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Magnetic hysteresis loss in Bi-2223/Ag tapes with different filament arrangement

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Abstract

Hysteresis losses in perpendicular AC magnetic field were investigated experimentally on a set of six Bi-2223/Ag tapes with different filament architecture. Along with a monocore tape and a tape with overlapping filaments, tapes with filament arranged in less or more regular stacks, as well as a tape with filaments perpendicular to the tape wide face were tested. AC susceptibility technique was used, allowing to present the loss behavior in terms of two multiplicative parameters: the external susceptibility at low amplitudes, χ_0 , and the imaginary part of internal susceptibility, χ'' . We show that both the filament stacking and its parallel orientation with respect to the applied field suppress χ_0 , leading to hysteresis loss reduction. However, the unconventional filament architecture was accompanied by imperfections of filament microstructure that broadened the susceptibility peak. Then, the loss reduction in these tapes was less than expected. In the temperature interval 77–95 K, excellent scaling of the susceptibility data was found, indicating the validity of the critical state model for these systems. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Tapes from high- T_c superconductor Bi₂Sr₂Ca₂-Cu₃O₁₀ in the form of filaments embedded in a silver matrix are now considered in range of power engineering applications. When these so-called Bi-2223/Ag tapes are exposed to an alternating magnetic field, a part of the magnetic energy converts

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into heat during every cycle. This "AC loss" has origin in various mechanisms. The most important are the magnetic hysteresis of type II superconductor with flux pinning, and the inter-filament currents that flow across the resistive matrix. The first give rise to the hysteresis loss, and its value per cycle does not depend on the AC field frequency. The inter-filament currents generate the so-called coupling loss. The hysteresis loss, that will also remain when the inter-filament currents would be suppressed e.g. by increasing enough the matrix resistivity, is the object of the present work. Its calculation is based on the critical state model [1]

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for magnetic hysteresis of superconductors. Analytical expressions were derived for superconductors of simple shapes like slab in parallel field, and disk [2] or strip [3] in perpendicular field.

However, Bi-2223/Ag tapes contain the superconductor in the form of filaments. The crosssection of these filaments is roughly rectangular, with aspect ratios typically exceeding 10. The models derived for simple shapes are then not immediately applicable. Exception is the case of field parallel to the wide face of filaments, when the approximation by a single slab with the thickness equal to that of the single filament is commonly used. However, the case of magnetic field perpendicular to the filaments is of key importance in practical applications. In tapes of common filament architecture this orientation means also that the magnetic field is perpendicular to the tape wide face. In this "perpendicular geometry" the distortions of the applied field caused by the electrical currents flowing in individual filaments modify the distribution of the magnetic field in a manner that depends on filament architecture. Generally, this effect is interpreted in terms of a magnetic coupling between filaments. Analytical expressions have been derived for the case of an infinite stack of thin filaments [4]. The enhancement of magnetic coupling by decreasing the distance between filaments was found to cause the transition from striplike to slab-like behavior.

For the filament architectures met in practice, the problem was studied in the limiting case when filaments are entirely diamagnetic [5]. It was found that the effect of applied field distortion due to filament architecture is nicely seen in conditions of perfect diamagnetism. The complex AC susceptibility calculated with respect to the applied field, the so-called "external" AC susceptibility [6], has only the real part in these conditions. Its absolute value, χ_0 , is a good measure of the field enhancement due to the diamagnetic shielding. This quantity has a direct connection to the demagnetizing factor, D, in the case of shapes with elliptic symmetry. It is well known, that in the perfectly diamagnetic state the magnetization of such a body (e.g. cylinder in perpendicular field), when exposed to the applied field B_{ext} , will be $M_{\text{dia}} =$ $-B_{\rm ext}/(1-D)$. From the definition of external

susceptibility $\chi_{\text{ext}} = M/B_{\text{ext}}$ then follows that $\chi_0 = 1/(1-D)$. For tapes with different filament architecture we have found χ_0 values varying in one order of magnitude [7].

