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The frequency dependence of AC transport losses in stacked Bi-2223/Ag superconducting tapes*

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AC transport losses in a single superconducting tape, double- and triple-stacked Bi-2223/Ag superconducting tapes were measured by use of electrical method. The measurements were carried out at 77K with the frequency of AC transport currents ranging from 50 to 1000Hz. The dependence of AC losses on frequency and the number of tapes in the stack were presented and analysed.

Keywords: AC losses, stacked Bi-2223 tapes, frequency dependence
PACC: 7430F, 7470L, 7460G

1. Introduction

The knowledge of AC losses is essential for designing superconducting devices and developing low-loss superconducting wires. Until now, a large amount of investigations on AC losses of high-temperature superconductors (HTS) have been carried out at power frequency.[1,2] Recently, several works concerning the frequency dependence of AC transport losses in Bi-2223/Ag tapes were also reported.[3−10] Some experiments showed that the hysteresis loss of a Bi-2223/Ag tape is dependent on frequency, and it has been suggested that such a behaviour is caused by thermally activated flux creep.[11] This is out of accord with the critical-state model which regards the hysteresis losses per cycle as independent of frequency. To clarify the mechanism of AC losses of high-temperature superconductors, the frequency dependence of AC losses needs to be further investigated. Up to now, most of such investigations of AC losses have been focused on a single tape. In practical applications, the stacked superconducting tapes are often adopted to obtain higher current carrying capacity. Thus, it is useful to study the frequency dependence of AC losses in stacked superconducting tapes. In this paper, AC transport losses of a single tape, double- and triple-stacked superconducting tapes are measured by use of electrical method at different frequencies. The dependence of AC losses on frequency and the number of tapes in a stack is analysed.

2. Experimental

All the specimens (tapes) were cut from a non-twist 55 filaments multi-filamentary Bi-2223/Ag bare tape with a critical current of 57A. The length of each sample is 10cm and the cross-sectional area is 4mm×0.2mm.

Table 1. The critical currents of the specimens.

Specimen	Critical current I_c (total)/A
No.1	60
No.2	59.5
No.3	58.4
No.1 and No.2 stack	108
No.1, No.2 and No.3 stack	138.5

The critical currents of the samples were measured according to the criterion of 1μV/cm. The measured results of the critical currents for single, double- and triple-stacked superconducting tapes are listed in Table 1. It can be seen that the total critical current of a stack is lower than the sum of the critical current of the individual tape. Such a decay of critical current is caused by the magnetic interaction among the tapes in the stack.

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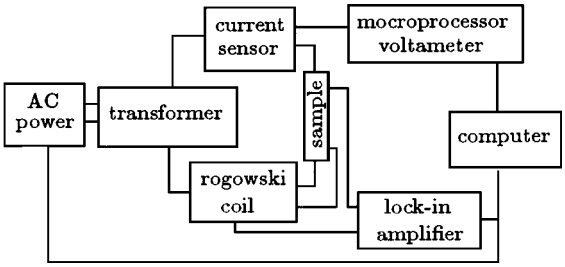


Fig.1. Schematic drawing of the set-up for AC loss measurement.

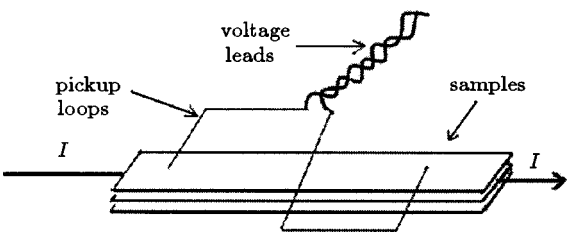


Fig.2. Schematic drawing of stacked tapes with voltage taps and pickup coils.

