Hysteresis losses in fine filament internal-tin superconductors

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Hysteresis losses were measured on a series of fine filament Nb_3Sn superconductors made by the internal-tin process. Hysteresis was measured as a function of filament diameter and interfilament separation using a vibrating sample magnetometer in transverse magnetic field. Losses were greater than expected from the critical state model that expresses loss as a function of filament diameter. Micrographs of the reacted wire cross-sections showed some interfilament bridging for all wires. This gave rise to effective filament diameters that were greater than actual diameters. The critical interfilament separation, above which the losses would be expected to follow the critical state model, was determined.

Keywords: Nb_3Sn; superconductors; fine filament internal-tin superconductors; a.c. losses; hysteresis; magnetization

Fine filament superconductors are of interest in a.c. loss studies because, according to the critical state model, hysteresis loss is proportional to filament diameter. Thus, one would expect that wires composed of fine filaments would exhibit small losses. In this study we used a vibrating sample magnetometer in transverse magnetic field to measure the d.c. hysteresis loss for a series of Nb_3Sn superconductors made by the internal-tin process. There was no transport current. Filament diameter and edge to edge interfilament separation were systematically varied to determine whether filament coupling caused larger than expected hysteresis losses. Such magnified losses may be expressed in terms of an effective filament diameter that is greater than the actual filament diameter. The effective diameter is deduced from the hysteresis loss using the critical state model.

There has been some previous work on hysteresis losses in fine filament superconductors. Dubots *et al.*[1] compared measured and calculated hysteresis in Nb–Ti conductors with filament diameters ranging from 10 to 0.1 μm. They found that, for diameters < 1 μm, effective filament diameters remained at ≈ 1 μm. Information on interfilament separation was not given. Carr and Wagner[2] attributed the asymmetrical hysteresis curve they observed in Nb–Ti with 1.6 μm filament diameter to relatively large surface currents. Ghosh and Sampson[3] studied fine filament Nb–Ti with filament diameters in the range 1–5 μm. They note that, for diameters < 3 μm, the magnetization (and therefore hysteresis loss) is larger than expected from the critical state model. They attribute this to degradation of the magnitudes of critical current owing to filament necking or damage.

In this Paper we show that certain Nb_3Sn internal-tin conductors with filament diameters < 5 μm have effective filament diameters greater than expected from the critical state model. The ratio of effective to actual Nb_3Sn filament diameters appears to be a linear function of interfilament separation. The slope of the line is a function of the local area ratio of matrix material to Nb for each wire. The greater effective filament diameters appear to be a consequence of bridging between filaments.

Sample preparation and measurement

The multifilamentary Nb_3Sn wires used in this study were composed of subelements containing 150 filaments each. The array of subelements was surrounded by a tantalum diffusion barrier. Unreacted Nb_3Sn wires were wrapped on the threads of size 10–24 stainless steel screws. The thread pitch was such that the windings were not in contact with each other. The screws had been previously oxidized to prevent the wires from sticking to the screws. The internal-tin process wires were reacted in a vacuum, with the cold ends out of the furnace, according to the following schedule: one day at 340°C, four days at 580°C and four days at 700°C. This schedule is adequate to fully react the wires for the filament diameters in this study[4]. The residual tin content of each wire after reaction was estimated by the manufacturer to be 8 wt%.

After reaction, the wire coils were unscrewed from the stainless steel screws and the long ends cut off. Each coil was ≈ 1.3 cm in height. The wire volumes were measured using Archimedes' principle. The wire diameter was the same for each sample, 0.681 mm. Thus, the wire length for each coil was obtained.

