**AC loss characteristics of Bi-2212 multifilamentary round wires and their cables**

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The AC losses of Bi-2212 multifilamentary round wires and the Rutherford-type cables were measured in transverse AC magnetic fields at liquid helium temperature by means of a standard pickup-coil method. The AC losses obtained for the strands were scarcely dependent upon the frequency of the external field in the range from 0.02 Hz to 10 Hz. This suggested that the hysteresis loss in a tightly coupled filament bundle be dominant. A remarkable improvement in the AC loss characteristic by reducing an effective diameter of the filament bundle are observed, while twisting the filaments itself does not contribute to the reduction in the AC loss. It was also found from the comparison between the AC losses in the strands and the cables that the AC losses in the cables mainly came from the individual strands.

## INTRODUCTION

Oxide-superconductors such as Bi- and Y-systems have feasibilities of the applications in a wide range of temperature between liquid helium temperature and liquid nitrogen one, because the critical temperatures are higher than liquid-nitrogen temperature. Especially for the Bi-system superconductors whose long wires have been fabricated are expected as advanced materials of windings for developing electrical devices with high performances in near future and the electromagnetic properties including AC losses have been measured in the wide range of temperature from fundamental viewpoints. In the design of the individual wires and the cables, however, it is not always considered to optimize the electromagnetic properties, in particular AC losses, in the environments to be applied to, while the wires and cables are designed and fabricated for constructing R&D models of superconducting electrical devices such as power cables and transformers under the restriction of developing HTS wires.

The present paper describes AC loss properties of Bi-2212 multifilamentary round wires and their Rutherford-type cables, which may be one of candidates for large-capacity windings in the electrical devices such as future superconducting magnetic energy storages (SMES) and so on, from a viewpoint of feasibility study. The strands were not twisted. Their AC loss properties in a transverse magnetic field were to be like those of monofilamentary wires in spite of the multifilamentary structure. The experimental results partially support the prediction that the AC loss is hysteretic. The experiments also give unexpected results that the effective diameters of the filamentary region evaluated from the measured AC losses are much smaller than the actual ones. It is also shown that the electromagnetic coupling among the strands is not dominant in the cables in the transverse field parallel to the flat surface.

## SAMPLE PREPARATIONS AND AC LOSS MEASUEMENT

We designed and fabricated Ag-sheathed Bi-2212 multifilamentary round wires and their Rutherford-type cables to evaluate the AC loss properties, which are developed as large-capacity conductors for future HTS coils. They were heat-treated by a wind-and-react method. The characteristics of the wires and the cables are listed in Tables 1 and 2, respectively. Table 1 includes the critical currents measured with a criterion of $10^{-6}$ V/cm both in the terminal parts of each coiled specimen. The set of wires were prepared for estimating the effects of material of the first-stack sheath and twist of filaments on the AC loss properties. Each pair of twisted and untwisted wires has the common fabrication process except for

Table 1 Characteristics of Bi-2212 multifilamentary wires

| No. | Diameter | Filament structure | 1st-stack sheath | Silver ratio | Twist pitch | Ic(upper) at 4.2K,0T | Ic(lower) at 4.2K,0T | $d_{eff}/d_{fr}$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.81 mm | 61×7 | pure Ag | 4.1 | -- | 163 A | 179 A | 1/3 |
| 2 | 0.71 | 61×7 | pure Ag | 4.1 | 9.5 | 141 | 150 | 1/3 |
| 3 | 0.81 | 61×7 | pure Ag | 3.0 | -- | 333 | 315 | 1/8 |
| 4 | 0.81 | 61×7 | pure Ag | 3.0 | 9.5 | 327 | 165 | 1/8 |
| 5 | 0.81 | 61×7 | Ag alloy | 3.0 | -- | 378 | 267 | 1/25 |
| 6 | 0.81 | 61×7 | Ag alloy | 3.0 | 9.5 | 381 | 321 | 1/25 |
| 5’ | 0.81 | 61×7 | Ag alloy | 3.0 | -- | 393 | 372 | 1/8 |

Table 2 Specifications of Bi-2212 Rutherford-type cables

| No. | Strand Diameter | Filament structure | 1st-stack sheath | Silver ratio | No. of strands | Cabling pitch |
|---|---|---|---|---|---|---|
| A | 1.02 mm | 127×7 | pure Ag | 2.8 | 20 | 73 mm |
| B | 0.81 | 61×7 | pure Ag | 3.0 | 30 | 87 |

