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MAGNETIZATION AND CRITICAL CURRENTS OF

NbTi WIRES WITH FINE FILAMENTS*

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ABSTRACT

In high energy accelerators such as the SSC, the magnetization of the superconductor is an important component in determining the harmonic fields at injection ($\sim 0.3T$). In an effort to reduce these residual fields, interest has focused on NbTi conductors with fine filaments which are expected to have a reduced magnetization as dictated by the critical state model. With this in view, the magnetization and critical currents were measured at 4.3K for a set of NbTi wires with filament diameters, d , ranging from 1.0 to 5.0 microns. The data show that, although the magnetization scales linearly with d , it does not do so with the product $J_c d$ for d less than 3 μm . However, at these d values, the critical transport current density, J_c , of NbTi was observed to decrease rapidly as a function of d . The origin of this J_c degradation and its effect on the scaling of magnetization within the framework of the critical state model is explored. We also examine the question of the observed asymmetry of the hysteretic magnetization.

INTRODUCTION

The effects of magnetization currents in the superconductor of accelerator dipoles appear at low fields as a non linear transfer function and systematic sextupole and higher multipole fields which are hysteretic in nature. These magnetization fields, which were first measured extensively by Sampson et al.¹ in early ISABELLE dipoles, dominate the systematic field errors at injection which must be corrected by trim coils. For the Superconducting Super Collider (SSC) which is envisioned to have an acceleration range of 1-20 TeV, the injection field is nominally 0.3T for the high field SSC Reference Design D². At present prototype Design D dipoles which are being wound with NbTi cables with a large filament size ($\sim 20 \mu m$), exhibit significant magnetization fields at 0.3T. This has motivated conductor R&D in an effort to produce NbTi wires, with high critical current density and small filament size (~ 2 to 5 micron), which are expected to show a significantly lower magnetization.

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We report here magnetization and critical current measurements on NbTi conductors with filament diameters ranging from 5 to 1 micron. These data provided the basis for testing the scaling of magnetization with current density and filament diameter.

EXPERIMENTAL DETAILS

The average magnetization, M , of several multifilamentary NbTi samples were determined in these experiments as a function of applied transverse magnetic field, H , and magnetic history at 4.35K. Measurement of changes of flux through appropriate pickup coils during changes in H were integrated to yield a complete set of values of M as a function of H . The field dependence of the critical transport current I_c was determined in a separate experiment³.

The details of the magnetization apparatus and the measurement techniques are given elsewhere⁴. The test samples were in the form of a stack of 30 cm long pieces of wire of volume $\sim 2-3 \text{ cm}^3$, held together by epoxy and fiberglass and mounted in a non-magnetic holder. Since the measurement involves taking the difference of the measuring coil signal with and without the sample, the net susceptibility of the holder and the material other than the superconductor influences the shape of the hysteretic loop at high fields. Data were taken with an external ramp rate of $\sim 20 \text{ mT/s}$. No eddy currents were detected for these rates.

Samples

A description of the NbTi samples are given in Table I. The IGC, MCA and Furukawa wire which have been manufactured recently represent possible future conductor for the SSC magnet program and some of the metallurgical details and critical current measurements are to be found in a report by Garber et al.⁵. The 0.22 mm Furukawa wire was drawn without any heat treatment to the smaller sizes. The OST conductors manufactured in 1981 as a qualification test for the Tore II Supra project have a Cu+CuNi matrix and twist lengths ranging from 12 mm to 1.1 mm. The first four OST wires were drawn down from the same billet whereas the 0.20 mm wire was from a different billet. Eddy current loss measurements⁶ have been reported for conductor similar to the 0.20 mm wire, while Carr and Wagner⁷ have studied the magnetic hysteresis loop for the 0.367 mm wire.

Analysis of Measurements

The magnetization measurements gave reproducible hysteresis curves after the samples were cycled once to high fields. To compare conductors, the "width" of the hysteresis loop defined as $2 \mu_0 M$ was determined at the field of interest.

