AFRL-PR-WP-TP-2006-232

HYSTERETIC LOSS VS. FILAMENT WIDTH IN THIN YBCO FILMS NEAR THE PENETRATION FIELD

M.D. Sumption, E. Lee, Coleman B. Cobb, Paul N. Barnes, Timothy J. Haugan, Justin Tolliver, Charles E. Oberly, and E.W. Collings

AUGUST 2002

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YY)*** August 2002	**2. REPORT TYPE** Journal Article Postprint	**3. DATES COVERED** ***(From - To)*** 08/06/2001 – 08/06/2002

4. TITLE AND SUBTITLE

HYSTERETIC LOSS VS. FILAMENT WIDTH IN THIN YBCO FILMS NEAR THE PENETRATION FIELD

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
61102F/62203F

6. AUTHOR(S)

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5d. PROJECT NUMBER
3145

5e. TASK NUMBER
32

5f. WORK UNIT NUMBER
314532Z9

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Power Generation Branch (AFRL/PRPG)
Power Division
Propulsion Directorate
Air Force Research Laboratory, Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7251

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Columbus, OH 43210

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-PR-WP-TP-2006-232

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Propulsion Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson AFB, OH 45433-7251

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL-PR-WP

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-PR-WP-TP-2006-232

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

Journal article published in IEEE Transactions on Applied Superconductivity, Vol. 13, No. 2, June 2003.

PAO case number: ASC-02-2823; Date cleared: 18 Nov 2002.

14. ABSTRACT

Magnetization vs. applied field measurements (*M-H* loops) were taken on YBCO thin films with filaments patterned into them. The YBCO was deposited onto $LaAlO_3$ substrates using PLD, and the filaments were formed by laser ablation. *M-H* loops were taken at 4.2 K in fields up to ±9 T using a vibrating sample magnetometer technique, the field applied perpendicular to the film width, *d*. The losses were seen to be greatly reduced by filament width reductions following the standard expression $Q_h/H_m \alpha dJ_c/10$. The penetration field was also well described by the standard "high field" expression = $H_p = (0.4J_c t) \ln(d/t + 1)$, where *t* is the film thickness. The regimes of applicability of the loss expression were investigated, in particular near $H_m \approx H_p$. A more general form of the loss equation was obtained and compared with the high-field approximation. The result was that although Q_h/H_m still increased in proportion to *d*, the rate of increase decreased as H_m approached H_p.

15. SUBJECT TERMS
AC loss, hysteretic loss, penetration field

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT:**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Paul N. Barnes
Unclassified	Unclassified	Unclassified	SAR	10	**19b. TELEPHONE NUMBER** *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Hysteretic Loss *vs.* Filament Width in Thin YBCO Films Near the Penetration Field

M. D. Sumption, E. Lee, Coleman B. Cobb, Paul N. Barnes, Timothy J. Haugan, Justin Tolliver, Charles E. Oberly, and E. W. Collings

***Abstract*—Magnetization vs. applied field measurements (M-H loops) were taken on YBCO thin films with filaments patterned into them. The YBCO was deposited onto $LaAlO_3$ substrates using PLD, and the filaments were formed by laser ablation. M-H loops were taken at 4.2 K in fields up to ±9 T using a vibrating sample magnetometer technique, the field applied perpendicular to the film width, d. The losses were seen to be greatly reduced by filament width reductions following the standard expression $Q_h/H_m \propto dJ_c/10$. The penetration field was also well described by the standard "high field" expression $H_p = (0.4J_ct)\ln(d/t+1)$, where t is the film thickness. The regimes of applicability of the loss expression were investigated, in particular near $H_m \approx H_p$. A more general form of the loss equation was obtained and compared with the high-field approximation. The result was that although Q_h/H_m still increased in proportion to d, the rate of increase decreased as H_m approached H_p.**

***Index Terms*—AC loss, hysteretic loss, penetration field, YBCO.**

I. INTRODUCTION

AC loss in HTSC strand, and YBCO coated conductor in particular, is a topic of considerable interest. YBCO thin films have considerable promise for AC applications [1]–[3]. While the geometries of present day coated conductors are perhaps appropriate for DC application [3]–[6], one of the limitations to its use will be the difficulty in obtaining low loss strand designs [1], [2], [7]. In the context of applied external fields, one of the dominant factors in the loss is the hysteretic component, Q_h, generated by the fact that the conductor is relatively wide. The closest approximation to the multifilamentary treatment common in low temperature superconductors is the technique of filamentarization by cutting or forming grooves in the YBCO layer. We will refer to this as striation.

