AC Loss Properties Of Cu-Sheathed MgB₂ Composites With Nb Barriers

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Abstract. We designed and fabricated Cu-sheathed MgB₂ composites with Nb barriers for low AC loss property. The wires were produced with powder-in-tube method after mixing Mg and B powders. The wires have a diameter of 0.7 mm and six MgB₂ filaments. Each filament has a thin Nb barrier to suppress reaction between Mg and Cu. The volume ratio of the filaments is 0.13. The averaged critical current of an about 1-m coiled specimen with a twist pitch of 10 mm is 55 A at 1 T and liquid helium temperature. The AC losses of the coiled specimen exposed to the applied magnetic field parallel to the coil axis were measured by a standard pickup-coil method in liquid helium. The ranges of the amplitude and the frequency were extended up to 1 T and 5 Hz, respectively. The AC loss property including the frequency dependence was also estimated for the multifilamentary structure with a usual theoretical expression of the coupling loss among the filaments. It is found that the experimental results observed cannot be explained by the theoretical prediction. We discuss the discrepancy from viewpoint of a coupling among the filament with the Nb barrier. The theoretical estimation shows that the six filaments surrounding the Nb barrier are equivalent to a cylindrical hollow superconductor.

1. Introduction

Since the critical temperature of MgB₂ exceeds liquid hydrogen temperature and the wires can be fabricated in relatively simplified processes, the future feasibility is expected in various industrial fields such as electric power devices, MRI, magnetic levitation and so on.

Several groups have reported on the conductor fabrication of the MgB₂ wires and tapes using a Powder-In-Tube (PIT) method. It is common to employ an ex-situ PIT method [1-3], in which commercial MgB₂ powder is used as a raw material. On the other hand, there is a possibility of improving the $J_c$ with an in-situ PIT method [4-6], by controlling the grain size and doping of other elements.

For an in-situ method, the sheath material plays a very important role in determining the transport properties. Cu is an ideal stabilizing metal for low-$T_c$ superconducting wires. Moreover, Cu is advantageous for its low resistance and weak paramagnetism. Also, round wires are ideal for solenoid coils that generate precise uniform magnetic fields. In the case of the MgB₂ wires, it is considered that a Cu sheath reduces $J_c$ values since it reacts with Mg. Therefore, many groups have applied Fe or Nb as sheath materials [7-9].
Table 1. Characteristics of MgB$_2$ multifilamentary wire.

| Characteristic                              | Value          |
|--------------------------------------------|----------------|
| Wire radius $r_w$                          | 0.35 mm        |
| Volume ratio MgB$_2$/Nb/Cu                 | 0.13/0.18/0.69 |
| Critical current $I_c$ at self field and 1 T (4.2 K) | 330 A and 60 A |
| Twisting pitch $L_p$                       | 10 mm          |
| Estimated filament diameter $d_f$          | 0.10 mm        |
| Estimated radius of filamentary region $r_{fr}$ | 0.17 mm      |
| Estimated outer radius of hollow cylinder $r_{holo}$ | 0.19 mm      |
| Estimated inner radius of hollow cylinder $r_{holi}$ | 0.15 mm      |
| Adjusted electric conductivity of matrix $\sigma_m$ | $3.3 \times 10^9$ S/m |

We designed and fabricated Cu/MgB$_2$ composite wires with six filaments surrounded by a Nb barrier to prevent chemical reaction between Cu and MgB$_2$ in the heat treatment process. We measured AC losses by a standard pickup coil method in a transverse alternating magnetic field. In order to evaluate the observed AC losses, we calculated the AC losses with a critical state model for an intrinsic multifilamentary composite and a virtual hollow-cylindrical superconductor composed of coupled filaments.

2. Design and fabrication of specimens

The Cu/Nb composite tube had an outer diameter of 10 mm and an inner diameter of 6.5 mm. MgB$_2$ wire was then produced applying the \textit{in-situ} method using Mg ($< 45$ $\mu$m) and B ($< 1$ $\mu$m) powders. The powder mixture was tightly packed into the Cu/Nb composite tube. After packing, the tube was drawn into wires with an outer diameter of 1.9 mm. The Cu/Nb sheathed mono-core wires were inserted into a Cu tube. The Cu tube had an outer diameter of 8 mm and an inner diameter of 6mm. The Cu/(Cu/Nb) composite tube was drawn into wires with an outer diameter of 0.7 mm, and a length of 10 m, without any breaking. This shows that the wire has good workability. Table 1 shows the characteristics of MgB$_2$ multifilamentary wire. Figure 1(a) is the cross-sectional view. The MgB$_2$ core ratio was 13%, and the twist pitch was 10 mm.

