INTERACTION OF TRANSPORT CURRENT AND EXTERNAL FIELD IN COMPOSITE CONDUCTORS

MASTER

S. S. Shen* and R. E. Schwall**

MASTER

ABSTRACT

Investigations of transient field losses in superconducting composites carrying transport current are presented. The magnetization and terminal voltage of a variety of composites have been measured as a function of transport current and external field. The losses are analyzed as a sum of magnetization losses and those due to dynamic resistivity. Results are presented for slowly changing external fields where the magnetization losses are purely hysteretic and for higher $\dot{B}$ where coupling losses are important.

INTRODUCTION

Conventional loss measurements are commonly performed on an open-circuited sample in a time-varying external field.

In actual use, however, the superconductor carries a transport current and the influence of the self-field generated by this current must be taken into account. While the additional dissipation due to self-field may be calculated in the slab model, systematic measurements or calculations of loss in a composite conductor in the presence of transport current have not been reported. The present work, which involves simultaneous measurement of magnetization and dynamic resistivity with a time-varying external field and constant transport current, is an extension of some preliminary work by Turck¹ et al.

Sample and Measurements

Conductors tested in this study are summarized in Table I.

Sample Identification	Wire Diameter	CuNi:Cu:NbTi	Filament Size	No. of Filaments
A	1.01 mm	0.22:7.9:1.0	61 μ m	30
B	0.40 mm	0:2.0:1.0	18 μ m	160
C	0.40 mm	0:1.85:1.0	5.1 μ m	2162

Table I

Samples are wound bifilarly and placed inside the bore of a background pulse solenoid. The sample coil has a diameter of 3.82 cm and height of 10 cm, and the conductor length is approximately 10 meters. In addition to the magnetization, the measurement of which has been described previously,² we also have measured the terminal voltage of the sample coil during the field cycle. Extreme care has been taken

Manuscript received September 28, 1978.

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

*Oak Ridge National Laboratory, Oak Ridge, TN 37830.

**Present address: Intermagnetics General Corporation, Guilderland, NY 12084.

to detect the dynamic resistance of the wire rather than the inductive coupling between the imperfect bifilar sample winding and the background solenoid. This is accomplished by a compensation technique which subtracts the inductive component from the terminal voltage. The inductive phase reference voltage is obtained from a Rogowski coil coupled to the current leads of the background magnet. The effect of compensation is discussed in the next section.

Three samples were employed in this study. Samples B and C are standard copper matrix NbTi materials. Sample A was fabricated from a small prototype billet of mixed matrix material developed in collaboration with Intermagnetics General Corporation for use in high rate pulsed coils.³ This material is illustrated in Fig. 1.

RESULTS AND DISCUSSION

1. Sample A

Magnetization. The magnetization measurement was performed first and the results are shown in Fig. 2, where trace 1 is the virgin run and trace 2 is the successive one indicating the amount of flux trapped in the sample after the external field was cycled to 4 T. The rate of field change was maintained low (average value of 0.084 T/s) to ensure that the shielding current only flows inside the filaments.

Fig. 1. Cross Section of Sample A.

Fig. 2. M-H curves for Sample A without transport current. 1-virgin run, 2-successive run.

Next, the transport current of 107 A was applied at zero field.* Figure 3 shows the following two successive runs. Note that the gap at $\mu_0 H_e = 0$ represents the amount of trapped flux introduced by constant transport current. Since the transport current of 107 A is very close to the critical current at 4 T, the sample should show no shielding strength at the maximum field and this is clearly seen in traces 2 and 3 of Fig. 3.

Fig. 3. M-H curves for Sample A as $I_T = 107$ A is applied. 1- $I_T = 0$, 2 & 3-after $I_T = 107$ A is applied at $H_e = 0$.

Dynamic Resistivity. Dynamic resistance was measured across the sample coil as a constant I_T was maintained and the external field was applied. Although the winding is bifilar, there exists some residual inductance formed either by imperfect winding or the voltage leads, which gives rise to an inductive signal superimposed on the in-phase resistive signal. As discussed earlier, we used a compensation technique to overcome this problem.

