of Ni barrier in fine filamentary NbTi superconductors.

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