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ANOMALOUS LOW FIELD MAGNETIZATION IN FINE FILAMENT NbTi CONDUCTORS

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Abstract

The first cable conductors for SSC were made with NbTi filaments whose diameters were in the 18-23 micron range. In an effort to reduce the magnetization effects in accelerator dipoles resulting from these large filaments, second generation conductors are now being manufactured with much smaller filaments. As part of this development a series of NbTi conductors were made with filament diameters ranging from 8.0 to 2.8 μm and having an average interfilament spacing of approximately 12% of filament diameter. Measurements at 4.3 K show that as the filament spacing decreases below a certain critical value the low field magnetization increases rapidly. This increase is seen to be strong function of interfilament distance, magnetic field and temperature. Details of these measurements and its implication for practical high current SSC wire design are discussed.

Introduction

The first generation NbTi conductors for SSC were optimized to improve the high field critical current, with J_c in the superconductor exceeding 2400 A/mm^2 at 5.0 Tesla. These initial conductors [1] were made with ~ 500-600 NbTi filaments in a copper matrix with filament diameters, d, of the order of 20 microns in the final size wire. The conductors were found to have rather high magnetization consistent with the high J_c and the large filament size. In prototype SSC dipoles this superconductor magnetization produced significant harmonic components (to the main field) at ~ 0.3 Tesla, the injection field for the present SSC design. To compensate for these error fields trim coils would be required for each dipole.

In previous studies it has been shown that the magnetization scales linearly with d down to ~ 1 μm.[2] If high quality (i.e. $J_c \geq 2400$ A/mm at 5T) conductors with filament diameters in the 2 to 5 micron range could be manufactured, the reduced superconductor magnetization would ease the requirements of the trim coils and possibly eliminate individual windings in favor of lumped correctors.

The material used in this investigation was developed by Supercon Inc. under contract to the Lawrence Berkeley Laboratory and the U. S. Dept. of Energy. It was described originally over a year ago[3] and has a Cu:Sc ratio of approximately 1.2:1 and 4164 filaments which are 8.5 μm. diameter when the wire is 0.81 mm. (0.0318") in diameter. This is the wire size for the inner cable to be used in the SSC prototype magnets. Previously high current densities had been reported in material with 20 μm diameter filaments [1] but filaments smaller than 10 μm in diameter frequently exhibited uneven cross sections which led to an overall lowering of J_c. It was believed that this was primarily due to the formation of copper titanium compounds.[4]

In order to prevent the formation of this intermetallic, a barrier layer was put around the filaments [3] but it was also known at Supercon Inc. that filament "sausagin" can occur in the absence of compound formation. This is particularly the case where the filaments are widely or unevenly spaced. "Doubly stacked" billets were thought to be particularly subject to such filament non-uniformity [5] and therefore, a "singly stacked" design with the filaments uniformly and closely spaced and a centrally located copper area for stability, was decided upon, (Fig.1).

The additional requirement of fine filaments for SSC conductors necessitates the use of a large number of filaments. Approximately 40,000 2.5 μm diameter filaments would be necessary if the Cu/Sc ratio and the 0.81 mm diameter is to be maintained. Since such material was not available it was decided to draw the 4164 filament wire down to finer and finer sizes and to attempt to optimize its properties in these finer size ranges. This paper is a preliminary report of the J_c and magnetization measurements that have been made on these conductors. Tentative conclusions drawn for the data and its impact on conductor fabrication for SSC are discussed.

Experimental Details

The magnetization, M, of the samples were measured in transverse applied field, H, at 4.35K. Voltage signals from appropriate pick up coils were integrated to yield a set of M values as a function of H. Details of the magnetization apparatus and the measurement technique is given elsewhere.[6] The test samples were in the form of a stack of 12.7 cm long pieces of wire of volume ~ 3 cm^3 held together by epoxy and Kapton and mounted in a non magnetic holder. Data were taken with a typical external ramp rate of ~ 20 mT/s. The critical transport current, I_c, as a function of H was measured in a separate experiment.[7]