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

where M^- (M^+) denotes the increasing (decreasing) applied field branch of the magnetization loop. In the critical state model this is related to the critical current density for fields greater than the full penetration field H_p , as

$$2\mu_0 M(H) = 2\mu_0 \frac{2}{3\pi} v J_c(H) d \quad (1)$$

where v is the volume fraction of NbTi, d is the nominal filament diameter and J_c is the current density in the NbTi. To facilitate comparison of conductors with different copper-superconductor ratio we also define

$$2\mu_0 M_s = 2\mu_0 M/v \quad (2)$$

Table 1. Sample Description

Manufacturer	Wire Dia. (mm)	Vol. fraction of NbTi	# of filaments	Filament Dia. (μm)
1. IGC	0.29	0.42	1953	4.3
2. MCA	0.114	0.48	367	4.0
3. Furukawa	0.226	0.48	3000	2.9
	0.142	0.48		1.8
	0.114	0.48		1.5
4. OST (Airco)	0.91	0.31	10285	5.0
	0.57	0.31		3.1
	0.455	0.31		2.5
	0.36	0.31		2.0
	0.20	0.31		1.1

The asymmetry of the magnetization loop for $H > H_p$ can be characterized by

$$2\mu_0 M_a = \mu_0 (M^- + M^+) \quad (3)$$

I_c , the critical current defined for a conductor resistivity, ρ , of $10^{-14} \Omega\text{-m}$, was 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^{3,5}

$$\rho = 10^{-14} (I/I_c)^n \quad (4)$$

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

RESULTS AND DISCUSSION

In Fig. 1 the measured J_c at 5T and the width of the magnetization loop for unit volume of superconductor, $2\mu_0 M_a$, at 1 Tesla are plotted as a function of filament diameter. The data show that although the J_c drops rapidly for $d < 3$ microns, the magnetization scales linearly with d . In fact this linear trend can be shown to extend up to filament sizes as large as $\sim 23 \mu\text{m}$ ⁸. This indicates that for those conductors of interest to the SSC magnet program (i.e. $J_c(5T) \geq 2400 A/\text{mm}^2$), the systematic error fields produced in the dipoles would be proportionally reduced as the filament size went from 23 to $\sim 3.0 \mu\text{m}$.

Validity of the Critical State Model

Table 2 lists some of the measured quantities. J_c^M is the critical current density calculated from the magnetization data using Eq. 1. J_c^* is the transport critical current density which has been corrected for self field using the relation $(\mu_0 H)_{sf} = 10^{-7} (2I/R)$ where R is the wire radius. In Fig. 2 the ratio J_c^*/J_c^M at 1 Tesla is plotted against filament diameter. At first glance the data would seem to indicate that for $d < 3 \mu\text{m}$ the magnetization is larger than what would one expect from the critical state model. However, we argue that for $d < 3 \mu\text{m}$ the transport critical current is not intrinsic to the superconductor. The reason that unusually

Fig. 1. Plot of $J_c(5T)$ and $2\mu_0 M_s(1T)$ versus filament diameter. The open symbols are the J_c data. The closed symbols give the magnetization "width" at 1 Tesla.

high M values are observed in fine filament wires of low current capability is due to the fact that magnetization is unaffected by filament breakage or "necking", whereas transport current is directly affected by such geometric defects. Thus a sample with severe filament necking will have a larger magnetization than would be expected from the measured current. In fact, it is not the magnetization that is high but the current that is low. We have observed that the magnetization of cable samples is not affected by compaction even when significant degradation has been induced by excessive rolling. In one example the cable transport current was

Table 2. Critical Current and Magnetization Data

Sample	$J_c(5T)$ A/mm ²	n at 5T	$2\mu_0 M(1T)$ mT	$J_c^M(1T)$ A/mm ²	J_c^*/J_c^M
IGC-0.29	2835	31.5	6.5	6710	-
MCA-0.114	2497	31.1	7.1	6980	0.98
FUR-0.226	2381	24.5	5.1	6770	1.00
-0.142	1580	18.1	3.1	6740	.64
-0.114	1320	15.5	-	-	-
OST-0.91	2100	17.6	6.0	7190	1.00
-0.57	1950	10.8	3.1	6000	1.05
-0.455	1330	5.5	2.3	5513	0.75
-0.36	920	4.5	1.8	5393	0.55
-0.20	830	9.5	1.0	5450	0.48

Fig. 2 Plot of J_c^*/J_c^M at 1 Tesla versus filament diameter

reduced by 30% while the magnetization was identical to an equivalent volume of uncabled wire. This is because the bulk of the superconductor is unaffected but the filaments are serrated at edges reducing the transport current⁵. In the following section, the cause of the J_c degradation in fine filament NbTi is discussed.