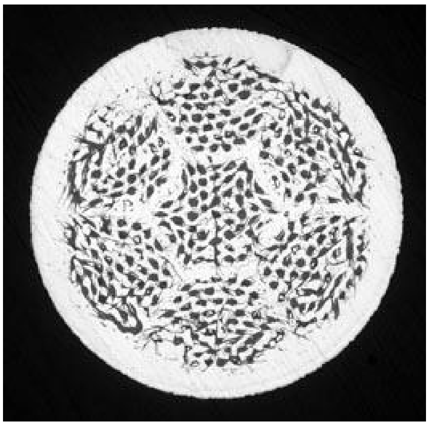

Figure 1 Photograph of cross section of wire #5 after drawing and heat treatment.

twisting process. Two types of cables listed in Table 2 were also prepared to evaluate some additional losses in which the untwisted strands have no insulation layer and only an oxide layer of the Ag outermost layer. A photograph of the cross section of the wire #5 is given in Fig. 1.

We measured the AC losses of the coiled specimens of Bi-2212 the strands and their cables in liquid helium by a standard pickup coil method [1]. AC magnetic field of 0.02 Hz to 10 Hz was applied in the direction parallel to the coil axis. The concentric arrangement of the pickup coils and the coiled specimen are based on the standard method.

## RESULTS AND DISCUSSION

### Effects of twisting strand on AC loss properties

As seen in Table 1, we prepared a set of strands, twisted and untwisted wires, to estimate the effect of twisting on the AC losses in the strands. Figure 2 shows the comparison between the AC loss properties for the amplitude of the external field in the twisted and untwisted wires, No. 5 and 6 at the frequencies of 0.1 Hz and 10 Hz. It is suggested from the comparison that the effects of twisting can be almost neglected in the internal loss of the strands. This means that the strands behave as monofilamentary ones due to electromagnetic couplings and/or direct touch among the strands in spite of the multifilamentary structure. We obtained the same results for other two sets of specimens, No. 1 and 2, and No. 3 and 4. The frequency dependence of AC loss property, on the other hand, may come from relatively low *n* value of the specimens. In these cases, we can only estimate the AC loss properties approximately by means of the critical state model and more quantitative evaluation of AC

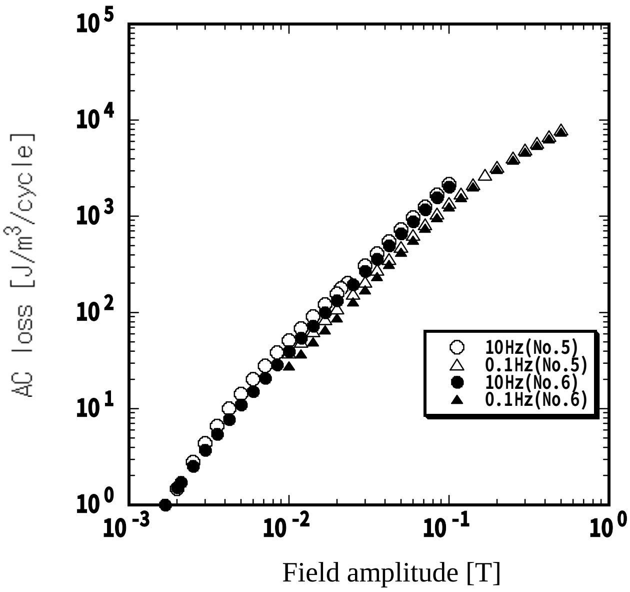


Figure 2 Effects of twisting on AC loss in strands

losses could result from some numerical simulation on the basis of $E$-$J$ characteristics. For simplicity, however, we use the critical state model to discuss AC loss properties of the strands in the present paper.

AC loss estimation using effective diameter of filamentary region

Under the condition that the Bean model can be applicable to the AC loss estimation for columnar superconductors with diameter $d$ and critical current density $J_c$ exposed to a transverse magnetic field, the hysteresis loss density per cycle [J/m$^3$] is expressed as [2]

$$W_\perp = \begin{cases} \dfrac{4}{3}\left(2h_{m\perp}{}^3 - h_{m\perp}{}^4\right)\mu_0 H_{p\perp}{}^2 & : h_{m\perp} \le 1 \quad (1) \\ \dfrac{4}{3}\left(2h_{m\perp} - 1\right)\mu_0 H_{p\perp}{}^2 & : h_{m\perp} \ge 1 \quad (2) \end{cases}$$

$$h_{m\perp} = H_m / H_{p\perp} \quad (3)$$

where $H_m$ is the amplitude of external magnetic field and $H_{p\perp} = J_c d/\pi$ is a penetration field. The above theoretical prediction shows that the hysteresis loss is almost proportional to the penetration field, namely the diameter, in a region of $h_{m\perp} >> 1$. If the filaments are electromagnetically independent of each other in the multifilamentary wires, $d$ in $H_{p\perp}$ corresponds to the filament diameter $d_f$. For the tight coupling among the filaments, on the other hand, $d$ is equal to the diameter $d_{fr}$ of the filamentary region. In this way, if we substitute an effective diameter $d_{eff}$ for $d$ in $H_{p\perp}$, we can estimate the degree of equivalent filament coupling by $d_{eff}$, whose value is obtained in the region of $d_f \le d_{eff} \le d_{fr}$ by fitting the above theoretical prediction to experimental AC loss properties of the wires.

