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Temperature dependence of critical currents and ac transport losses in $(Bi, Pb)_2Sr_2Ca_2Cu_3O_x$ and $YBa_2Cu_3O_y$ tapes

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Abstract
The critical currents and self-field ac losses of $YBa_2Cu_3O_y$ coated conductors and $(Bi, Pb)_2Sr_2Ca_2Cu_3O_x$ tapes were measured at several temperatures between 45 K and the respective critical temperature. The temperature dependence of ac losses was measured at 50 Hz using the lock-in method for a transport current. The frequency dependence of ac loss was measured at 55 K for transport current frequencies from 25 to 400 Hz. The results show that variation of ac transport loss as a function of normalized critical current is nearly the same at all temperatures in the measured temperature range for both $YBa_2Cu_3O_y$ and $(Bi, Pb)_2Sr_2Ca_2Cu_3O_x$ tapes. The temperature dependence of the loss factor, however, is different for $(Bi, Pb)_2Sr_2Ca_2Cu_3O_x$ and $YBa_2Cu_3O_y$ tapes because of the ferromagnetic loss in the NiW-based coated conductor substrate. Similarities and differences in the temperature and frequency dependence of ac transport losses between $(Bi, Pb)_2Sr_2Ca_2Cu_3O_x$ and $YBa_2Cu_3O_y$ tapes are discussed.

1. Introduction

One of the major contributors to thermal load in superconducting ac utility power equipment is ac losses generated in the superconducting windings. Since ac loss occurs at low temperatures, its effective value is increased by a factor of 20 to 50 due to the room-temperature refrigeration power required to remove it [1]. The effective thermal load on the refrigerator is dependent on the operating temperature; the lower the operating temperature, the higher the effective thermal load. It is well known that ac loss in superconducting materials depends on operating temperature. So, knowledge of the exact nature of the temperature dependence is needed for optimal design of superconducting machines and their cryogenic refrigeration systems.

Most measurements of ac losses on high temperature superconducting tapes have been at 77 K and measurements at other temperatures are rare [2–4], especially for $YBa_2Cu_3O_y$ (YBCO) tapes. In this work, the critical currents and ac transport losses of YBCO and $(Bi, Pb)_2Sr_2Ca_2Cu_3O_x$ (BSCCO) tapes were measured at different temperatures. The frequency dependence of the ac transport losses was measured from 25 to 400 Hz at 55 K. The temperature and frequency dependences of ac transport losses are presented and the results on YBCO and BSCCO tapes are compared.

2. Experimental details

The measurements were carried out on a copper-stabilized YBCO coated conductor and a silver-sheathed, multifilamentary BSCCO tape. Both samples were supplied by the American Superconductor Corporation. The conductor parameters are listed in table 1. More details of the conductors are described in [5].

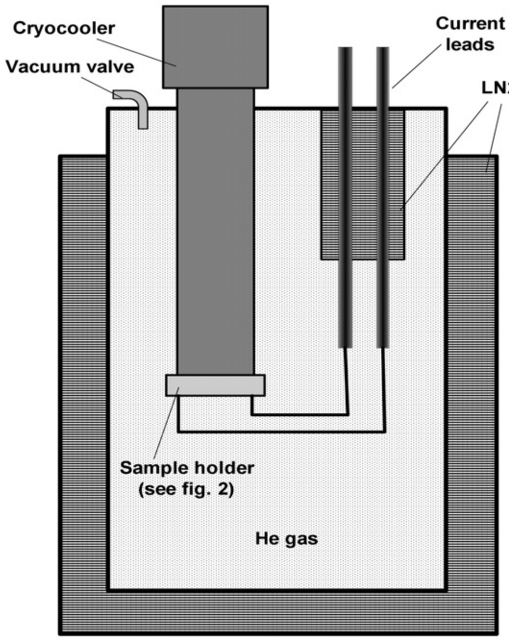

Figure 1. The experimental set-up.