The average Nb filament diameters before reaction and number of filaments in each sample were provided by the manufacturer. The reacted filament diameters and total volume of Nb_3Sn in each coil were calculated based on a presumed increase of 38% in filament cross-sectional area after reaction[5]. Local area ratios of matrix to Nb were determined by the manufacturer from the arrangement of the Nb rods in the billets before drawing: the Nb may be thought of as enclosed by adjacent hexagons and the

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Table 1 Parameters for six Nb_3Sn multifilamentary superconductors

Sample	Nb diameter (μm)	Nb_3Sn diameter (μm)	Local area ratio	Nb separation (μm)	Nb_3Sn separation (μm)	Number of filaments	Length (cm)	Volume Nb_3Sn (mm^3)
3	4.2	4.9	1.5	2.1	1.4	2850	17.8	9.71
6	4.0	4.7	1.8	2.4	1.7	2850	17.3	8.55
9	3.0	3.5	1.5	1.5	1.0	5550	17.1	9.24
12	2.8	3.3	1.8	1.7	1.2	5550	17.0	8.01
15	2.3	2.7	1.5	1.2	0.8	9150	17.0	8.89
18	2.2	2.6	1.8	1.3	0.9	9150	16.8	8.04

cross-sectional areas of Nb and matrix material measured. The average centre to centre filament distance, s, may be determined from the local area ratio, L, and Nb filament diameter, d, by the equation

$$L = (2\sqrt{3}/\pi)\,(s/d)^2 - 1 \qquad (1)$$

The edge to edge Nb separation is simply $s - d$.

Table 1 gives relevant parameters for the six samples. Note that the Nb diameter plus Nb separation equals the Nb_3Sn diameter plus Nb_3Sn separation. Both sums are equivalent to the centre to centre filament distance (not shown). The matrix to Nb local area ratios of 1.5 and 1.8 correspond to area ratios for reacted Nb_3Sn of 1.0 and 1.2, respectively.

The magnetic moment was measured at 4.2 ± 0.2 K with a vibrating sample magnetometer in the axis of the coil (i.e. field transverse to the wire if we ignore thread pitch of $\approx 5.5°$). The maximum applied field was 1.6 MA m^{-1} (20 kOe). There was no transport current and the coils were open circuited. Magnetization was computed as magnetic moment per unit volume of Nb_3Sn (i.e. not including the volume of the matrix material). Magnetization was plotted *versus* external (applied) magnetic field. A typical magnetic hysteresis loop for one of the samples (sample 18) is shown in *Figure 1*.

Results

Hysteresis loss was computed by numerically integrating the loop area, ignoring the initial branch. According to the critical state model, for transverse field geometry[6]:

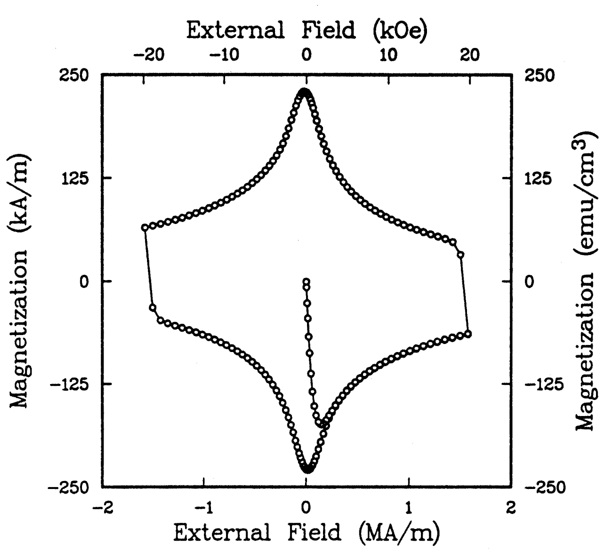

Figure 1 Typical hysteresis loop for a multifilamentary Nb_3Sn wire made by the internal-tin process (sample 18). Magnetization was computed as magnetic moment per unit volume of Nb_3Sn