Some properties of the AC loss of striated samples have been published previously [8], [9]. However, one of the areas that needed closer scrutiny was the validity of the proportionality of Q_h to d for relatively thin conductors, in moderate fields. This work focuses on this question, in the regime of 1 to 2 T, which is a regime of practical interest for motors and generators.

II. EXPERIMENTAL

A. Sample Fabrication

YBCO was deposited onto single-crystal $LaAlO_3$ (LAO) substrates by pulsed laser deposition as described elsewhere [10], [11]. The LAO substrates measured 3.2 mm × 12 mm and the deposited YBCO films varied in thickness from 0.25 μm to 0.33 μm. A YAG laser was used to ablate the film at room temperature and atmospheric pressure to create the striations in the YBCO films. The actual ablations were performed by Mound Laser & Photonics Center, Inc. [12]. The beam energy was reduced to mitigate the thermal effects on the YBCO film, and a steady flow of argon gas aided in the removal of the ablated materials. Samples were created with average filament widths of 82 μm, 254 μm, and 492 μm. The cuts between filaments, where the YBCO was ablated, ranged in width from 49 μm to 82 μm on each of the samples. The striated samples, as well as a control (nonstriated) sample, were taken from a single batch of processed samples. A separate unstriated sample, TJ309, was also fabricated.

B. Measurements

All measurements were made with a vibrating sample magnetometer (VSM) technique. Two different machines were used, a low field, 1.7 T machine, and a high field, 9 T machine. Both used PAR EG&G M4500 instrumentation and were computer controlled. The 1.7 T system used a small varitemp helium dewar with a tail inserted into a water-cooled magnet. Samples were measured in transverse fields using ramp rates of up to 700 Oe/s. The large VSM was mounted on an Oxford dewar which had an associated varitemp cryostat. Ramp rates similar to the 1.7 T machine were available, and the field sweep was a bipolar ±9 T. M-H loops were measured at 4.2 K. All magnetization measurements were taken at fixed field sweep amplitudes, H_m, with the applied field parallel to the c-axis (perpendicular to the sample face). The field profile for the magnetization measurements in this work was triangular.

III. RESULTS

The M-H loop for sample TJ309 is shown in Fig. 1. The loop height, ΔM, is strong out to 9 T, showing that the sample has respectable in-field properties, thus meriting further analysis. Separate studies have confirmed the T_c and M-H properties of these tapes at higher temperatures [8]. M-H loops for the striated sample set are shown in Fig. 2. Here we see the generally expected effect; hysteretic losses are significantly lower for striated samples. An earlier study on these samples showed

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Manuscript received August 6, 2002. This work was supported by the U.S. Department of Energy under Grant DE-FG02-95ER40900, the AFRL Propulsion Directorate Summer Faculty Program, and the Air Force Office of Scientific Research.

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Digital Object Identifier 10.1109/TASC.2003.812396

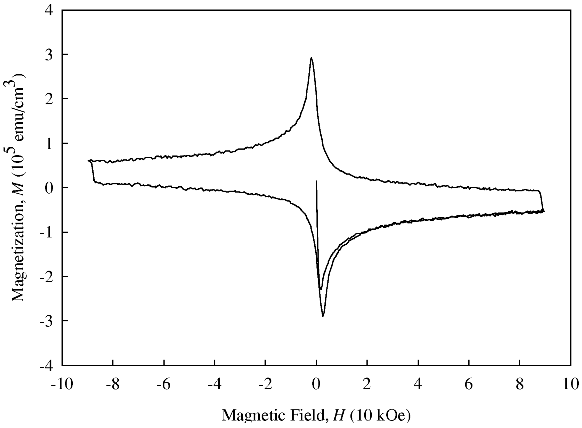

Fig. 1. M-H loop at 9 T and 4.2 K for sample TJ309.