Samples

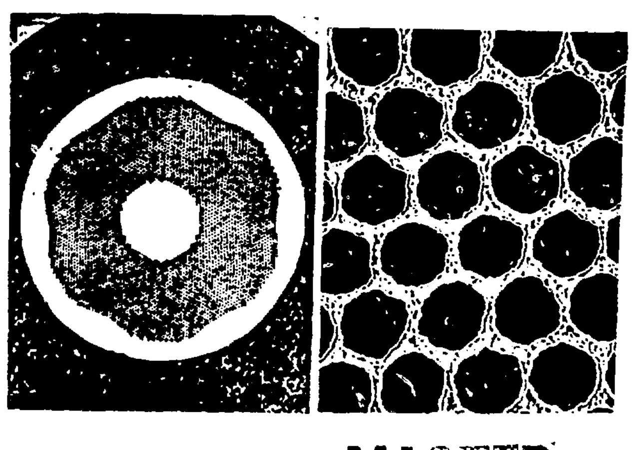

Figure 1. Cross section of the filament conductor used in this study and a closeup of the filaments showing the small spacing.

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In Table 1 the relevant parameters of the samples studied are listed. Cu/Sc is the overall copper to superconductor ratio. The critical current is defined for a conductor resistivity of 10^{-14} Ω-m, measured in transverse external fields from 0 to 8T. The resistive transition is characterized by I_c and a "quality factor" n defined empirically by the relation

$$\rho = 10^{-14}\,(I/I_c)^n$$

A transport J_c is calculated using the known Cu/Sc ratio and quoted at 5T in units of A/mm^2.

Table 1. Sample Parameters

Sample #	Diameter (mm)	Cu/SC	d (μm)	J_c(5T) A/mm^2	"n"
1	0.297	1.2	3.1	711	83
2	0.737	1.01	8.0	1995	56
3	0.61	1.01	6.7	2222	45
4	0.513	1.01	5.6	2365	47
5	0.358	1.01	3.9	2723	41
6	0.305	1.01	3.3	2359	
7	0.274	1.2	2.9	2632	39

Analysis of Measurement

The initial magnetization in a transverse field for a multifilamentary composite wire is given by the expression

$$M = 2\lambda H \qquad (1)$$

where λ ($\equiv [\mathrm{Cu/Sc}+1]^{-1}$) is the fraction of superconductor. Eq(1) can be used to determine the Cu/Sc ratio from the initial slope of the M-H curve. After the sample is cycled once to high fields the hysteresis curve is reproducible. To compare conductors, the "width" of the hysteresis loop defined as $2\mu_0 M$ was determined at the field of interest, which for the SSC dipole magnets is taken to be the injection field of ~ 0.3T.

$$2\mu_0 M = \mu_0(M^- - M^+)$$

where M^- (M^+) denotes the *increasing (decreasing)* applied field branch of the magnetization curve. For fields greater than the full penetration field H_p, the critical state model relates M to the critical current density as

$$2\mu_0 M(H) = 2\mu_0 \frac{2}{3\pi} \lambda J_c(H) d \qquad (2)$$

Since M is usually given in terms of unit volume of conductor we also define M_s, the magnetization per unit volume of NbTi, as $M_s = M/\lambda$. Usually d in eq. (2) is equal to the geometrical filament diameter. However, if the filaments are coupled whether metallurgically or via the "proximity effect" then d is replaced by an "effective diameter" d_{eff}[6]. In comparing the $J_c(H)$ derived from magnetization and that obtained from transport current measurements, the self field generated during a transport I_c measurement has to be taken into account. Self field for a wire was calculated using $(\mu_0 H)_{sf} = 10^{-7}(2I/R)$ where R is the wire radius.

Results and Discussion

In Table 1 the measured J_c at 5T are listed. The high "n" values indicate that the filaments are quite uniform which is confirmed by metallurgical examination which showed no evidence of "sausaging" along the filament length. Samples #2-7 have high J_c whereas #1 which was unheat-treated has a low J_c.

This sample was included in the study primarily because its transport I_c measurement could be extended to fields as low as 0.26T (self field corrected). For the high J_c conductors the transport I_c could not be measured at very low fields because of self field limitation. All of the samples were adequately twisted so that the magnetization was found to be independent of ramp rate to values of 30 mT/s.

