MAGNETIZATION OF IN SITU MULTIFILAMENTARY SUPERCONDUCTING NB_3SN-CU COMPOSITES*

CONF-800980--12

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Summary

Magnetic properties are reported for in situ superconducting Nb_3Sn composites that have exhibited attractive electrical properties and superior mechanical characteristics. Magnetization measurements were conducted up to 4 T at 4.2 K on a variety of samples of different sizes and twist pitches, and the results are presented in absolute M-H curves and losses per cycle. It is observed that the magnetization of such composites is generally proportional to the size of the wire (~0.25 to 0.51 mm) rather than the fiber size (~10^{-7} m), which indicates a strong coupling effect among Nb_3Sn fibers.

Introduction

The in situ process was first utilized for producing multifilamentary Nb_3Sn wires by Tsuei.[1] In this process, a filamentary structure was produced metallurgically by casting and drawing an alloy of Cu-Nb-Sn (or Cu-Nb with tin added afterward). After appropriate heat-treatment the final product should contain discontinuous, but well aligned, long Nb_3Sn fibers uniformly distributed in the bronze matrix. Because of its greater simplicity (as compared with the bronze method currently being employed to produce commercial Nb_3Sn composites), the process has been extensively studied and developed in the last few years. Techniques have been improved to fabricate composites with superior electrical and mechanical properties for high-field applications.[2,3,4] Nevertheless, more information is needed to provide insight into the superconducting mechanism involved in such a complex structure in order to explore the possibility for immediate technical applications. In particular, the magnetic properties of such wires need to be determined in order to study the magnetic stability and ac loss properties — a deep concern in most potential applications.

The successful application of continuous multifilamentary composite conductors has been based on a well understood, time-dependent electromagnetic theory. It was conceived that although all filaments are physically separated they tend to react collectively to any field or current change with a well defined time constant determined by matrix properties, filament distribution, and the twist pitch. A large time constant generally results in a large magnetization field and large coupling losses, which, in turn, may increase the refrigeration load or, possibly, cause an instability. However, it has been demonstrated that by carefully choosing the above parameters, one can design the conductor for almost any mode of stable operation.[5] The present study was initiated to characterize carefully the ac loss properties, such as magnetic diffusion time constant and losses per cycle, by analyzing the magnetization results of these in situ composites. Most importantly, the degree of coupling among the randomly dispersed, discontinuous fibers of the composites is investigated and discussed in comparison with continuous multifilamentary composites.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

Samples and Experiments

Samples for these measurements were fabricated at Ames Laboratory by a tin cores process,[2] with diameters of 0.25 and 0.5 mm and with different twist pitches (as listed in Table I). A typical cross section of one of these samples is illustrated in Fig. 1.

Table I: Test sample parameters

Sample	Diameter d_o (mm)	Twist parameter $\left(x_o = \frac{\pi d_o}{\ell_p}\right)$	$2\mu_0\Delta M_s$ (T) at $\mu_0 H_e = 3$ T
1	0.25	0	0.31
2	0.25	0.079	0.15
3	0.25	0.17	0.049
4	0.25	0.31	0.042
5	0.51	0.48	0.042

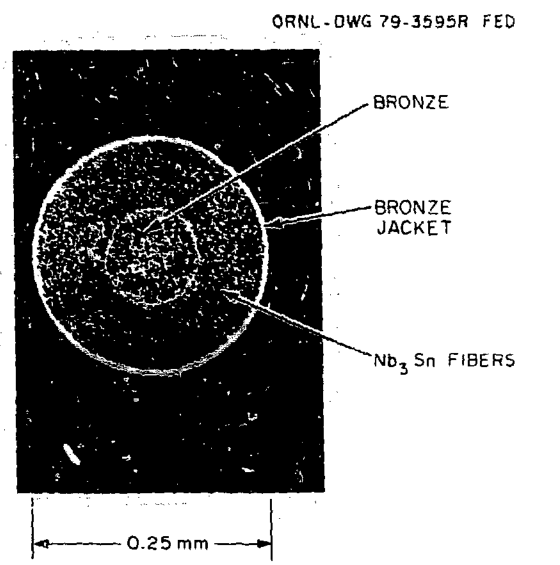

Fig. 1. Cross section of a tin-core-processed composite fabricated by Ames Laboratory.

Samples were heat treated on a steel mandrel with the same diameter (38 mm) as that of the sample holder used in the measurements. This arrangement prohibited any possible winding stress on the composites which could have affected the superconducting properties of the Nb3Sn fibers. Samples of more than 1 m in length were co-wound with an insulating spacer into a single layer and open-ended coil to be placed in the bore of a low loss, superconducting pulse magnet. A magnetization measurement system and its calibration technique have been described in detail previously.[6] The results are presented in absolute transverse M-H curves and losses per unit of conductor volume per cycle* and are discussed in terms of the degree of coupling among fiber structures.

