Strain characteristics of BMO doped REBCO coated conductors fabricated by hot-wall PLD

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Abstract. REBCO coated conductors (CCs) are expected to show high performance for superconducting applications due to their high tensile strength and high critical current density under magnetic fields. Fujikura Ltd. (Fujikura) has developed REBCO CCs with high performance by ion beam assisted deposition (IBAD) and pulsed laser deposition (PLD) method. It is generally known that the critical current (\(I_c\)) of a common superconducting wire varies with the applied longitudinal tensile strain, but that of Fujikura's commercial CC hardly varies due to the peculiarities of the REBCO crystal orientation. Recently, we have developed BaMO\(_3\) (BMO, M : Zr or Hf) doped REBCO CCs in order to enhance their in-field critical current density. In this study, we investigated the strain dependence of the BMO doped REBCO CCs. As a result, it was confirmed that the \(I_c\) change with strain increased by BMO doping, even though the crystal orientation did not change.

1. Introduction

Introduction of artificial pinning centers (APCs) such as BaZrO\(_3\) (BZO), BaHfO\(_3\) (BHO) into REBa\(_2\)Cu\(_3\)O\(_x\) (REBCO, RE = rare earth) film has been studied by many researchers in order to improve the in-field critical current (\(I_c\)) [1-2]. Especially, excellent properties are reported for BHO doped REBCO film by the pulsed laser deposition (PLD) method [3-5]. Fujikura Ltd. (Fujikura) has developed the production techniques for REBCO coated conductors (CCs) by using large-area ion-beam-assisted deposition (IBAD) and hot-wall type PLD [6-8]. Recently, we have been developing the BMO (M = Zr or Hf) doped REBCO CCs using these techniques. On the other hand, the REBCO CCs have very high tensile strength due to the Hastelloy\textsuperscript{TM} substrates and they are expected for high field magnet applications [9]. It is well known that the \(I_c\) of the REBCO CCs varies with applied strain [10-12]. However, it has been reported that the \(I_c\) of Fujikura's commercial REBCO CCs hardly varies with applied strain [13]. This phenomenon is considered to depend on the orientation direction of the REBCO crystal due to the structure of the buffer layers. Although the strain effect of the BMO doped REBCO CCs on \(I_c\) has also been studied [14], there are few reports. In addition, the mechanical properties of the BMO doped REBCO CCs with our CC structure are completely unknown. In this study, we investigated the axial tensile and the bending strain characteristics of the BMO doped REBCO CCs fabricated by IBAD and hot-wall PLD.

2. Experimental
2.1. Evaluation samples

The structure of the evaluation CC samples is shown in figure 1. The width of the CC was 4 mm or 5 mm, and the stabilization layer was copper-plated with 20 μm thickness. The REBCO layer was deposited by using hot-wall type PLD apparatus. The specifications of the fabricated samples are shown in table 1. Sample A is a standard CC of Fujikura (FYSC-SCH04). In sample B, in order to change the crystal orientation of REBCO, an LaMnO₃ (LMO) layer is deposited by PLD between the MgO layer and the CeO₂ layer. The other structures were the same as sample A. Samples C, D and E were doped with BMO in the REBCO layer. The structure of these buffer layers was the same as sample A. As a method of BMO doping, REBCO (RE = Gd or Eu) targets mixed with BZO or BHO were used. In samples A, C, D, and E, the a- or b-axis of REBCO crystals was rotated by 45° from the longitudinal direction as shown on the right side of figure 2. In sample B, the a- or b-axis was parallel to the longitudinal direction as shown on the left side of figure 2 due to the presence of LMO.

![Figure 1. The structure of the evaluation samples.](image1)

![Figure 2. The schematic diagram of the REBCO crystal orientation.](image2)

**Table 1. Specifications of the evaluation samples.**

| Sample (CC width) | REBCO layer (thickness) | Buffer layer structure | REBCO crystal orientation | \( I_c \) at 77 K, self-field [A] |
|-------------------|-------------------------|------------------------|---------------------------|---------------------------------|
| A (4 mm)          | GdBCO                   | \( \text{Al}_2\text{O}_3/\text{Y}_2\text{O}_3/\text{MgO/CeO}_2 \) | 45°                        | 219                            |
| B (5 mm)          | GdBCO                   | \( \text{Al}_2\text{O}_3/\text{Y}_2\text{O}_3/\text{MgO/LMO/CeO}_2 \) | parallel                   | 229                            |
| C (5 mm)          | GdBCO                   | \( \text{Al}_2\text{O}_3/\text{Y}_2\text{O}_3/\text{MgO/CeO}_2 \) | 45°                        | 154                            |
| D (4 mm)          | GdBCO                   | \( \text{Al}_2\text{O}_3/\text{Y}_2\text{O}_3/\text{MgO/CeO}_2 \) | 45°                        | 91                             |
| E (4 mm)          | EuBCO                   | \( \text{Al}_2\text{O}_3/\text{Y}_2\text{O}_3/\text{MgO/CeO}_2 \) | 45°                        | 88                             |
2.2. Measurement procedure