The measurements of AC losses were carried out at 77K for different frequencies ranging from 50 to 1000Hz by use of the four-probe electrical technique. The measurement set-up is shown in Fig.1. The superconducting tapes were vertically stacked without insulators and spacings between the tapes. Figure 2 presents the schematic drawing of a stack with voltage taps and pickup coils. To avoid the influence of the inductive voltage caused by noise fields, we adopt '8' shaped pickup coils with a width three times larger than the half-width of the tape. The potential taps are soldered on the outer sample and placed 6cm apart.

3. Results and discussion

The experimental results of AC transport losses as a function of normalized transport current ($i = I_m/I_c$) for a single tape are given in Fig.3. Here I_m is the amplitude of transport current and I_c is the (total) critical current.

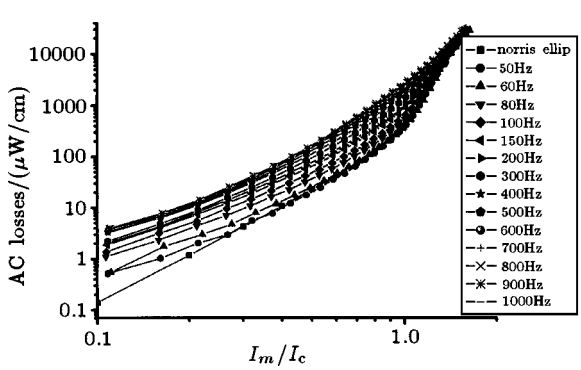


Fig.3. Variation of AC losses of a single tape with the normalized transport current for different frequencies.

For 50Hz power frequency, the AC transport loss of a single tape can be well described by the Norris ellipse formula (1) in the range of i=0.3–1, with the power exponent value n of 3.5.

$$P = \frac{I_c^2 \mu_0}{\pi}\{(1-i)\ln(1-i) + (2-i)i/2\}. \quad (1)$$

The deviation from Norris curve for $i < 0.3$ is caused by the contribution of eddy-current loss. The relative contribution of eddy-current loss to transport loss is inversely proportional to i. With increasing frequency, the slopes (n values) decrease. Hence, Norris formula can no longer be used for AC transport losses at higher frequencies.

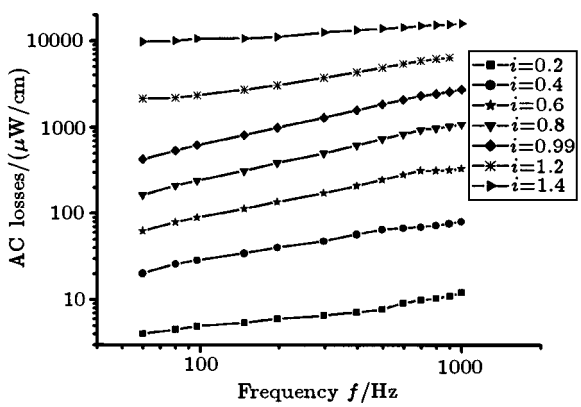


Fig.4. Variation of AC losses of a single tape with the frequency at different normalized transport currents.

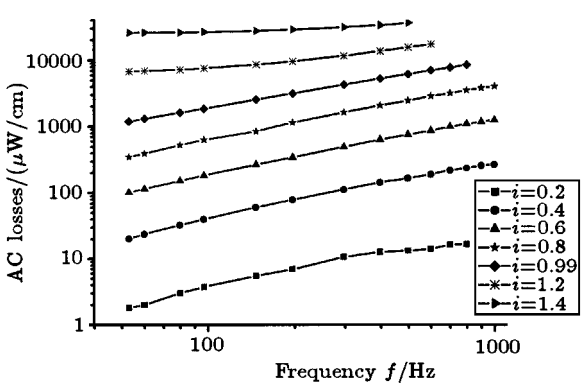


Fig.5. Variation of AC losses of a two-tape stack with the frequency at different normalized transport currents.

