Hysteresis Loss in a Superconducting Bi-2223 Tape with Fine Filaments

Edmund S. Otabe[1] and Teruo Matsushita[1,2]
[1] Department of Computer Science and Electronics, Kyushu Institute of Technology, 680–4 Kawazu, Iizuka 820–8502, Japan
[2] Graduate School of Information Science and Electrical Engineering (ISEE), Kyushu University, 6–10–1 Hakozaki, Higashi-ku, Fukuoka 812–8581, Japan

Jun Fujikami[3] and Kazuya Ohmatsu[3]
[3] Basic High Technology Laboratories, Sumitomo Electric Industries, Ltd., 1–1–3 Shimaya, Konohana-ku, Osaka 554–0024, Japan

Abstract—**The energy loss density was measured for a Bi-2223 tape wire with superconducting filaments of average thickness 2.5 μm to confirm the reduction of energy loss density due to the reversible fluxoid motion. The energy loss density is compared with the prediction by the modified Kim model. It is lower than the prediction at AC field amplitudes below the penetration field at temperatures above 77 K. The slope of the minor magnetization curve is less than unity and the estimated AC penetration depth is longer than the filament thickness in the same regime. This result supports the speculation that the reduction of the energy loss density is due to the reversible fluxoid motion.**

I. Introduction

Bi-2223 silver-sheathed tapes are used as wires for electrical power cables or transformers because of their mechanical flexibility and easy fabrication of long wires [1]. The reduction of the AC loss at the commercial frequency is a key issue for such power application. It is well known for metallic multifilamentary wires with fine superconducting filaments that the energy loss density can be drastically reduced from the prediction of the critical state model due to the reversible fluxoid motion [2], [3]. The hysteresis energy loss density was previously measured for a Bi-2223 silver-sheathed multifilamentary tape wire with 61 filaments with the average thickness of about 10 μm [4]. Although the energy loss density was lower than the prediction of the critical state model due to the reversible fluxoid motion at temperatures above 100 K, the reduction was not achieved at 77.3 K. It is desired to achieve such a reduction of the energy loss density even at 77.3 K.

When the effective size of superconductor, d, is larger than the AC penetration depth, λ_0', defined by Campbell [5], the pinning energy loss of hysteresis type is well described by the critical state model. This loss occurs mostly when fluxoids fall in and jump out of pinning potential wells. Hence, the phenomenon is expected to be almost reversible when the movement of fluxoids is restricted inside the pinning potential wells. This condition is achieved when d is comparable to or smaller than λ_0' and when the AC magnetic field amplitude is smaller than $2\sqrt{3}(2\lambda_0'/d)^2 H_{\rm p} = \widehat{H}_{\rm p}$, where $H_{\rm p} = J_{\rm c} d/2$ is the penetration field with $J_{\rm c}$ denoting the critical current density. The AC penetration depth is theoretically given by

$$\lambda_0' = \left(\frac{B a_{\rm f}}{\mu_0 J_{\rm c} \zeta} \right)^{1/2}, \qquad (1)$$

where $a_{\rm f}$ is the fluxoid spacing and ζ is a constant of the order of 4 depending on the kind of pinning centers [2]. According to (1), λ_0' becomes shorter with increasing of $J_{\rm c}$, i.e., decreasing temperature and magnetic field. Therefore, it was pointed out that the reduction of the filament thickness less than 2 μm is necessary to achieve the reduction of the energy loss density at 77.3 K in Bi-2223 multifilamentary tape wire [4].

In this study, the energy loss density is measured and AC penetration depth is estimated from the slope of magnetization curve at various temperatures for a Bi-2223 tape wire with fine filaments of the average thickness of about 2.5 μm. The measured result is compared with our previous work and also with the prediction by the modified Kim model, and the reduction of the energy loss density due to the reversible fluxoid motion is discussed.

