Relaxation properties of persistent current in
YBCO-coated conductors

K. Himeki\textsuperscript{a}, M. Kiuchi\textsuperscript{a}, E.S. Otabe\textsuperscript{a}, T. Matsushita\textsuperscript{a,1},
S. Miyata\textsuperscript{b}, A. Ibi\textsuperscript{b}, Y. Yamada\textsuperscript{b}, Y. Shiohara\textsuperscript{c},

\textsuperscript{a} Faculty of Computer Science and Systems Engineering, Kyushu Institute of
Technology, 680-4 Kawazu, Iizuka 820-8502, Japan

\textsuperscript{b} Superconductivity Research Laboratory, 2-4-1 Matsuno, Atsuta-ku, Nagoya,
456-8587, Japan

\textsuperscript{c} Superconductivity Research Laboratory, 1-10-13 Shinonome, Koto-ku, Tokyo,
135-0062, Japan

\textbf{Abstract}

The relaxation properties were investigated for PLD processed YBCO coated
conductors deposited on IBAD substrates in the region of 0.25 – 1.50 \mu m for the
thickness of superconducting layer to clarify the thickness dependence of the re-
laxation of magnetization. The apparent pinning potential \( U_0^* \) was estimated from
the relaxation rate. It was found that \( U_0^* \) increases with increasing temperature in
the low temperature region. The weak thickness dependence of \( U_0^* \) in this temper-
ature region comes from the three-dimensional flux pinning mechanism. Then, \( U_0^* \)
has a peak followed by a decrease with increasing temperature. The peak value of
\( U_0^* \) increases with increasing thickness. Hence, the thicker superconductor is more
advantageous for applications in the middle temperature range and higher. The flux
pinning mechanism in the medium and higher temperature region is two-dimensional
and the larger \( U_0^* \) value in the thicker specimen originates mainly from the thickness.
For the improvement of \( U_0^* \) in the low temperature region, it is required to enhance
the flux pinning strength and to increase the thickness without deterioration in the
critical current density.

\textit{Keywords:} YBCO, thickness, relaxation, \( U_0^* \), flux creep-flow model

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\textsuperscript{1}Corresponding author.
T. Matsushita
Postal address: Department of Computer Science and Electronics, Kyushu Institute
of Technology, 680-4, Kawazu, Iizuka 820-8502 Japan

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1 Introduction

Various applications of YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) tapes at low and medium temperatures and at high magnetic fields are expected because of very high critical current density. Candidates for such applications are superconducting magnets for nuclear magnetic resonance (NMR) and superconducting magnetic energy storage (SMES), etc. For these applications, the stability of superconducting persistent current is a fundamental issue.

It is known that the superconducting current originated from the flux pinning mechanism is not a true persistent current but decreases with time due to thermal activation of pinned flux lines. This phenomenon is caused by the flux creep. For this reason, it is necessary to improve the relaxation properties of the pinning current in YBCO tapes for application to equipments operating in a persistent current mode.

The important parameter in the flux creep is the pinning potential, $U_0$. It is known that $U_0$ has a dependence on the thickness of superconducting layer in the two-dimensional pinning regime. Hence, it seems to be important to investigate the relaxation property of superconducting current for coated tapes with different superconducting layer thickness. In fact, it was reported that the $n$-value is larger for thicker superconducting layer in the low electric field region at low temperatures [1]. In this paper, the thickness dependence of relaxation of IBAD/PLD processed YBCO tapes is investigated in the range of 0.25 – 1.5 $\mu$m.

Phone: +81–948–29–7663; Fax: +81–948–29–7661
E-mail address: matusita@ose.kyutech.ac.jp
2 Experiments

The specimens were PLD-processed YBCO-coated conductor deposited on IBAD substrate with GZO inner layer and CeO$_2$ cap layer [2]. The thicknesses of YBCO layer were 0.25, 0.50, 1.00 and 1.50 $\mu$m. The specifications of these specimens are listed in Table 1.

The DC magnetization and its relaxation were measured by a SQUID magnetometer in a magnetic field parallel to the c-axis of the specimen. Measurements were done up to 7 T over the temperature region of 5—70 K. $E$-$J$ characteristics were estimated from the relaxation measurements and $J_c$-$B$ characteristics were estimated with the electric field criterion of $E_c = 10^{−9}$ V/m. From the logarithmic relaxation rate of the magnetization, the apparent pinning potential $U_0^*$ was estimated:

$$\frac{d}{d \ln t} \left( \frac{M}{M_0} \right) = \frac{U_0^*}{k_B T}. \quad (1)$$

The initial magnetization $M_0$ was determined by extrapolating the relaxation curve from the time range of $10^2 - 10^3$ s to $t = 1$ s.