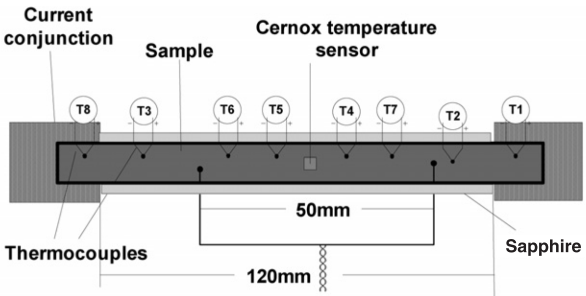

Figure 2. Schematic of the sample with voltage leads and temperature sensors.

Table 1. Sample properties.

Sample	(Bi, Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_x$	YBa$_2$Cu$_3$O$_x$
Number of filaments	55	1
Substrate	Ag sheathed	NiW with copper stabilizer
Filament twist	No	No
Length	15 cm	15 cm
Dimensions	4.1 mm × 0.22 mm	10 mm × 0.15 mm
T_c	109 K	90 K

Figure 1 shows the experimental set-up used for the measurements. The samples were mounted on a sapphire plate and face cooled by a cryocooler. Eight thermocouples were used to monitor the temperature along the sample (see figure 2). To ensure uniform temperature along the sample, the cryostat was backfilled with He gas. Before each measurement, the cryostat was first pumped to a pressure of $\sim 10^{-6}$ mbar, filled with He gas, and cooled down to the required temperature.

Temperature was monitored using a Cernox temperature sensor attached to the sample. Temperature was controlled using a Lakeshore temperature controller and a resistive heater mounted on the sample holder. Between successive measurements, enough time was allowed for temperature stabilization.

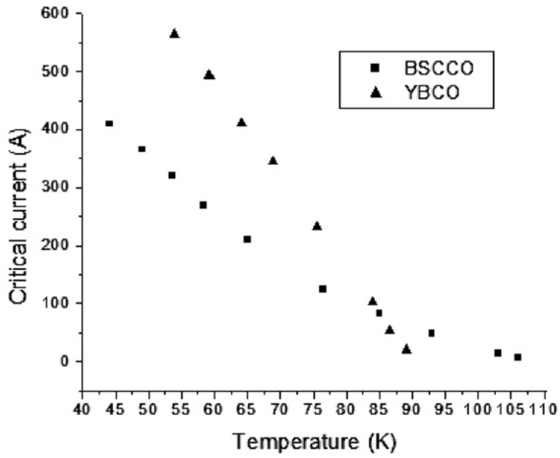

Figure 3. Self-field critical currents of the YBCO and BSCCO tapes as a function of temperature.

Critical currents were measured with a 1 μV cm^{-1} electric field criterion. The ac losses were measured using the electrical method with a lock-in amplifier [6]. The distance between the voltage taps was 5 cm for both critical current and ac loss measurements.

3. Results and discussion

3.1. Critical current versus temperature

The self-field critical currents of the YBCO and BSCCO tapes were measured as a function of temperature from 50 to 90 K for YBCO and 45 to 105 K for BSCCO. The measurement results are shown in figure 3. The results show that the critical currents decrease almost linearly with increasing temperature from 54 to 86 K for the YBCO sample, 45 to 77 K for the BSCCO tape. The decrease of critical current with increasing temperature is steeper for YBCO than for BSCCO. Above 84 K, the critical current of YBCO is lower than that of BSCCO. Figure 4 depicts the temperature dependence of the normalized critical current, $(I_c(T)/I_c(77\text{ K}))$, of both samples. The normalized critical current curves of YBCO and BSCCO coincide with one another below 77 K.

