Suppression of Flux Jumps in Marginally Stable Niobium-Tin Superconductors

Ron B. Goldfarb, Loren F. Goodrich, Taeyoung Pyon, and Eric Gregory

***Abstract*—Niobium-tin superconductor wires with coalesced filaments may have reduced adiabatic stability. Magnetization measurements on such marginally stable conductors exhibit flux jumps, which appear as a sudden decrease in magnetization as the applied field is changed, caused by the unpinning of flux vortices and resistive heat generation. Flux jumps preclude estimation of the hysteresis loss from the area of the magnetization-versus-field loop. Here, we show that flux jumps can be minimized or suppressed during the measurement of hysteresis loss by immersing the specimen in helium liquid instead of helium gas. The better thermal conductivity of the liquid affords additional dynamic stability against flux jumps. This allows one to determine the loss upon field cycling and to calculate an effective filament diameter, often used to gauge losses and the extent of metallurgical interfilament coupling.**

***Index Terms*—AC losses, flux jumps, hysteresis losses, magnetization measurements, niobium-tin superconductors, superconductor stability.**

I. Introduction

To increase critical-current densities in multifilamentary Nb_3Sn superconductors made by the internal-tin diffusion process, wire manufacturers can decrease the local-area ratio of matrix to Nb. However, with the coalescence of filaments during reaction, such conductors may be only marginally stable, which sometimes makes it difficult to characterize their electromagnetic properties, such as critical-current density and hysteresis loss.

One measures magnetic hysteresis loss on wire samples to try to estimate the heat load on a cryogenic system upon cycling magnets made from superconducting wire. The sample length must be several times the twist pitch of the filaments in the wire for such ac loss measurements to be representative of losses in long lengths of wire [1], [2]. To accommodate an adequate length of sample in a magnetometer, with an applied field approximately transverse to the wire axis, samples are often coiled.

Measurements of hysteresis loss on marginally stable conductors often exhibit flux jumps caused by the unpinning of flux vortices and resistive heat generation. Flux jumps appear as a sudden decrease in magnetization as the applied field is changed. Such flux jumps may indicate that a conductor is not stable enough for certain applications. From a metrological point of view, flux jumps preclude estimation of the hysteresis loss from the area of the magnetization-versus-field loop.

In this paper, we show how flux jumps can be minimized or suppressed during the measurement of hysteresis loss by measuring in He liquid instead of He gas, as is typical. This has no bearing on the suitability of the conductor for specific applications, but allows one to determine the loss upon field cycling and to calculate an "effective filament diameter," a quantity often used as a figure of merit to gauge the extent of metallurgical interfilament coupling or "bridging."

II. Sample Preparation and Magnetic Measurements

The specimen consisted of a strand of multifilamentary Nb_3Sn wire, 0.6 mm diameter, with 19 subelements. A cross section of the wire prior to reaction is shown in Figs. 1 and 2. Wire characteristics are listed in Table I. The sample for measurement was wound on a 4 mm stainless steel mandrel with UNC 10-24 screw threads and reacted in vacuum. The reaction schedule was 25 °C/h to 575 °C for 200 h, 25 °C/h to 700 °C for 70 h, cool at 25 °C/h. The mandrel was pre-oxidized to prevent the wire from welding to it. The reacted wire was threaded off the mandrel and cut, without straining the conductor, to a sample coil of 7 turns with height 7 mm. The length of wire in the coil was about 10.5 cm. A cross section of the reacted wire is shown in Fig. 3. After reaction, most of the filaments in each subelement have coalesced.

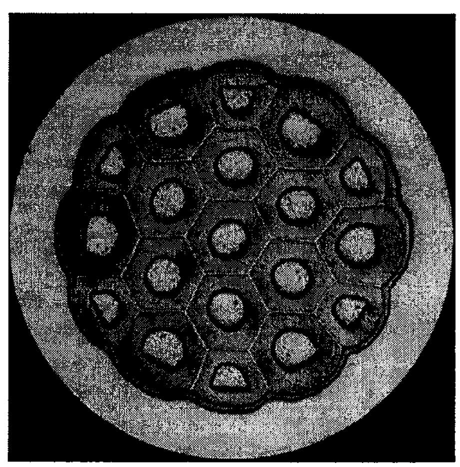

Fig. 1. Scanning electron micrograph of total wire cross section before reaction, showing the Nb filaments and Sn core of each subelement.