*It should be noted that all results were obtained after the sample had been subjected to a peak field many times larger than the penetration field at least once.

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Results, Analyses, and Discussions

Untwisted Samples

Samples that reacted without twisting were measured first. Their losses per volume are plotted versus peak field as trace (1) in Fig. 2. The losses

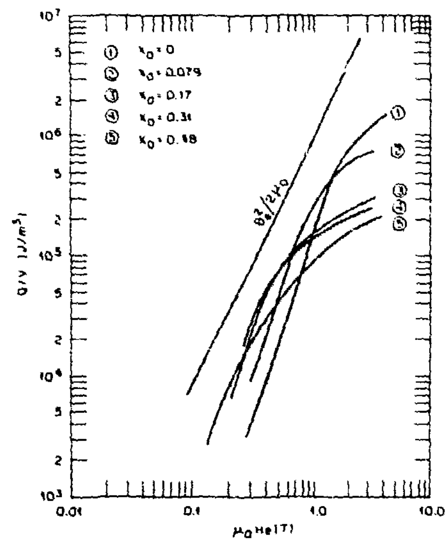

Fig. 2. Hysteresis losses of composites with different twist parameters.

are found to be purely hysteretic in nature and to have a magnitude equivalent to what would be expected for a solid wire. This effect is also seen in M-H curves, illustrated in Fig. 3. There are a number of other

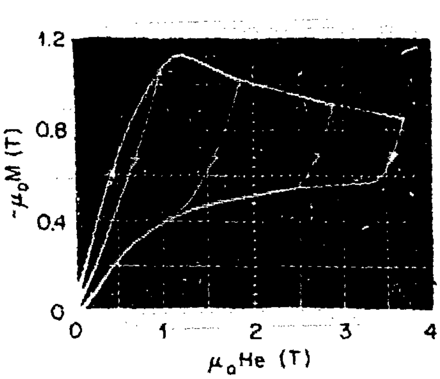

Fig. 3. Series of M-H curves of an untwisted composite.

features of these curves that are worth noting. First, the magnitude of the magnetization field and the penetration field are both on the order of 1 T — at least one order of magnitude higher than that observed in conventional multifilamentary wires. Second, there is the steep initial slope of the M-H curve, which generally represents the diamagnetic properties of the superconducting elements.[7] Results here indicate nearly complete shielding within the sample coil winding, including the insulating space between conductors. Such complete shielding, which can only result from complete coupling among fiber structures, is a general feature of all untwisted filamentary conductors. Third, one should note the high field region ($\mu_0 He \sim 3$ T) of the M-H curve, where the field-penetration condition is attained. Theoretically, for hollow cylinder geometry, the transverse magnetization can be expressed as

$$-M = \frac{4}{3\pi} \langle J_c \rangle r_2 \left[\frac{1 + \left(\frac{r_1}{r_2}\right) + \left(\frac{r_1}{r_2}\right)^2}{1 + \left(\frac{r_1}{r_2}\right)} \right] \ (\text{A/m}) \ , \qquad (1)$$

where $\langle J_c \rangle$ is the average critical current density over the whole composite and r_1, r_2 are the inner and outer radii, respectively, of the Nb_3Sn shell region. For the case $\ell_p = \infty$, one applies $r_2 = 125$ μm, $r_1 = 49$ μm, and $\langle \mu_0 M \rangle_{measured} = 0.155$ T into Eq. (1) to get

$\langle J_c \rangle = 2.1 \times 10^9$ A/m^2.

A short sample transport current measurement yields $\langle J_c \rangle_t = 1.4 \times 10^9$ A/m^2. The difference in these two values for $\langle J_c \rangle$ can be accounted for by the shielding effect.

Twisted Wires

One group of composites was twisted before heat treatment, and the critical current densities of the group were measured by the transport current method to ensure that twisting had no ill effect on the electrical properties. The magnetic effect of the twisting can be seen in Fig. 4, where the M-H curves for both