The dependences of AC losses on the field amplitude are shown for the strands #1, #3 and #5 in Figs. 3, 4 and 5, respectively. In each figure, we can find the loss properties are a little dependent upon frequency of applied field in the region between 0.02 Hz and 10 Hz as mentioned in the previous section. Since the loss property is scarcely influenced by the frequency in the region of $h_{m\perp} > 1$, we evaluated the effective diameter $d_{eff}$ by fitting in the higher amplitude region. The effective diameter normalized by $d_{fr}$ is listed for all pairs of wires in Table 1. Each pair of wires fabricated in the common process has the same value. The theoretical prediction with each effective diameter is indicated by a solid line for the strand #1, #3 and #5 in Figs, 3, 4 and5, respectively. In these figures, the theoretical results for the case of $d_{eff} = d_{fr}$ are also indicated by dashed lines for comparison. We can find a remarkable reduction in the effective diameter, which leads to the suppression of the hysyeresis loss in the region of higher amplitude. Since the reduction in the hysteresis loss is not influenced by twisting, this effect is not equivalent to the so-called 'twist effect' observed in twisted in-situ $Nb_3Sn$ multifilamentary wires [3].

From the comparisons of the normalized $d_{eff}$ in Table 1, we first find a tendency that the 1$^{st}$-stack sheath with higher resistivity results in more effective reduction in the normalized $d_{eff}$, namely hysteresis