Transport critical current $I_c$ measurement was carried out for the short samples in magnetic fields of 0-1 T at 4.2 K using a standard four-probe method. The short samples of 40mm-long wires were cut from the drawn wire and heat treated at 600$^\circ$C for 1hr for the $I_c$ measurements.

![Fig. 1 (a) Cross-section of MgB$_2$ wire, (b) Structure as a multifilamentary superconductor model and (c) Structure as a hollow cylindrical superconductor model](image-url)
3. Experiments
We measured the AC loss of a coiled MgB$_2$ specimen by a standard pickup coil method. Since the MgB$_2$ wire has no insulation layer, the coiled specimen was prepared by winding the MgB$_2$ wire on a FRP former with a non-metallic wire for electrical insulation between the neighboring turns. We paid attention to cutting both ends of the coiled specimen, where the filaments do not connect with each other. In the measurements, the coiled specimen was set between concentric main pickup and compensation coils. The height of the coiled specimen was three times larger than those of the pickup coils. The sizes and the arrangements of the coils were in accordance with recommended conditions in an international standard of the AC loss measurements for superconducting wires [10]. The external AC magnetic field was applied in the direction of the axis of the coiled specimen in liquid helium. Experimental results are plotted by symbols in Fig. 2 in the ranges of the frequency from 0.1 Hz to 5 Hz and the amplitude of external magnetic field between 0.01 T and 1 T.

4. Results and Discussion
We first estimated the AC loss properties by using a usual model for composite superconductors with fine filaments (a multifilamentary superconductor model). In the case where the specimen behaves as a superconductor with multifilamentary structure, the filamentary region may be inside a dashed circle in Fig. 1(b), which joins the centers of six filaments. The expressions of the AC loss composed of hysteresis loss in the filaments and coupling-current loss among the filaments are presented in A.1. The theoretical results obtained in a usual way are indicated by lines in Fig. 2. In the estimation, we use a mean value of the critical currents measured at self field and 1 T as a constant critical current density and adopt an adjusted value for the electric conductivity of the matrix as mentioned below. Parameters used are summarized in Table 1. In a range of larger amplitude of applied magnetic field at 0.1 Hz, the measured AC loss is about four times larger than the estimated levels with the first model. Supposing the AC loss at 0.1 Hz is mainly composed of the hysteresis loss, the filamentary region may behave as a thick monofilament. While the MgB$_2$ wire developed has a multifilamentary structure with
only six filaments, a discrepancy between the experimental results and the theoretical ones including their frequency dependences suggests that the specimen does not behave as such multifilamentary superconductor. The negative results may not be improved only by modifying the adjusted value in a reasonable range.

Alternative model for the AC loss estimation is a hollow-cylindrical superconductor model. This model may be suitable to a superconducting hollow cylinder surrounded by two dashed circles shown in Fig. 1(c). The outer and inner radii of the hollow cylinder are calculated by using the volume ratio of MgB₂. The expressions of the AC loss composed of hysteresis loss of the hollow-cylindrical superconductor and eddy-current loss in an outer layer are presented in A.2. Calculated results are also shown by lines in Fig. 3, where the experimental ones are indicated again for comparison. From two viewpoints, the dependences of the AC loss on the amplitude of transverse magnetic field at a low frequency region and on the frequency in a wide range of the field amplitude, we have a good agreement between the experimental and theoretical results. The first viewpoint means that the AC loss observed at 0.1 Hz is almost reproduced by the hysteresis loss predicted for the hollow cylinder except for a slight divergence to be attributed to the dependence of the critical current density on magnetic field. Since the adjusted value for the electric conductivity of matrix σₘ corresponds to a typical one for copper, it is also suggested that the frequency dependence of the AC loss can be explained by that of the eddy-current loss in the outer copper layer in Fig. 1(c).