3 Theory

The critical current properties were analyzed using the flux creep-flow model [3]. In the virtual flux-creep free case, the critical current density takes a value determined only by the flux pinning and its temperature and magnetic field dependence is assumed as

$$J_{c0} = A \left( 1 - \frac{T}{T_c} \right)^m B^{\gamma-1} \left( 1 - \frac{B}{B_{c2}} \right)^2, \quad (2)$$
where \( A, \ m, \ \gamma \) are pinning parameters. The pinning potential \( U_0 \) depends on \( J_{c0} \). The superconducting layers thickness \( d \) is also a key factor which determines \( U_0 \), and \( U_0 \) is proportional to \( d \) in the two-dimensional pinning regime, while \( U_0 \) is independent of \( d \) in the three-dimensional pinning regime:

\[
U_0 = \frac{0.835 g^2 k_B J_{c0}^{1/2}}{(2\pi)^{3/2} B^{1/4}}; \quad d > L, \tag{3}
\]

\[
= \frac{4.23 g^2 k_B J_{c0} d}{2\pi B^{1/2}}; \quad d < L.
\]

In the above \( L \) is the pinning correlation length is given by

\[
L = \left( \frac{B_{c0}}{2\pi \mu_0 J_{c0}} \right)^{1/2} \tag{4}
\]

with \( a_f \) denoting the flux line spacing. It should be noted that even if the pinning is in the three-dimensional case at low magnetic fields for fairly thick superconductor, the pinning may change to the two-dimensional one at high magnetic fields due to the increase in \( L \) with decreasing \( J_{c0} \). The parameter \( g^2 \) is the number of flux lines in a flux bundle, and is proposed to be given by

\[
g^2 = g_c^2 \left[ \frac{5k_B T}{2U_c} \log \left( \frac{B a_f \nu_0}{E_c} \right) \right]^{4/3} \tag{5}
\]

so that the critical current density under the flux creep is maximized [4]. In the above \( g_c^2 \) is the maximum value of \( g^2 \) for the perfect three-dimensional triangular flux line lattice, \( U_c \) is the pinning potential when \( g = g_c, E_c \) is the electric field criterion to determine \( J_c \), and \( \nu_0 \) is the attempt frequency of the flux bundle. \( g_c^2 \) is given by

\[
g_c^2 = \frac{C_{66}}{2\pi J_{c0} B a_f}, \tag{6}
\]

where \( C_{66} \) is the shear modulus of flux line lattice. In practical superconductors the flux pinning strength is statistically distributed. Here it is simply assumed
that only the parameter $A$ which represents the pinning strength is distributed as

$$f(A) = K \exp \left[ -\frac{(\log A - \log A_m)^2}{2\sigma^2} \right],$$

(7)

where $A_m$ is the most probable value of $A$ and $\sigma^2$ is a parameter representing a distribution width and $K$ is a normalization constant. The electric field $E$ caused by flux creep and flow is calculated as a function of the current density $J$ and averaged with respect to the distributed $A$. The details of the theoretical calculation are described elsewhere [3]. The theoretical critical current density is determined from the obtained $E$-$J$ curve with the same electric field criterion of $E_c = 10^{-9}$ V/m as done in experiments. The pinning parameters $A_m$, $\sigma$, $m\gamma$ and $g^2$ are determined so that the calculated $E$-$J$ curves agree with the experiments.

$E$-$J$ characteristics is also evaluated experimentally by magnetic relaxation. In the external magnetic field normal to the tape surface, the current density $J$ is estimated by the magnetic moment $m_m$ using the Bean-London model:

$$J = \frac{12m_m}{w^2d(3l - w)},$$

(8)

where $l$, $w$ and $d$ are length, width and thickness of the specimen, respectively.

The electric field $E$ can be estimated from the relaxation of the magnetic moment as

$$E = -\frac{\mu_0 G}{2d(l + w)} \cdot \frac{dm_m}{dt},$$

(9)

where $G$ is a factor determined by the geometry [5].
4 Results and Discussion

Fig. 1 shows the $J$-$B$ characteristics of the four specimens at 20, 50 and 70 K in the magnetic field ranges of (a) $0 - 6.5$ T and (b) $0 - 1.25$ T, respectively. It is found that $J_c$ decreases with increasing thickness at low magnetic fields except for specimen #4. This comes directly from the structural degradation of the superconducting layer such as porosities and/or $a$-axis aligned grains in thick specimen. However, it is found that $J_c$ of the thinnest specimen decreased rapidly with increasing magnetic field due to the strong influence of the flux creep. Fig. 2 (a) shows the relaxation of normalized magnetization for specimen #1 at 1 T in the temperature region of $5 - 60$ K. The relaxation rate increases monotonically with increasing temperature. Fig. 2 (b) shows the relaxation of magnetization of the four specimens at 1 T at 60 K. It is found that the relaxation late increases generally with decreasing thickness. This phenomenon is directly associated with the dependence of the pinning potential on the thickness of superconducting layer. The $E$-$J$ curves of specimen #1 obtained from the relaxation of magnetization are shown in Fig. 3.

