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MAGNETIC FIELD PROFILES OF NbTi TAPES*

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ABSTRACT

Magnetic field profile measurements were performed on stabilized NbTi tapes in zero applied field carrying large transport current densities. Field profile data were taken on large diameter superconducting sample loops at temperatures between 2 K and T_c (about 9.2 K) and several persistent currents up to $I_c(T)$, the maximum. The field profiles scaled with current, independent of temperature, at temperatures below 8.5 K and were well described by an elliptical shell approximation which left a current-free, field-free central region. Critical state models applied to this self-field situation proved inadequate. Complex profiles produced by trapped flux in the tape loop were described quantitatively by assuming concentric elliptical shells each with a different current density. The maximum current which could be persisted in the loop at each temperature was linear from 4 to 8.5 K. The effective resistance of the superconducting loop including its joint was less than 10^{-13} ohms.

INTRODUCTION

The study of the behavior of hard type-II superconductors carrying large transport current densities in zero applied field is of particular importance to superconducting power transmission lines. The zero field limit is of interest to the study of critical state phenomena as well because all fields present are generated by a measurable transport current and hence, magnetization effects need not be considered as such.¹

Because the surface magnetic field in a type-II superconductor carrying near critical currents² usually exceeds H_{c1} , it would seem reasonable to apply a Kim³ type critical state model to describe the magnetic fields and current distribution inside the conductor. However, it can be shown that no local or Kim type critical state model can accurately describe partial flux penetration in a long straight type-II superconductor in zero applied field⁴ because such a model cannot provide zero magnetic field inside the portion of the conductor where $J = 0$, a condition that must be satisfied by a superconductor if all currents are transport currents.

That the field B must be zero where the transport current density J is zero is supported by previous results for Nb₃Sn tapes^{1,2} where measurements were made with a Mössbauer effect magnetic field probe and Hall probes. Data were well described by a constant current density shell model whose principal feature was a zero-current zero-field hole; attempts to fit a critical state model to the results failed. However, the Nb₃Sn used for the measurements suffered in that it was a layered structure having both Nb and Nb₃Sn components and its performance degraded with cycling. Improved measurements required a homogeneous system; NbTi was a logical choice because of its ductility and availability as well as a moderately high critical current density J_c .

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EXPERIMENT

The apparatus used to obtain the data on NbTi was based on a previously established technique¹ whereby a loop of the sample material was formed with a superconducting joint and then placed around a superconducting primary to form a dc transformer. Heaters on this secondary loop enabled us to drive it normal independent of the current in the primary. A germanium thermometer and heater on the loop combined with an integrating temperature controller could be used to regulate the temperature of the sample to within 0.01 K from 2 K to 14 K. By making the diameter of the sample much greater than its thickness, a reasonable approximation to a long straight tape conductor was achieved. Total persistent current in the sample loop was measured to a precision of 4 A and an accuracy of 8 A with a calibrated Hall probe ammeter located at the loop's center. Parallel and perpendicular components of the magnetic field were measured by two movable Hall probes that could be swept across the tape loop's surface to provide a field profile near the superconductor. The sample itself was made from 0.76-cm thick rolled Nb 45%Ti plate with a measured T_c of 9.45 K. This plate was explosively bonded on one surface to an equal thickness of OFHC Cu. The resulting sandwich was then rolled to thicknesses of 0.183 cm and 0.091 cm where the NbTi thicknesses were 0.091 cm and 0.045 cm, respectively. T_c of the material after bonding dropped to 9.19 K presumably because of a 400°C anneal prior to the bonding operation. The sheets were then sheared into strips 1.96-cm wide and formed into loops 10 cm in diameter with the NbTi on the outside. The superconducting joint was made by spot welding one or two additional strips of unclad NbTi over the break in the loop. The area of the spot welds was much larger than the cross section of the tape.

RESULTS AND DISCUSSION

In Fig. 1 we show the maximum persistent current achieved in a sample loop as a function of temperature. This current was obtained by maintaining the sample at a fixed temperature and inducing more current than could be carried in a persistent mode. After a rapid decay, the current reached a stable and reproducible value. At temperatures below 8.5 K, because of the added thickness of the joint, this current probably represented an accurate value for the critical current of the main tape because the maximum decay rate for the observed current indicated that the loop's effective resistance was less than 10^{-13} Ω . This corresponded to a voltage drop of 10^{-11} V/cm for a straight section, a level well below the minimum detectable voltage drop used to determine I_c by other methods. Near T_c , however, spotwelding of the joint may have lowered its T_c below that of the rest of the tape and therefore currents above 8.5 K were probably joint limited.

In Fig. 2 we show field profiles of the 0.091-cm thick NbTi sample. Current was induced by raising the temperature of the loop above T_c while maintaining current in the primary, lowering the temperature to 4 K, and then reducing the primary current to zero very slowly. At the end of this procedure the observed current in the sample was 2690 A at 4 K, a value about 82% of I_c . By slowly increasing the tape's temperature until the persistent current just started to drop we obtained a critical current of 2680 A at 5.0 ± 0.1 K. The field profiles were obtained simultaneously with two Hall probes, one to scan the component of the field parallel to the surface of the sample, the other the component perpendicular. Scan positioning accuracy was about

Fig. 1. Maximum persistent current as a function of temperature for 0.091-cm thick NbTi-0.091-cm thick Cu superconducting loop 1.96-cm wide is shown. The open circles represent values obtained with no flux trapping present. The boxes represent values obtained with some observable trapping. In both cases the final stable value was reached after a decay from a somewhat higher current. T_c measured for this material was 9.19 K; thermometry errors were about 0.1 K.