As a result, the fabricated composite has an unexpected structure like the hollow-cylindrical superconductor instead of the expected multifilamentary composite, which may come from some bridging effect between neighboring filaments through the Nb barrier surrounding the filament. While such effect must disappear in a relatively high magnetic field, other materials such as Ta may be desirable to design the barrier of the filaments. It is suggested, on the other hand, from the theoretical estimation shown in Fig. 2 that the Cu matrix and outer sheath may generate a major component of the AC loss in a region of higher frequency in the present composite.

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Fig. 3  Comparison of experimental results to theoretical ones by a hollow-cylindrical superconductor model
5. Conclusions

We fabricated Cu-sheathed superconducting composites with six MgB₂ filaments surrounded by a Nb barrier as the first step of developing low-AC-loss MgB₂ wires. We measured the AC loss properties by a standard pickup coil method and theoretically estimated them with two types of structural models, a multifilamentary superconductor model and a hollow-cylindrical one. It is found from the comparison between the experimental and theoretical studies that the electromagnetic behaviors cannot be explained as those of the multifilamentary superconductor but they correspond to the hollow-cylindrical one. These results can be understood by considering the Nb barrier has a bridging effect between the filaments. We have a plan to fabricate advanced wires with Ta barriers around the MgB₂ filaments and CuNi sheath in addition to diminishing the filament diameter in the following step.

Appendix

A.1. A multifilamentary superconductor model

AC loss per unit volume and per cycle, \( W_{\text{multi}} \), generated in a multifilamentary superconductor exposed to a transverse alternating magnetic field with the amplitude \( B_m \) and the frequency \( f \) is composed of hysteresis loss \( W_{h1} \) in the filaments and coupling-current loss \( W_c \) among the filaments. These components are expressed with a critical current density \( J_c \), a filament diameter \( d_f \), a twisting pitch \( L_p \), a matrix conductivity \( \sigma_m \) as follows [11], [12]:

\[
W_{\text{multi}} = W_{h1} + W_c \quad (A.1)
\]

\[
W_{h1} = \begin{cases} 
\frac{4 B_{pf}^2}{3 \mu_0} \left[ 2 - \left( \frac{B_m}{B_{pf}} \right)^4 \right] \left( \frac{r_{fr}}{r_w} \right)^2 & \text{for } B_m \leq B_{pf} \\
\frac{4 B_{pf}^2}{3 \mu_0} \left[ 2 - \left( \frac{B_m}{B_{pf}} \right)^4 - 1 \right] \left( \frac{r_{fr}}{r_w} \right)^2 & \text{for } B_{pf} \leq B_m 
\end{cases} \quad (A.2)
\]

\[
W_c = \frac{2 \pi \omega \tau_{\text{eff}}}{\mu_0} B_m^2 \left( \frac{r_{fr}}{r_w} \right)^2 \quad (A.3)
\]

where the volume fraction of a filamentary region, \( \lambda_{fr} \), is equal to \( \left( \frac{r_{fr}}{r_w} \right)^2 \) in Fig. 1(b) and \( \omega = 2\pi f \). The equations (A.2) and (A.3) are deduced with the critical state model assuming that a circle is substituted for a front of magnetic flux in a superconducting cylinder with the radius \( r_r \) exposed to the transverse magnetic field [11]. The equation (A.4) is a good approximation for \( \omega \tau_{\text{eff}} \ll 1 \), which is almost satisfied under the present experimental conditions. Some characteristic parameters, the penetration field for filaments \( B_{pf} \), the critical current density of superconductor \( J_c \), the effective coupling time constant \( \tau_{\text{eff}} \) and the effective transverse conductivity \( \sigma_{\text{eff}} \) are given, respectively as

\[
B_{pf} = \frac{2}{\pi} \mu_0 J_c \frac{d_f}{2}, \quad J_c = \frac{I_c}{0.13 \pi r_w^2}, \quad \tau_{\text{eff}} = \frac{1}{2} \left( \frac{L_p}{2\pi} \right)^2 \mu_0 \sigma_{\text{eff}}, \quad \sigma_{\text{eff}} = \sigma_m + \sigma_m \frac{r_w^2 - r_{fr}^2}{r_w^2 + r_{fr}^2} \quad (A.5)
\]