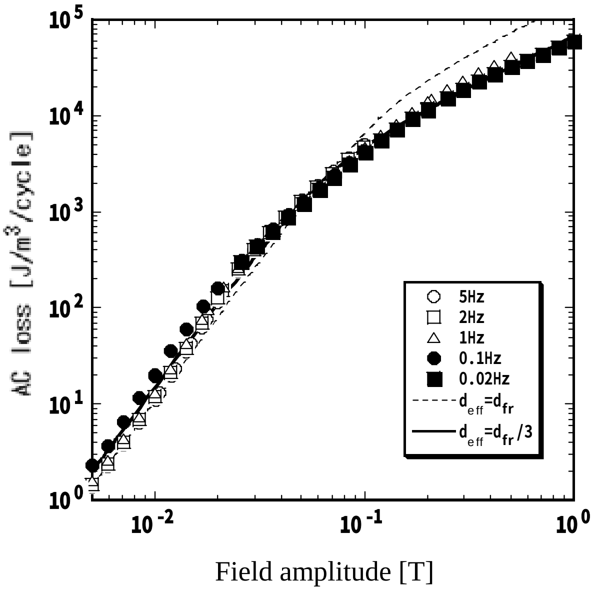

Figure 3 AC loss properties of strand #1

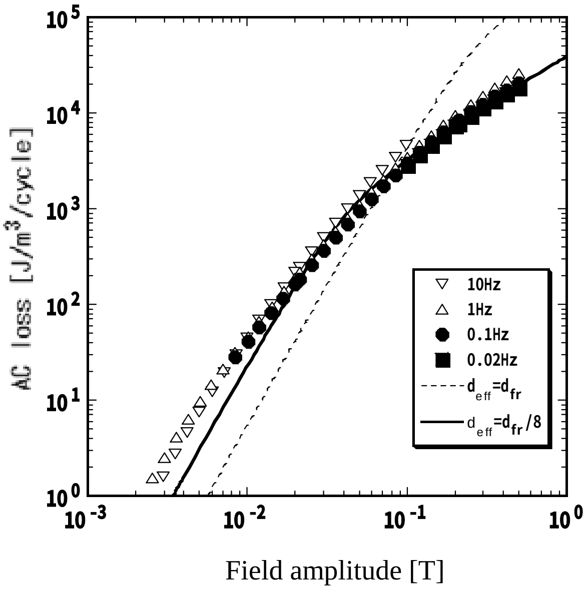

Figure 4 AC loss properties of strand #3

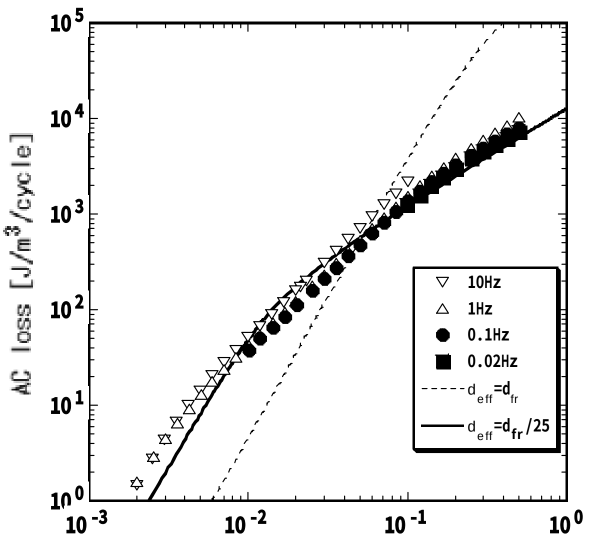


Figure 5 AC loss properties of strand #5

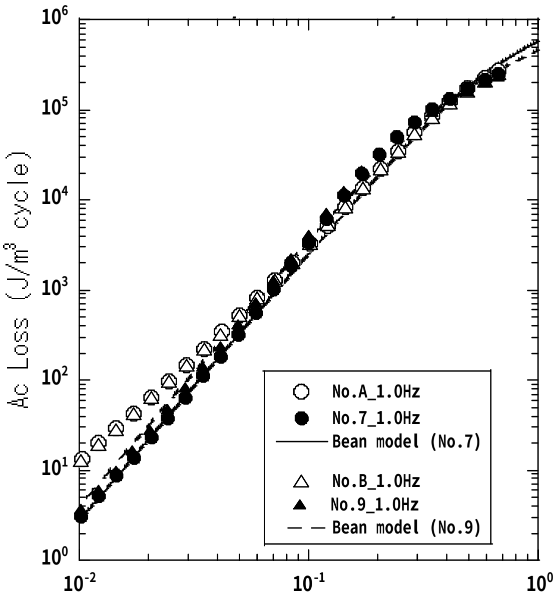


Figure 6 AC losses in strands and cables

loss density. As shown from the further comparisons of the normalized $d_{\mathrm{eff}}$ between the wire #1 and #3, or #5 and #5', we cannot control the reduction in the present fabrication processes. We have to need consideration on electromagnetic origin of the reduction in the normalized $d_{\mathrm{eff}}$ to design it quantitatively.

Additional AC loss by cabling

According to two types of Rutherford cables, in order to evaluate additional AC losses due to cabling, we also measured the AC losses of the cables and the individual strands by the usual pickup coil method. The coiled specimens of Rutherford-type cables were wound in a flat-wise manner. The results are shown both for the cables #A and #B in Fig. 6, where the AC losses measured for the strands are also plotted. It can be seen from the comparison in Fig. 6 that the difference between the AC losses of the strands and their cable is not dominant in the region of higher amplitude of applied field, where AC losses generated give a major contribution to the total loss in the practical windings. In this way, the additional loss due to cabling can be almost neglected for the present Rutherford-type cables from the practical viewpoint. We understand this result comes from an oxide layer on the surface of strands.

## CONCLUDING REMARKS

The AC losses of Bi-2212 multifilamentary round wires and the Rutherford-type cables were measured in transverse AC magnetic fields at liquid helium temperature by means of a standard pickup-coil method. The AC loss of strands was scarcely dependent upon the frequency. This implies that the AC loss of the strands is almost hysteretic and the filaments are electromagnetically coupled with each other in the filamentary region. A remarkable improvement in the AC loss characteristic by reducing an effective diameter of the filament bundle are observed, while twisting the filaments itself does not contribute to the reduction in the AC loss. Its mechanism is not clear at present. The additional loss due to cabling can be almost neglected for the present Rutherford-type cables from the practical viewpoint, because of an oxide layer formed on the surface of each strand

## REFERENCES


1. AC loss measurement--Total AC loss measurement of Cu/Nb-Ti composite superconducting wires exposed to a transverse alternating magnetic field by a pickup coil method, IEC International Standard 61788-8 (2003) First Edition 4-43
2. Noda, M., Funaki, K., Yamafuji, K, Hysteresis loss in a superconducting rod with a round cross section exposed to a transverse AC magnetic field, Mem. Faculty Eng. Kyushu Univ. (1986) 46 63-76
3. Carr, Jr., W.J., Effect of twist on wires made from *in situ* superconductors, J. Appl. Phys. (1983) 54, 6549-6552