Here we investigate the behavior of tapes in an alternating field $B_{ac} = B_a \cos \omega t$, with amplitude B_a and frequency $f = \omega/2\pi$. The fields are ranging from those completely shielded by the superconductor up to the large ones that drive the tape completely into the critical state. The technique of complex AC susceptibility is used to establish the AC loss. The imaginary part of the internal AC susceptibility, χ'' , is determined with the help of a lock-in amplifier. Then, the volume density of AC loss per cycle, q, is found as [2]

$$q = \chi_0 \chi'' \frac{\pi B_a^2}{\mu_0},\tag{1}$$

where $\mu_0 = 4\pi \times 10^{-7}$ H/m. The importance of χ_0 is obvious-it enters the loss formula as a proportionality constant. However, when one has in mind the link between χ_0 and the demagnetization factor D, the use of χ_0 at applied fields high enough to induce the critical state could be doubted. It is natural to consider that the magnetic coupling between filaments changes when the currents flow in the whole section of filaments. In our previous paper [8] we brought strong argument in favor of χ_0 as a constant characterizing the filament architecture also in the critical state: the height of χ'' maximum, obtained from measured external susceptibility by division with the χ_0 found in perfectly diamagnetic state, was similar for different tapes and also in agreement with theoretical models. Here we extend this type of analysis to tapes with filaments put in regular stacks and one tape with filaments perpendicular to the tape wide face.

2. Samples

Experimental results are presented for six tapes with quite different filament architectures, as can be seen from the cross-sections presented in Fig. 1. The simplest object is the monocore tape A. All



Fig. 1. Optical micrographs of the tape cross-sections. Please take into consideration that the scale can vary from tape to tape and is not necessarily the same for both directions.

the rest are multifilamentary tapes. Of common type is the tape B with overlapping filaments that was prepared by flat rolling technique [9]. In the tapes C–E, the filaments are arranged in stacks that represent an intermediate structure. Among themselves, these tapes differ in the regularity of stacking and the frequency of inter-filament bridging by superconducting paths. During manufacturing of tape C, the significant step was the two axial rolling [10], while the tapes D and E were prepared by the tape-in rectangular-tube process [11]. This technique allowed to prepare also the tape F, with the filament orientation perpendicular to that one commonly used.

As we will demonstrate further, both the columnar structure (samples C-E) and the perpendicular filament orientation (sample F) could lead to the hysteresis loss reduction. We do not address in this work the problem of the coupling loss, that would require to twist the filaments. Clearly, for the tapes with unconventional filament architecture, twisting could not be accomplished by a

Table 1 Geometric characteristics of the tapes

simple screw-like deformation used for conventional tapes, and remains an issue that should be solved separately.

Evaluation of the filament dimensions is charged by serious errors in the case of tapes where these vary significantly (tape B, in part also C), or for the tapes with heavy inter-growth frequency (tapes D and E). Therefore the average filament dimensions presented in Table 1 are only indicative.

3. AC susceptibility

In order to perform AC susceptibility measurements, for each tape a sample of 6–7 mm length has been cut, and placed in an AC magnetic field perpendicular to its wide face. The voltage from a pair of identical pick-up coils (one containing the sample and other empty) was processed by a two channel lock-in amplifier. To obtain the values of the external AC susceptibility, the calibration at low AC field amplitudes was performed for each sample. The procedure is described in detail in our previous paper [8]. It results in the establishing of χ_0 , the absolute value of the external susceptibility in perfectly diamagnetic state, as

$$\chi_0 = G_{\rm c} \frac{\Delta U_{\rm dia}}{U_{\rm empty}} \frac{V_{\rm coil}}{V_{\rm sample}}.$$
(2)

Here, U_{empty} is the voltage induced in the empty pick-up coil and ΔU_{dia} is the difference between voltages from the empty pick-up coil and that one containing the sample, in conditions of a perfectly diamagnetic superconducting portion, $\Delta U_{\text{dia}} = U_{\text{empty}} - U_{\text{samp,dia}}$. For a cylindrical pick-up coil with the height h_c and the mean winding radius R_c ,