II. Experiments

The specimen was a Bi-2223 multifilamentary tape wire and the specification of specimen is shown in Table I. The DC magnetization measurement was performed using a SQUID magnetometer (MPMS-7). The temperature of

TABLE I
Specification of Bi-2223 multifilamentary tape wire.

cross section (mm)	3.0 × 0.22
volume fraction of superconductor (%)	14
number of filaments	1369
average filament thickness (μm)	2.5
critical temperature (K)	109.5

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E.S. Otabe, tel & fax +81–948–29–7683, otabe@cse.kyutech.ac.jp, http://aquarius10.cse.kyutech.ac.jp/~otabe/

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the specimen was controlled in the range of 10–110 K. The magnetic field was applied parallel to a wide surface of the specimen and perpendicular to the long axis of filaments. The amplitude of magnetic field was varied from 1 mT up to 1.0 T. Thus, the effective size of the superconductor, d, is given by the thickness of the filaments. For simplicity, the distribution of the filament thickness is disregarded and we use $d = 2.5$ μm in the following.

III. Results and Discussion

Fig. 1 shows the observed magnetization curves at 77.3 K. The magnetization hysteresis decreases abruptly according to increasing magnetic field. This is considered due to the effect of the flux creep at high fields at this temperature. The effect of diamagnetism is remarkable and the magnetization curve is asymmetry, since the critical current density is relatively low and filaments are thin.

The influence of the reversible fluxoid motion is also seen in the reduction of the slope of a minor DC magnetization curve, S, just after reversing the sweep of the external magnetic field. According to the irreversible Bean critical state model, S is predicted to be unity. However, S reduces when the effect of the reversible fluxoid motion is remarkable. This slope depends only on λ_0' and is theoretically given by

$$S = 1 - \frac{2\lambda_0'}{d}\tanh\frac{d}{2\lambda_0'}. \qquad (2)$$

Therefore, λ_0' can be estimated from a measured value of S [3]. The magnetic field dependence of S at various temperatures is shown in Fig. 2. At low temperatures, S is closed to unity in low magnetic field region, since λ_0' is smaller than d and the fluxoid motion is almost completely irreversible. However, S decreases drastically with increasing magnetic field, especially at high temperatures. This result is explained by (1) and (2), i.e., J_c decreases with increasing temperature and/or magnetic field, resulting in the elongation of λ_0'. The value of S in the present specimen is lower than the previous specimen with the filament thickness of about 10 μm. This means that the effect of the reversible fluxoid motion is more significant in the present specimen, which is attributed to the reduced filament thickness. Hence, the reduction of the energy loss density is expected even at lower temperatures.

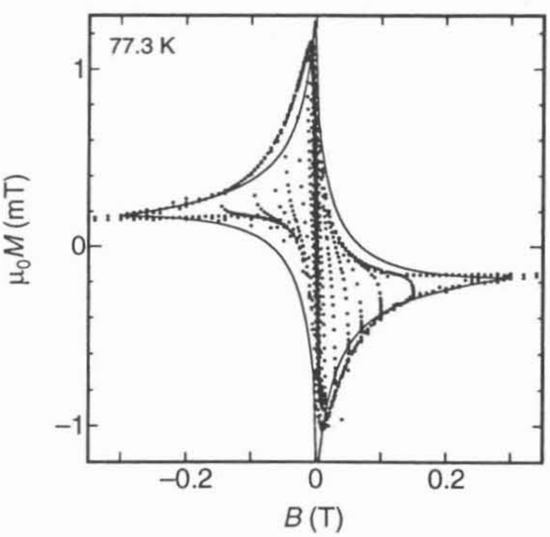

Fig. 1. Magnetization curves in Bi-2223 multifilamentary tape wire at 77.3 K. Solid line represents theoretical prediction from the modified Kim model with diamagnetism. Parameter are determined so as to obtain a good fit with experimental magnetization hysteresis as shown in Table II.

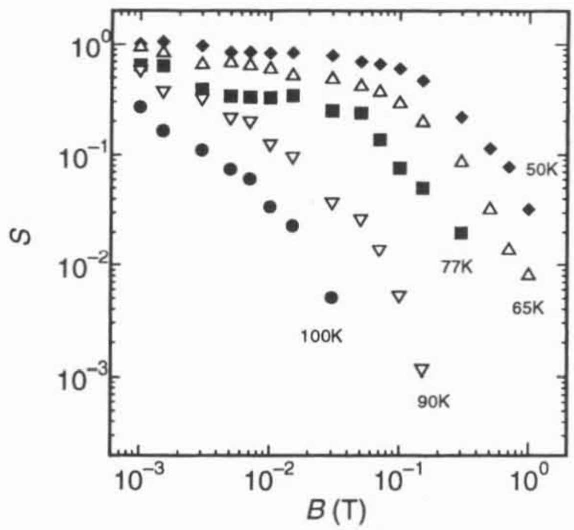

Fig. 2. Slope of minor magnetization curve vs. magnetic field at various temperatures.