3.2. ac transport losses versus temperature

The ac transport losses were measured with the ac transport current at 50 Hz, from 55 to 84 K for YBCO and from 45 to 93 K for BSCCO. Figures 5 and 6 show the measured results as a function of normalized transport current $(I_m/I_c(T))$ at different temperatures. The ac transport losses are clearly temperature dependent. The ac transport loss per cycle for both YBCO and BSCCO samples decreases with increasing temperature for the same normalized current. For BSCCO (figure 5), the ac transport loss curves at different temperatures are almost linear with slopes n of about 3.3. This shows that ac transport losses of the BSCCO sample are dominated by

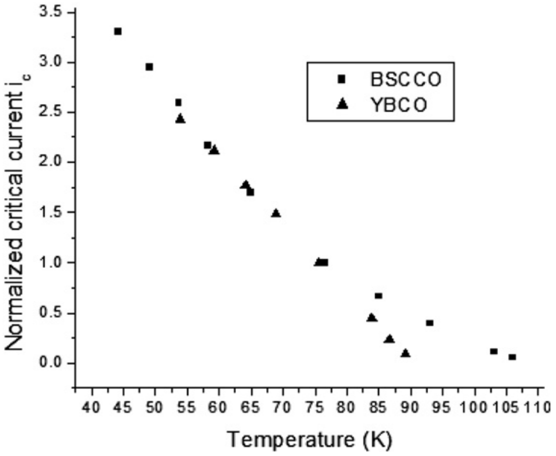

Figure 4. Normalized critical current of YBCO and BSCCO tapes as a function of temperature. Critical current values were normalized by the corresponding critical current value at 77 K.

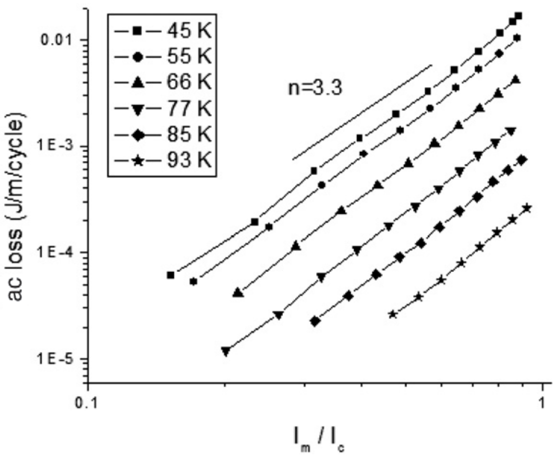

Figure 5. The ac loss of BSCCO tape, at 50 Hz, as a function of normalized transport current ($I_m/I_c(T)$) for different temperatures. I_m is the peak value of the transport current and $I_c(T)$ is the critical current at temperature T.

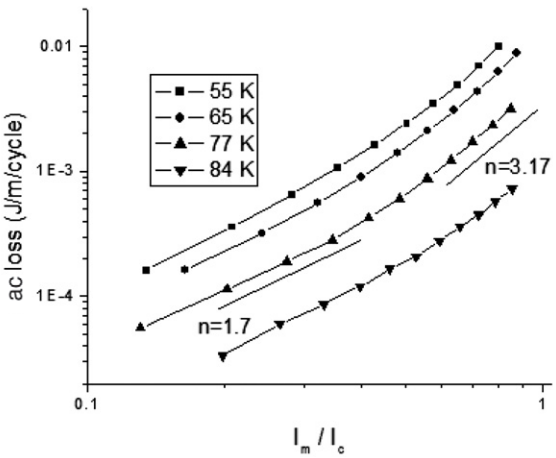

Figure 6. The ac loss of YBCO at 50 Hz as a function of normalized transport current ($I_m/I_c(T)$) for different temperatures. I_m is the peak value of transport current and $I_c(T)$ is the critical current at temperature T.

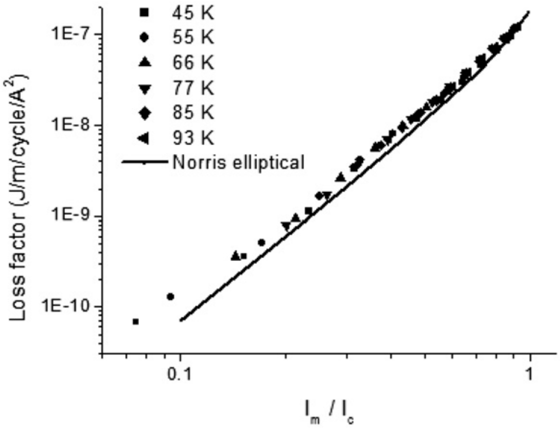

Figure 7. Loss factor of BSCCO, at 50 Hz, as a function of the normalized transport current ($I_m/I_c(T)$) for different temperatures.