The effect of compensation is demonstrated in Fig. 4, where both external field and voltage are plotted vs time. Trace 1 is the uncompensated

Fig. 4. Dynamic resistivity measurements on Sample A. 1-original signal containing inductive component, 2-compensated resistive voltage.

sample voltage while the trace 2 is the compensated one. The loss due to sample resistivity, $\oint \mathbf{v} \cdot \mathbf{I} dt$ has been computed for both the compensated and uncompensated waveforms and the results agree to within 1%. It is to be noted that the compensated sample voltage is always nonnegative independent of the sign of dH_e/dt . This voltage (V_T) represents the dynamic resistance which is present only when dH/dt is nonzero. It has been shown that^{4,5} in a slab model, V_T can be expressed as

$$V_T = \ell \cdot \frac{dB}{dt} \cdot \frac{I_T}{I_c} \cdot a \quad (1)$$

where ℓ is the sample length and a is the effective radius of the shielding current region which may vary from filament radius to composite wire radius.

Therefore the shapes of the voltage form are primarily determined by the product of $\mu_0 \frac{dH_e}{dt}$ and $\frac{I_T}{I_c}$. In Sample A, the peak voltage occurs where $\mu_0 \frac{dH_e}{dt}$ is a maximum of 0.154 T/s. Using $\frac{I_T}{I_c} = 0.8$ at $\mu_0 H_e = 3.43$ T, a_f (filament radius for such slow ramp) = 30.5×10^{-6} m and $\ell = 8.62$ m, Eq. (1) yields

$$V_T = 32.4 \mu V$$

while the measured value is 34.0 μV .

In Fig. 5, we show a composite picture of I_T close to I_c ($I_T = 102; 106; 107; 109$ A). At the top of the ramp where $\mu_0 \frac{dH_e}{dt}$ is zero, with no current flowing in the matrix, V_T should approach zero as indicated for $I_T = 102$ A. However, as I_T approaches I_c , the outside filaments saturate and the transport current shifts to the inner filaments. This shifting process causes current to flow in the matrix and gives rise to a normal voltage. In this specific conductor,

*This sequence was chosen because of the experimental convenience. Note that different sequences can induce different flux profiles in the conductor and hence different magnetization.

Fig. 5. Dynamic resistivity measurements on Sample A showing current-sharing effect.

because of the high Cu:SC ratio, the process is very stable and reproducible. As shown in Fig. 5, all the currents of 106, 107, 109 A show current-sharing at 4 T, corresponding to an equivalent resistivity value of the composite wire of $1.4 \times 10^{-14} \Omega\text{-m}$, $3 \times 10^{-14} \Omega\text{-m}$, and $1 \times 10^{-13} \Omega\text{-m}$, respectively. The technique thus has a sensitivity of at least $1 \times 10^{-14} \Omega\text{-m}$ for defining critical current of the composite wire. More important, the measurements reveal the fact that the nonuniform current distribution is playing a very crucial role in defining the I_c value for composite wires. This distribution is strongly dependent on the sequence of I_T and H_c being applied, which in this experiment is quite different from the conventional short-sample measurement technique in which H_c is kept constant and I_T is ramped. Therefore, one has to give more thought about the definition of I_c value and bear in mind that in a composite wire the current distribution can never be uniform.⁶ In Fig. 6, we show sequence effect on the dynamic voltage between runs. Trace 1 is the voltage for the first time $I_T = 106$ A is applied.* Trace 2 is the successive one, and Trace 3 is the next run after I_T is removed at $H_c = 0$. The difference between 3 traces at lower field has been observed by Turck¹ and well explained in terms of self-field effect.

2. Sample B

The sample was chosen to study the dynamic resistance of a wire under conditions where the filaments are coupled as shown in Fig. 7. The sample was first slowly cycled so that a static hysteretic M-H curve is obtained. Then he was discharged from 4 T with $\tau = 0.314$ sec to obtain the coupling magnetization curve, ensuring that coupling current is generated under this external field condition. The extra area represents coupling losses and yields an effective resistivity of $8 \times 10^{-10} \Omega\text{-m}$ and a matrix resistivity of $4 \times 10^{-10} \Omega\text{-m}$.² After the transport current $I_T =$

*Before this run, the sample was cycled at least once to the same field without any transport current.

