Dependence of superconducting layer thickness on critical current density of YBCO-coated conductors at high temperatures

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Abstract

The critical current properties were investigated in the superconducting layer thickness range of 0.5 to 1.5 μm for PLD processed YBCO coated tapes deposited on IBAD substrates. The measurements were done in low and high electric field regions around the order of 10^{-8} V/m and 10^{-4} V/m, respectively. As a result, it was found that the critical current density J_c decreased with increasing thickness in both measurements at low magnetic fields. However, the thickness dependence of the irreversibility field B_i were different between the both measurements: B_i increased with decreasing thickness in the high electric field region, while B_i decreased with decreasing thickness in the low electric field region. The n value increased monotonically with increasing thickness. The observed results were approximately explained by the irreversible thermodynamic principle that the transverse flux bundle size is determined so that the critical current density is maximized.

Keywords: YBCO, thickness, n value, irreversibility field, flux creep-flow model
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1 Introduction

YBCO-coated conductor is expected to be used for superconducting equipments in various fields because of its critical current characteristic superior to Bi tapes at high temperatures and/or high magnetic fields. For realization of applications, it is necessary to further improve the critical current properties. Hence, it is necessary to clarify all the mechanisms which influence the critical current properties to find out the method of optimization of J_c. One of the factors which influence those properties is the thickness of the superconducting layer.

It was reported that the critical current density in YBCO tape made by the IBAD/PLD process decreased with increasing thickness due to the degradation in the superconducting layer structure coming from formation of voids and a-axis aligned grains [1]. In addition to such a thickness dependence due to the deterioration of the structure, J_c characteristics depend on the thickness also from the thermal agitation of flux lines, since the pinning potential is limited within a small value for two-dimensional pinning at high magnetic fields and high temperatures, where the pinning correlation length becomes longer than the thickness. Thus, the thickness dependence is complicated.

Recently, it was found that although the magnetization J_c of the thinnest specimen measured by a SQUID magnetometer was highest at low magnetic fields, it decreased most rapidly with increasing magnetic field at high temperatures [2–4]. This was attributed to the strong influence of the flux creep against the thinnest specimen with small pinning potential energy limited by its thickness, and could be approximately explained by the theoretical model of flux-creep and flow.

In most applications of superconductors as in AC equipments, the electric field strength is much higher than that in the previous DC magnetization measurement. That is, the characterization at the electric field strength above 10^{-4} V/m is needed. In this paper, the critical current characteristics are measured by using the usual four terminal method and are compared with that in the previous DC magnetization measurement [4].

2 Experiments

The specimens were PLD-processed YBCO-coated conductors deposited on IBAD substrates with GZO inner layer and CeO_2 cap layer [5]. The thicknesses of YBCO layer were 0.5, 1.0 and 1.5 μm. The specifications of these specimens are listed in Table 1. E-J characteristics of specimens were measured by the four terminal method in a magnetic field parallel to the c-axis of the specimens. Measurements were done up to 7 T over the temperature range of 70 to 85 K. J_{c} was determined using the electric field criterion of $E_{\mathrm{c}} = 1.0 \times 10^{-4}$ V/m. The irreversibility field was determined by the magnetic field at which J_{c} reduced to 3.0×10^{8} A/m^2. The n value was also estimated in the electric field range of $E = 10^{-4}$–10^{-3} V/m.

3 Results and Discussion

Fig. 1 shows the E-J curves of the specimen #2 in respective magnetic fields at 77.3 K. The results obtained by SQUID magnetometer are also shown for reference. It is clearly seen that these characteristics in different ranges of electric field are consistent to each other. It is found that the n value is lower at low electric fields and this tendency becomes remarkable at high magnetic fields. Fig. 2 shows the J_{c}-B characteristics of the specimens measured by the two methods at different electric field regions at 77.3 K. It is found that J_{c} decreases with increasing thickness in the both measurements at low magnetic fields. This comes directly from the structural degradation of superconducting layer in thick specimen. On the other hand, it is found that the high J_{c} of the thinnest specimen is kept up to high magnetic fields in the usual resistive measurements at higher electric field. This is attributed to the weak influence of the flux creep. However, these results differ from the previous results that J_{c} of the thinnest specimen decreased rapidly with increasing magnetic field due to the strong influence of the flux creep at low electric fields. This is associated with the significant reduction in the n value with decreasing thickness at low electric fields. Fig. 3 shows the temperature dependence of the irreversibility field obtained by the both measurements. The thinnest specimen has advantage in the high electric field region, although the thickest specimen has advantage in the low electric field region.

The critical current properties were analyzed using the flux creep-flow model [6]. 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

$$J_{\mathrm{c}0} = A\left(1-\frac{T}{T_{\mathrm{c}}}\right)^{m} B^{\gamma-1}\left(1-\frac{B}{B_{\mathrm{c}2}}\right)^{2}, \tag{1}$$

where A, m, γ are pinning parameters. The pinning potential U_0, which is an important quantity to determine the flux creep characteristics, depends on $J_{\mathrm{c}0}$. In the two-dimensional pinning regime for thin superconductors, U_0 depends also on the superconducting layers thickness d, and is given by

$$\begin{aligned} U_0 &= \frac{0.835 g^2 k_\mathrm{B} J_\mathrm{c0}^{1/2}}{(2\pi)^{3/2} B^{1/4}}; \quad d > L, \\ &= \frac{4.23 g^2 k_\mathrm{B} J_\mathrm{c0} d}{2\pi B^{1/2}}; \quad d < L. \end{aligned} \tag{2}$$

In the above L is the pinning correlation length is given by

$$L = \left(\frac{B a_\mathrm{f}}{2\pi \mu_0 J_\mathrm{c0}} \right)^{1/2} \tag{3}$$

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

$$g^2 = g_\mathrm{e}^2 \left[\frac{5 k_\mathrm{B} T}{2 U_\mathrm{e}} \log \left(\frac{B a_\mathrm{f} \nu_0}{E_\mathrm{c}} \right) \right]^{4/3} \tag{4}$$

so that the critical current density under the flux creep is maximized [7]. In the above g_e^2 is the maximum value of g^2 for the perfect three-dimensional triangular flux line lattice, U_e is the pinning potential when $g = g_\mathrm{e}$, E_c is the electric field criterion to determine J_c, and ν_0 is the attempt frequency of the flux bundle.