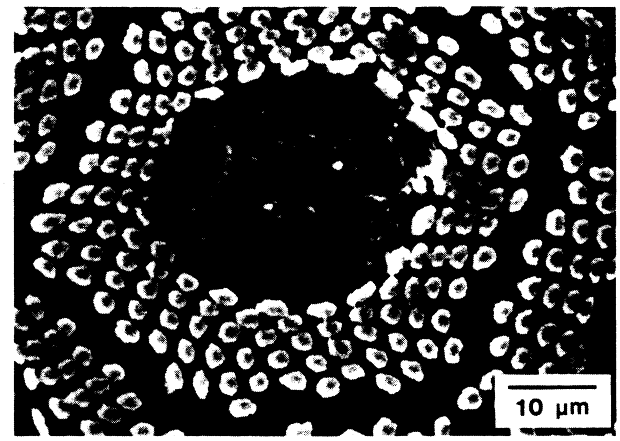

Figure 2 Typical scanning electron micrograph showing some interfilament bridging (sample 18, centre subelement)

$$W = 8\,J_c\,d_{eff}\,\mu_0\,H_0/3\pi \quad \text{(SI units)} \qquad (2)$$

Thus, an effective filament diameter, d_{eff}, may be defined that is a function of the hysteresis loss, W, for a maximum applied field, H_0. Since we did not have data for the critical current density, J_c, at 1.6 MA m^{-1} (20 kOe), we deduced these J_c based on the critical current of each wire measured at 6.4 MA m^{-1} (80 kOe) together with the total Nb_3Sn cross-sectional area and the measured value of the full penetration field, H_p, at 1.6 MA m^{-1} (20 kOe). J_c, H_p and filament diameter, d, are related according to the critical state model[6]:

$$H_p = d\,J_c/\pi \quad \text{(SI units)} \qquad (3)$$

H_p may be obtained as one half of the field required to reverse the magnetization[7]. From the hysteresis loops, H_p at 1.6 MA m^{-1} (20 kOe) is $\approx$75 kA m^{-1} (940 Oe) for all the loops. This suggests a factor of 10 increase in J_c compared to the measured value of J_c at 6.4 MA m^{-1} (80 kOe). Applying this factor of 10 to each conductor gives the values of J_c at 1.6 MA m^{-1} (20 kOe) shown in *Table 2*. We then compute the effective filament diameters of the wires and, additionally, the ratio of the effective to actual Nb_3Sn filament diameters.

Optical and scanning electron microscopy revealed that some of the filaments in each wire were not entirely isolated but were connected by 'bridges'. An example of this is shown in *Figure 2*. Such filaments had typically lost their original hexagonal spacing and aligned themselves in rows in the process of wire drawing*.

*Evidence for interfilament bridging in these wires was first presented by A.K. Ghosh and W. B. Sampson[8]

Table 2 Hysteresis loss and effective filament diameters for Nb_3Sn

Sample	Estimated value of J_c at 1.6 MA m^{-1} (20 kOe) (GA m^{-2})	W (MJ m^{-3})	Effective Nb_3Sn filament diameter (μm)	Effective to actual Nb_3Sn diameter ratio
3	49.4	0.870	10.46	2.12
6	50.6	0.714	8.37	1.78
9	50.6	1.369	16.05	4.55
12	54.3	0.885	9.67	2.94
15	53.8	1.419	15.66	5.80
18	51.9	0.805	9.20	3.56

Discussion

As shown in *Figure 3*, the relationship between actual and effective Nb_3Sn diameters is not monotonic. However, some insight is obtained by plotting the ratio of effective to actual Nb_3Sn diameters *versus* Nb_3Sn interfilament separation (see *Figure 4*). It appears that effective filament diameter is a function of both actual filament diameter and interfilament separation. Thus, loss per volume of Nb_3Sn superconductor is a function of both parameters.

Further refinement is possible by distinguishing among those conductors with the same matrix to Nb local area ratios. These are identified in *Figures 3* and *4* for the two ratios. We see in *Figure 3* that there is less of an increase in effective filament diameter for the conductors with the larger local area ratio. However, we note that in *Figure 4* the abscissa (Nb_3Sn interfilament separation) is not independent of local area ratio [see Equation (1)]. The apparently linear dependence of the effective to actual diameter ratio on interfilament separation has no physical significance.