J_c Degradation for $d < 3 \mu\text{m}$

Garber et.al.^{5,9} have shown that high J_c wire have filaments with smooth surfaces and uniform cross sections. Filaments in low J_c wires show Cu_3Ti compound particles $1 \sim 2 \mu\text{m}$ size on their surfaces and large variations in cross section (i.e. necking). Scanning electron microscope (SEM) photographs of the Furukawa wires shows the presence of these nodules of Cu-Ti on the filament surface which would account for the J_c degradation as this wire is drawn down.

In the case of the OST wires, evidence of filament damage or necking is reflected in the reduced n values characterizing the resistive transition (see Table 2). In Fig. 2 the dashed curve is the $J_c(\text{ST})$ normalized to the $J_c(\text{ST})$ of the 0.91mm wire, which shows the degradation in critical current as the wire is drawn down. Although these wires had Nb barriers around each filament to prevent Cu-Ti compound formation extensive necking was observed in SEM micrographs, with the 0.20 mm wire showing a lot of filament breakage. At this wire size, 1 micron ZrO_2 inclusions were found at the necking sites. Contamination of the alloy with ZrO_2 from grinding wheels used in a centerless grinding operations likely led to this inclusion and the degradation of the wires for $d < 3 \mu\text{m}$.

Asymmetry of the Magnetization Loop

Carr and Wagner⁷ showed that for fine filaments the magnetization hysteresis has an up-down asymmetry. This they attribute to a surface current which is non zero (in the positive field region) for positive $\frac{dH}{dt}$, i.e. the M^+ branch, and is zero for $-\frac{dH}{dt}$, i.e. the M^- branch. This asymmetry was observed in the fine filament wires reported here an example of which is shown in Fig. 3. In this case most of the normal material susceptibility was eliminated by taking the difference of the signal with the conductor at 4.35K and when heated to $\sim 20K$ without removing the sample from the measuring coils. The asymmetric term $2\mu_0 M_a$ is ~ 1 mT at an external field of 1 Tesla and is similar in magnitude to the $1.1 \mu m$ filament wire.

Although the critical state model predicts up-down symmetry, data in the literature show asymmetry at high fields for even large filament diameter superconductors¹⁰. It is argued that an asymmetric contribution describing the equilibrium magnetization of any Type II superconductor should be present at all fields. This equilibrium magnetization M_e is described by the models of Abrikosov and Ginzburg-Landau theory¹¹. It is assumed that this term is independent of the critical state magnetization and depends only on the magnitude of the applied field and is therefore reversible.

For extreme Type II ($\kappa \gg 1$) superconductors and for $H \gg H_{c1}$, the Abrikosov solution of the "London model" gives an analytical expression for M_e for a cylinder in parallel applied field¹¹. Although the applied field in these experiments is transverse, nevertheless one can estimate the magnitude of this term. Using an upper critical field, $H_{c2} = 11.2T$,¹² and heat capacity data of Nb-46.5 wt.%Ti,¹³ the following values are estimated: $\kappa = 38$, $H_{c1}(4.3K) \sim 10mT$, λ , the penetration depth, $= 2.5 \times 10^{-7}m$. Using these values M_e at 1 Tesla is calculated to be $\sim 1.7mT$. The observed magnitude of M_a is consistent with this interpretation.

Fig. 3 Magnetization data for the OST-0.455 mm wire.

CONCLUSIONS

From these experiments, the following conclusions are drawn: (1) at low fields the "width" of the hysteresis loop scales with filament diameter down to ~ 1 micron. This indicates that the magnetization effects seen in the current SSC Design D prototype magnets would be reduced by an order of magnitude by using the fine filament conductors with high J_c at 5T. These wires represent the next generation of SSC conductors. (2) The J_c degradation seen in wires with filament diameter $< 3 \mu m$ are believed to be the result of local "necking" of the filaments caused by the drawing down of filaments with Cu-Ti compound on their surface or with micron size inclusions. These geometric defects of the filaments do not degrade the magnetization properties which reflect the intrinsic critical current of the filaments. (3) The asymmetry of the M-H curve can be explained by the presence of the reversible equilibrium magnetization of Type II superconductors and should be present even in wires with large filaments. This contribution to the total magnetization is assumed to be independent of the hysteretic contribution of the critical state model, and is apparent when the critical state contribution is small due to fine filaments.

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