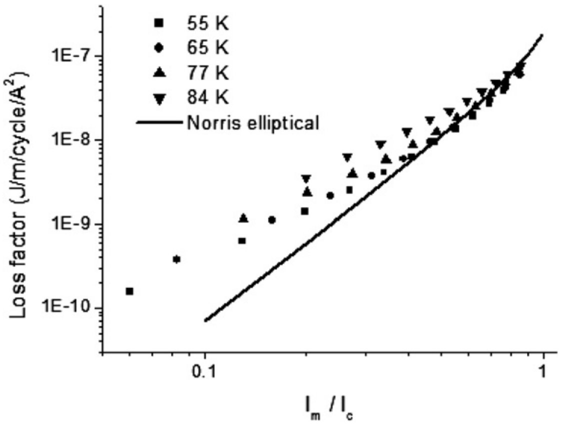

Figure 8. Loss factor of YBCO, 50 Hz, as a function of the normalized transport current ($I_m/I_c(T)$) for different temperatures.

hysteresis loss. For YBCO (figure 6), however, the slope of the ac transport loss curves at different temperatures increases with increasing transport current. At 77 K, the slope is about 1.7 for a normalized transport current less than about 0.4 and increases to about 3.17 when the normalized transport current becomes greater than about 0.6. The lower values of slope of ac loss curves are caused by the contribution of ferromagnetic loss in the nickel substrate of the YBCO coated conductor [7, 8]. Figure 6 shows that, for a normalized transport current less than about 0.4, the contribution from ferromagnetic loss is significant.

Figures 7 and 8 show the temperature dependence of loss factor and the Norris elliptical prediction [9] for BSCCO and YBCO tapes, respectively, as a function of normalized transport current. The loss factor is obtained by dividing ac transport loss by the square of the critical current. It can be seen from figure 7 that although ac transport loss curves are different at different temperatures, the loss factor curves of BSCCO coincide with one another, i.e. the loss factors are independent of temperature for BSCCO. This indicates that ac transport losses at any temperature can be predicted from the relation between the critical current and temperature, such as figure 3. Because of the contribution of ferromagnetic loss

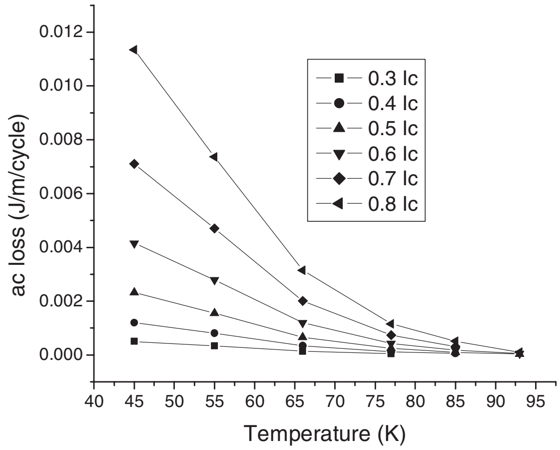

Figure 9. Temperature dependences of ac losses, at 50 Hz, of BSCCO tape for different transport currents.

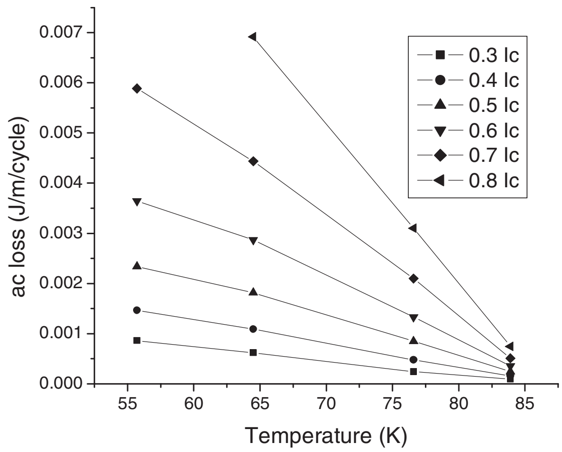

Figure 10. Temperature dependences of ac losses, at 50 Hz, of YBCO for different transport currents.