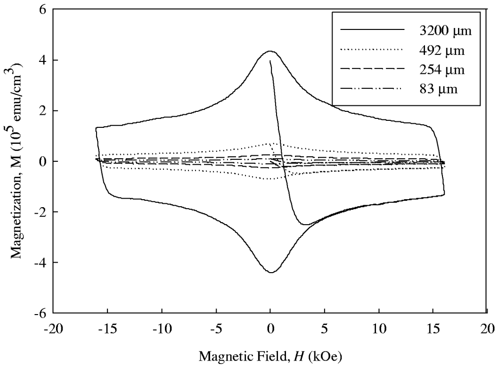

Fig. 2. M-H loops for striated sample set at 4.2 K.

that, for fixed H_m, Q_h/H_m (and hence ΔM) was linearly proportional to d [8], as expected based on Bean theory, following for example Carr's [12] expression for specific loss per cycle

$$\frac{Q_h}{H_m} = \frac{J_c d}{10} \tag{1}$$

valid for $H_m \gg H_p$, the penetration field. Under this condition the field lines are relatively perpendicular to the wide face of the sample, and expectation of linearity is relatively straightforward. However, at lower fields, the field lines become quite distorted, and it is not intuitively obvious that this would be true. Indeed, for these types of very thin samples the penetration field is proportional to the thickness, t, since the field first penetrates along the t-axis. It is of interest, then to see the proportionality of ΔM to d in this lower field range.

We present the data of Fig. 2 in the format ΔM vs filament width, d, in Fig. 3. Here we can see the results for various fields. In all cases, the d-dependence is linear. In order to understand this more fully, we can look more closely at the theoretical expectation.

IV. CALCULATION

A. Penetration Field

From Carr [12], the penetration field for these conductors (where $d \gg t$) is

$$H_p \approx 0.4 J_c t \left[\mathrm{Ln}\left(\frac{d}{t}\right) + 1\right]. \tag{2}$$

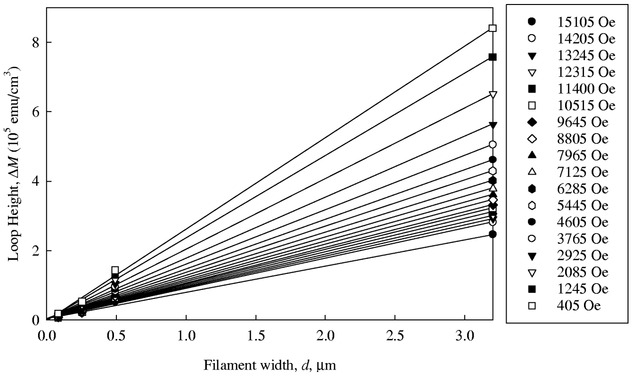

Fig. 3. Loop height, ΔM vs d for the striated sample set at 4.2 K.

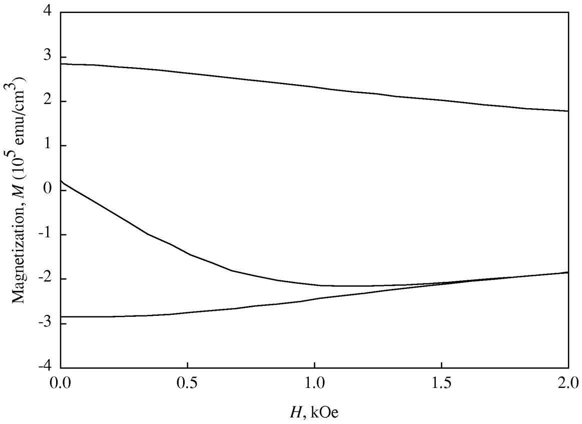

Fig. 4. M-H loop at 4.2 K for sample TJ309 showing the penetration field, $H_p \cong 1.5$ kOe.