Observed results of the energy loss density, W, vs. the AC magnetic field amplitude, B_m, at various temperatures are shown in Fig. 3 (a). The temperature dependence of W is consistent with the prediction of the critical state model at low temperatures. That is, W decreases at high B_m, while it increases at low B_m according to decreasing H_p with increasing temperature. At high temperatures, however, W decreases with increasing temperature even in the low magnetic field region, deviating from the prediction of the critical state model. This seems to be explained by the effect of the reversible fluxoid motion. In Fig. 3 (b) the present results at 77 K and 100 K are compared with the previous results [4] for the thicker filament thickness. In both temperatures, W is smaller than the previous result in the whole region of AC magnetic field amplitude. This is also contradictory to the critical state model. Therefore, it is concluded that the effect of the reversible fluxoid motion causes the lower AC loss at temperatures higher than 77 K.

The chained line in Fig. 3 (b) indicates the theoretical calculation based on the modified Kim model in which the diamagnetism of superconductor is taken into account [4].

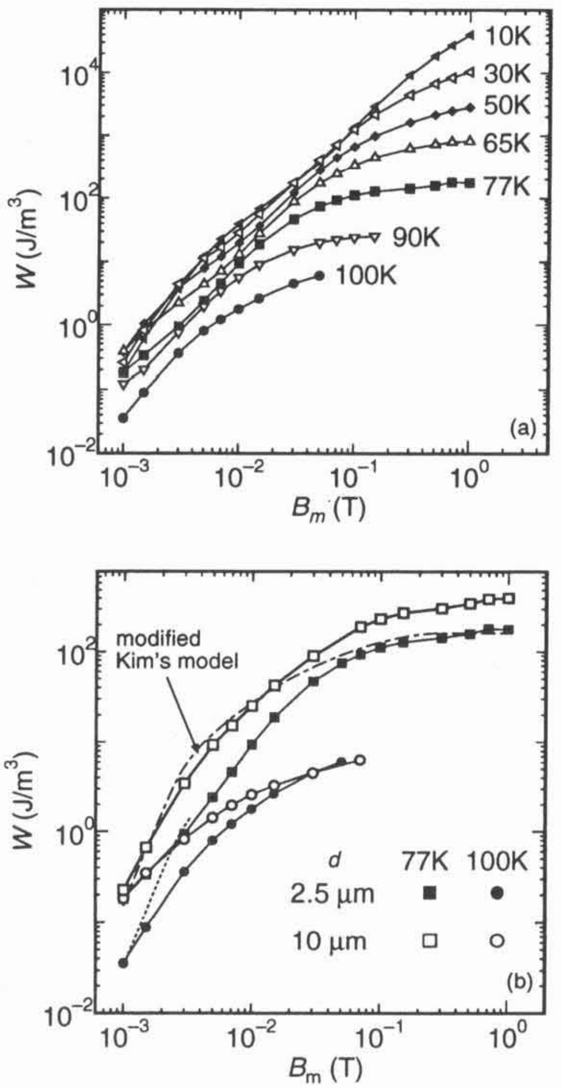

Fig. 3. (a) Energy loss density vs. AC field amplitude at various temperatures. (b) Comparison with previous result on specimen of $d = 10$ μm [4] at 77 K and 100 K. Chained line and dotted line represent prediction from the modified Kim model and corrected value multiplied by $(d/2\lambda_0')^4/4$ at 77 K, respectively.

The magnetic field dependence of J_c is assumed as

$$J_c(B) = \frac{\alpha_0}{|B| + B_0}\left(1 - \frac{|B|}{B_i}\right), \tag{3}$$

where α_0 and B_0 are parameters, and B_i is the irreversibility field. The effect of diamagnetism can be approximately incorporated by introducing a difference between the external magnetic field, H, and the magnetic flux density at the surface of the superconductor, $B(0)$, as

$$B(0) = \mu_0(H + H_s), \tag{4}$$

where H_s (< 0) represents the diamagnetic magnetization.