in the nickel substrate, the loss factors of YBCO at different temperatures are scattered and do not fit onto one curve. The variation is more pronounced for higher temperatures such as at 84 K. For BSCCO, the loss factors at all temperatures are close to (a little higher than) the Norris elliptical formula prediction. But for YBCO, the loss factors are much higher than the Norris elliptical prediction for normalized current (I_m/I_c) less than $\sim$0.5 (at 77 K) because of ferromagnetic loss. The higher the temperature, the higher the loss factor than the Norris formula value for small normalized currents.

From figures 5 and 6, the temperature dependences of ac transport loss of BSCCO and YBCO tapes are obtained for different transport currents at 50 Hz, as shown in figures 9 and 10. It is shown that ac transport loss decreases with increasing temperature in a similar way to critical current for both BSCCO and YBCO tapes. This indicates that the temperature dependence of ac losses is mainly determined by the corresponding temperature dependence of critical currents.

To further understand the temperature dependence of ac transport losses, ac transport losses at different temperatures were normalized by the measured loss value at 77 K. Figures 11 and 12 show the temperature dependences of normalized ac transport loss of BSCCO and YBCO, respectively, for different normalized currents. It is seen that for both BSCCO and YBCO the temperature dependence curves of normalized ac transport losses almost coincide with each other for transport current greater than $0.5I_c$. For lower transport currents (lower than $0.4I_c$) and lower temperature (below 65 K), the normalized ac losses are only slightly higher for BSCCO, but significantly higher for YBCO. This is because the influence of eddy current loss, coupling loss (only in BSCCO) and ferromagnetic loss (only in YBCO) becomes pronounced at low temperature and low transport currents. The coincidence of the normalized ac transport losses for higher transport currents means that the normalized ac transport losses behave in the same way with changing temperature for transport currents greater than $0.5I_c$. This may be helpful for the choice of operating current and the estimation of ac loss in practical applications.

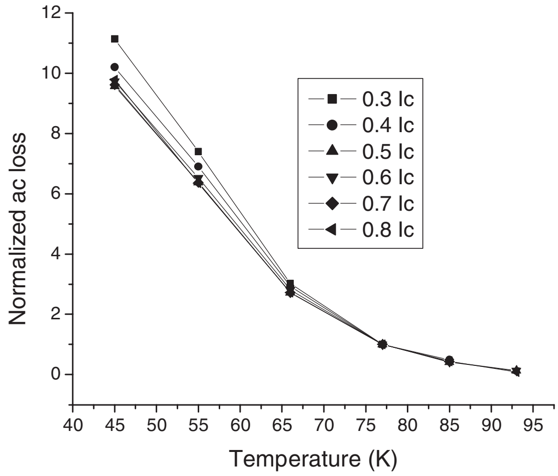

Figure 11. The temperature dependences of normalized ac losses of BSCCO for different transport currents at 50 Hz. Here ac losses are normalized by the measured value at 77 K.

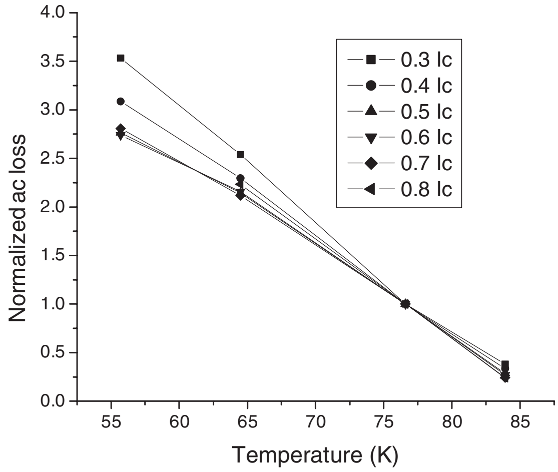

Figure 12. The temperature dependences of normalized ac losses of YBCO for different transport currents at 50 Hz. Here ac losses are normalized by the measured value at 77 K.