The apparent pinning potential, $U_0^*$, is the value of activation energy extrapolated linearly from the measurement point to $J = 0$, and is usually smaller than the real pinning potential, $U_0$. Especially, it is known that $U_0^*$ reduces to zero at $T = 0$. For example, Welch [6] argued the effect of the shape of pinning potential on $U_0^*$ and derived theoretically:

$$U_0^* = 1.65(k_B T U_0^{1/2})^{1/3}.$$  \hspace{1cm} (10)

The temperature dependence of $U_0^*$ at 1 T obtained from the relaxation rate of the four specimens is shown in Fig. 4. In the low temperature region $U_0^*$ increases linearly with temperature and only weakly depends on the thickness.
Then, $U_0^*$ has a peak followed by a decrease with further increase in temperature. It is found that the peak temperature is almost unchanged for specimens #1 - #3, while that of specimen #4 is higher than others. The result on a melt-processed bulk YBCO [6] is also shown in Fig. 4 for comparison.

The behavior that $U_0^*$ approaches zero at $T = 0$ was partly ascribed to the shape of the pinning potential well as described by Eq. (10). However, the prediction of Eq. (10) leads to the larger $U_0^*$ value at low temperatures than observed. This seems to be attributed to the neglect of the distribution of the flux pinning strength $A$ and the reduction in $g^2$ from $g_c^2$ [7].

The pinning parameters obtained from the $E$-$J$ curves are listed in Table 2. The value of $A_m$ increases with decreasing thickness except for #4 due to the structural degradation of the superconducting layer. It is found that $\sigma^2$ increases with decreasing thickness. The theoretical results of $E$-$J$ curves and the $J_c$ characteristics are compared with experiments in Figs. 3 and 5, respectively. It can be seen that agreement is satisfactory. The pinning potential $U_0^*$ estimated with the obtained pinning parameters are compared with experiments in Fig. 6.

In the low temperature region, the flux pinning is three-dimensional and the pinning potential given by Eq. (3) is proportional to $g^2A_m^{1/2}$. Hence, $U_0^*$ is proportional to $A_m^{1/3}$ due to $g^2 = 1$ for the whole specimens. For this reason, the value of $U_0^*$ at low temperature is not so much different among specimens.

In the medium temperature region, the value of $U_0^*$ becomes to be dependent on the thickness, deviating from the linear relationship with temperature. This indicates that the flux pinning changes from three-dimensional to two-dimensional due to the increase in pinning correlation length $L$ over the
thickness. In the two-dimensional pinning regime, the pinning potential given by Eq. (3) is proportional to $g^2A_m d$. The value of $A_m$ decreases gradually and the value of $g^2$ increases with the thickness $d$ as can be seen from Table 2. Eq. (6) leads to that $g^2$ is proportional to $g_e^{-2/3}$ and hence to $J_{c0}^{-1/3}$. Thus, the thickness dependence of $g^2$ given in Table 2 can be explained from the negative correlation between $A_m$ and $d$. As a result, the increase in $U_0^*$ with increasing $d$ in the medium and high temperature region can be explained. Since the dimensional cross-over of flux pinning occurs at lower temperature in the thinner specimen, the thicker specimen is more advantageous. Specimen #4 has a fairly high critical current density, although it is thick. Hence, the change in the flux pinning mechanism from three-dimensional to two-dimensional occurs at high temperature. This causes the high peak value of $U_0^*$.

However, the deviation of the theoretical result of $U_0^*$ from experiments becomes larger at higher temperature. This simply comes from the present assumption that $\sigma^2$ is kept constant up to high temperatures. It is natural that the distribution width of $J_{c0}$ becomes relatively larger, if the distribution originates from the nonuniform critical temperature.

For realization of applications of YBCO coated conductors in a persistent current mode, it is necessary to increase $U_0^*$ to a sufficient value especially at low temperatures. For this purpose, it seems to be important to enhance the flux pinning strength and introduction of strong artificial pinning centers is desirable. In addition, it is necessary to increase superconducting thickness without deterioration in the critical current density.
5 Summary

The magnetic relaxation property was investigated for YBCO tapes made by the IBAD/PLD process of superconducting thickness of 0.25, 0.50, 1.00 and 1.50 \( \mu \text{m} \) to clarify the superconducting thickness dependence of relaxation. It is found that the apparent pinning potential \( U^*_0 \) increases with increasing temperature in the low temperature region followed by a decrease. In this region \( U^*_0 \) is rather insensitive to the thickness of the superconductor, since it is predicted to be proportional to \( A_m^{1/3} \) in the three-dimensional pinning regime. In the medium temperature region, \( U^*_0 \) has a peak which becomes higher with increasing thickness. In this temperature region the flux pinning is considered to be in two-dimensional regime. This thickness dependence can be explained by the theoretical model of flux creep and flow.

