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AC LOSSES OF 19-STRAND SUBCABLES FOR THE ANL 3.3-MJ COIL*

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INTRODUCTION

Designs of multistrand-cable conductors for poloidal field and energy storage coils require low ac losses and cryostability. Even if the electromagnetic forces of these pulsed coils are generally supported by separate structural components the mechanical rigidity of the cable can significantly influence the performance of the coil. One way to improve the above factors is compacting or solder filling of the subcables. There have been considerable studies related to solder filling and ac losses of several kinds of subcable structures.^{1,2}

The 19-strand subcable of the previously tested ANL 3.3 MJ coil³ has been compacted and filled with Sn-50% Pb soft-solder to ensure stable current sharing within the subcable and to improve the mechanical rigidity of the final cable. The purpose of this study is to examine the effects of soldering and cable compacting

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Table 1. Sample No. 1, Superconducting Composite Strand

Diameter, mm	0.51
Cu/NbTi ratio	1.8
Filament diameter, μm	6
Number of filament	2041
Filament twist pitch length, mm	12.7 for Samples Nos. 1 & 2 6.35 for 19-strand subcables

on the ac losses of the 3.3 MJ coil and to evaluate the overall cable coupling due to the weakly insulated subcables.

SAMPLES AND EXPERIMENTAL PROCEDURES

The superconducting composite strand and multistrand subcables used for this study are listed in Tables 1 and 2. The 7-strand subcable has 6 copper wires around one superconducting strand. The 19-strand subcables consist of 6 superconducting strands and 13 copper wires. The 6 strands were twisted around a copper wire at the center with a twist pitch length of 12.7 mm. For the case of compacted samples, the finished strand is compacted by drawing it through a 1.45-mm compacting die. Then, 12 additional copper wires were twisted around the compacted strand and run through another 2.41-mm die. Prior to the cabling, the diameters of the copper and superconducting strands were 0.51 mm, and the resistivity of the copper wire at 4.2 K was $1.89 \times 10^{-10} \Omega\text{-m}$. The filament twist pitch lengths for Samples Nos. 1 and 2 were 12.7 mm and those for all the 19-strand subcables were 7.35 mm.

Coupling and eddy current losses of Samples Nos. 1, 2, 3, and 4 were measured from the magnetizations of 6-m long samples in discharging external field. Details of the experimental method have been described elsewhere.⁴ In this method the fields applied to the samples were uniform and the maximum field was 2 T.

Measurements of Samples Nos. 5, 6, and 7 were performed by making small coils as listed in Table 3. The coils were pulsed up to a peak field of 4.8 T by a triangular current. A typical pulsing mode of the coil is shown in Fig. 1. All the charging times were set to 1 s and discharging times were varied depending on the peak current. The losses of the coils were determined from the liquid helium boil-off during the pulsing and also from an electronic integrator method. In this method the inductive component of the coil terminal voltage was cancelled by an

Table 2. Sample Cable Description

Cable	Description
Sample No. 2	7-strand (one NbTi/Cu strand and 6 Cu wires), not compacted, Sn-50% Pb soldered.
Sample No. 3	19-strand (6 NbTi/Cu strands and 13 Cu wires), not compacted but soldered.
Sample No. 4	19-strand, not compacted nor soldered; strands are tinned.
Sample No. 5	19-strand, compacted (5% reduction in subcable diameter) and soldered.
Sample No. 6	19-strand, compacted; strands are tinned but not soldered.
Sample No. 7	19-strand, not compacted; inner 7 strands (one Cu wire and 6 NbTi/Cu strands) are soldered but outer 12 Cu wires are not soldered nor tinned.

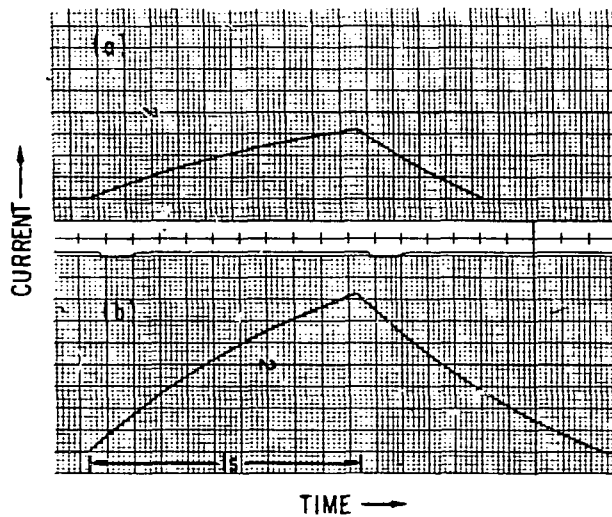


Fig. 1. Typical pulsing mode, (a) current = 320 A, $t_u = 1.0$ s, $t_d = 0.48$ s; (b) current = 720 A, $t_u = 1.0$ s, $t_d = 0.88$ s.