Tape	Number of filaments	Tape overall cross-section (mm ²)	Fill factor (%)	Average filament cross-section (μm ²)	χο
А	1	1.8×0.31	36	1470×145	3.20
В	19	2.5×0.14	18	320×10	12.4
С	6×6	2.5×0.20	16	171×10	2.19
D	3×20	3.9 imes 0.27	33	909 imes 7	4.22
Е	4×15	3.8 imes 0.28	26	533×8	3.93
F	21	2.2 imes 0.55	39	60×342	1.37

its volume is $V_{\text{coil}} = h_c \pi R_c^2$ and the constant characterizing the coil geometry is $G_c = (1 - (2R_c/h_c)^2)^{1/2}$. The volume to which the loss is to be attributed, is V_{sample} . In our previous works, we used to find it as the sum of volumes of all the superconducting filaments. However, now we are interested in the AC loss as a characteristic of the tape. Then, it is reasonable to use the volume defined by the tape's overall dimensions for this purpose. This is why the values of χ_0 , reported here, differ from those published previously [8]. They are simply recalculable to χ_0 values attributed to the superconducting fraction only, with the help of the fill factors given in Table 1.

We used to determine χ_0 at 77 K. Low fields $-B_a < 0.01$ mT—allowed perfect screening of filaments. Then χ_0 does not involve the quality of superconducting material and is given entirely by the filament architecture. Therefore it is given in Table 1 together with other geometrical characteristics. A simple test of reaching the perfect diamagnetic state of superconducting filaments is the independence of χ_0 , derived according to Eq. (1), on AC field. Because the empty coil signal is proportional to both *f* and B_a , invariance of χ_0 is accomplished only if

$$\Delta U_{\rm dia} = A_{\rm s} B_{\rm a} \omega, \tag{3}$$

where A_s is a constant with dimensions of an area. It does not contain any new information compared to χ_0 , when the state of perfect diamagnetism is treated. It was introduced to allow the extrapolation of diamagnetic signal values even for larger amplitudes when the sample is in part penetrated by the magnetic flux. In this way, the parts of internal AC susceptibility are determined from the lock-in amplifier read-outs as

$$\chi' = \frac{\operatorname{Re}\{\Delta U\}}{A_{s}B_{a}\omega},\tag{4a}$$

$$\chi'' = -\frac{\mathrm{Im}\{\Delta U\}}{A_{\mathrm{s}}B_{\mathrm{a}}\omega}.\tag{4b}$$

The index for diamagnetic state was dropped out from the symbol for the differential pick-up coil signal $\Delta U = U_{\text{coil}} - U_{\text{samp}}$ because now we treat a sample that is in the critical state. Evaluation of χ' has no relevance for the AC losses. It served to test the correctness of χ_0 determination by checking that its value approaches -1 at low fields and rises to 0 at larger ones. Therefore in the following we concentrate on the data of χ'' , the imaginary part of internal AC susceptibility.

Our AC loss experiments were performed at frequencies ranging from 8 to 140 Hz. At low frequencies, the $\chi''(B_a)$ curves are frequency independent, because of negligible coupling currents and eddy currents in the silver matrix. We are convinced that such data represent the magnetic hysteresis in superconductor. Those taken at 80 K are plotted in Fig. 2. Common feature of all the curves is a bell-like shape: χ'' first increases with B_a , reaching the maximum at the amplitude that can be denoted as B_{max} , and then decreases. This is in qualitative agreement with theoretical models that also predict the height of $\chi''(B_{max})$ and the value of $B_{\rm max}$ in terms of the critical current density, $j_{\rm c}$, and of a characteristic dimension of the sample [12]. For a slab in parallel field, this is its thickness d, transversal to the applied field, and at $B_{\rm max}$ = 0.667 $\mu_0 j_c d$ one finds the peak height $\chi''_{max} = 0.239$. In the case of a strip in perpendicular field, its thickness in the field direction, h, is significant. It is interesting that at the $B_{\text{max}} = 0.785 \mu_0 j_c h$ maximum value $\chi''_{max} = 0.237$ is quite close to that of the slab.



Fig. 2. Dependence of the imaginary part of complex AC susceptibility on the AC field amplitude at the temperature of 80 K.

