Effects of a ferromagnetic substrate on hysteresis losses of a YBa$_2$Cu$_3$O$_7$ coated conductor in perpendicular ac applied magnetic fields

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Abstract. The effects of a ferromagnetic substrate on ac losses of a YBa$_2$Cu$_3$O$_7$, YBCO, coated conductor in perpendicular ac magnetic fields were investigated by measuring the losses of a set of the specimens which were made by placing one Ni-5 at. % W tape on one or both sides of a YBCO layer on a Hastelloy tape. For applied field amplitude, $\mu_0 H_0 < ~ 5$ mT, the losses with the Ni-W tape(s) were higher than those of the YBCO tape, but for $~ 5$ mT < $\mu_0 H_0 < ~ 0.1$ T, the losses were reduced by putting the Ni-W tape(s) on the YBCO tape. For $\mu_0 H_0 > ~ 0.1$ T, the losses became the same for all of the specimens. Also, the geometric actor $\chi_0$ of the susceptibility $\chi$ was determined from the hysteresis loops for these specimens, and was found to decease with the addition of the magnetic substrate. These observations agreed very well with the theoretical calculations for the losses and $\chi_0$ for a YBCO layer on a ferromagnetic substrate by Y Mawatari (unpublished).

1. Introduction
Recently significant developments in the fabrication of so-called coated conductors, which are metallic tapes coated with a high-critical-temperature superconductor, YBa$_2$Cu$_3$O$_7$, (YBCO), layer, have been made such that model magnets and electric power-transmission lines are being studied for possible use as the conductors for technological applications. One type of metallic substrates, which is currently used for the conductors, is a textured Ni-5 at. % W alloy.$^1$ Since this alloy is ferromagnetic, possible effects of the substrate on ac (hysteresis) losses of the conductors are of considerable interest for their uses in electrical utility applications. In order to investigate the possible effects, two finite-element calculations were previously made for the losses of an imaginary conductor, which consisted of a superconducting layer sandwiched by two ferromagnetic layers with high relative permeability $\mu_r$ in perpendicular applied fields.$^2$ The results showed that significant reductions in the losses are expected for the field amplitude $H_0$ in the regions of and below the full penetration field of the tape.
Experimentally, circular disks of a YBCO layer on a Ni-5 at. % W substrate were also measured for ac losses in perpendicular magnetic fields. In general, the observed trends of the effects of the magnetic substrates on the losses were in agreement with the results of the finite-element calculations, although some important details of the experimental results differed from the calculated ones. More recently, an analytical calculation was made employing a conformal-mapping technique to investigate the effects. Importantly, this work was in the form such that the calculated results were readily and quantitatively compared with the results of experimental loss measurements. Thus, the losses were measured using a YBCO tape with a nonmagnetic substrate, which was stacked with magnetic tapes to simulate a conductor with a magnetic substrate, in order to further investigate the effects of magnetic substrates on the losses.

In this paper, the experimental setup is described for the measurements of the ac losses and the geometrical portion $\chi_0$ of the susceptibility $\chi$ of the tapes in perpendicular magnetic fields. (See Ref. 6 for the definition of the susceptibility and their relationship to the losses.) Then, the experimental results are summarized for the losses and $\chi_0$, and these are discussed in term of the results of theoretical calculations.

2. Experimental procedure

The superconducting tapes were made by depositing a YBCO layer on an oxide-buffered 100-μm-thick Hastelloy (a Ni-base nonmagnetic alloy) tape by a pulsed laser deposition technique. The thickness $d$ of YBCO was 2.3 μm and the size of the specimens was 10 mm in width $2W$ and 100 mm in length. The self-field critical-current density $J_c$ of the tape was $1.17 \times 10^{10}$ A/m² in liquid nitrogen. The losses were measured in liquid nitrogen at 20 Hz using a pair of rectangular pickup coils. Perpendicular magnetic fields were supplied by a Cu-wire-wound solenoid which was also immersed in the liquid. The losses were determined by plotting hysteresis loops, ($\mu_0M$ vs. applied field amplitudes $\mu_0H_0$), and calculating the areas of the loops for the preselected values of $\mu_0H_0$. The details of the measurement setup are described elsewhere. In order to determine the effects of the magnetic substrates on the losses of YBCO, the losses were measured for the following sets of three tape stacks; #1) (YBCO-Hastelloy), #2) (YBCO-Hastelloy)/(Ni-W), and #3) (Ni-W)/