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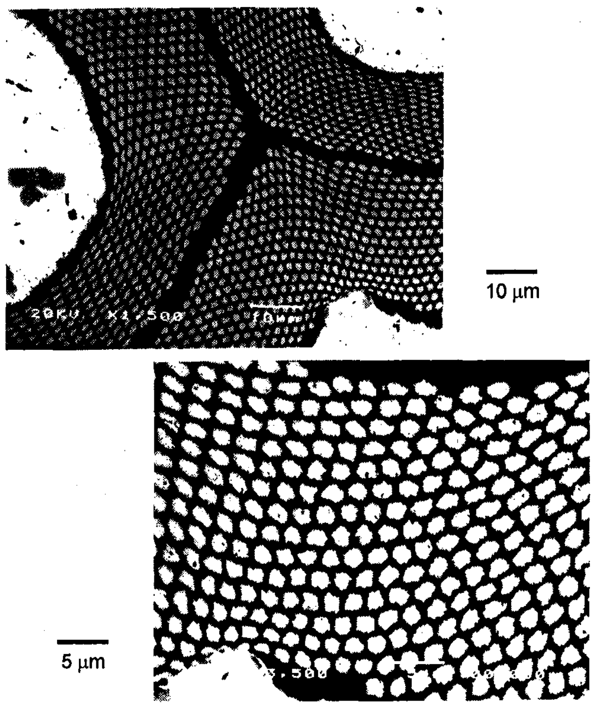

Fig. 2. Scanning electron micrographs of wire cross section before reaction.

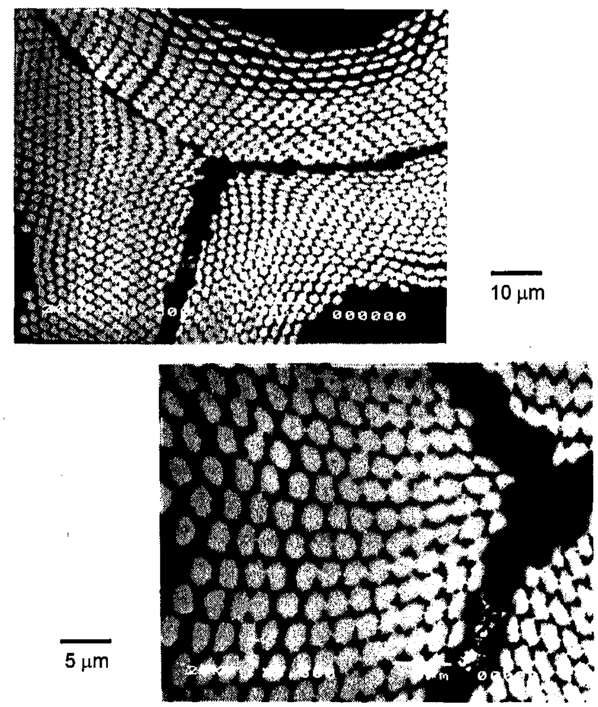

Fig. 3. Scanning electron micrographs of wire cross section after reaction. Note coalescence of filaments.

Measurements were made with a commercial magnetometer based on a superconducting quantum interference device (SQUID). The magnetic field, parallel to the sample coil axis and approximately transverse to the wire strand, was supplied by a Nb-Ti superconducting solenoid not in persistent mode. Field uniformity was better than 0.01 percent over the 4 cm scan length for each measurement. The field was swept at a rate of 0.4 T/min and paused for each measurement of magnetization.

We first measured the initial magnetization curve from 0 to +3 T. Hysteresis loss was calculated using the trapezoidal rule from the area of the full magnetization-versus-field loop from +3 T to –3 T to +3 T. Twenty measurements were taken per quadrant.

Magnetization was calculated as magnetic moment per total wire volume. Critical-current density J_c, referenced to the total wire cross section ("engineering" J_c), was measured at 10, 11, and 12 T and extrapolated to 3 T and 5 T using an exponential fit. Two values of effective filament diameter d_{eff} were calculated from those J_c, the widths of the hysteresis loops ΔM at 3 T and 5 T, and the critical-state model: $d_{eff} = 3\pi\, \Delta M / (4\, J_c)$ [3]. (The field was first ramped to 5.5 T to ensure full penetration of flux into the specimen when measured at 5 T in the first quadrant of the hysteresis loop.)

TABLE I
CHARACTERISTICS OF Nb_3Sn STRAND

Property	Value
Sample name	DT01-681
Wire density	8.52 g/cm^3
Non-Cu fraction	0.631
Wire diameter	0.6 mm
Twist pitch	1.0 cm
Number of subelements	19
Approximate subelement diameter	0.1 mm
Total number of filaments	38 000
Average filament diameter (before reaction)	1.4 µm
Local area ratio Cu/Nb (before reaction)	47/53 = 0.89
Diffusion barrier	Ta
Hysteresis loss for ± 3 T cycle (from Fig. 6, based on total wire volume)	3.54 J/cm^3
Wire critical-current density (extrapolated from exponential fit, based on total wire area)	6.54 kA/mm^2 at 3 T 4.24 kA/mm^2 at 5 T
Effective filament diameter (from critical-state model)	0.21 mm at 3 T 0.17 mm at 5 T

III. TEMPERATURE CONTROL

Normally, the SQUID magnetometer regulates specimen temperature by means of low-pressure He exchange gas in the sample chamber, and flowing, temperature-controlled He gas in a "cooling annulus" surrounding the sample chamber. The cooling annulus is separated from the He reservoir by a vacuum space. For normal operation below the standard boiling temperature of He, the cooling annulus is partially filled with liquid and pumped. Many other magnetometers use gas-flow cryostats.