Here H_s is simply assumed as

$$\begin{aligned} H_s &= \frac{-H_{c1}}{H^* - H_{c1}}(H^* - H); \quad H > H_{c1}, \\ &= -H; \qquad\qquad\qquad H_{c1} > H > -H_{c1}, \\ &= \frac{H_{c1}}{H^* - H_{c1}}(H^* + H); \quad -H_{c1} > H. \end{aligned} \tag{5}$$

In the above H_{c1} is the lower critical field and H^* is the magnetic field at which the diamagnetism diminishes to zero. These parameters are determined so as to obtain a good agreement for the magnetization hysteresis between the theoretical calculation and the experimental result as shown in Fig. 1 and the values at 77.3 K are shown in Table II. The calculated result of W agrees with the experiment at high AC magnetic field amplitudes, while it is higher than the experiment at low amplitudes. This convinces us that the reduction in the loss is caused by the reversible fluxoid motion.

On the other hand, W does not decrease monotonically with decreasing B_m except 100 K. This seems to be partly attributed to the additional loss due to bridging of filaments. In practical application, the bridging of the filament is a serious problem. However, the energy loss density will be surely reduced due to the reversible fluxoid motion as shown in the present work, if the bridging of filaments is completely extinguished by development of fabrication technology in the future. The other possibility of this increase of W will be discussed later.

Finally, we shall discuss the AC penetration depth, λ_0'. Fig. 4 shows the magnetic field dependence of the AC penetration depth at various temperatures estimated by observed S and (2). According to increasing temperature and/or magnetic field, λ_0' elongates. The solid lines indicate the theoretical result of (1). In the above, J_c is estimated from the magnetization hysteresis using the Bean model. A good agreement is obtained between theoretical and experimental results. The reason for slight deviations at low temperatures is that S is close to unity and the error becomes large in (1). Therefore, (1) can be used for the estimation of λ_0' except the case where S is close to unity.

The reversible fluxoid motion is significant at $d/2\lambda_0' \lesssim 1$. In the previous specimen with $d = 10$ μm, this condition is satisfied only above 100 K. On the other hand, this condition is satisfied above 77.3 K in the present specimen with $d = 2.5$ μm. This is consistent with the result in Fig. 3.

According to the theoretical analysis by Takács and Campbell [6] based on the Campbell model [7] in which

TABLE II

Parameters used for the modified Kim model at 77.3 K.

α_0 (N/m^3)	B_0 (T)	B_i (T)	$\mu_0 H_{c1}$ (T)	$\mu_0 H^*$ (T)
3.0×10^7	2.5×10^{-2}	3.0×10^{-1}	2.5×10^{-4}	1.0

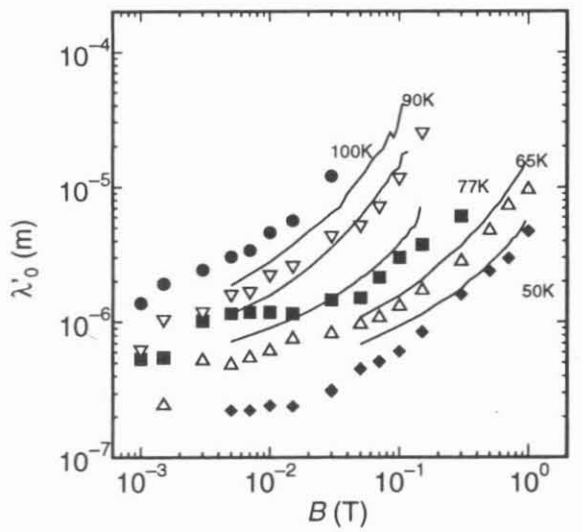

Fig. 4. Magnetic field dependence of AC penetration depth at various temperatures. Solid lines are theoretical values of (1) with J_c estimated from magnetization hysteresis by the Bean model.