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

$$f(A) = K \exp \left[- \frac{(\log A - \log A_\mathrm{m})^2}{2\sigma^2} \right], \tag{5}$$

where A_m is the most probable value of A and σ^2 is a parameter representing a distribution width and K is a normalization constant. The electric field caused by flux creep and flow is calculated as a function of the current density and averaged with respect to the distributed A. The pinning parameters A_{m}, σ, m and γ are determined so that the calculated E-J curves agree with the experiments. The obtained parameters are listed in Table 2.

In Fig. 4, the observed J_{c}-B characteristics of specimen #1 are compared with the theoretical results at each temperature. In the low electric field region, it is found that there exists a slight disagreement between theoretical and experimental results at high magnetic fields. However, in the high electric field region, the experimental results is explained well by the theory. Fig. 5 shows the thickness dependence of B_{i} at 77.3 K. In the high electric field region, B_{i} decreases with increasing thickness, and the theoretical results explain the experimental results well. On the other hand, B_{i} increases with decreasing thickness in the low electric field region. Although, the theoretical results shows the same tendency with experimental results, the quantitative difference between experimental and theoretical results is observed.

Then, the parameter g^2 is adjusted as a fitting parameter so that the calculated E-J curves agree well with the experiments. Fig. 6 shows the magnetic field dependence of g^2 at 77.3 K determined in this way, and the results are compared with the prediction of Eq. (5). Although the good agreement is obtained in the high electric field region, a slight disagreement is found around 2 T in the low electric field region. In particular, this disagreement is larger in thicker specimen. The reason for this disagreement is not clear. However, the behavior of g^2 is approximately explained by the prediction of Eq. (5). That is, g^2 becomes larger when the magnetic field increases and/or the thickness decreases. These are caused by the reduction in U_{e} in Eq. (5). The same thing occurs when the temperature increases. Equation (5) also explains that g^2

changes also with the electric field strength. Such a behavior is explained that the transverse flux bundle size increases to reduce the strong effect of the flux creep especially for thin superconductors, although such a change weakens the flux pinning strength.

Fig. 7 shows the experimental and theoretical n values. It is found that the n value in the low electric field region is considerably smaller than that in the high electric field region, suggesting a flux motion close to TAFF (Thermally Activated Flux Flow). The n value increases with the increasing thickness. This can be simply explained by the increase in the pinning potential with the thickness.

Thus, thicker tapes have generally better performance for applications of superconductors when the high n value is required. Typical cases are applications in the very low electric field region. On the other hand, thin tapes have better performance when those are used in the high electric field region, where the rather low n value is required from a viewpoint of protection from thermal runaway.

4 Summary

Dependence of the critical current density in the usual electric field region on the superconducting layer thickness was investigated for YBCO-coated conductors from a viewpoint of an application for AC equipments. It is found that J_c in the thinnest specimen is the largest at high magnetic fields in the high electric field region. However, J_c in the thinnest specimen decreases rapidly with increasing magnetic field in the low electric field region. The thickness dependence of B_i was different between the low and high electric field regions. That is, B_i increased with decreasing thickness in the high electric field region, while B_i decreased with decreasing thickness in the low electric field region. These results were approximately explained by the irreversible thermodynamic principle. The n value is larger in thick specimen in the both measurements due to the increases in the pinning potential. However, the dependence becomes smaller in the high electric field region.

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Figure captions

Fig. 1 E-J characteristics of specimen #2 obtained by the two measurement methods at various magnetic fields at 77.3 K.

Fig. 2 Critical current density of the three specimens in high and low electric field regions at 77.3 K.

Fig. 3 Temperature dependence of irreversibility field in (a) high and (b) low electric field regions.

Fig. 4 J_{c}-B curves of specimen #1 in (a) high and (b) low electric field regions. Solid symbols and lines represent the experiment and theoretical results, respectively.

Fig. 5 Thickness dependence of irreversibility field at 77.3 K in (a) high and (b) low electric field regions. Solid and open symbols represent the experiment and theoretical results, respectively.

Fig. 6 Magnetic field dependence of g^2 at 77.3 K in (a) high and (b) low electric field regions. Symbols and lines represent the values obtained from experiments and the theoretical prediction, respectively.

Fig. 7 Thickness dependence of n value in (a) high and (b) low electric field regions. Solid and open symbols represent the experiment and theoretical results, respectively.

Table 1: Specifications of specimens.

Specimen	Thickness d (μm)	T_c (K)
#1	0.5	87.2
#2	1.0	87.1
#3	1.5	87.9

Table 2: Pinning parameters of specimens at 77.3 K in the low and high electric field regions.

Specimen	A_m	σ^2	γ	m
#1	5.0×10^{12}	0.073/0.050	0.7/0.8	2.0
#2	4.0×10^{12}	0.083/0.048	0.5/0.7	2.0
#3	3.1×10^{12}	0.080/0.046	0.4/0.6	2.0