Fig. 6. Sequence effect on V_T of Sample A. 1-first run after $I_T = 106$ A is applied at $H_c = 0$, 2-second run, 3-first run after $I_T = 106$ A is removed at $H_c = 0$.

Fig. 7. Static and discharge M-H curves for Sample B without transport current.

76 A ($I_c \approx 90$ A) is applied at $H_c = 0$, both static and coupled magnetization decrease as expected and this is shown in Fig. 8. However, a large dynamic voltage drop (compensated) is detected across the sample coil in the transport current direction as shown in Fig. 9. The measured V_T in the initial part of the discharge is 20 mV. At this point, $I_T/I_c = 0.9$, $l = 20$ m, and $\mu_0 \frac{dH_c}{dt} = 12.5$ T/sec. Equation (1) yields

$$a_{eq} = 80 \times 10^{-6} \text{ m}$$

Comparing to $a_f = 9 \mu\text{m}$ and a_0 (wire radius) = 200 μm , it is concluded that the fast field change has increased the effective radius of the shielding current from the size of filament to the one-third on the wire. Moreover, we have found that without the transport current, the

Fig. 8. Static and discharge M-H curves for Sample B with $I_T = 76$ A.

dissipation during the discharge is 6.9×10^4 J/m³. With the transport current $I_T = 76$ A, the losses, which are the sum of the magnetization and the dynamic resistance, becomes 9.2×10^4 J/m³. Generally, this is in good agreement with that predicted by slab model, i.e., $Q \propto [1 + (I_T/I_c)^2]$ if appropriate average value of (I_T/I_c) over the field change is used.

Fig. 9. Discharge dynamic resistivity voltage for Sample B at $I_T = 76$ A.

3. Sample C

The sample is a Cu matrix composite of high current density with a large number of very fine filaments (5.11 μ m). Under the same field ramp condition, it is found that indeed the dynamic resistivity is proportional to the filament size. In Fig. 10, a sequence of M-H curves is shown for I_T values at 90 A, which is about 75% of the critical value. The gap between the start and the end of the first run (trace 2) is somewhat larger than that of Samples A and B due to the fact that the wire has higher self-field effect as a result of its high superconductor ratio and large number of uniformly distributed filaments.

CONCLUSIONS

Experimental investigations of transient losses on superconducting composite wires have been carried out with the presence of both dc transport current and external field change.

Fig. 10. M-H curves for Sample C as $I_T = 90$ A is applied. 1- $I_T = 0$, 2 & 3-successive runs after $I_T = 90$ A is applied at He = 0.

It is found that the experimental results can be explained by the slab model not only in the slow field-change condition but also in the coupled region; this reveals some unique features of the composite wire, e.g., self-field effect of the filaments and effect of sequence of applying the current and the field. From these limited results it would appear that a reasonable approximation of the total losses in a composite conductor carrying transport current may be made using the simple slab model where $Q \propto [1 + (I_T/I_c)^2]$. This approximation appears to hold even when B is high enough to produce significant coupling between the filaments.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to J. P. Rudd for his consistent technical assistance in preparing and mounting the samples.

REFERENCES

1. B. Turck, L. Krempasky, and M. Polak, "Self-Field and External Field Effects on the Current Distribution in Superconducting Wires," Proceedings of 6th International Conference on Magnet Technology, Bratislava, 1977, pp. 716-722.
2. R. E. Schwall, S. S. Shen, J. W. Lue, J. R. Miller, and H. T. Yeh, "Superconductors for Tokamak Poloidal Field Coils," Advances in Cryogenic Engineering, Vol. 24, pp. 427-435.
3. M. S. Walker, B. A. Zeitlin, and R. E. Schwall, "Fast Ramp Superconductor for Ohmic Heating Coils," Proceedings of 7th Symposium on Engineering Problems of Fusion Research, Knoxville, TN, October 1977, pp. 1310-1314.
4. H. B. Brecchna, Superconducting Magnet System, Springer, 1973, p. 245.
5. G. H. Morgan, "Theoretical Behavior of Twisted Multicore Superconducting Wire in a Time-Varying Uniform Magnetic Field," JAP Vol. 41, No. 9, 3673-3679, August 1970.
6. T. Ogasawara et al., Paper EA-4, this Conference.