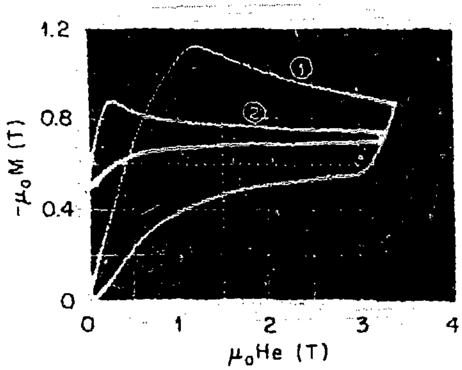

Fig. 4. Effect of twisting on M-H curves.
(1) Sample #1 $\ell_p = \infty$
(2) Sample #4 $\ell_p = 2.5$ mm

twisted ($\ell_p \sim 2.5$ mm) and untwisted wires are shown for comparison. The losses per unit volume are plotted in Fig. 2 for different twist parameters $x_0 = \pi d_0/\ell_p$. And, the magnetization field at 3 T is listed in Table I. All of these results indicate that the magnetization decreases with twisting, but it only does so to a quite limited extent. Moreover, measured magnetization is still of a hysteretic nature; i.e., no time-dependent magnetization is detected for external field ramps time from 0.1 to 100 s. This contrasts with what has been observed in conventional continuous multifilamentary wires, in which twisting effectively decouples the filaments and the magnetization is lowered to a level only proportional to the filament. Since it is well known that in a continuous multifilamentary conductor the coupling time constant can be expressed as

$$\tau_0 = \frac{\mu_0}{4\pi^2} \frac{\ell_p^2}{\rho_e} ,$$

with ℓ_p = 2.5 mm and τ_0 = 1000 s, one obtains the effective resistivity

$$\rho_e \sim 2 \times 10^{-16}\ \Omega\text{-}m .$$

which agrees with previous findings.[8] The coupling effect may also be ascribed in part to the short effective fiber length in comparison to the twist pitch. There are also encouraging aspects of these results to be noted. For example, the fact that the twisting can decrease the magnetization indicates that helical shielding current flows have been introduced by twisting the fibers. It further suggests that the microscopic currents in the composite are highly inhomogeneous and anisotropic, — far different from those in a solid conductor.

0.51 mm Sample

In Fig. 2 results are also presented for a 0.51 sample, (5). The purpose of using this sample was to see whether the distance between fibers could affect the coupling. The results show less than a factor of 2 decrease in losses per cycle, which is more likely due to the smaller twist parameter than to the decoupling effect of increased separation.

In Fig. 5, the M-H curve is shown for this wire. Also shown is the measured magnetization field

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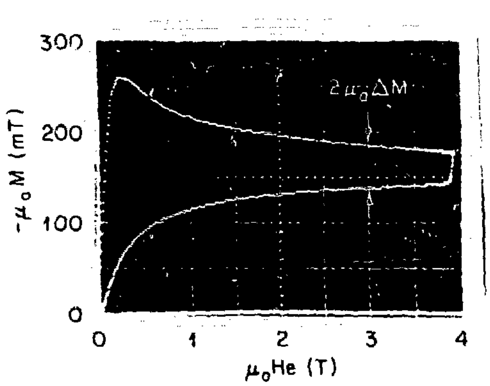

Fig. 5. M-H curve of twisted 20-mil sample.

$\mu_0 M = 2.1 \times 10^{-2}$ T at a 3-T field, which is about a factor of 7 smaller than that of untwisted sample (Table I). The results can be expressed in terms of an "effective diameter" defined by

$$-\mu_0 M \sim \mu_0 \frac{2}{3\pi} \langle J_c \rangle d_{eff} .$$

If one uses $\langle J_c \rangle \sim 1.6 \times 10^9$ A/m^2, he finds $d_{eff} \sim$ 49 μm, a number still two orders of magnitude higher than the physical size of the Nb_3Sn fibers (∿1000 Å). Thus, one may infer that all fibers are electromagnetically coupled, and the twisting introduces a collective helical shielding current that reduces the effective diameter by a factor of 7.

Discussions and Conclusions

Samples that have been measured so far are all of high niobium content (∿20%). With these samples, dense Nb_3Sn fibers are formed. In further studies, it would be interesting to measure some lower niobium (∿15%) and lower tin content composites. Although conductors with lower Nb content may have lower current density a drastic decrease in coupling may be found. Moreover, low niobium and tin composites have been found to exhibit better mechanical properties along with higher matrix conductivity,[9] which may further compensate for the loss of current density. It is important to realize that an effective diameter on the order of the individual fiber size may not be achievable, yet it may be neither necessary nor even desirable. From conductor design point of view, $d_{eff} \sim 5$ μm, which is very attractive to even fast pulse magnet applications, may be already in the stride of current technology.

In conclusion, results of magnetization measurements of in-situ composites are reported. Fiber structure is found to be electromagnetically coupled. It is recommended that future development work should be directed toward producing low niobium composites in which very small effective superconducting elements may exist.

Acknowledgments

The authors are indebted to D. K. Finnemore of Ames Laboratory and M. S. Lubell of ORNL for their interest and encouragement. J. P. Rudd's technical assistance is also greatly appreciated.

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