Fig. 2. Magnetic field profiles of a NbTi superconducting loop described in Fig. 1 carrying 2680 A at 5.0 K are shown. The Hall probe used to measure the parallel component of the field was 0.25 cm from the surface of the NbTi, and the one for the perpendicular component was 0.05 cm away. Data (shown as dots) have been adjusted to compensate for the fact that measurements were taken on a loop and not an infinite straight conductor. The fits (solid lines) were to an elliptical shell model with total current equal to the measured current and with the inner ellipse 0.87 ± 0.02 times the outer ellipse (see text). No other parameters were adjustable. The center of the tape was at zero and the edge at 0.98 cm.

± 0.01 cm and field accuracy about 5×10^{-4} T with repeatability to 2×10^{-4} T. Because the unclad side of the NbTi was almost in contact with the housing of the small (0.06 cm x 0.008 cm active area) Hall probes, spatial resolution was sufficiently high to almost fully resolve the peaks.

For the data of Fig. 2, the field profile was independent of temperature from 4 to 5 K. Scans taken from 5 to 8.5 K, shown in Fig. 3, displayed no observable change in shape and scaled accurately with the decrease in persistent current with rising temperature. Furthermore, the field profiles were observed to

Fig. 3. Magnetic field profiles as a function of temperature for the NbTi superconducting loop described in Fig. 1 with the Hall probes in the same position as described in Fig. 2 are shown. The current carried at each temperature is displayed in Fig. 1. The data at 5.0 K are identical to other scans (not shown) taken with the same total current at 4.5 K, 4 K, and 2 K. The data have not been adjusted for the effects of stray fields from portions of the loop not close to the Hall probes and the ripple noise visible is a result of run-out in the lead screw used to move the Hall probes. All data have the correct symmetry about the center of the tape at 0: the edge of the tape is located 0.98 cm from its center. Other data, not shown, were taken at lower temperatures and higher currents with no deviation from the expected scaling behavior. Data taken at 4 K and at currents down to a small fraction of I_c also scaled with current. The only noticeable deviation from a current-scaling behavior was above 8.5 K, as is apparent.

scale accurately with the persistent current induced both at 4 K with peak fields below H_{c1} and below 4 K where the critical current no longer varied linearly with temperature. As temperature was increased above 8.5 K, the persistent current dropped from about 600 A to zero at 9.3 ± 0.1 K. In this region a slight decrease in spacing between the edge peaks of the perpendicular component of the field was observed, indicating that current had penetrated more deeply into the tape. Qualitatively this effect is consistent with a field profile partially governed by λ , the penetration depth which varies rapidly only near T_c .

In Fig. 2 we also show a good fit of the data to an elliptical shell model which approximates the actual current distribution of a tape as a region of constant current density bounded by two similar concentric ellipses, the outer one with a major axis equal to the tape's width and minor axis equal to the tape's thickness. The only adjustable parameter is the size of the inner ellipse. A property of this distribution, one which cannot be achieved by a critical state model (except for circular symmetry), is that where $J = 0$, $B = 0$. A previous application of this model to results for Nb_3Sn also resulted in excellent agreement with experiment. Neither the Nb_3Sn or NbTi results could be fit well with any reasonable critical state model. It seems, therefore, that I_c was reached in both Nb_3Sn and NbTi

tapes well before the tape was fully penetrated with current and that the unpenetrated fraction had both $J = 0$ and $B = 0$ simultaneously. Thus the shape of the unpenetrated region and the current distribution elsewhere are not described by a local Kim type critical state model. Clearly the ellipse model is a phenomenological one which only crudely approximates a tape. The physical phenomena which govern the size of the inner ellipse are not understood at this time; however, the success of the model should lead to a better understanding of the large transport current density-low field regime. Local flux trapping was observed during several runs on the 0.045-cm thick NbTi loop. In Fig. 4 one field profile set with trapping effects present is shown together with a fit to an extension of the ellipse model using two concentric elliptical shells with antiparallel currents.

Fig. 4. The perpendicular component of the magnetic field (circles) of a 0.046-cm thick NbTi-0.046-cm thick Cu superconducting loop 1.96-cm wide exhibiting symmetrical flux trapping at 4.0 K is shown. The center of the tape was at zero, its edge at 0.98 cm, and the Hall probe was 0.05 cm from the surface of the NbTi. The net current carried was 180 A. The fit (solid line) used two elliptical shells, the inner one extending from 0.50 to 0.90 and the outer one extending from 0.90 to 1.00 times the outer elliptical boundary (see text). The outer shell carried a uniform current density 2.475 times the current density in the inner shell and antiparallel to it. The outer shell carried a net current opposite in direction to and 84% in magnitude of the net current carried in the inner shell.

The conditions required to generate trapping are not fully understood, nor was it determined whether a return path existed at some point on the loop or whether the current distribution was necessarily circularly symmetric. It was clear that the observed field profile and analysis based on the ellipse model strongly suggested antiparallel components of J . In addition, trapping has been observed to lower I_c at higher temperatures as shown in Fig. 1

SUMMARY

Measured magnetic field profiles of inhomogeneous Nb-Nb₃Sn and NbTi tapes carrying near critical transport currents in zero applied field are well described by an ellipse approximation and are not in agreement with critical state models. Any temperature dependence of the shape of the NbTi field profile appears to be small and only evident near T_c . Trapping effects have been observed and are well described by the ellipse model with antiparallel components of J .

Future experiments will examine more closely the temperature dependence of the field profiles as a function of width, thickness, stabilization, and trapped flux.

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