the reversible fluxoid motion is taken into account, the energy loss density is $(d/2\lambda_0')^4/4$ times as small as the prediction of the completely irreversible Bean model, when $d/2\lambda_0' \ll 1$. This holds approximately for the AC field amplitude smaller than H_p. Strictly speaking, the correction factor of $(d/2\lambda_0')^4/4$ for W is valid only for the Bean model. However, this factor can also be approximately used for another critical state models such as the Irie-Yamafuji model [3]. If we use this factor for the present case, W at 77.3 K is predicted to reduce to values shown by the dotted line in Fig. 3 (b), where the prediction by the Kim model is represented by the chained line for comparison. It is found that the tendency of W can be explained by this correction factor. In the above, $\lambda_0' = 1.3$ μm was assumed, although it is slightly larger than the observed value of 1.0 μm at 3.5 mT ($= \mu_0 H_p$) in Fig. 4. Therefore, the increase in W at low B_m might partly come from the shortening of λ_0' at these fields shown in Fig. 4. Thus, the above correction factor seems to be useful for an approximate estimate of the AC loss. This seems to be attributed to the fact that the magnetic field dependence of λ_0' below H_p is small as observed.

To estimate the AC loss more exactly, however, a more exact theoretical analysis is needed. In such theory magnetic field dependences of J_c and λ_0' are necessary to be incorporated. It is also important to clarify which of bridging of filaments and disappearance of reversible fluxoid motion causes the increase of the energy loss density.

IV. Summary

In this paper, the energy loss density was measured for a Bi-2223 multifilamentary tape wire and the possibility of reduction of the energy loss density due to the reversible fluxoid motion was discussed using the AC penetration depth estimated from the slope of minor magnetization curve. Following results were obtained.

- The energy loss density at temperatures higher than 77.3 K was lower than the prediction of the modified Kim model at low AC magnetic field amplitude, when the average filament thickness was reduced to $d = 2.5$ μm.
- The slope of minor magnetization curve, S, was smaller than unity and the estimated λ_0' from S was comparable to or longer than the filament thickness, d, at high temperatures, where the reduction of the energy loss density from the prediction of the critical state model was observed.
- It is concluded that the effect of the reversible fluxoid motion brings about the lower AC loss at temperatures above 77.3 K.

References

[1] K. Sato, K. Hayashi, K. Ohkura, K. Ohmatsu, T. Hikata, T. Kaneko, T. Kato, M. Ueyama, J. Fujikami, M. Ito, S. Kobayashi, N. Saga, S. Hahakura, T. Shibata, T. Masuda and S. Isojima, "Bismuth-Based HTS Wires and Their Application Progress", Proc. of ICEC 16/ICMC (Kitakyushu, 1996) pp. 1347–1350.

[2] F. Sumiyoshi, M. Matsuyama, M. Noda, T. Matsushita, K. Funaki, M. Iwakuma and K. Yamafuji, "Anomalous Magnetic Behavior due to Reversible Fluxoid Motion in Superconducting Multifilamentary Wires with Very Fine Filaments," *Jpn. J. Appl. Phys.* , vol. 25, pp. L148–L150 1986.

[3] T. Matsushita, E.S. Otabe, M. Iwakuma, K. Funaki, K. Yamafuji, O. Miura, K. Matsumoto and Y. Tanaka, "Measurement of AC Penetration Depth in Superconducting Wires with Fine Filaments," *Adv. in Cryo. Eng.*, vol. 40, pp. 551–558, 1994.

[4] E.S. Otabe, H. Matsuoka, T. Matsushita, J. Fujikami and K. Ohmatsu, "Possibility of Reduction in Hysteresis Loss Due to Reversible Fluxoid Motion in a Superconducting Bi-2223 Multifilamentary Wire," *Jpn. J. Appl. Phys.*, vol. 37, L382–L385, 1998.

[5] A.M. Campbell, "The Response of Pinned Flux Vortices to Low-Frequency Fields," *J. Phys. C*, vol. 2, pp. 1492–1501, 1969.

[6] S. Takacs and A.M. Campbell, "Hysteresis Losses in Superconductors with Very Fne Filaments," *Supercond. Sci. Technol.*, vol. 1, pp. 53–56, 1988.

[7] A.M. Campbell, "The Interaction Distance between Flux Lines and Pinning Cetntres," *J. Phys. C*, vol. 4, pp. 3186–3198, 1971.