For this paper, some measurements were made with the sample immersed in liquid He. To accumulate liquid He in the sample chamber, the system temperature is first set to 2.10 K. Once equilibrium is established, the sample chamber is filled with gas by opening the "vent" valve to the He reservoir. At the same time, the sample chamber "flush"

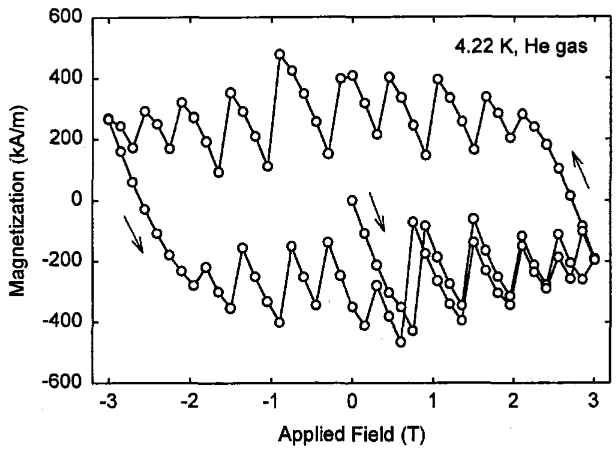

Fig. 4. Volume magnetization (magnetic moment per total sample volume) at 4.22 ± 0.01 K as a function of applied magnetic field for a marginally stable, multifilamentary Nb_3Sn conductor. As the critical state is repeatedly established, flux jumps and their associated resistive heating cause runaway propagation of a normal zone and quenching of the conductor, seen here as a drop in the magnetization. Magnetic field was stepped in increments of 150 mT. The time for each field step and acquisition of data was 66 s.

valve to the pump is closed. This allows clean He to condense and fill the sample chamber.

IV. Flux Jumps

One advantage of multifilamentary superconductors with high local-area ratios of matrix to superconductor is an improvement in stability. In *cryostabilized* superconductors, current can transfer to the matrix in response to local heating and transformations to the normal state [4]. Even in wires with smaller amounts of copper, fine filaments promote *adiabatic* stability because the amount of energy dissipated when a single filament reverts to the normal state is small [5]. The enhanced surface heat transfer in fine-filament conductors also promotes *dynamic* stability [5], [6].

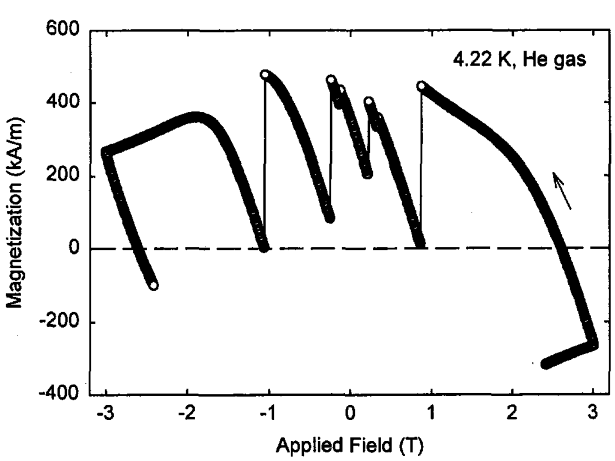

Fig. 5. Same as Fig. 4, except field steps were 10 mT, about 60 s per datum. The smaller field steps result in fewer flux jumps. Complete quenching of superconductivity is seen when the magnetization collapses to zero.

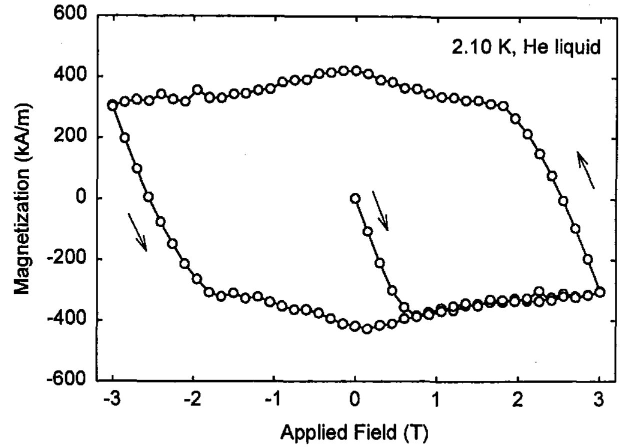

Fig. 6. Flux jumps can be suppressed by measuring in He liquid instead of He gas. The improved dynamic stability allows hysteresis loss to be gauged accurately. The lack of perfect smoothness indicates flux jumps that do not cause catastrophic quenches. The field steps and the time for data acquisition were the same as for Fig. 4. The temperature was 2.10 ± 0.02 K.