Table 2 Critical state and AC susceptibility characteristics of the tapes

Tape	$j_{\rm c}$ (80 K, self field) (A/cm ²)	B _{max} (80 K) (mT)	$h_{\rm eq}$ or $*d_{\rm eq}$ (μ m)	$h_{ m eq}/h_{ m fil} st d_{ m eq}/d_{ m fil}$
А	4900	8.5	173	1.2
В	8700	0.73	8.4	0.84
С	4500	1.2	27	2.7
D	7150	6.8	95	14
Е	14 100	10.2	72	9
F	2450	1.13	*55	*0.92

Because the critical current density j_c has been determined independently in a DC transport measurement, the values of B_{max} observed for our samples can be used to determine either h_{eq} , the thickness of an equivalent strip, or d_{eq} , that of an equivalent slab that will produce the χ'' maximum at the same position. The results of such analysis are given in Table 2. We found reasonable to apply the strip model to all the tapes but the slab model for the tape F. In the last column of the table, the ratio between the equivalent filament dimension and the geometrical one is shown. For the tapes A, B and F that is close to 1, suggesting that the magnetic field does interact with individual filaments when fully developed critical state is reached. On the other hand, this ratio is larger than 10 in the case of tapes D and E with densely stacked filaments. Tape C with loosely stacked and well separated filaments represents an intermediate case. The ratio $h_{\rm eq}/h_{\rm fil} \gg 1$ means that the magnetic flux does not "meander" between the filaments in the stack and the penetration is rather to the stack as a whole.

To perform a comparative analysis of $\chi''(B_a)$ dependences, let us replot the experimental data by scaling B_a by the B_{max} registered for each curve. Resulting curves are shown in Fig. 3 together with those predicted by theoretical models for strip [3] and slab [6]. We see that the shape is close to the theoretical predictions in the case of tapes A and B, where also the values of B_{max} agree with expectations. For the tape F this is also true for the region close to the maximum, even if there is a lateral maximum observable at low amplitudes that we cannot explain at this moment. The tapes with stacked filaments exhibit significant broad-



Fig. 3. Comparison of the shapes of the susceptibility curves from Fig. 2 by normalization of AC field amplitudes to B_{max} .

ening of the bell-like curve. In the case of tapes C and D, it is accompanied by the reduction of the maximum. One can speculate that this reflects the interplay between the penetration of the filament and that of the whole stack. Such considerations could be only qualitative because of lacking theoretical model.

4. AC loss

The AC susceptibility data have been used to determine the loss per cycle in the volume unity of the tape according to Eq. (1). To take into account the tape quality as well, we divided it by the engineering critical current density—related to the tape's whole cross-section, S_{tape} —to obtain the value of hysteresis loss per unit length of the tape and ampere of its critical current

$$q' = q \frac{S_{\text{tape}}}{I_{\text{c}}}.$$
(5)

The resulting $q'(B_a)$ curves are plotted in Fig. 4 for all the tapes investigated. The conclusions that can be drawn from this comparison, for the design of Bi-2223/Ag tapes with a low level of magnetic hysteretic losses, are the following:

Homogeneity of superconducting filaments, resulting in a narrow χ"(B_a) dependence, is essential—compare the losses of tapes A and C.



Fig. 4. AC loss per cycle, unit length and ampere of the critical current, calculated from the susceptibility data measured at 80 K.

- Parallel orientation of filaments with respect to the applied magnetic field—as in tape F—is of great advantage.
- In the perpendicular magnetic field, the stacking of filaments reduces the losses due to depressing of χ₀. Tape B is a negative example in this context.

We repeat that the purpose of the present study was to investigate only one component of AC losses, namely the hysteretic magnetic loss in perpendicular field. Conditions for depression of other loss mechanisms could be different, as demonstrate e.g. the works on reduction of coupling current loss [13]. However, also when a complete reduction of other significant loss mechanisms will be accomplished, hysteresis loss will remain because it stems from the very nature of hard superconductors.