Sample #1

In Fig. 2 the magnetization data for sample #1 are shown, which is seen to be quite unlike a typical hysteresis loop by virtue of its anomalously high magnetization at low fields. Additionally, from the initial slope it was found that $\lambda \sim 0.75$, showing that the composite was behaving as a solid superconductor with a diameter enclosed by the filament boundary. Microphotographs of this sample show that the filaments are uniform and have an average interfilimentary spacing d_n, ~ 0.3 μm. From the width $2\mu_0 M$ the measured I_c, d_{eff} is calculated for $H \geq 0.26$T. If we assume that the filament magnetization, M_f is

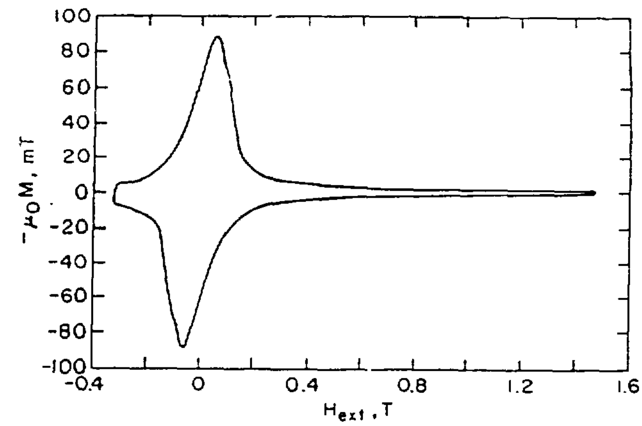

Figure 2. Magnetization data for sample #1. H_{ext} is the applied transverse field.

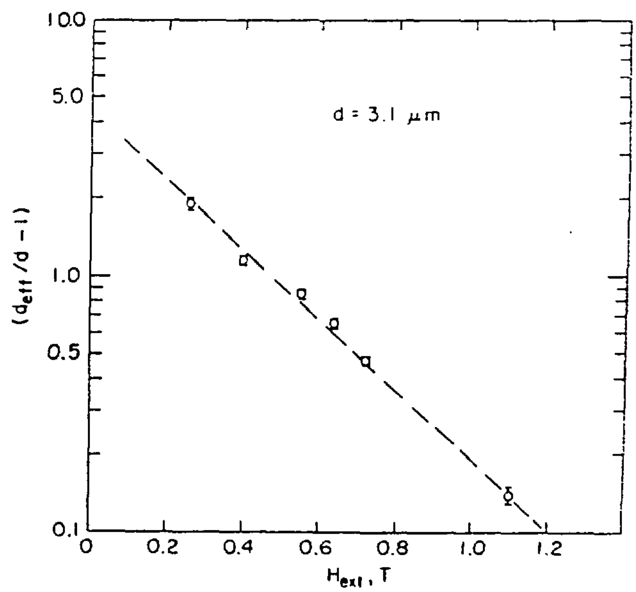

Figure 3. Plot of log (d_{eff}/d - 1) versus the applied transverse field for sample #1.

still given by the critical state model with d equal to the nominal filament diameter then the excess magnetization as a fraction of M_f is given by $(d_{eff}/d-1)$. In Fig. 3 is plotted this excess magnetization as a function of H, and is found to vary strongly with H. The data suggest that the functional dependence is given by $\exp(-H/H_0)$.

Samples #2-7

The magnetization data for the high J_c samples #2 and #6 are shown in Fig. 4. At fields ~ 1.0T, a comparison of the magnetization of the two samples, one with d = 8.0 μm the other with d = 3.3 μm, shows that M scales down linearly with d. However at low fields < 0.5T, M no longer scales with d. In fact at zero applied field the remnant magnetization of sample #6 is almost two and half times that of sample #2.

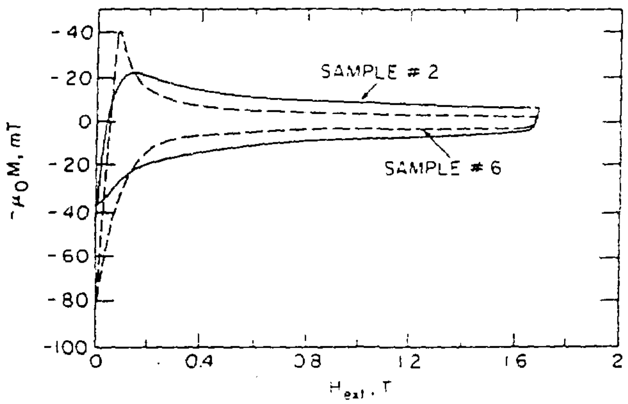

Figure 4. Magnetization data for sample #2 (d ~ 8.0 μm) and sample #6 (d ~ 3.3 μm).