![Figure 1](image_url). Examples of the hysteresis loops, [$\mu_0M$ vs. applied magnetic field amplitudes ($\mu_0H_0$)], are shown for the specimens, (1) (YBCO-Hastelloy), (2) (YBCO-Hastelloy)/(NiW), (3) (NiW)/(YBCO-Hastelloy)/(NiW) for $\mu_0H_{0\max} = (a) 1.8$ mT and (b) 20 mT.
(YBCO-Hastelloy)/(Ni-W). In making the stacks, a Ni-W tape(s) was placed on the YBCO tape with a thin (~ 25 μm) insulating tape between them. The magnetic substrates were 100 μm thick (Ni-5 at. % W) alloy tapes of the same size as the (YBCO-Hastelloy) tape. Examples of the hysteresis loops for the stacks #1 - #3 are shown in figure 1 (a) and (b) for \( \mu_0H_0 = 1.8 \) and 20 mT, respectively. The hysteresis losses of the Ni-W substrate tapes were also measured in the fields applied parallel and perpendicular to the face of the tapes. In both cases, the losses were substantially lower than those from the YBCO stacks, and thus did not play any role in the measurements of the losses of the above stacks.

In addition to the measurements of the losses, approximate values of the susceptibility \( \chi_0 \) were determined from the hysteresis loops such as those in figure 1 by measuring the slopes of the loops right after the directions of the increasing or decreasing field amplitudes were reversed at the maximum field amplitudes of each cycle. Although \( \chi_0 \) was defined as the slope of the \( \mu_0M \) vs \( \mu_0H_0 \) curve in the Meissner state of a superconductor, \( (\chi_0 = -dM/dH, \mu_0H \Rightarrow 0) \), this method provided good approximate values for \( \chi_0 \) which were sufficient for the present purpose. For example, at the lowest field amplitude, i.e., \( \mu_0H_0 = 1.8 \) mT, the hysteresis was very small for the YBCO-Hastelloy tape as shown in figure (1-a), and the value of \( \chi_0 \), which was determined for this case by this method, was in very good agreement with the value which was obtained from equation (2) in reference 6, i.e., the theoretical and the measured values were 3.41 and 3.48 x 10^3, respectively. However, at higher fields, the measurements became more difficult than at low fields, and the values tended to vary \( \sim \pm /- 5 \% \) of the average value.

At this point, somewhat uncommon units for power dissipation, magnetization, and magnetic susceptibility, \( \overline{P}/(J/m/\text{cycle}), \mu_0M/(\text{Tm}^2) \) or \( M/(\text{Am}) \), and \( \overline{\chi_0}/(m^3) \), respectively, which are used in figure 1 and below, need to be explained. As pointed out by Y Mawatari, the need for these units arises from the fact that the appropriate volume, more precisely the thickness, for a composite specimen for calculating the volume magnetization is unknown when it includes a ferromagnetic substrate. Since the length and the width of the specimen are well described, it is convenient to use the above units for the pertinent variables in this study. In order to change the variables from the standard units, such as those in equation (1) – (3) in reference (6), to the new units, one simply needs to multiply the standard variables by the cross-sectional area of the superconductor.

