Influence of nanoparticles on critical current properties in TFA-MOD processed YGdBCO coated conductor

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Abstract. For investigation of the flux pinning properties of nanoparticles in TFA-MOD processed Y\textsubscript{1-x}Gd\textsubscript{x}Ba\textsubscript{2}Cu\textsubscript{3}O\textsubscript{y} (YGdBCO) coated conductors, the critical current density was compared in various directions of the magnetic field for YGdBCO+BaZrO\textsubscript{3} (BZO) and YGdBCO coated conductors with the superconducting layer of 0.5 \mu m thickness. It was found that \textit{J}\textsubscript{c} for \textit{\theta}= 0^\circ (B//c) is larger but \textit{J}\textsubscript{c} for \textit{\theta}= 90^\circ (B//ab) is smaller in YGdBCO+BZO than in YGdBCO. The increase in the normal field is attributed to the pinning of nanoparticles, while the decrease in the parallel field is considered to be caused by limitation of extension of stacking faults by distributed BZO nanoparticles. In addition, the \textit{n}-value \textit{E} \propto \textit{J}^{n}\textsuperscript{-1} decreases by introduction of BZO nanoparticles for \textit{\theta}= 90^\circ, while it is unchanged for \textit{\theta}= 0^\circ. These results are well described by a theoretical model of flux creep and flow.

1. Introduction

Trifluoroacetates (TFA) metal organic deposition (MOD) is expected to be a low cost process for the fabrication of REBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{y} (RE = rare earth: REBCO) coated conductors, and the critical current density \textit{J}\textsubscript{c} under a magnetic field is desired to be improved for the REBCO coated conductors made by this method. The critical current density is required to be high for all directions of the magnetic field for applications for electric power devices such as transformer and superconducting magnetic energy storage (SMES). It is known that \textit{J}\textsubscript{c} of REBCO thin films in the magnetic field is greatly improved by introduction of a non-superconducting phase at the nanometer scale [1-5]. Recently, it was reported that a very high flux pinning force in a magnetic field has been obtained at 77 K for the MOD processed Y\textsubscript{1-x}Gd\textsubscript{x}Ba\textsubscript{2}Cu\textsubscript{3}O\textsubscript{y} (YGdBCO) coated conductor with BaZrO\textsubscript{3} (BZO) fabricated from a starting solution containing Zr-naphthenate salt [6]. In addition, the field angle anisotropy could also be reduced. However, the detailed mechanism of flux pinning of BZO nanoparticles which derives such high critical current characteristic in YGdBCO coated conductors was not reported. In this study, the critical current density in YGdBCO+BZO and YGdBCO coated conductors with the superconducting layer of 0.5\mu m thickness is measured in various directions of the magnetic field and the result is theoretically analyzed to clarify the flux pinning mechanism.
2. Experimental

The measured coated conductors were fabricated on CeO$_2$/LaMnO$_3$/IBAD-MgO/Gd$_2$Zr$_2$O$_7$/Hastelloy C276\textsuperscript{TM} substrates by the TFA-MOD process. Detailed sample preparation method was published elsewhere \cite{6}. The measured samples in this study were YGdBCO coated conductors with (#1) and without BZO nanoparticles (#2). The superconducting layer is about 0.5 $\mu$m thick. The critical temperature of specimens #1 and #2 measured by SQUID magnetometer was 90.2 and 90.0 K, respectively.

The coated conductors was patterned into a micro-bridge shape of about 50 $\mu$m wide and 1 mm long by the photolithography and chemical etching process. Transport properties were measured by a four-probe method. The temperature was controlled by an energy input to a heater near the sample and by changing the flow rate of gas Helium. The accuracy of temperature was $\pm$ 0.3 K. The angle of the magnetic field $\theta$ was defined as the angle between the magnetic field and the $c$-axis. The critical current density, $J_c$, was defined using the criterion of $E_c = 4.0 \times 10^{-3}$ V m$^{-1}$.

3. Results and discussion

Figure 1 shows the magnetic field dependence of $J_c$ in YGdBCO+BZO and YGdBCO for $\theta = 0^\circ$ ($B//c$) and $\theta = 90^\circ$ ($B//ab$) obtained by the four-probe method. It is found that $J_c$ for $\theta = 0^\circ$ is larger in YGdBCO+BZO than in YGdBCO. However, $J_c$ for $\theta = 90^\circ$ is smaller in YGdBCO+BZO than in YGdBCO. This means that the introduction of nanoparticles is effective for improvement of $J_c$ around $\theta = 0^\circ$ and also for reduction of field angle anisotropy.

Figure 2(a) and (b) show the obtained angular dependence of $J_c$ at 77 K and in the magnetic field range of 1-3 T for YGdBCO+BZO and YGdBCO, respectively. It is found that the less anisotropic angular dependence of $J_c$ was obtained except at angles around $\theta = 90^\circ$, and the $J_c$ value in the flat area increased. That is, the average $J_c$ value increased by the introduction of BZO nanoparticles. This is considered to be attributed the random pinning by these particles of isotropic shape. On the other hand, the $J_c$ value at around $\theta = 90^\circ$ decreased by the introduction of BZO. The decrease of $J_c$ in this field angle is consider to be caused by limitation of extension of stacking faults parallel to the $ab$-plane by distributed BZO nanoparticles. Figure 3 shows the anisotropy of $J_c(90^\circ)/J_c(0^\circ)$ at 77 K. The decrease in the anisotropy at these magnetic fields is attributed to the isotropic pinning by BZO nanoparticles and also the deterioration of pinning by stacking faults. On the other hand, the peak at $\theta = 90^\circ$ becomes sharper at higher magnetic field. This comes from the intrinsic anisotropy of electron mass in high temperature superconductors.