A.2. A hollow cylindrical superconductor model

AC loss per unit volume and per cycle, \( W_{\text{hollow}} \), generated in a hollow-cylindrical superconductor exposed to a transverse alternating magnetic field is composed of hysteresis loss \( W_{h2} \) in the hollow superconductor and eddy-current loss \( W_e \) in the outer sheath, where the superconducting hollow cylinder has an inner radius \( r_{holi} \) and an outer one \( r_{holo} \). Each loss component is expressed as
\[ W_{\text{hollow}} = W_{h2} + W_e \quad (A.6) \]

\[
W_{h2} = \begin{cases} 
\frac{4 B_{\text{pcyl}}}{3 \mu_0} \left[ \frac{2}{3} \left( \frac{B_m}{B_{\text{pcyl}}} \right)^3 \left( \frac{r_{\text{holo}}}{r_w} \right)^2 \right] & \text{for } B_m \leq B_{\text{phol}} \quad (A.7) \\
\frac{4 B_{\text{pcyl}}}{3 \mu_0} \left[ 2 \left( 1 - k_{\text{holo}} \right)^3 \frac{B_m}{B_{\text{pcyl}}} - 1 + 4k_{\text{holo}}^3 - 3k_{\text{holo}}^4 \right] \left( \frac{r_{\text{holo}}}{r_w} \right)^2 & \text{for } B_{\text{phol}} \leq B_m \quad (A.8) 
\end{cases}
\]

\[ W_e = 2\pi \sigma_{\text{outer}} \omega B_m^2 r_w^2 \left( 1 - \frac{r_{\text{holo}}^4}{r_w^4} \right)^2 \quad (A.9) \]

where \( \sigma_{\text{outer}} \) is an electric conductivity of the outer layer and equal to \( \sigma_m \). The other parameters are given by

\[ B_{\text{pcyl}} = \frac{2}{\pi} \mu_0 J_{\text{chol}} r_{\text{holo}} \quad , \quad J_{\text{chol}} = \frac{I_e}{\pi r_{\text{holo}}^2 \left( 1 - k_{\text{holo}}^2 \right)} \quad , \quad B_{\text{phol}} = B_{\text{pcyl}} \left( 1 - k_{\text{holo}} \right) \quad (A.10) \]

with a radius ratio \( k_{\text{holo}} \) equal to \( r_{\text{holo}} / r_{\text{holo}} \). \( B_{\text{pcyl}} \) and \( B_{\text{phol}} \) is the penetration field for superconducting solid and hollow cylinder, respectively. Equations (A.7) and (A.8) are also obtained by assuming a circular flux front for the superconducting hollow cylinder in a similar way to eqs. (A.2) and (A.3).

References
[1] Grasso G, Malagoli A, Ferdeghini C, Roncallo S, Braccini V and Siri A S 2001 Appl. Phys. Lett. 79 230
[2] Kumakura H, Matsumoto A, Fujii H and Togano K 2001 Appl. Phys. Lett. 79 435
[3] Tanaka K, Okada M, Hirakawa M, Yamada H, Kumakura H and Kitaguchi H 2004 IEEE Trans. Appl. Supercond. 14-2 1039
[4] Goldacker W, Schlachter S I, Zimmer S and Reiner J 2001 Supercond. Sci. Technol. 14 787
[5] Matsumoto A, Kumakura H, Kitaguchi H and Hatakeyama H 2003 Supercond. Sci. Technol. 16 926
[6] Tanaka K, Kitaguchi H, Kumakura H, Hirakawa M, Yamada H and Okada M 2005 IEEE Trans. Appl. Supercond. 15-2 3180
[7] Glowacki B A, Majoros M, Vickers M, Evetts J E, Shi Y and Mcdougall I 2001 Supercond. Sci. Technol. 14 193
[8] Collings E W, Lee E, Sumption M D, Tomsic M, Wang X L, Soltanian S and Dou S X 2003 Physica C 382 555
[9] Sumption M D, Bhatia M, Wu X, Rindfleisch M 2005 Supercond. Sci. Technol. 18 30
[10] IEC61788-8 Superconductivity-Part 8: AC loss measurements- Total AC loss measurement of Cu/NbTi composite superconducting wires exposed to a transverse alternating magnetic field by a pickup coil method, First edition 2003-4
[11] Kato Y, Hanawaka M and Yamafuji, K 1976 Jpn. J. Appl. Phys. 15 695
[12] Turk B 1982 Cryogenics 22 466