A critical interfilament separation can be defined. It corresponds to the separation above which the hysteresis losses would depend on filament diameter as expected from the critical state model. We determined the critical separation for reacted Nb_3Sn, as shown in *Figure 4*, by linearly extrapolating the data to a unity value of effective to actual diameter ratio. The critical separation appears to be a function of the local area ratio. Critical values for the separation between reacted Nb_3Sn filaments were $\approx 1.6\,\mu$m for an area ratio of 1.5 and $\approx 2.0\,\mu$m for a ratio of 1.8. The corresponding critical values for the separation between *unreacted* Nb filaments were 2.4 and 1.5 μm, respectively.

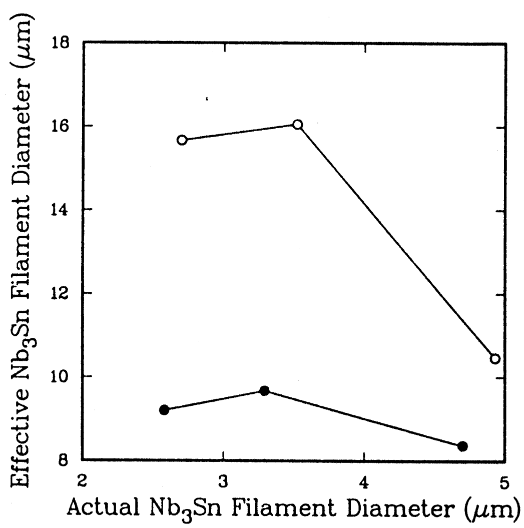

Figure 3 Effective filament diameter as a function of actual Nb_3Sn filament diameter for two local area ratios of matrix to Nb. Matrix to Nb area ratio: ○, 1.5; ●, 1.8

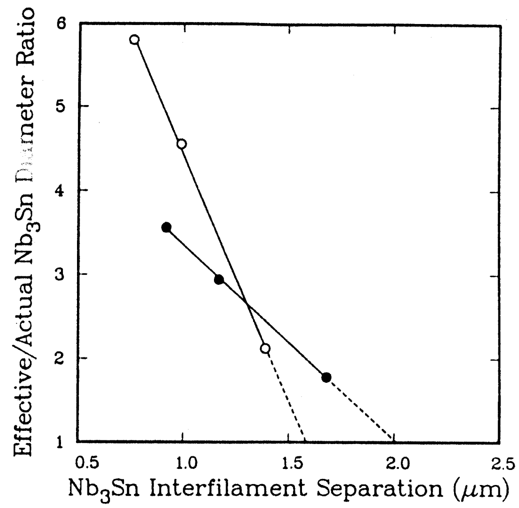

Figure 4 Ratio of effective to actual Nb_3Sn filament diameter as a function of Nb_3Sn interfilament separation for two local area ratios of matrix to Nb. Matrix to Nb area ratio: ○, 1.5; ●, 1.8

Conclusions

Certain fine filament superconductors made by the internal-tin process have effective filament diameters that are greater than actual filament diameters. The differences between effective and actual diameters increase as actual diameters decrease, the effect being more pronounced in those wires with the smaller local area ratio of matrix material to Nb. When the ratio of effective to actual diameters is plotted as a function of edge to edge interfilament separation, a more refined picture emerges. The diameter ratio increases linearly with decreasing interfilament separation for each local area ratio. The larger than expected effective filament diameters are likely to be due to interfilament bridging in these wires.

For the practical purpose of conductor design, a critical interfilament separation can be determined. It corresponds to the spacing above which the hysteresis loss would depend on filament diameter as expected from the critical state model. The critical Nb_3Sn interfilament separation for the conductors used in this study was ≈ 1.6 and 2.0 μm for matrix to Nb area ratios of 1.5 and 1.8, respectively. The critical separation is offered simply as a practical design parameter related to the critical state model and for guidance in the manufacture of fine filament internal-tin superconductors such as those described in this Paper.

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*Certain commercial materials are identified to adequately specify the experimental study. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material is the best available for the purpose

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