The deviation from the critical state model as the filament size decreases is shown in Fig. 5 where $2\mu_0 M_s$ at some select fields are plotted as a function of d. The dashed line indicates the expected behavior as given by eq. (2). Data show that the enhancement of M is a strong function of both the filament diameter and the external field. The excess magnetization contribution, $\Delta M_s(H)$, is taken as the difference of $2\mu_0 M_s(H)$ measured and that obtained from the dashed line extrapolation, and in Fig. 6, this is plotted as function of d for various fields, showing the exponential dependence on d.

A preliminary temperature dependence study has been made for sample #7. Measurements indicate that the anomalous magnetization decreases with increasing temperature. However, a detailed analysis is not presented here pending further studies.

Coupling Mechanism

Based on the data, it is proposed that the enhanced magnetization at low fields, which is now labeled as M_c, is due to the filaments being coupled together by transverse persistent currents through the normal copper matrix via the "proximity effect". Unlike the case of Nb_3Sn conductors where the electromagnetic coupling of filaments is due to the metallurgical linking of filaments [6], any

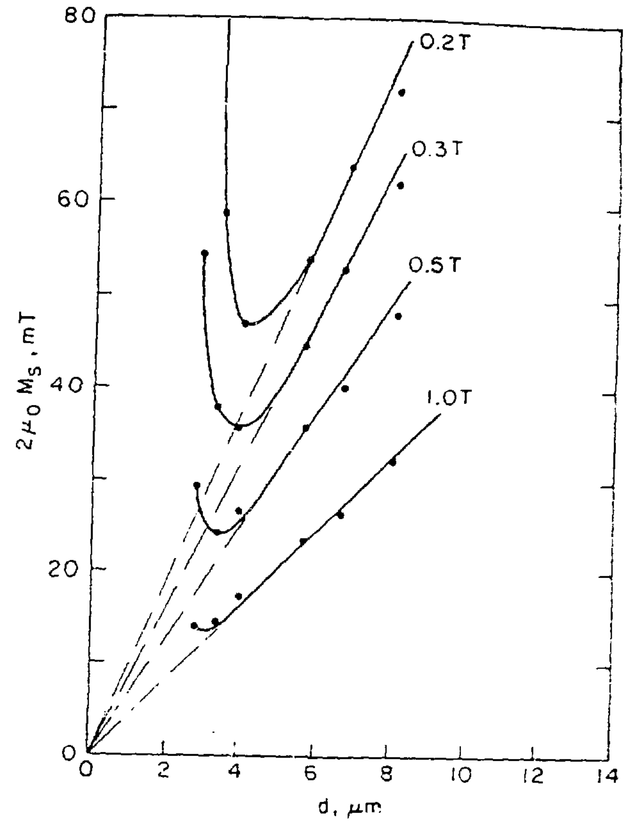

Figure 5. The width of the hysteresis loop $2\mu_0 M_s$ at different applied fields plotted versus the nominal filament diameter. The dashed lines are the expected behavior from eq.(2).