Here J_c is the critical current density, d is the strand or filament width, and t is the thickness. The units are cgs-practical (A, cm, Oe).

We can use this expression to calculate the penetration field for our samples. Taking, e.g., the unstriated sample we get a ΔM of about 4×10^5 emu/cm^3 at field penetration, leading to a critical current density of about 2.5×10^7 A/cm^2 (at 4.2 K). Using this number, in conjunction with $d = 0.32$ cm and $t = 0.25$ μm, we find that $H_p = 2.6$ kOe, which is in reasonable agreement with the experimental result, Fig. 4, given the approximations involved. However, it is clear that the condition $H_m \gg H_p$ is not fulfilled where we have taken ΔM. Nevertheless, by comparing [13, Eq. 19 and 21], we were able to see that under this condition (1) was roughly applicable but with a prefactor that varied rapidly with H_m/H_d. This brings up the general applicability of the typical loss expressions.

B. Hysteresic Losses

The Carr expression, (1) is valid only for $H_m \gg H_p$. For much smaller values of H_m/H_p we would like to know whether Q_h/H_m is still directly proportional to d, and if so its rate of increase with d. Muller's expressions for hysteretic power loss [13], [14] provided us with a point of entry. After converting Muller's expressions from power to loss/cycle we find after

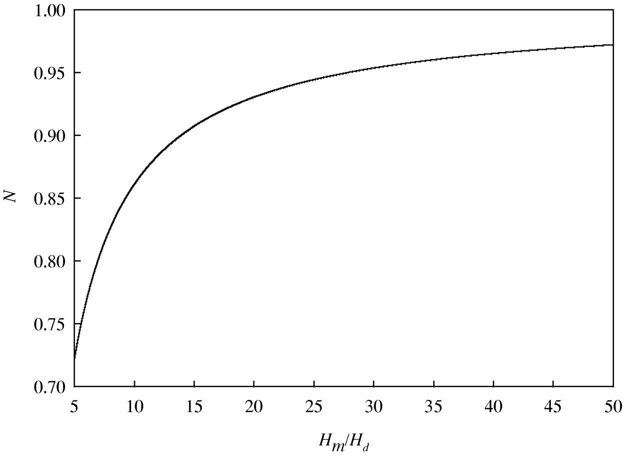

Fig. 5. N vs H_m/H_d for large H_m/H_d.

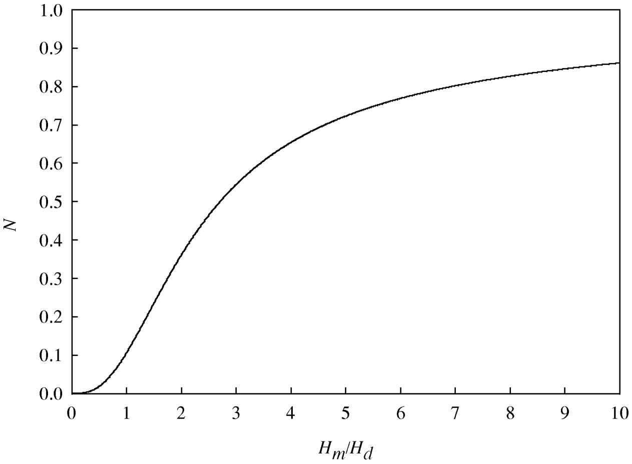

Fig. 6. N vs H_m/H_d for small H_m/H_d.