![Figure 1. Magnetic field dependence of critical current density for $\theta = 0^\circ$ and $\theta = 90^\circ$ at 77 and 80 K. Dotted lines show the theoretical results.](image-url)
Figure 2. Field angular dependence of $J_c$ for (a) #1 and (b) #2.

Figure 3. Field angle anisotropy as a function of magnetic field at 77 and 80 K.

Figure 4. Magnetic field dependence of $n$-value for $\theta = 0^\circ$ and $\theta = 90^\circ$ at 77 and 80 K for (a) #1 and (b) #2. Dotted lines show the theoretical results.
Figure 4(a) and (b) show the magnetic field dependence of $n$-value ($E \times J^* \propto$) at $\theta = 0^\circ$ and $\theta = 90^\circ$ estimated from the $E$-$J$ curves in the range of electric field of $10^{-3}-10^{-2}$ V m$^{-1}$. It can be seen that the $n$-value decreases by introduction of BZO nanoparticles for $\theta = 90^\circ$, while the $n$-value is unchanged for $\theta = 0^\circ$.

These results are analyzed using a flux creep and flow model [7]. The important quantity which determines the pinning property is the pinning potential, $U_0$, which is described with the virtual critical current density, $J_{c0}$, in a creep-free case and the number of the flux lines in a flux bundle, $g^2$. The value of $g^2$ cannot be foreseen due to the sensitive dependence on the state of flux lines, and it is assumed that $g^2$ is determined so that the critical current density under the flux creep is maximized [8]. The temperature and magnetic field dependence of $J_{c0}$ is assumed to be expressed as

$$ J_{c0} = A \left(1 - \frac{T}{T_c}\right)^\gamma_1 \left(B - B_{c1}\right)^2, $$

where $A$ is constant representing the magnitude of $J_{c0}$ and $m$ and $\gamma$ are pinning parameters. In high temperature superconductors, it is empirically known that the local flux pinning strength is statistical distributed widely [9]. In the present specimens the statistically distribution of $A$ in (1) is partly ascribed to non-uniform spatial distribution of nanoparticles. Here, it is assumed that $A$ is distributed as

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

where $A_m$ is the most probable value of $A$, $\sigma$ is a parameter representing the statistical distribution width and $K_p$ is a normalization constant. The $E$-$J$ characteristics are calculated based on the mechanism of flux creep and flow. Further details of the theoretical analysis were presented in ref. [10]. These parameters $A_m$, $\sigma$, $\gamma$, and $m$ are determined so as to obtain good agreement between experiment and theory. The theoretical results on the critical current density and the $n$-value are also determined in the same manner as in experiments. The parameters used in this calculation are listed in Table 1. In this analysis, $g^2$ is used as a fitting parameter for simplicity. The $g^2$ value for $\theta = 0^\circ$ is compared in figure 5. For $\theta = 90^\circ$, the $g^2$ value is 1.0 in the entire region of investigation.

**Table 1.** Parameters used this calculation.

| Sample | $\theta = 0^\circ$ | $\theta = 90^\circ$ |
|--------|-------------------|-------------------|
| #1     | $A_m$ = $6.60 \times 10^{11}$ | $1.25 \times 10^{12}$ |
|        | $\sigma$ = 0.055 | 0.057 |
|        | $\gamma$ = 0.48 | 0.48 |
|        | $m$ = 1.5 | 1.5 |
| #2     | $A_m$ = $2.13 \times 10^{11}$ | $9.60 \times 10^{11}$ |
|        | $\sigma$ = 0.029 | 0.027 |
|        | $\gamma$ = 0.45 | 0.66 |
|        | $m$ = 1.5 | 1.5 |

**Figure 5.** $g^2$ for $\theta = 0^\circ$ at 77 and 80 K. $g^2$ value is 1.0 for $\theta = 90^\circ$. 
The theoretical results of $J_c$-$B$ properties and the $n$-value are compared with the experimental results in figure 1 and figure 4(a) and (b), respectively. It can be seen that the theoretical results explain the experimental results well. It is found that the value of $A_m$ and $\sigma^2$ increases by the introduction of BZO nanoparticles. The nanoparticles is effective to improve $A_m$ for the both magnetic field directions. On the other hand, the increment of $\sigma^2$ means that the distribution of pinning strength becomes broader by the introduction of nanoparticles. This is simply understood as a result of addition of strong pinning centres to relatively weak natural pinning centres. The speculation is consistent with the reduction in the $n$-value. It is concluded that the introduction of BZO nanoparticles is effective to enhance $J_c$ under these magnetic fields.

4. Summary
The critical current density in YGdBCO+BZO and YGdBCO coated conductors with the superconducting layer of 0.5 $\mu$m thick was measured in various directions of magnetic field and the results were theoretically analyzed using the flux creep and flow model. The above results show that the introduction of BZO nanoparticles is effective for improvement of $J_c$ around $\theta = 0^\circ$ and also for reduction of field angle anisotropy. However, the $n$-value decreases by the introduction of BZO nanoparticles.

From these results, the introduction of BZO nanoparticles is promising for improvement of the flux pinning properties of MOD coated conductors and a further improvement is expected by optimizing of process conditions.

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