For the improvement of \( U^*_0 \) especially at low temperatures, it is required to enhance the flux pinning strength. For this purpose introduction of strong artificial pinning centers seems to be effective. In addition, it is necessary to increase the superconducting layer thickness larger than the pinning correlation length without deterioration in the critical current density.

6 Acknowledgement

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References


Table 1: Specifications of specimens.

<table>
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<th>Specimen</th>
<th>Thickness $d$ ($\mu$m)</th>
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<tr>
<td>#1</td>
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<td>88.6</td>
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<tr>
<td>#2</td>
<td>0.50</td>
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<tr>
<td>#3</td>
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<td>86.7</td>
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<td>#4</td>
<td>1.50</td>
<td>87.9</td>
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</table>

Table 2: Pinning parameters of specimens in (a) low temperature region and (b) high temperature region, respectively.

(a) $A_m$ $\sigma^2$ $\gamma$ $m$ $g^2$ temperature region

<table>
<thead>
<tr>
<th></th>
<th>$A_m$</th>
<th>$\sigma^2$</th>
<th>$\gamma$</th>
<th>$m$</th>
<th>$g^2$</th>
<th>temperature region</th>
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<tr>
<td>#1</td>
<td>$5.0 \times 10^{11}$</td>
<td>0.015</td>
<td>0.63</td>
<td>1.50</td>
<td>1.0</td>
<td>5 – 30 K</td>
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<tr>
<td>#2</td>
<td>$3.5 \times 10^{11}$</td>
<td>0.013</td>
<td>0.60</td>
<td>2.00</td>
<td>1.0</td>
<td>5 – 30 K</td>
</tr>
<tr>
<td>#3</td>
<td>$1.8 \times 10^{11}$</td>
<td>0.007</td>
<td>0.60</td>
<td>1.89</td>
<td>1.0</td>
<td>5 – 30 K</td>
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<tr>
<td>#4</td>
<td>$4.0 \times 10^{11}$</td>
<td>0.006</td>
<td>0.74</td>
<td>2.98</td>
<td>1.0</td>
<td>5 – 30 K</td>
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(b) $A_m$ $\sigma^2$ $\gamma$ $m$ $g^2$ temperature region

<table>
<thead>
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<th></th>
<th>$A_m$</th>
<th>$\sigma^2$</th>
<th>$\gamma$</th>
<th>$m$</th>
<th>$g^2$</th>
<th>temperature region</th>
</tr>
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<tr>
<td>#1</td>
<td>$6.2 \times 10^{12}$</td>
<td>0.023</td>
<td>0.64</td>
<td>1.80</td>
<td>2.5</td>
<td>40 – 60 K</td>
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<tr>
<td>#2</td>
<td>$3.4 \times 10^{11}$</td>
<td>0.014</td>
<td>0.64</td>
<td>1.90</td>
<td>2.3</td>
<td>40 – 60 K</td>
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<td>0.65</td>
<td>2.30</td>
<td>1.8</td>
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<td>0.70</td>
<td>2.08</td>
<td>1.0</td>
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Figure captions

Fig. 1 $J_c$-$B$ characteristics obtained by SQUID magnetometer in the magnetic field ranges of (a) $0 - 6.50$ T and (b) $0 - 1.25$ T at 20, 50 and 70 K.

Fig. 2 (a) Relaxation of magnetization of specimen #1 at 1 T in the temperature range of 5 - 70 K, and (b) relaxation of magnetization of four specimens at 1 T and at 60 K.

Fig. 3 $E$-$J$ characteristics of specimen #1 at 1 T in the temperature range of 5 - 70 K. Symbols and lines represent the experimental and theoretical results, respectively.

Fig. 4 Temperature dependence of apparent pinning potential of four specimens and bulk specimen [6] at 1 T in the temperature range of 5 - 70 K.

Fig. 5 $J_c$-$B$ curves of specimen #1. Symbols and lines represent the experimental and theoretical results, respectively.

Fig. 6 Temperature dependence of apparent pinning potential for (a) specimens #1 and #3 and for (b) specimens #2 and #4 at 1 T in the temperature range of 5 - 70 K. Solid symbols represent the experimental results and open symbols with lines represent the theoretical results.
Fig. 1: K. Himeki *et al.* WTP–112/ISS2007
Fig. 2: K. Himeki et al. WTP-112/ISS2007
Fig. 3: K. Himeki et al. WTP–112/ISS2007
Figure 4: K. Himeki et al. WTP–112/ISS2007
Fig. 5: K. Himeki et al. WTP-112/ISS2007
Fig. 6: K. Himeki et al. WTP–112/ISS2007