Axial tensile tests and bending tests were conducted in liquid nitrogen. Both ends of the sample were clamped by two copper electrodes in order to measure $I_c$ in self-field which was defined at 1 $\mu$V/cm of the electric field. For the axial tensile tests, the tensile testing machine and the jig as shown in figure 3 were used. The distance between chuck electrodes was 160 mm and the distance between voltage taps was 100 mm. Axial tensile stresses and axial tensile strains were measured using a load cell (10 kN) and a strain gauge glued onto the surface near the center of the sample respectively. The velocity of the tensile stroke was 4.8 mm/min. For the bending tests, a Goldacker type bending apparatus [15] as shown in figure 4 was used. The minimum bending radius in this apparatus was 5 mm. Bending strain is applied to the sample by turning the handle at the top of the apparatus. Depending on the bending direction, either tensile bending strain or compressive bending strain can be applied. The bending strain $\varepsilon_b$ was converted from the bending radius $R$ using the following equation:

$$\varepsilon_b = \frac{d^2}{R}$$

where $d$ is the thickness of the Hastelloy substrate. In these tests, the $I_c$ under the strained state ($I_c^{\text{load}}$) and under the unloaded state after applying strain ($I_c^{\text{unload}}$) were measured, and the applying strain was gradually increased until the $I_c^{\text{unload}}$ obviously decreased.

![Figure 3](image1)
![Figure 4](image2)

**Figure 3.** The schematic(a) and the picture(b) of the tensile test apparatus in liquid Nitrogen (LN$_2$).

**Figure 4.** The schematic(a) and the picture(b) of the bending test apparatus in liquid Nitrogen (LN$_2$).
3. Results and discussion

3.1. Axial tensile tests

The axial tensile strain dependence of $I_c$ at 77 K in self-field are shown in figure 5. The values of the vertical axis are the normalized $I_c$ with the initial $I_c$ ($I_{c0}$) before loading. The round plots indicate $I_c^{\text{load}}$ and the square plots indicate $I_c^{\text{unload}}$. Although sample A had almost no decline in $I_c^{\text{load}}$ with applied strain, sample B in which the crystal orientation was changed obviously decreased $I_c^{\text{load}}$ with applied strain. These results are attributable to the REBCO crystal orientation as described in [13]. Samples C, D and E doped with BMO in the REBCO layer also decreased $I_c^{\text{load}}$ with applied strain, although the REBCO crystal orientation was the same as in sample A. This phenomenon is not fully understood, but it is considered that BMO have some influence on $I_c$-strain characteristics of REBCO. It cannot be explained by crystal orientation, and there is the possibility of distortion effect of $I_c$ at the grain boundaries in REBCO as described in [14]. The BMO doped REBCO seems to have larger $I_c$ irreversible degraded strain than pure REBCO, but this is considered to be due to the thin film thickness [12].

![Figure 5](image-url)
### 3.2. Bending tests

Figure 6 shows the $I_c/I_{c0}$ at 77 K, self-field as a function of the bending strain. The solid lines indicate quadratic function fitting lines. As with the results of the axial tensile test, the $I_c$ changes due to applied strain increased in the case of the BHO doped REBCO compared to the pure GdBCO. Furthermore, the $I_c$ on the compressive strain region increased in the case of BHO doped REBCO, and the magnitude of the increase was larger in sample E than in sample D. The $I_c$ peak strain ($\varepsilon_p$) also shifted to the compressive strain direction in the order of sample A, sample D and sample E. The graph drawn by normalizing the vertical axis with the maximum $I_c$ ($I_{c\text{ max}}$) and converting the horizontal axis to $\varepsilon_b-\varepsilon_p$ is shown in figure 7. The solid lines were fitted with the following equation [11, 12]:

$$\frac{I_c}{I_{c\text{ max}}} = 1 - a(\varepsilon_b - \varepsilon_p)^2$$

(2)

Here, the coefficient $a$ is called strain sensitivity or $a$-value. It can be seen that sample D and sample E are located on almost the same curve. This suggests that the strain sensitivity hardly changes depending on the type of rare earth, although the peak strain shifts. The values of $\varepsilon_p$ and $a$-value derived from measurement results are listed in table 2. As for sample A, the $a$-value almost agrees with the value of Fujikura CC shown in [13], and the $\varepsilon_p$ is also close to the value of pure GdBCO in [14]. The $a$-value increased with the doping of BHO, but it is still much smaller than that of the other studies [14, 16]. This difference is considered to be due to the REBCO crystal orientation.

#### Figure 6. Bending strain dependence of $I_c$ at 77 K in self-field for samples A, D, E.

#### Figure 7. Normalized bending strain with peak strain dependence of the normalized $I_c$ with the maximum $I_c$ at 77 K in self-field.

#### Table 2. The values of $\varepsilon_p$ and $a$-value derived from measurement results.

| Sample | $\varepsilon_p$ | $a$-value |
|--------|----------------|----------|
| A      | -0.457 %       | 0.012    |
| D      | -0.602 %       | 0.024    |
| E      | -0.724 %       | 0.024    |

### 4. Conclusion

The axial tensile strain and the bending strain dependences of $I_c$ for pure GdBCO and BMO (M = Zr, Hf) doped REBCO (RE = Gd, Eu) fabricated by hot-wall PLD were investigated at 77 K in self-field.
It was confirmed that the pure GdBCO film deposited on our IBAD substrate had a significantly low strain sensitivity, while the strain sensitivity increased by changing the crystal orientation by means of adding an LMO buffer layer between the MgO layer and the CeO$_2$ layer. Furthermore, the strain sensitivity increased similarly by doping of BMO. In the bending tests, it was confirmed that the $I_c$ peak strain shifted in the direction of increasing compressive strain by introducing BHO, but EuBCO was larger in shift than GdBCO. Also, the strain sensitivity was not changed depending on the type of rare earth.

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