3. Experimental results and discussions
The losses from all of the specimen configurations are summarized in figure 2. In order to illustrate clearly the differences among the losses for the YBCO tape with and without the magnetic substrate(s), the normalized power losses, \( \overline{P}/4\mu_0W^2H_0^2 \), were plotted against the normalized applied-field amplitudes, \( H_0/J_d \), in a log-log plot. There are some outstanding differences in the behavior of the loss characteristics as a function of applied fields among these specimens. When one or two magnetic substrates were stacked with a (YBCO-Hastelloy) tape, the losses were increased substantially at the lowest fields, \( (H_0/J_d) < \sim 0.15 \) or \( (\mu_0H_0) < \sim 5 \) mT, over those of the YBCO alone. These increases in the losses were not due to the hysteretic nor eddy current losses of the magnetic substrates since they were substantially lower than those of the YBCO tapes as mentioned above. As the fields were increased, the loss curves for three specimens crossed over such that the losses for the stacks with the Ni-W substrate(s) became well below those of the (YBCO-Hastelloy) tape. In fact, the losses for the stack with two magnetic substrates, whose losses were the highest among the three stacks at the lowest fields, became the lowest in the “middle field” region, \( \sim 0.15 < \mu_0H/J_d < \sim 2 \). Upon further increases in the fields, \( H_0/J_d > \sim 2 \) or \( \mu_0H_0 > \sim 0.1 \) T, the losses for all of the stacks became essentially the same. In order to understand, the differences in the behavior of the losses observed above with and without the magnetic substrate(s), it is very informative to compare the above results with those which were calculated by Y Mawatari for the specimens consisted of a superconducting layer placed directly on a normal-metallic and a ferro-magnetic substrate of the equal
Figure 2. A summary of the normalized losses ($\frac{P}{4\mu_0 W^2 H_0^2}$) as a function of the normalized applied field amplitude $H_0/J_c d$ for all of the stacks.

Figure 3. The values of the susceptibility, $\chi_0 (m^2)$, vs. applied magnetic field amplitudes $\mu_0 H_0$ are plotted for all of the stacks.

The behaviors of the calculated normalized losses $\frac{P}{4\mu_0 W^2 H_0^2}$ as a function of applied fields $H_0/J_c d$ were extremely close to those for Fig. 2 for the losses of a (YBCO-Hastelloy) and a (YBCO-Hastelloy)/(Ni-W) tape. In fact, some of clearly identifiable features of the losses can be quantitatively compared. For example, the predicted upper-limit ($H_0/J_c d$)$^*$ of the lowest field regime, where the loss curves crossed over, was $\sim 0.14$. This was essentially equal to the experimentally determined value of $\sim 0.13$. Also, the maximum value ($\frac{P}{4\mu_0 W^2 H_0^2}$)$_{\text{max}}$ of the losses was calculated to be $\sim 0.34$ which occurred at ($H_0/J_c d$)$_{\text{max}}$ $\sim 1.2$. Experimentally these were $\sim 0.28$ and $\sim 0.9$ ($\mu_0 H_0 = 30 \text{ mT}$), respectively. These minor differences between the calculated and the observed values are likely attributable [1] to the use of the Bean critical state model for $J_c$ in the calculations while $J_c$ of the YBCO specimen exhibits a significant applied-perpendicular-field dependence at these low fields, and [2] to the difference in the geometry of the composite tapes for the calculation and the experiment. Furthermore, the calculations$^5$ showed that the enhanced losses at the low fields were caused by flux concentration at the edges of a magnetic substrate when the widths of the substrate and a superconducting film were the same. This conclusion was supported by the calculations that the enhancement of the low-field losses was not present when the magnetic substrate was made wider than the superconductor. In this case the losses were lower for the specimen with the magnetic substrate than those for a superconducting layer alone for the entire field region until the losses became equal at higher fields.