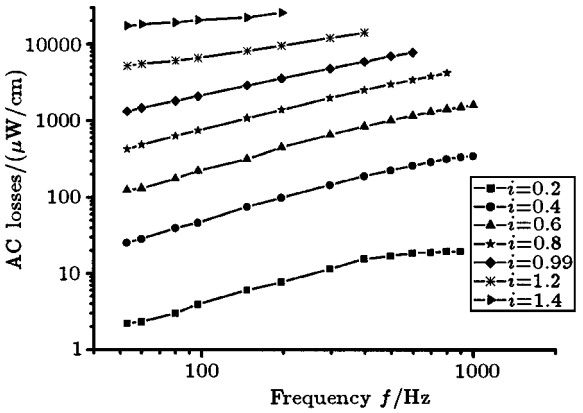


Fig.6. Variation of AC losses of a three-tape stack with the frequency at different normalized transport currents.

Generally, AC losses can be classified as the hysteresis loss (P_h) in superconductor core, the coupling loss (P_c) among the superconductor filaments, the eddy current loss (P_e) in the matrix, and the flux flow loss (resistive loss) caused by the flux flow. According to the traditional theory, P_c and P_e are quadratic dependence on frequency (f), P_h is linearly increased with f, and P_r is independent of the frequency. The frequency dependence of AC losses mentioned above can be expressed as follows

$$P = P_h f^1 + (P_e + P_c) f^2 + P_r f^0. \qquad (2)$$

Figures 4, 5 and 6 show the frequency dependence curves of AC transport losses for single, double- and triple-stacked tapes at different normalized transport currents, respectively. We see that the dependence of AC losses on frequency behaves quite different for $i < 1$ and $i > 1$. For $i < 1$, the frequency dependence of AC losses exhibits a similar behaviour. The slopes (n values) of the loss curves are about 0.6, 0.83 and 0.84 for single, double- and triple-stacked tapes, respectively. The nearly linear dependence of AC transport losses on frequencies indicates that the transport losses are mainly composed of hysteresis loss and that the tapes in the stack have coupled even at power frequency. At higher frequencies (higher than about 300Hz), the slopes decrease slightly. This implies that the hysteresis loss per cycle is actually less than that of linear dependence as in Eq.(2). The mechanism can be understood as follows: for $i < 1$, the depth of self-field penetrating into the superconductor decreases with increasing the frequency, and decreasing the penetration causes the thermally activated flux creep to decrease in HTS, which leads to decreasing hysteresis loss per cycle and increasing the slope (n). Such a decrease of hysteresis loss has been confirmed in HTS by some experiments and computer simulation.[12−15] In the case of $i > 1$, the slopes decrease with increasing normalized transport current. It can be seen that AC losses are dominated by flux flow losses. At $i = 1.4$, for all the three cases the slope is near zero (lower than about 0.18), which behaves like normal conductors.

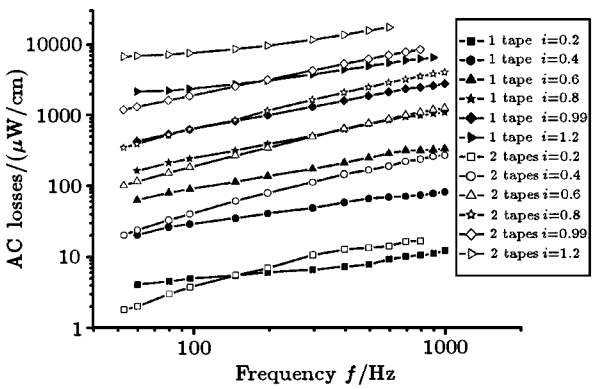


Fig.7. Comparison of AC losses between the single tape and two-tape stack at different normalized currents.