making some other appropriate modifications the following expression for hysteretic loss in the relatively small H_m regime:

$$\frac{Q_h}{H_m} = N\frac{J_c d}{10} \tag{3}$$

where

$$N = \left(\frac{H_m}{H_d}\right) g\left(\frac{H_m}{H_d}\right). \tag{4}$$

Here H_{c1} is assumed to be zero, $g(H_m/H_p)$ is given by

$$g\left(\frac{H_m}{H_d}\right) = \frac{H_d}{H_m}\left[\frac{2H_d}{H_m}\mathrm{Ln}\left(\cosh\frac{H_m}{H_d}\right) - \tanh\frac{H_m}{H_d}\right] \tag{5}$$

and H_d is defined as $0.4J_c t$ (in this particular case about an order of magnitude smaller than H_p). In the low H_m limit, $N \to 0$ as H_m^3, leading to a $Q_h \propto H_m^4$ (as compared to the H_m^3 of the usual situation). In the high-H_m limit, $N \to 1$, leading to a recovery of (1). N is displayed in Figs. 5 and 6 for two ranges of H_m/H_d. Our practical region of interest is not the very high and very low extremes but rather the H_m/H_d range between about 2 and 10. For use in this regime we combine (4) and (5) into the following approximation for N for use in (3):

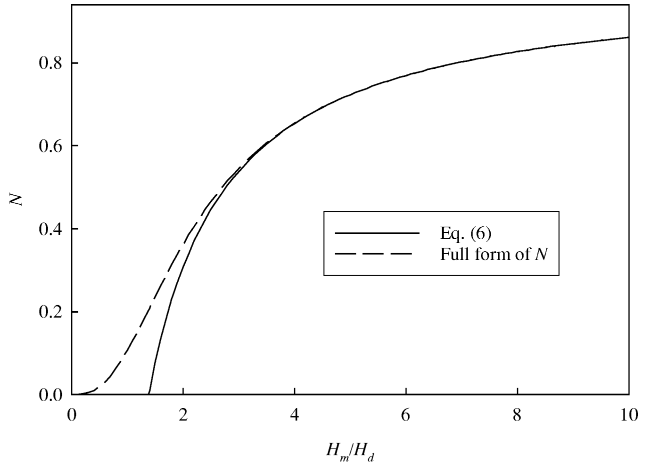

Fig. 7. The full form of N compared to the approximation of (6).

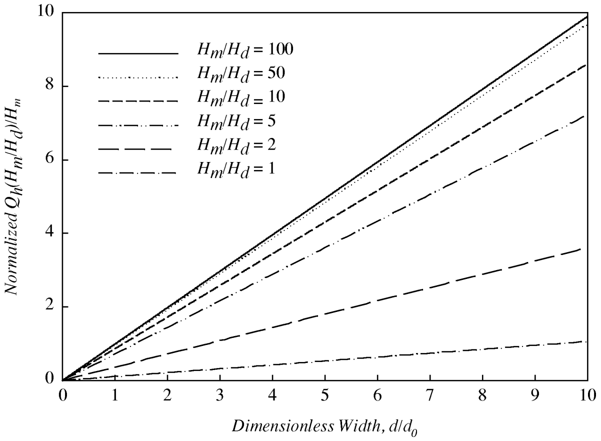

Fig. 8. Normalized Q_h/H_m as a function of dimensionless width.

$$N\left(\frac{H_m}{H_d}\right) = \left[1 - \frac{2\mathrm{Ln}2}{\left(\frac{H_m}{H_d}\right)}\right]. \tag{6}$$

This expression is plotted in Fig. 7, along with the full form of (4). The agreement is fairly good above $H_m/H_d = 3$.

In general, looking at (3)–(6), we can see that, except for the smallest H_m/H_d ratios, $Q_h/H_m \propto d$, but with a prefactor that varies with H_m/H_d. In normalized format we have plotted the variation of Q_h/H_m (proportional to ΔM in the Bean approximation) with d in Fig. 8 for comparison with the experimental results of Fig. 3. The results of theory and experiment together indicate that Q_h/H_m is indeed proportional to d, but that its rate of increase is a function of H_m/H_d, and hence H_m/H_p.

V. SUMMARY AND CONCLUSIONS

We have investigated the variation of Q_h with d for various striated thin YBCO films. We find that even outside the range of the simple Bean approximation ($H_m/H_p \gg 1$) Q_h/H_m still increases in proportional to d, but more slowly depending on the value of a loss-prefactor N. Furthermore we have computed the dependence of N on the quantity (H_m/H_d) within a practical range of interest.

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