AC current loss of a meander-shaped QMG current limiting device

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Abstract

The AC current loss of a meander-shaped QMG current limiting device was measured. Although the frequency was changed in the range of 35∼200 Hz, an obvious frequency dependence of the AC current loss was not observed. Hence, the pinning loss is dominant in the observed AC current loss. The specimen seemed to be homogeneous and not to be damaged during a manufacturing process, since the voltages in the measured sections were nearly the same and the energy loss density coincided with the result on the bridge specimen. The experimental result of the AC loss agreed well with Norris's formula for an elliptic cross section. However, the theoretical prediction by Irie-Yamafuji's model does not agree well with experimental result.

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1 Introduction

Fault current limiters (FCLs) are one of the most promising applications of oxide superconductors. Two types of FCL, shielding and resistive types, have been mainly investigated in oxide superconductors. Resistive type of FCL with thin film oxide superconductors were also developed. However, their critical current capacity is not enough for power applications [?]. Therefore, bulk oxide superconductors are considered as candidates for FCL.

QMG is an oxide superconductor which consists of a pseudo single crystal of $YBa_2Cu_3O_{7-\delta}$ dispersed with 1 μm size of Y_2BaCuO_5. The critical current density of QMG is about 2×10^8 A/m^2 at 77.3 K and 1 T [?,?]. The electrical resistivity of QMG is about 5×10^{-6} Ωm at room temperature. Hence, QMG seems to be a promising bulk material for FCL application.

One of common problems of FCL of bulk oxide superconductor is plastic damages due to the joule heat when superconducting-normal (S-N) transition occurs. Mechanical properties of metal coated QMG short specimens were investigated and a drastic improvement was found in endurance [?]. However, the metal coating led to a lower resistance per unit length. On the other hand, the reduction of AC current loss is also a key issue for practical application. Therefore, it is necessary to estimate the accurate AC current loss and compare with the theoretical prediction.

In this paper, a meander-shaped FCL of QMG was prepared and the AC current loss was measured. The experimental results are analyzed by Norri's model and Irie-Yamafuji's model.

2 Experimental

The meander-shaped specimen was cut from a disk-shaped QMG superconductor, diameter and thickness of which were 45 mm and 15 mm, respectively. The cross section of the linear part of the specimen was 1.5 mm×0.5 mm and the effective length was about 170 mm. In addition, Ag was coated on the specimen by sputtering for the purpose of reducing the unnecessarily high voltage in the resistive transition and contact to current leads. Schematic illustration of the meander-shaped QMG current limiting device is shown in Fig. 1.

The transport AC current was applied to the specimen by a superconducting transformer in which a Bi-2223 tape is used for the secondary winding [?]. The maximum peak current for the present measurement was about 200 A. The frequency of the AC current was varied from 35 to 200 Hz. One of the advantages in using a transformer is that plastic damages will not occur when the current reaches to the critical current of the QMG specimen, since the impedance in the primary circuit becomes remarkably large, and the secondary current is damped immediately. The AC current loss measurement was done in liquid N_2 (77.3 K). The resistive voltage was measured by a lock-in amplifier from the voltage taps as shown in Fig. 1. The total voltage of V_1 to V_5 was also measured from the both edges of voltage taps. A short specimen of a bridge shape (10 mm × 1.0 mm × 0.5 mm) was prepared for the comparison. The magnetization hysteresis of the short specimen was measured by a SQUID magnetometer for estimation of the parameters used in the theoretical prediction of the AC current loss.

3 Results and Discussion

Fig. 2 shows the AC peak current dependence of the energy loss density, W, at various frequencies at 77.3 K for the meander-shaped QMG current limiting device. According to the variation of the frequency in the range of 35–200 Hz, an obvious change of W is not observed. Therefore, the pinning loss is dominant in the observed W. It is also found that W of the bridge shaped short specimen agrees well with the that of the meander-shaped specimen. Hence, the specimen seemed not to be damaged during a manufacturing process.