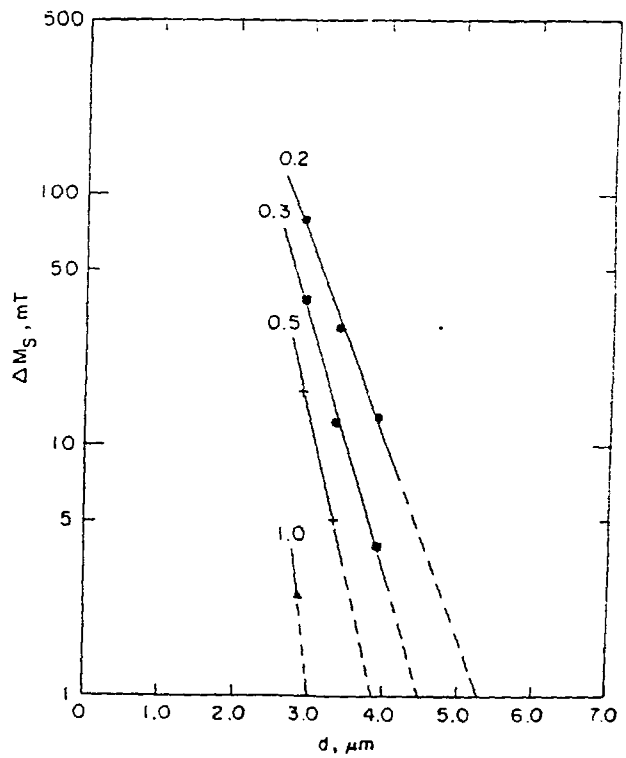

Figure 6. Plot of log (ΔM_s) at different applied fields versus filament diameter. The dashed lines intercepting the d-axis indicate the filament size at which the excess magnetization is $<$. mT.

coupling mechanism for these conductors must involve the normal matrix. That M_c depends on the interfilamentary normal metal separation d_n rather than d is clear since other conductors with d_n ~(0.2-0.3)d have not shown the presence of this term for d as low as 2 μm[2]. For the present sample d_n ~ 0.12 d which implies that average d_n varies from 0.35 to 1 μm. However, the minimum approach between filaments is ~ 1/2 d_n. Also since there is a niobium barrier around the NbTi, the copper matrix remains clean and so probably is the Nb-Cu interface. It is estimated that the electron mean free path, ℓ_n, in copper is ~ 7 μm at 4.2K, whereas the coherence length, ξ_n, is of the order of fraction of a micron.

Assuming this coupling mechanism, the magnetization of the composite in transverse field can be written as

$$M = M_f + M_c + M_e \qquad (3)$$

where M_f is given by eq. (2), M_e is the normal eddy current term which is proportional to dB/dt and M_c is the coupling magnetization given by

$$M_c = J_\perp r \qquad (4)$$

where r is the diameter of the filament boundary and $J_\perp$ the transverse supercurrent density is given by

$$J_\perp \propto J_c \exp\left(-k_n d_n\right) \qquad (5)$$

where the penetration length $k_n^{-1} = f(\ell_n, \xi_n, T, H)$.

The above model model would explain all of the observed facts, and allows one to control the coupling term by changing k_n or d_n. At a given field and temperature, $J_\perp$ can be reduced by increasing k_n. This can be achieved by introducing impurities in Cu which will reduce ℓ_n and thereby ξ_n. Replacing copper in the inter-filamentary region by Cu-Ni would significantly reduce the "proximity" coupling. Magnetic impurities in this respect will be more effective than non-magnetic impurities.[8] However, changing the nature of the matrix may introduce changes in the conductor properties which may not be desirable. Further R&D has to be done to explore the limitations of this approach.

$J_\perp$ can also be reduced by increasing the local Cu/Sc ratio thereby increasing d_n for the same filament size. A recent billet with a larger local ratio [9] than the present one shows that the onset of detectable M_c at 0.3T decreased to a d ~ 3μm. (Compare with data shown in Fig. 6). This approach may be a simpler one than changing the matrix. However, it has limitations in that increasing the local ratio beyond a certain value increases the filament cross section inhomogeneity and thereby limits J_c at high fields.[5]

Conclusions

The anomalous magnetization which is persistent and hysteretic in nature is seen to be a strong function of d_n and the external applied field and is theorized to be due to the "proximity" coupling of the filaments. From Fig. 6 we conclude that in these types of NbTi/Nb/Cu composites, coupling will not be evident even at fields ~ 0.01 T if d_n is greater than ~ 1 μm. At a d_n ~ 0.5 μm "proximity" coupling will be insignificant at 0.3 T, however, at much lower fields the effect will persist. From a practical point of view the data imply that there is a minimum filament size allowable for a given local ratio below which the magnetization does not decrease linearly with decreasing d. For the SSC magnets, the prime consideration for the conductor is a high J_c > 2750 A/mm^2 at 5T. The magnetization at low fields should be made as small as practical, but it should be reproducible. Given these constraints for the NbTi/Nb/Cu composites, it might be prudent to limit d values such that d_n ~ 1 μm. This would insure that the coupling magnetization is insignificant at all fields.

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