One problem with Nb_3Sn wires made by the internal-tin diffusion process is that filaments tend to coalesce during reaction [2], [7]. A reduced local-area ratio of Cu/Nb further promotes coalescence. We see here that the effective filament diameter derived from the critical-state model is even larger than the approximate subelement diameter (Table I). The adiabatic stability that would be derived from independent, small filaments is not obtained. It is not surprising that such conductors may be marginally stable and subject to flux jumps during changes in applied field. The topic of stabilization is reviewed by Chester [8], Brechna [9], and Al'tov et al. [10]. Practical calculations for flux jumps and stability are given by Iwasa [11].

Fig. 4 shows a typical magnetization curve for marginally stable Nb_3Sn at 4.22 ± 0.01 K. Fig. 5 shows a magnetization

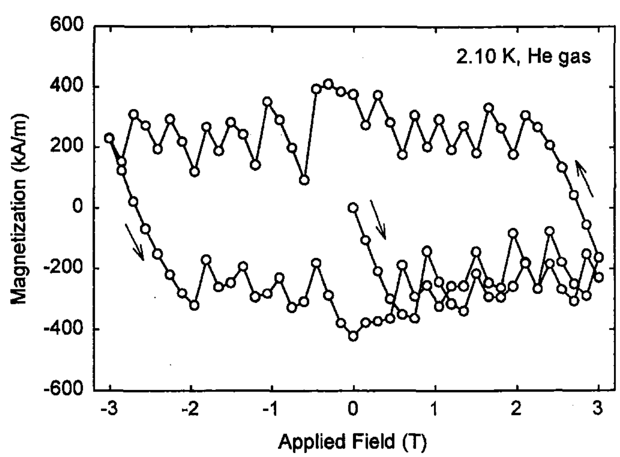

Fig. 7. Measurement at the same nominal temperature as for Fig. 6 (2.10 ± 0.01 K), but in gas instead of liquid. This demonstrates that the improved stability exhibited in Fig. 6 is due to improved thermal conduction of liquid He rather than the lower temperature. The field steps and the time for data acquisition were the same as for Fig. 4.

curve taken with very small field steps. We see here that a flux jump can actually drive the entire specimen normal, resulting in a collapse of the magnetization. Field scans with bigger steps, as in Fig. 4, allow the critical state to be reestablished before magnetization is measured.

In Fig. 6 we demonstrate that flux jumps can be eliminated when the specimen is immersed in liquid He at 2.10 ± 0.02 K, the main point of this paper. The improved heat-sinking of the conductor and enhanced dynamic stability solves the loss-measurement problem. The loss for the +3 T to –3 T to +3 T cycle is 3.54 J/cm^3 (referenced to the entire sample volume), 25 percent greater than that given by the area of the loop in Fig. 4.

A system temperature of 2.10 K allowed He to condense in the sample space of this magnetometer. However, there is no need to be below the He lambda point (2.17 K); similar measurements are obtained at 2.60 K in liquid. From the width of the hysteresis loop, the effective filament diameter is calculated to be much larger than the actual filament diameter (Table I), as expected for coalesced filaments. In such conductors, losses can be reduced by twisting the wire (before reaction) [1].

As a check, a measurement at 2.10 ± 0.01 K in He gas, Fig. 7, shows that the suppression of flux jumps is not due to lowering the measurement temperature from 4.22 K. In fact, the slightly higher critical-current density at the lower temperature would tend to reduce stability. This could account for the greater number of flux jumps at 2.10 K. (A similar increase in critical-current density at low fields is known to cause "low-field instability.")

Others have observed differences in flux-jump behavior depending on the cryogenic environment. Guillot et al. noted a difference in both the magnitude and field intervals of flux jumps for a Y-Ba-Cu-O monocrystal in He liquid and gas at 4.2 K [12].

V. Conclusion

Filaments tend to coalesce in Nb_3Sn conductors made by the internal-tin diffusion process. Especially when filaments have reduced local-area ratio of matrix to superconductor, effective filament diameters may become large, and conductors may become marginally stable. Immersing samples in liquid He provides additional dynamic stability that inhibits the thermal runaway in flux jumps and allows for the measurement of a smooth hysteresis loop.

Although some superconductor samples with high critical-current densities may experience flux jumps when cooled in He gas and subjected to changes in applied field, it does not mean that they are unsuitable for all applications. The strategy outlined here allows one to modify the operation of a typical magnetometer in order to measure hysteresis losses.

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