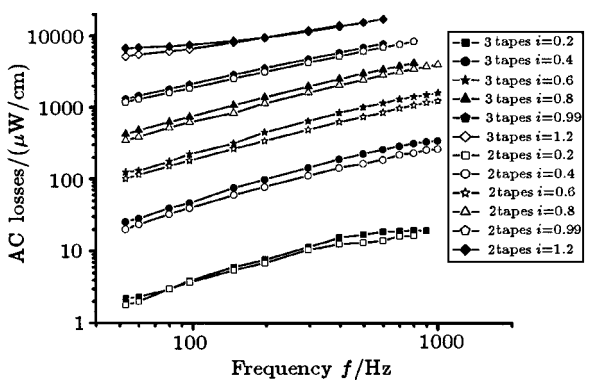


Fig.8. Comparison of AC losses between the two-tape and three-tape stacks for different normalized currents.

To see clearly the difference of the frequency dependence of AC transport losses between single tape and a stack, we give the comparison of AC transport losses between single tape and stacked tapes as shown in Figs.7 and 8. It can be seen from Fig.7 that the slopes of the two-tape stack are larger than those of a single tape for $i < 1$. This means that the hysteresis loss per cycle of the two-tape stack are larger than those of a single tape. For $i > 1$, e.g., $i = 1.2$, the loss slopes for the two cases are about the same. This indicates that AC losses are dominated by flux flow losses. Figure 8 shows that the loss curves of the three-tape stack are slightly higher than those of the two-tape stack for any normalized currents $i < 1$. Experiments

also indicate that, at fixed frequency and i, AC transport losses increase with the number of tapes in the stack; while at fixed transport current amplitude, AC losses decrease with the number of tapes in the stack.

4. Summary

AC transport losses of a single tape, double- and triple-stacked superconducting tapes have been measured at 77K at frequencies ranging from 50 to 1000Hz. According to the measurement results, Norris formula can be used to describe AC transport losses of the single tape at power frequency, but cannot be used for higher frequency. The dependence of AC losses on the frequency behaves similarly for single tape and stacked tapes. In the case of $i < 1$, the transport losses, both for single and stacked tapes, are mainly composed of hysteresis losses. For higher frequencies (higher than about 300Hz), hysteresis losses exhibit a frequency-dependent behaviour. In the case of $i > 1$, AC losses are dominated by the flux flow losses. With increasing i, they eventually become ohmic losses. Experiments also show that, for a fixed frequency and i, AC transport losses increase with the number of the tapes in the stack; while at fixed transport current amplitude, AC losses decrease with the number of tapes in the stack.

References

[1] Wang J X *et al* 1999 *Acta Phys. Sin.* **48** 148 (in Chinese)

[2] Chattopadhyay M K 2000 *J. Supercond.: Incorporating Novel Magn.* **13** 429

[3] Staverv S and Dutoit B 1998 *Physica* C **310** 86

[4] Beduz C *et al* 1998 *Physica* C **310** 67

[5] Tsukamoto O *et al* 1999 *IEEE Trans. Appl. Supercond.* **9** 1181

[6] Miyagi D, Tsukamoto O and Ciszek M 2001 *IEEE Trans. Appl. Supercond.* **11** 2449

[7] Wakasugi K, Murase S, Naito F and Himamoto S 2001 *Physica* C **357-360** 1209

[8] Dhalle M *et al* 1999 *IEEE Trans. Appl. Supercond.* **9** 782

[9] Friend C M *et al* 1999 *IEEE Trans. Appl. Supercond.* **9** 1165

[10] Gömöry F, Frolek L, Šouc J, Laudis A, Kovác P and Hušek I 2001 *IEEE Trans. Appl. Supercond.* **11** 2967

[11] Paasi J, Masti M, Lehtonen J and Kalliohaka T 2000 *IEEE Trans. Appl. Supercond.* **10** 1212

[12] Nie H F, Liu Y F, Huang Y M and Yan S S 2000 *Chin. Phys.* **9** 141

[13] Iwakuma M *et al* 1994 *Cryogenics* **34** 193

[14] Passi J *et al* 1996 *IEEE Trans. Magn.* **32** 2792

[15] Meerovich V *et al* 2001 *Physica* C **354** 260