The results of the measurements of $\chi_0$ for all of the stacks are shown in Fig. 3 as a function of $\mu_0 H_0$. As mentioned above, the value of $\chi_0$ ($\chi_0 = 8.0 \times 10^{-5} \text{ m}^2$) of the YBCO-Hastelloy (#1) tape was in good agreement with the value calculated from equation (2) in reference 6, and as expected it was independent of $\mu_0 H_0$ as shown in figure 3. Putting a ferromagnetic substrate on the YBCO tape, the (YBCO-Hastelloy)/(Ni-W) stack, decreased the value of $\chi_0$ to $5.93 \times 10^{-5} \text{ m}^2$. This was also in extremely good agreement with the predicted value$^5$ of $\chi_0$ [\(\frac{3}{4\pi} W^2 = 5.89 \times 10^{-5} \text{ m}^2\)]. The addition of the second magnetic substrate further decreased the value of $\chi_0$ to $4.14 \times 10^{-5} \text{ m}^2$. These
reductions in $\chi_0$ by the additions and the associated lowering of the losses in “the middle field range” in figure 2 are consistent with what one expects from equation (1) in reference (6) even though the expression for $\chi''$ for a superconductor/ferromagnet composite would be different from equation (3). However, in the lowest field regime, the same trend between the losses and $\chi_0$ was not observed, i.e., the losses were higher while $\chi_0$ was smaller for the stacks with the magnetic substrates than that for the (YBCO-Hastelloy). Although this appears contrary to what one expects from equation (1) in reference (6), this is likely the consequence of the fact that $\chi_0$ or $\chi_0$ is the measure of the amount of the magnetic field, which is excluded from a superconductor in magnetic fields prior to the magnetic vortex penetration into a superconductor. On the other hand, the losses are due to the hysteretic motion of the vortices after the fields penetration. Thus, $\chi_0$ with a ferro-magnetic substrate(s) is solely the geometrical property of a superconductor/magnet composite and not being influenced by the edge fields. However, $\chi''$ is strongly affected by the manner for which the fields are penetrated into a superconductor. The flux concentration at the edges of a magnetic tape will make the edge fields of a thin superconductor to increase above the sharp field profile which already exists in a thin superconductor in magnetic fields. This promotes initially deeper penetration of the vortices into the superconductor with the magnetic substrate than that for the superconductor alone. This enhanced vortices penetration causes higher losses with a magnetic substrate(s) at the lowest fields. As the fields increased, the influence of the enhanced fields at the edges on the losses will be diminished and the losses qualitatively follow what one expects from equation (1) of reference (6). We also note that the values of $\chi_0$ are increased as $\mu_0H_0$ is increased for the stacks with the magnetic substrates, particularly for the stack #3, and this is possibly related to the magnetic saturation of Ni-W tapes. At $\mu_0H = \sim 25$ mT, the alloy tape reaches 75 % of its saturation in parallel applied fields. However, it is not understood whether this increase in the values of $\chi_0$ affects the losses.

Finally, it was interesting to note here that the calculation assumed an infinite relative magnetic permeability, $(1/\mu_r << 1)$, for the magnetic substrate, while the value of $\mu_r$ for the Ni-5 at. % W, which is used in this experiment, is an order of 30 as estimated from the hysteresis curves of the alloy tape. In spite of this, as discussed above, the calculated and the experimentally measured losses are in such good agreement. This suggests that the values of $\mu_r$ of the substrates do not significantly affect $\chi_0$ nor the losses significantly when $1/\mu_r << 1$. This is contrary to the findings of the finite-element calculation.  

4. Summary

The effects of the placement of a ferromagnetic sheet(s) on a YBCO film on a nonmagnetic substrate on hysteretic losses of the YBCO were experimentally studied. The placement lowered the losses at applied fields around and below the full penetration fields of the YBCO film. But, at low fields, $(H_0/J_c d) < \sim 0.15$, the losses were substantially greater than those for the YBCO specimen without a ferromagnetic tape. These low-field increases were attributed to the enhanced fields at the edges of the magnetic substrate when the widths of the YBCO and the substrate(s) are the same. Also, the geometrical portion of the magnetic susceptibility, $\chi_0$ or $\chi_0$, were determined from the hysteresis loops. These values were decreased by the placement of the magnetic substrates. All of the above experimental observations were in excellent agreement with the predictions of the theoretical calculations by Y Mawatari.

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[6] It is often convenient to express ac losses in terms of the complex magnetic susceptibility parameter, $\chi$, where $-dM/dH = \chi = \chi' + i\chi''$, and the losses are given by an expression,9

$$P = \pi\mu_0\chi''H_0^2$$ \hspace{1cm} (1)

where $P$ and $H_0$ are the losses in J/m$^3$/cycle, and applied magnetic-field amplitudes, respectively. Also, $\chi_0$ is only a function of specimen geometry, the thickness $d$ and the width $2W$, of the superconductor while $\chi''$ is a function of $H_0$, $d$, and $J_c$, the critical current density of the superconductor. $\mu_0$ is the permeability of space. For a thin superconducting strip, these are given by $^{10,11}$

$$\chi_0 = \pi W/2d$$ \hspace{1cm} (2)

and $\chi'' = (4/\pi x)g(x)$ \hspace{1cm} (3)

where $g(x) = (2/x)\ln(\cosh x) - \tanh x$, $x = H_0/H_C$, and $H_C = J_C d/\pi$.

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