Table 3. Coil Parameters of Samples Nos. 5, 6, and 7

Central field at 850 A, T	4.9
Inner diameter, mm	32
Outer diameter, mm	141
Axial length, mm	94
Inductance, mH	12.5
Number of turns	602
19-strand subcable length, m	162

inductive voltage of a Rogowski coil coupled to the pulsing current of the coil.

RESULTS AND DISCUSSION

The coupling and eddy current losses of Sample Nos. 1, 2, 3, and 4 as a function of the exponential decay time constant of the external field are shown in Fig. 2. Here, the losses are normalized to the composite volume of the sample and its magnetic stored energy. The magnetic diffusion time constants and the effective resistivities of the samples obtained from the loss measurements are listed in Table 4.

For a full cycle of a long charging time and exponential decay time τ ($t_u \gg \tau$), the effective ramping time, t_e , can be approximated as $t_e = \tau/4$. From the expression for the coupling and eddy current losses in the case of $t_e \gg \tau_0$ ⁵

$$W_p = (B_m^2 / 2\mu_0) (R_f/R)^2 (4\tau_0/t_e), \quad (1)$$

τ_0 of Sample No. 1 is determined as 10×10^{-3} s. For Sample No. 1 R_f/R is approximately one. Substituting this into the expression for the magnetic diffusion time constant⁴

$$\tau_0 = (\mu_0 / \rho_e) (l_p / 2\pi)^2, \quad (2)$$

one finds the effective coupling resistivity 5.14×10^{-10} $\Omega\text{-m}$.

By comparing the data of Samples Nos. 1 and 2 in Fig. 2, it is clear that the losses from the 6 copper wires in the outer sheath of Sample No. 2 ($R_f/R = 1/3$) are relatively low compared to the losses in the superconducting strand region. This means that the soldered copper wires enhance the cryostability of the subcable without significantly increasing the losses.

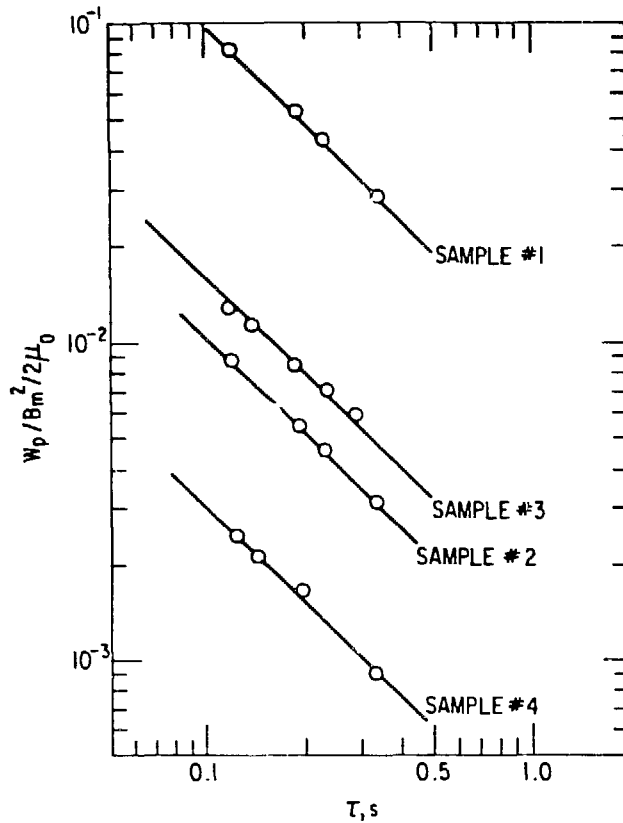


Fig. 2. Normalized coupling and eddy current losses vs decay time constant.

Choosing $R_f/R = 0.6$ from the geometry of the 19-strand sub-cable, one obtains $\tau_0 = 4.6 \times 10^{-3}$ s from the data of Sample No. 3. Effective coupling resistivity of the subcable depends on the

Table 4. Time Constant and Effective Resistivity

Sample No.	$\tau_0 (10^{-3} \text{ s})$	$\rho_e (10^{-10} \Omega\text{-m})$
1	10	5.1
2	9	5.7
3	4.6	11.2
4	0.83	61.6
5	9.4	5.4
6	3.1	16.5
7	4.3	18

choice of the effective twist pitch length (filament twist pitch or the strand twist pitch). Using the strand twist pitch length of 12.7 mm in Eq. (2), the effective coupling resistivity of Sample No. 3 is found to be $11.2 \times 10^{-10} \Omega\text{-m}$. It should be noted that due to the soldering of the subcable the losses of Sample No. 3 are increased by a factor of 5 compared to Sample No. 4.