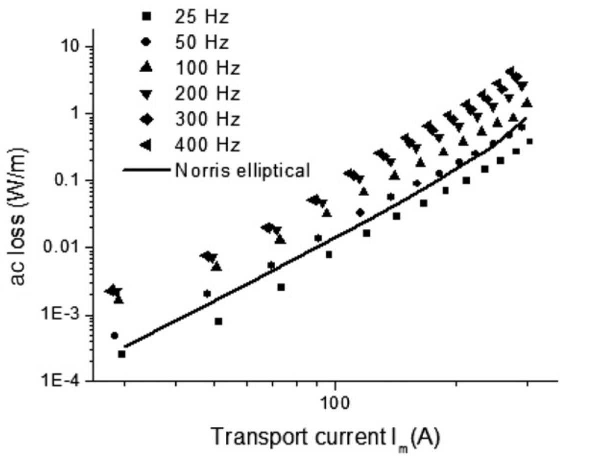

Figure 13. The ac losses of BSCCO at 55 K for different frequencies of transport current. Here the Norris prediction is calculated for a 50 Hz transport current.

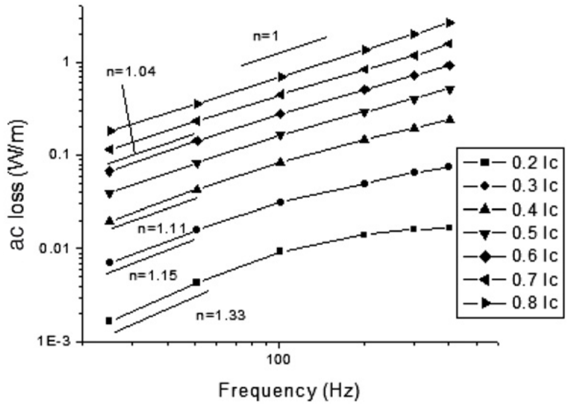

Figure 15. The ac losses of BSCCO as a function of frequency for different transport currents at 55 K.

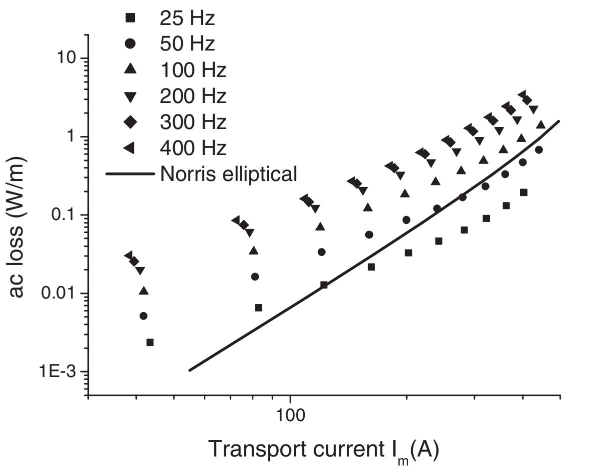

Figure 14. The ac losses of a YBCO coated conductor at 55 K for different frequencies of transport current. Here the Norris prediction is calculated for a 50 Hz transport current.

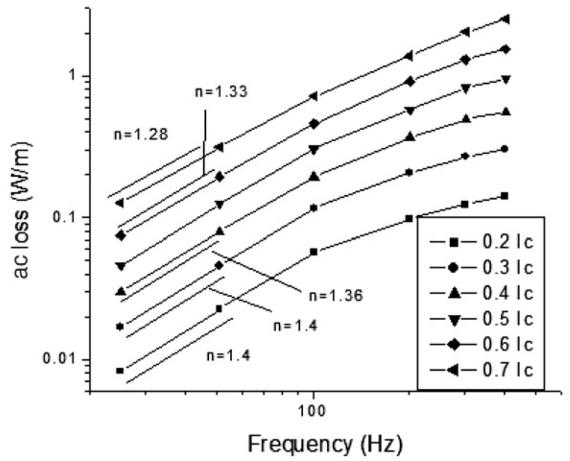

Figure 16. The ac losses of YBCO as a function of frequency for different transport currents at 55 K.

