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TITLE: ENERGY LOSSES IN MIXED MATRIX SUPERCONDUCTING WIRES UNDER FAST PULSED CONDITIONS

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ABSTRACT

Energy losses have been measured on a set of mixed matrix (CuNi, Cu, NbTi) superconducting wires at $\dot{B}$'s up to 1.5×10^7 G/s. The losses have been measured as a function of wire diameter, twist pitch, maximum applied field, and $\dot{B}$. Both static and dynamic losses were measured for a field applied perpendicularly to the wire axis. The dynamic losses were measured by slowly applying an external field to a sample and then causing the field to decay exponentially in roughly 1 ms to 10 ms. Under low B (9 kG) and $\dot{B}$ (10^6 G/s) conditions the hysteretic loss dominated. At high B (21 kG) and $\dot{B}$ (1.5×10^7 G/s) the matrix losses became dominant. The systematic variation of the losses with the mentioned parameters will be presented and will be compared to theoretical predictions.

I. INTRODUCTION

Much work, both theoretical and experimental,¹ has been done on characterizing energy losses in superconducting wires. The bulk of the work has been done for either dc or low frequency ac conditions. Such measurements characterize losses in superconductors as they relate to transmission lines, rotating machinery and other ac devices. Superconductors to be used in the various aspects of the fusion program are subject to conditions not encountered in the above mentioned devices. One aspect is the alternating longitudinal fields which will be seen by the conductor in tokamak toroidal field coils. Some investigations² of the losses under these conditions have already been made. Another application of superconductivity in fusion is in Magnetic Energy Transfer and Storage (METS). Future pulsed, or high-beta, theta-pinch machines will require³ large amounts (~ 500 MJ) of energy which can be pulsed into plasma compression magnets in very short times. The economics of such machines require that a METS system for such a device be made of superconducting coils. The very high $\dot{B}$'s ($> 10^7$ G/s) encountered in such coils and the very low energy loss criteria ($< 0.3\%$) place severe constraints on the conductor. Very little work⁴ has been done on energy losses in superconductors under such fast pulse conditions. To be better able to design the necessary conductors and to be better able to predict the losses in the conductor and the coils, energy loss measurements have been made on a variety of superconducting wires under fast pulse conditions. Measurements have been made on both copper matrix and mixed matrix (Cu, CuNi) wires. The results of the measurements on the copper matrix wires have been reported elsewhere.⁵ The results of the mixed matrix wires are reported here. Some comparisons with the copper matrix wire results are also made here.

The data presented is on 156 filament, mixed matrix (CuNi:Cu:NbTi::1.5:2.1) wires. Measurements were made as a function of external parameters - maximum applied field, B_m , and the rate of change of the field, $\dot{B}$, as well as wire parameters - wire diameter and twist pitch.

II. EXPERIMENT

Energy losses were measured using an electronic integrator technique. The experimental system is

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shown schematically in Fig. 1. An external field is applied transverse to the wire axis. The sample sits

Fig. 1. Schematic of loss measuring apparatus.

in one half of an astatically wound pick-up coil. The integral of the imbalance voltage induced in the pick-up coil is proportional to the sample magnetization. Standard hysteretic loss measurements are made by manually sweeping the applied field up to a maximum of 21 kG.

Pulsed loss measurements are made with the aid of the superconducting switch which is in series with the magnet. The switch can be driven normal with the bipolar capacitive discharge. The current, hence field, decays exponentially with a $\tau = L/R$ decay constant. The time constant can be varied from 0.7 ms to about 9 ms by means of a set of interchangeable external resistors in parallel with the superconducting switch. Pulsed loss measurements were made by slowly increasing the field on the sample and then having it decay exponentially.

The apparatus was calibrated by measuring the magnetization below H_{c1} of a high purity Nb wire. Because of demagnetizing factors the calibration is estimated to be accurate to no better than $\pm 10\%$.

The samples were made by winding about 100 g of wire on a phenolic spool. The spool had an inner radius of 0.95 cm, an outer radius of 1.9 cm and a sample length of 2.5 cm. The total number of turns on the samples varied from about 450 to 950 depending upon wire diameter. All measurements were done in LN_2 at 4.0 K.

Matrix resistivity ratios (ρ_{273K}/ρ_{20K}) were made using a standard four-probe technique and the results varied between 45 and 60.

III. THEORY

Energy losses in superconductors can be broken down into two main components. First, there are the static or hysteretic losses in the superconducting filaments which are due to the irreversible nature of hard Type II superconductors. These losses are frequency independent. Second, there are the dynamic losses in the matrix which are due to coupling currents between filaments and/or eddy currents in the matrix itself. These losses are frequency or $\dot{B}$ dependent.