Figure 3 shows the data for the ac loss measurements of Samples Nos. 5, 6, and 7. Assuming the current variations of the charge and discharge in Fig. 1 be linear, t_e is determined from the expression

$$2/t_e = 1/t_u + 1/t_d . \quad (3)$$

The maximum magnetic field B_m is averaged over the testing sample coil. The time constants for Samples Nos. 5, 6, and 7 in Table 4 are obtained from Eq. (1) and the data in Fig. 3 after subtracting the hysteresis losses of the subcables. The hysteresis losses of the samples measured up to 2 T are shown in Fig. 4. For the compacted samples the soldering increases the losses by a factor of 3. It is seen from the time constant of Samples Nos. 3 and 4

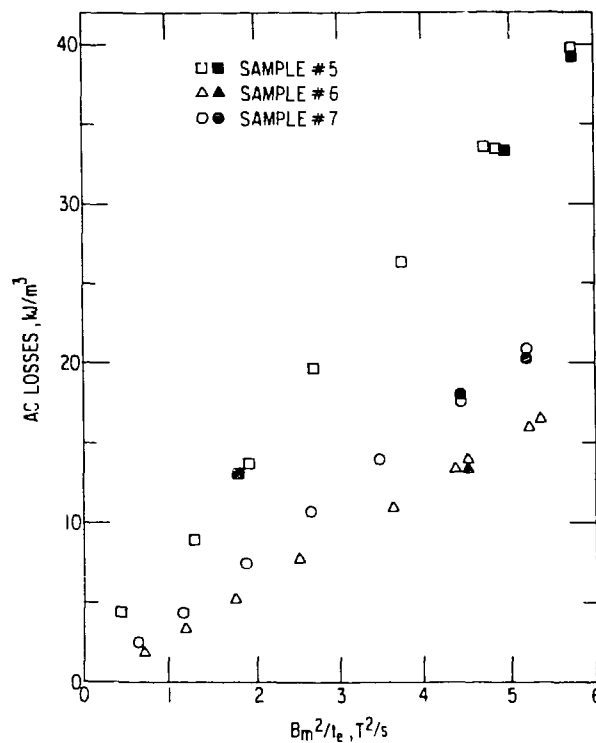


Fig. 3. AC losses of sample coils.

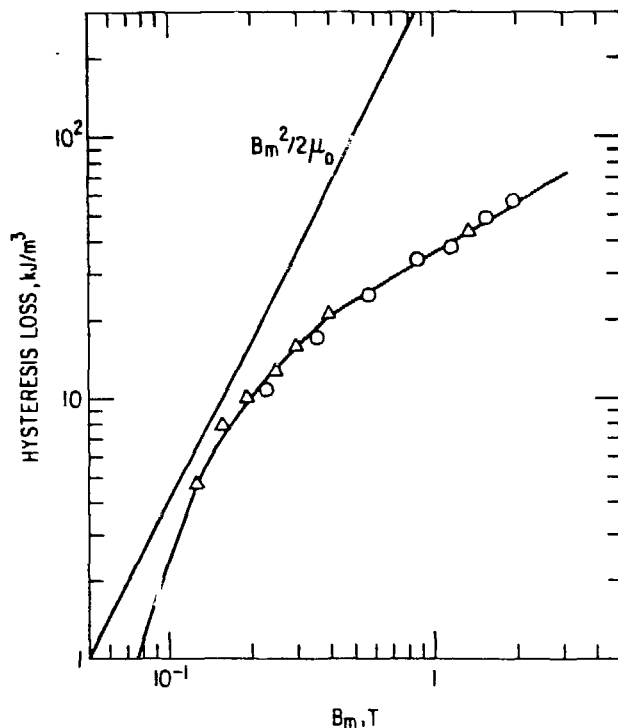


Fig. 4. Hysteresis losses per unit superconducting volume.

and Samples Nos. 5 and 6 that the losses are increased by a factor of 2 to 3 due to the cable being compacted. This is a rather large effect of the cable compacting. Some of the increase may be due to the abrupt change of the pulsing current at its peak for the tests of the coils as shown in Fig. 1.

It should also be noted that Sample No. 7 has higher losses than Sample No. 6. The data clearly shows that the inner superconducting strands are strongly coupled when they are soldered and the outer sheath copper wires do not contribute the losses significantly especially when they are not soldered together. This is consistent with the comparison of the data of Samples Nos. 1 and 2.

CONCLUSIONS

From the time constant of Sample No. 5 and the hysteresis loss measurements of the subcables, it is estimated that approximately 60% of the ac losses of the ANL 3.3 MJ coil at 6 T/s of the central field are due to the losses within the 19-strand subcable itself. The remaining 40% of the losses seem to come

mainly from the coupling among the weakly insulated 19-strand subcables in the final cable.

The outer sheath copper wires of the subcable improve the stability of the subcable, especially when it is soldered. It is shown, however, that the ac losses are not increased significantly due to the copper stabilizer.

NOTATION

W_p	= coupling and eddy current losses per unit composite volume.
B_m	= maximum applied magnetic field.
R_f	= radius of the superconducting strand or strands.
R	= radius of the subcable.
t_e	= mean effective ramping time.
l_p	= filament or strand twist pitch length.
t_u	= charging time.
t_d	= discharging time.

Greek Symbols

μ_0	= $4\pi \times 10^{-7}$ webers per ampere-meter.
τ_0	= magnetic diffusion time constant.
ρ_e	= effective coupling resistivity.
τ	= exponential decay time constant.

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