5. Temperature dependence

In the previous paragraphs we have seen that the electromagnetic behavior of all the investigated tapes could be explained on the basis of the critical state model [1]. In other words, the magnetic field distribution as well as the AC losses are controlled by the filament architecture and the critical current density, j_c . These two components can be nicely separated by checking the temperature dependence



Fig. 5. The shapes of susceptibility curves measured at different temperatures on sample E.

of the AC susceptibility, since the filament geometry does not change with temperature but the critical current density does. The temperature increase, that depresses j_c , should result in the shift of B_{max} towards lower values. However, until the critical state model would describe the flux dynamics correctly, the $\chi''(B_a)$ curves should be scalable, using proper $B_{\max}(T)$ for each temperature. This is indeed what we observed in the temperature range 77–95 K for all the investigated tapes. For illustration, the scaled data of the tape E are shown in Fig. 5. To fix slight changes in the height of susceptibility maximum (these were in any case less than 10%), also the χ'' values were normalized by $\chi''_{max}(T)$. A deviation from the single mechanism of flux pinning in the superconductor's bulk appears gradually with increasing temperature, seen as a modification in the curve shape. We expect that the weakening of the inter-grain currents compared to the intra-grain ones is responsible for the change clearly distinguishing the 102 K curve from the rest.

The temperature dependence of B_{max} is similar for all the tapes, as illustrated in Fig. 6. The abscissa was normalized by B_{max} at 80 K for each tape. The dashed line is a linear interpolation that can be expressed as

$$B_{\max}(T) = B_{\max}(T_{\text{ref}}) \frac{T_0 - T}{T_0 - T_{\text{ref}}},$$

where the reference temperature was $T_{ref} = 80$ K, and the temperature at which the linear interpolation breaks $T_0 = 100$ K. The temperature de-



Fig. 6. Temperature dependence of the position of the susceptibility peak. Data of different tapes are scaled to the 80 K value.

pendence of B_{max} , combined with the shape of $\chi''(B_{\text{a}})$ curve established at any temperature within the validity of the interpolation (5), supplies the formula for the amplitude and temperature dependence of χ'' :

$$\chi''(B_{\rm a},T) = \chi''_{\rm max}g\bigg(\frac{B_{\rm a}}{B_{\rm max}(T)}\bigg). \tag{6}$$

In this expression, the negligible temperature dependence of the maximum height was omitted. The function g(x) defines the shape of $\chi''(B_a)$ curve, with $x = B_a/B_{max}(T)$ reflecting the relative strength of AC field. The form of g(x) was characteristic for each tape. Taking into account, that χ'' is the only temperature dependent quantity in the loss formula (1), Eq. (6) allows to predict the hysteresis loss at an arbitrary temperature within the validity interval of the critical state model. For our samples this interval was 77–95 K, just that one attractive for power transmission applications.

6. Conclusions

Magnetic hysteresis losses were studied on a set of Bi-2223/Ag tapes with different filament architecture in an AC magnetic field oriented perpendicularly to the tape surface. It was observed, that the dependence of the maximum height in $\chi''(B_a)$ curve on tape architecture is insignificant. This indicates that χ_0 , the value of susceptibility in perfect diamagnetic state, is a purely geometric constant defined entirely by the filament geometry and distribution. Then it is possible to use it for calibration of the susceptibility data, and absolute values of AC loss can be found.

Entering the loss formula as a proportionality constant, a low value of χ_0 is of crucial importance when the lowering of hysteresis loss is a goal. One possible way, practically demonstrated here, is the arrangement of filaments into stacks rather then putting it in overlapping structure. Another possibility is to manufacture a tape with filaments that are parallel to the field which is perpendicular to the tape wide face. For both cases, the achieved values of χ_0 were distinctively lower than for the tape with ordinary filament architecture.

The manufacturing process for these uncommon filament structures is still far from being optimized from the point of view of filament regularity, density and texturing. This is manifested in the shape of $\chi''(B_a)$ curves, that are much broader and exhibit lateral maxima. As a result, the achieved AC loss reduction is not always so significant as expected from the lowering of χ_0 . Performing the experiments at different temperatures, we found that the flux dynamics is well described by the critical state model in the temperature range 77–95 K, and this allows to express the magnetic hysteresis AC loss in this interval by one general formula, that contains the function defining the shape of the susceptibility curve, and the temperature dependence of the peak position.

The magnetic hysteresis loss we dealt with in this paper is only one of the processes that contribute to heat generation in superconducting tapes in AC conditions. Therefore our conclusions about optimization of the filament architecture are valid only from the point of view of this mechanism. Other mechanisms should be taken into account separately and also in combination with hysteresis loss, depending on the conditions of application (temperature, frequency, field, ...). Therefore the design of low-loss tape could not be solved as a general problem, and further thorough studies are necessary for any particular case.

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