The nature of the hysteretic losses were first described by Bean⁶ and London⁷ in 1962-63 and resulted in well known critical state model. Numerous refinements¹ to the original theory have been made since. A somewhat different approach to predicting hysteretic losses in superconductors has been given by Wollan and Ohmer.⁸ Rather than starting from first principles, they derived

a pair of empirical equations based upon a reduced set of data. The equations for half cycle loss are

$$Q = \frac{(2.6 \times 10^{-8})}{R^{0.77}} B_m^{1.15}, \quad \frac{B_m}{B_{sat}} < 1.25 \quad (1)$$

$$Q = 14.1 R^{0.9} B_m^{2/3}, \quad \frac{B_m}{B_{sat}} > 1.25 \quad (2)$$

where Q is the energy loss per unit volume of superconductor in joules/m³-cycle, R is the filament radius in microns, and B_m is the applied field in gauss. B_{sat} is roughly the value of B which divides the partial penetration region from the full penetration region, and is given by

$$B_{sat} = 427R^{2/3} \quad (3)$$

The critical current density, j_c , does not appear explicitly in the equations, however it is assumed that it behaves approximately as $j_c = (7 \times 10^9 \text{ A-G/cm}^2)/B$.

The increased losses which result from changing fields were first treated fully by the Rutherford Group⁹ and later by Morgan¹⁰ and others.¹ They showed under certain conditions that the losses for multi-filament wires can be reduced by twisting. The critical twist length, l_c , is given by

$$l_c^2 = 2 \times 10^8 \frac{j_c d \rho_e}{B} \lambda' \quad (4)$$

where ρ_e is an effective transverse resistivity in ohm-cm, d is the filament diameter in cm, λ' is a geometry factor which equals about .25 for the wires discussed here, and the other terms are already defined. As B increases, coupling currents are induced to flow between filaments. A first order approximation of the increase in magnetization due to these coupling currents given by the Rutherford Group is

$$M = \frac{2}{3\pi} \mu_0 \lambda j_c d + \frac{2\mu_0}{3\pi} |\dot{B}| \frac{l_c^2}{\rho_e} \quad (5)$$

where λ is the volume fraction of superconductor. Considering only the second term and assuming an exponential discharge from the maximum applied field, B_m ,

$$B = B_m e^{-t/\tau} \quad (6)$$

then the increased energy dissipated during a discharge is

$$Q = \frac{10^{-10}}{3\pi} \frac{(l_c B_m)^2}{\tau \rho_e} \quad (7)$$

where Q is the energy per unit volume of conductor in joules/m³ and l_c is the twist pitch in cm.

If there is total coupling then Morgan¹⁰ has shown that the increased energy loss is essentially the same as for a solid matrix material wire

$$Q = \frac{10^{-10}}{16} \frac{(DB_m)^2}{\tau \rho_e} \quad (8)$$

where D is the wire diameter in cm. The effective resistivity, ρ_e , can be calculated from

$$\rho_e = \rho_{CuNi} \left(\frac{d_1 - d_2}{d_1} \right) \quad (9)$$

where d_1 is the diameter of the CuNi sheath and d_2 is the diameter of the copper around each NbTi filament.

IV. RESULTS AND DISCUSSION

Both hysteretic and dynamic energy loss measurements were made on nine superconducting wires. The wire parameters are given in table I. A sample wire cross section is shown in Fig. 2

TABLE I

Wire Diameter (in.)	Twist Pitch (Tw/in)	j_c (10^9 A/cm^2)
0.015	7, 8, 11	2.1-2.5
0.020	5, 6, 8	2.0-2.3
0.030	3.1, 4.5, 5.6	1.3

Fig. 2. Cross section of the conductor.

Table I gives j_c at 30 kG and at 10^{-12} ohm-cm for the wire. The j_c values for the 0.030-in. wires are considerably lower than for the other wires. The results, however, for the hysteretic losses do not show any increase in deviation from the predicted loss for these wires as compared to the 0.020-in. and 0.015-in. diameter wires. Typical data for the hysteretic loss as a function of B_m is shown in Fig. 3. The loss predicted by Eqs. 1 and 2 is also shown. The agreement is excellent. For other samples the difference between the measured and predicted loss varied by as much as 20%, mainly in the full penetration region. Because of the effectiveness of the high resistivity CuNi barriers in reducing coupling and eddy currents, the hysteretic loss constitutes greater than 50% of the total loss in all but a couple of measuring conditions.

Fig. 3. Experimental hysteretic loss for a 0.030-in. wire. The prediction of Eqs. 1 and 2 is also shown.

This is in contrast with the results for pure copper matrix wires⁵ where under some conditions they constituted only 10%.

The dynamic losses were measured for maximum applied fields of 8.8 kG, 17.6 kG and 20.9 kG and for decay constants of 1.42 ms, 2.61 ms, 5.14 ms and 8.84 ms. Two typical magnetization curves are shown in Figs. 4 and 5. The lower trace in each case is for the pulsed field decay. It is possible that the sample for Fig. 5 is starting to go normal at the end of the pulse. Typical loss results are shown in Figs. 6 and 7 where the total energy loss per cm³ of superconductor is plotted as a function of $1/\tau$. Figure 8 shows an example of the loss as a function of B_m . Also shown on the figures is the loss predicted by Eq. 7 where the theory has been fixed at the $1/\tau = 0$ point. The value of the effective resistivity used was 2.76×10^{-6} ohm-cm which was determined by fitting Eq. 7 to the data for $d = 0.030$ -in., $B_m = 2.09$ T, $p = 5.6$ Tw/in. and $\tau = 1.42$ ms. Calculating ρ_e from Eq. 9 taking $\rho_{CuNi} = 33 \times 10^{-6}$ ohm-cm for Cu-30Ni yields $\rho_e = 2.71 \times 10^{-6}$ ohm-cm.

