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Flux pinning properties of splayed columnar defects ranging from B || c-axis to B || ab-plane in GdBCO coated conductors

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ABSTRACT

$GdBa_2Cu_3O_y$ (GdBCO) coated conductors were irradiated using 270 MeV Xe ions at crossing angles $\pm\theta_i$ relative to the *c*-axis, in order to clarify the flux pinning properties of splayed columnar defects (splayed CDs) not only around *B* || *c*-axis, but also around *B* || *ab*-plane. For the splayed CDs with smaller θ_i (i.e. crossing around the *c*-axis), a single peak is observed around *B* || *c*-axis in the angular dependence of critical current density J_c, which are attributed to the splay effect by the crossed CDs. For the splayed CDs with larger θ_i (i.e. crossing around the *ab*-plane), on the other hand, two sharp J_c peaks emerge near two irradiation angles $\pm\theta_i$ and the J_c at *B* || *ab*-plane indicates not a peak but a dip structure. With diminishing the crossing angles of CDs relative to *ab*-plane, the value of J_c at *B* || *ab*-plane build up with the dip structure remained. These results suggest that the splayed CDs contribute to the flux pinning around the *ab*-plane, but do not induce the splay effect at *B* || *ab*-plane.

1. Introduction

The improvement of critical current density J_c at high magnetic fields and over a wide range of magnetic field orientations is required for the development of $REBa_2Cu_3O_y$ (REBCO, RE: Rare Earth element) coated conductors, because the large anisotropy of J_c peculiar to high-T_c superconductors is a obstacle especially to superconducting magnet applications. One-dimensional (1D) pinning centers (PCs), which are line-like defects such as dislocations and columnar defects (CDs), are most effective to immobilize flux lines and to enhance the J_c in high-T_c superconductors, even at high magnetic fields. In recent years, the 1D PCs have been easily introduced as nano-rods formed through self-assembled stacks of second phase materials such as $BaMO_3$ (M = Zr, Sn, Hf, etc.) into REBCO films [1,2]. Then, 1D PCs are flagship artificial PCs for the coated conductors at present. One feature of the 1D PCs is to exhibit the preferential direction for the flux pinning, i.e., remarkable increment of J_c is attained when an applied magnetic field is aligned along the 1D PC direction. Because of this feature, the 1D PCs have been usually installed along the *c*-axis direction in REBCO films, contributing to the reduction of the large anisotropy of J_c [3]. Furthermore to take advantage of this feature, the introduction of the 1D PCs in multiple directions is thought of as a simple way to make the J_c fairly isotropic over a wide range of magnetic field orientations, where the 1D PCs distributed over a wide range of the directions is expected to collapse the minimum of J_c.

As for flux pinning by direction-dispersed (splayed) 1D PCs, it was theoretically predicted that the flux pinning can be further improved at magnetic field aligned along the mid direction of the dispersion (usually at the *c*-axis direction) when the dispersion is slight [4]. The splay effect has been experimentally examined so far, especially for a bimodal splay configuration consisting of two parallel CD families at crossing angles $\pm\theta_i$ relative to the *c*-axis [5,6]. When 1D PCs are distributed over a wide range of the directions, similar splay effect is expected to occur in every magnetic field directions and may make the J_c further improved in all magnetic field directions. To our knowledge, however, the previous experiments have been aimed at the enhancement in J_c, for the most part, for *B* || *c*-axis; unexpectedly, the influence of the splayed 1D PCs on flux pinning at another direction has not been well studied so far. Recently, we reported that CDs crossing at ±30° relative to the *ab*-axis cause a dip structure at *B* || *ab*-plane on the angular dependence of J_c in YBCO films, whereas a single peak was observed at *B* || *c*-axis for the crossing angles ±30° relative to the *c*-axis [7].

In this paper, we investigate in detail the flux pinning properties of splayed CDs not only around *B* || *c*-axis but also around *B* || *ab*-plane through the angular dependence of J_c for GdBCO coated conductors with splayed CDs produced by heavy-ion irradiations.

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2. Experimental details

The samples were cut from a 5 mm-width tape of a PLD-processed GdBCO-coated conductor deposited on an IBAD substrate (Fujikura Ltd.). The thickness of superconducting layer was 2.2 μm and the critical current I_c of this tape is about 280 A. Note that the samples used here were selected so that the critical current estimated from the Tapestar was same in all samples before the irradiation. The Ag stabilizer layer on the superconducting layer was removed by chemical etching and the superconducting layer was patterned in bridge geometry with about 40 μm width and 1 mm length. After that, the samples were irradiated with 270 MeV Xe ions at the tandem accelerator of JAEA in Tokai, Japan. To install the crossed CDs, the incident ion beam was always directed perpendicular to the bridge of sample and was tilted off the c-axis by $\pm\theta_i$ in a range from ±15° to ±75°. It is noted that crossed CDs with $\theta_i = \pm 60°$ and ±75° relative to c-axis correspond to two parallel families of CDs crossing at ±30° and ±15° relative to the ab-plane, respectively (see Fig. 1). For $\theta_i = \pm 75°$ which has the longest projectile length in this study, the electronic stopping power S_e changes from 3.0 to 1.7 keV/Å through the superconducting layer. The threshold value of S_e for CD formation is 1.5–2.0 keV/Å [8]. Thus we can expect the creation of continuous CDs over the whole sample thickness, whereas the diameter is not constant but become thinner along the longitudinal direction. In all samples, the total fluence is 1.94×10^{11} ions/cm^2 and the fluence for each irradiation direction is half the total one. Table 1 lists the specifications of the samples in this work.