3.3. ac losses versus frequency

Generally, ac losses (Q) can be classified as hysteretic loss (P_h) in the superconductor core, coupling loss (P_c) among the superconductor filaments, eddy current loss (P_e) in the matrix, and flux flow or resistive loss (P_r) caused by flux flow. According to the traditional theory, the frequency dependence of ac losses mentioned above can be expressed as follows [10, 11]:

$$Q = P_h f^1 + (P_e + P_c) f^2 + P_r f^0 \tag{1}$$

where the first term increases linearly with frequency (f), the second term has quadratic dependence on frequency, and the third term is frequency independent.

For superconductor tapes with a ferromagnetic substrate, there is also ferromagnetic loss (P_f). Therefore, another term must be added to (1). Because ferromagnetic loss is a type of hysteretic loss, it is frequency independent [8]. Hence (1) becomes

$$Q = (P_h + P_f) f^1 + (P_e + P_c) f^2 + P_r f^0. \tag{2}$$

For monocore superconductor tapes, the coupling loss (P_c) becomes zero in expression (2).

Figures 13 and 14 show ac transport losses and the Norris prediction for BSCCO and YBCO tape at 55 K as a function of transport current and frequency. Here the prediction is calculated from the Norris elliptical formula for a 50 Hz transport current. From these figures, the frequency dependence curves of ac losses of BSCCO and YBCO shown in figures 15 and 16 are obtained. Figures 15 and 16 show that the slopes of the frequency dependence curves of ac transport losses decrease with increasing transport current for BSCCO and YBCO. For BSCCO, the slopes decrease from $n = 1.33$ (for $0.2I_c$) to $n = 1$ (for $0.8I_c$) at lower frequency. For YBCO tape, the slopes decrease from $n = 1.33$ (for $0.2I_c$) to $n = 1.28$ (for $0.7I_c$). This shows that the component of eddy current loss in YBCO is higher than that in BSCCO.

For YBCO (figure 16), the slopes of the ac loss versus frequency curves decrease with increasing frequency for transport currents from 0.3 to $0.7I_c$. For BSCCO (figure 15), the frequency dependence curves of ac transport losses behave differently for lower and higher transport currents. At higher transport currents ($0.5I_c$ or above), the frequency dependence curves of ac transport losses are almost linear with slopes close to 1 ($n \sim 1$). This indicates that the transport losses are dominated by hysteresis loss. But the slopes of the loss versus frequency curves decrease gradually with increasing frequency at lower frequencies and small currents (smaller than $\sim 0.3I_c$). Theoretical calculation of the coupling length shows that the sample is coupled. Thus the higher slopes (such as $n = 1.33$) at lower frequency and small currents come from the contribution of eddy current loss.

4. Conclusions

The temperature dependence of critical currents and ac transport losses of YBCO and BSCCO tapes were investigated. The frequency dependence measurements of ac loss were performed at 55 K.

It is shown that the critical currents decrease almost linearly with increasing temperature for YBCO and BSCCO for temperatures below about 77 K. The normalized critical current curves of YBCO and BSCCO tape fall on the same line for temperature below 77 K.

The temperature dependence of ac loss behaves differently for BSCCO and YBCO because of the ferromagnetic loss in the nickel substrate in coated conductors. The BSCCO loss factors are temperature independent, while those for YBCO are temperature dependent. For both BSCCO and YBCO, the temperature dependence curves of normalized ac transport losses coincide with each other for higher transport currents (greater than $0.5I_c$). The variation of ac transport loss with increasing temperature is similar to the variation of critical currents for both BSCCO and YBCO, indicating that temperature dependence of ac losses is mainly determined by the temperature dependence of the critical current. The slopes of ac transport loss versus frequency curves for YBCO and BSCCO decrease with increasing frequency and transport current. The higher slopes at lower transport currents are caused by the contributions from eddy current loss and coupling loss. The linear behaviour ($n = 1$) of ac transport loss versus frequency curves for BSCCO at high current indicates that ac transport losses are mainly composed of hysteresis losses.

Acknowledgments

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