Figs. 4 (top) and 5 (bottom). Half cycle magnetization curve for both static and pulsed conditions.

The critical twist length can be calculated from Eq. 4. The value of j_c is a function of B . For the present data if a value of 4×10^3 A/cm² is chosen, then l will exceed l_c for the lowest twist pitch only for $B_m = 20.9$ kG and $\tau = 1.42$ ms for the 0.020-in. and 0.030-in. wire and for $B_m = 17.6$ kG and $\tau = 1.42$ ms for the 0.030-in. wire. Hence, even at these high B 's the CuNi barriers are effectively keeping the filaments decoupled.

The predicted loss according to Eq. 7 is also shown in Figs. 6-8 where $\rho_e = 2.76 \times 10^{-6}$ ohm-cm was used for all calculations. The only adjustable parameter was to

fit the theory at $1/\tau = 0$ in each case. Under almost all conditions the agreement between data and theory is very good as shown in Fig. 6. In Fig. 7, however, the theory is roughly 20% low. Small differences in the stated versus actual twist pitch, because of the l^2 dependence of the loss, could easily account for the discrepancies. Also Eq. 7 does not take into account the eddy current losses, in particular, in the shell. These can be estimated using Eq. 8. The increase in the predicted loss is small; the increase in the dynamic losses ranges from 4% to 13%.

Figure 7 for the 0.030-in. wire at 3.1 Tw/in. shows the $\tau = 1.42$ ms and $\tau = 2.61$ ms points for $B_m = 20.9$ kG and 17.6 kG breaking away from the linear behavior at lower $1/\tau$. A similar break occurs for the 0.030-in. wire at 4.5 Tw/in. for $\tau = 1.42$ ms and $B_m = 20.9$ kG and 17.6 kG. For all other data Q is linear in $1/\tau$, Fig. 6

Figs. 6 (top) and 7 (bottom). Total energy loss per cm³ of superconductor as a function of decay constant. Dashed lines represent Eq. 7.

being an example, within experimental error. These breaks from the uncoupled theory agree well with the calculated values of j_c . It is also possible, however, that heating is reducing j_c , which in the full penetration region will decrease the hysteretic loss.

The amount of sample heating which occurs during the pulsed field decay is unknown. A calculation of the temperature rise for the highest loss case, $d = 0.030$ -in., $B_m = 20.9$ kG and $\tau = 1.42$ ms, assuming adiabatic conditions, yields a ΔT of about 10 K. Assuming uniform heat generation this corresponds to 0.9 watts/cm² of wire surface area. For a low loss case, $d = 0.015$ -in., $\tau = 8.84$ ms, $B_m = 8.8$ kG, again assuming adiabatic conditions, ΔT is about 2.5 K. Because the samples are a multilayer coil with no cooling channels, it is not possible to estimate to what degree the measurements are adiabatic. There is almost assuredly some effect on the data due to heating since only a 1 K temperature rise will decrease j_c by over 50%.

Fig. 8. Total energy loss per cm³ of superconductor as a function of maximum applied field. Dashed lines represent Eq. 7.

V. CONCLUSIONS

Energy losses for mixed matrix multifilament wires under fast pulsed conditions show good agreement with the hysteretic loss predicted Wollan and Ohmer⁸ and the dynamic losses predicted by the Rutherford Group⁹ and Morgan.¹⁰ There is also surprisingly good agreement between the values of the effective resistivity calculated from the wire geometry and from fitting the loss data to the theory. Unfortunately it is not possible to separate the effects of increased coupling from possible temperature effects for the present data. In future work a sample temperature sensor may be added.

Samples with the same geometry but with a Cu-10Ni shell will be measured to determine experimentally the contribution to the loss from eddy currents in the shell. Also some wire has been drawn to 0.006-in. diameter to evaluate the losses for small wire and filament diameters.

Figures 9 and 10 compare the losses in the mixed matrix conductor discussed here with a 234 filament copper matrix (2.6:1) conductor for $B_m = 20.9$ kG and for $\tau = 1.42$ ms and 8.84 ms. The losses in the mixed matrix conductors are from about three to six times smaller than for the copper matrix conductors. Also, the losses in the copper matrix conductors have decreased with τ and are almost independent of wire diameter and twist pitch at $\tau = 1.42$ ms, while the opposite is true for the mixed matrix conductors.

Figs. 9 (top) and 10 (bottom). A comparison of the total energy loss per cm³ of superconductor for mixed matrix and copper matrix wires as a function of twist pitch and wire diameter.

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