The transport properties were measured using a four-probe method. The transport current was applied in the direction perpendicular to the magnetic field, the c-axis, and CDs at all times (maximum Lorentz force configuration, see Fig. 2). The value of J_c was defined by the criterion of electric field, 1 μV/cm. In evaluating the angular dependence of J_c, the magnetic field was rotated in a splay plane where two parallel CD families are crossing each other.

Table 1
Samples in this work.

Sample	Crossing angle θ_i relative to c-axis (°)	T_c (K)
sp15	±15	89.7
sp30	±30	89.9
sp60	±60	90.0
sp75	±75	90.4

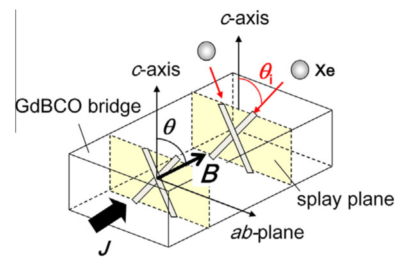

Fig. 2. Sketch of the irradiation procedure and the experimental arrangement in this work.

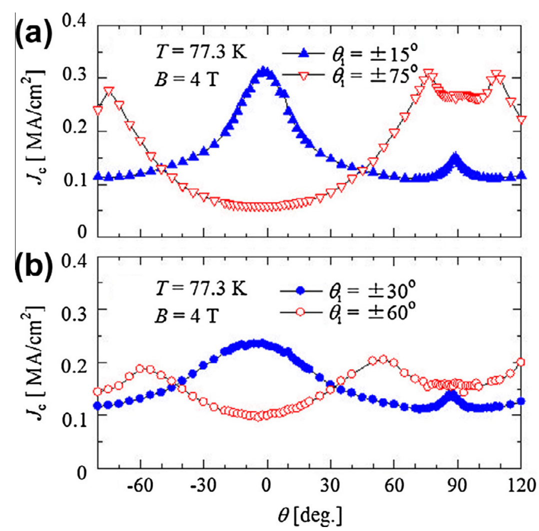

Fig. 3. Angular dependence of J_c at 77.3 K and 4 T in GdBCO coated conductors with CDs crossing at various angles.

3. Results and discussion

Fig. 3 shows the angular dependence of J_c at 77.3 K and 4 T for the irradiated samples, where θ is the angle between the magnetic field and the c-axis of GdBCO coated conductors. For sp15 and sp30, which contain CDs dispersed in the directions around c-axis, a single peak of J_c remarkably emerges around $B \parallel c$-axis ($\theta = 0°$) and its height is much larger than that of $\theta = 90°$. As the crossing angle becomes narrow, the height of the peak around $\theta = 0°$ increases and the width of the peak sharpens. These phenomena originate from the installed CDs crossing around the c-axis. A mere sum of the contributions from the CDs in each direction, however, cannot seem to describe the value of J_c at $\theta = 0°$ corresponding to the mid direction of the crossed CDs, for both sp15 and sp30. It has been reported that the effect of crossed CDs is larger by 24% than the sum of the effect of respective CDs in a YBCO film with CDs crossing at ±15° relative to the c-axis [9]. Thus, the crossed CDs create an extra effect, i.e. the splay effect, in which the motion of flux lines from one CD to another is suppressed by the slight dispersion in the direction of CDs [4]. Note that the Lorentz force is always parallel to the splay plane in this work, where the flux lines can move from one CD to another not only by nucleation of kink pairs but also by kink sliding along the CDs as there is a finite angle between the flux lines and the crossed CDs [10].

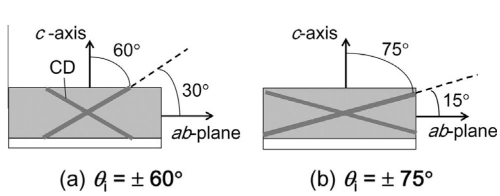

Fig. 1. Schematic representation of columnar defects crossing at ±60° and ±75° relative to c-axis.

The behaviour of J_c around $\theta = 90°$ is almost same between sp15 and sp30, as shown in Fig. 3. In general, the peak of J_c at $B \parallel ab$-plane ($\theta = 90°$) come from the intrinsic pinning or extrinsic correlated pinning centers oriented along the ab-plane. The introduction of the CDs crossing at small angles relative to the c-axis do not apparently contribute to flux pinning around $B \parallel ab$-plane, but only do damage to the superconductivity or the correlated pinning centers along the ab-plane [9,11].

For sp60 and sp75, the J_c has a minimum at $\theta = 0°$, far from showing a peak. In this work, the CDs are inclined at large angles relative to the c-axis for sp60 and sp75, which easily induces the formation of the staircase flux lines around $B \parallel c$-axis. The staircase flux lines slide along the CDs without pinning [10], which is more prominent due to the splay plane of CDs parallel to the Lorentz force direction, leading to the reduction of the J_c around $\theta = 0°$. It