The electrical voltage of each part of the meander-shaped current limiting device at 50 Hz and 77.3 K is shown in Fig. 3. All voltages agree well except for the lower peak currents where the error of measurement is large. The measurement of voltage from each voltage tap seems to be correct, since the sum of every voltage agrees with the total voltage. Therefore, the specimen is considered to be homogeneous.

Also, the experimental results are compared with the theoretical predictions. The dotted line in Fig 2. shows the theoretical result of Norris's formula for an elliptic wire with the cross-section area of $S = 7.5 \times 10^{-7}$ m^2 [?]. This agrees well with the experiment for the whole region of AC peak current. Since the aspect ratio of the cross-section is 3:1, it seems to be reasonable that the observed result agrees with the expression for the elliptic wire.

In the next, we assume Irie-Yamafuji's model [?] for the magnetic field dependence of the critical current density, J_c, at low fields:

$$J_c = \alpha B^{\gamma - 1} \tag{1}$$

where α and γ are parameters. The hysteresis energy loss density obtained by an area of the magnetization loop is shown in Fig. ??. The solid line in Fig. ?? is the theoretical prediction of Irie-Yamafuji's model with $\alpha = 4.9 \times 10^7$ and $\gamma = 0.82$ in Eq. (1). These parameters are determined so as to get a good agreement between experimental and theoretical results of magnetization hysteresis at low fields, since the self field of the transport AC current is estimated less than 0.04 T. It is seen that the model explains the experimental result of W well, especially at low fields.

The solid line in Fig. 2 represents the theoretically calculated results of the AC current loss density using Irie-Yamafuji's model for a long cylindrical rod [?]. It is found that the deviation between theoretical and experimental result is larger than in the case of Norris's model at high AC currents. This deviation may come from the reduction of the critical current density due to the flux creep during the DC magnetization measurement by a SQUID magnetometer. According to Irie-Yamafuji's model, W is proportional to $1/I_{\mathrm{c}}^{2-\gamma}$ at a fixed value of I_{p} [?]. Hence, I_{c} is underestimated by a factor 2.1 at $I_{\mathrm{p}} = 10$ A, since the ratio of the experimental result to the theoretical prediction for W is 1/2.4 as shown in Fig. 2. On the other hand, the electric field on the specimen surface is estimated as 1.2×10^{-5} V/m at 50 Hz and 10 A. The corresponding electric field measured by SQUID is about 10^{-9} V/m. If the relationship between the electric field and the current density is expressed as $E \propto J^n$, we have $n = 12$ in the present estimation. This value is not so much different from other observed result. However, this deviation occurs only at higher AC current region. This can not be explained by the effect of flux creep. Thus, the reason for the deviation from the theory is an open question.

4 Conclusion

In this work, the AC current loss of a meander-shaped QMG current limiting device was measured by using superconducting transformer. The following results are obtained:

- It is considered that the pinning loss is dominant, since the frequency dependence of the energy loss density is not significant. The theoretical prediction of the energy loss density by Norris's formula for an elliptic cross-section explains well the observed result.
- The voltage from each section shows the same value and the energy loss density of bridge-shaped short specimen is coincident with that of the meander-shaped specimen. Therefore, the specimen is considered to be homogeneous without damages.
- The theoretical prediction of the energy loss density by Irie-Yamafuji's model using the measured result of DC magnetization measurement does not agree with the observed result.

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Figure caption

Fig. 1. Schematic illustration of meander-shaped QMG current limited device.

Fig. 2. AC loss of meander-shaped QMG current limited device in various frequency at 77.3 K.

Fig. 3. Electrical voltage of each section of meander-shaped current limited device at 50 Hz and 77.3 K.

Fig. 4. Hysteresis energy loss density vs. AC field amplitude estimated from the area of DC magnetization loop. The solid line represents the prediction of Irie-Yamafuji's model.