Applied Strain Effect on Superconducting Properties for Detwinned (Y, Gd)BCO Coated Conductors

Takumi Suzuki, Satoshi Awaji, Hidetoshi Oguro, and Kazuo Watanabe

***Abstract*—We succeeded in the complete detwin of (Y, Gd)BCO coated conductors using a newly developed in-situ tensile apparatus at high temperature. The intensities of (020) and (200) peaks in a longitudinal and a transverse directions of the tape measured by XRD were similar to each other for usual (Y, Gd)BCO coated conductors before annealing. However, the (200) peak disappears for the longitudinal direction after annealing under the tensile stress. It means that the coated conductors are detwinned by annealing under the tensile stress. We found that T_c linearly decreases with increasing strain for the B-domain (b-axis). This behavior is similar with a uniaxial-pressure effect in (Y, Gd)BCO single crystals. However, the strain dependence of T_c for the A-domain (a-axis) behaves as a power-law function, whereas the uniaxial-pressure dependency of T_c for the a-axis is reported to be linear. In addition, the strain dependencies of J_c are similar with those of T_c.**

***Index Terms*—Coated conductor, detwin, strain effect, (Y, Gd)BCO.**

I. Introduction

The $REBa_2Cu_3O_y$ coated conductors (REBCO, RE: rare-earth element) have a large critical current density and strong mechanical properties. This high performance of the REBCO coated conductors enables us to develop the high field magnets operating at low temperatures. During an operation of a superconducting magnet, the coated conductor experiences various strains. Therefore the strain dependence of superconducting properties is a very important factor for superconducting magnet applications. The strain dependence of superconducting properties for REBCO coated conductors have been reported by many groups [1]–[5]. However, the strain effects of REBCO coated conductors are too complicated to be understood because of the existence of twin boundaries. This means that the a- and b-axis domains are mixed and aligned along the longitudinal direction of the tape. The volume fraction of the a- and b-axis domains in the longitudinal direction of usual conductors is about 50% [5].

On the other hand, it is reported that the T_c of a single crystal has a linear stress dependence [6]. The uniaxial pressure dependence of T_c for the a- and b- axes are opposite each other [6], [7]. However, the uniaxial strain dependence of J_c for the biaxially textured coated conductors in a self-field obeys a power-law function [2], [3]. Therefore, it is difficult to infer the strain dependence of J_c from that of T_c. In particular, the double peaks appear in the strain dependence of J_c in a low field region and disappear in a high field region above 3T [4]. The mixing of the a- and b-axis domains may be one of the origins for the complex strain dependence of J_c in the REBCO coated conductors.

Recently, the strain dependence of J_c is described by the 2D internal strain model, assuming the strain sensitivity for each crystal axis [5]. The internal strain state of a GdBCO layer in a coated conductor was evaluated at RT by a diffraction technique using synchrotron radiation. From the obtained results of internal strains, the strain sensitivities of J_c for the a- and b- axes were estimated using the strain sensitivities, assuming that they both obey a power-law function. Positive and negative strain sensitivities were derived for the a- and b-axes from this calculation. From these analyses, it is required strongly to determine the strain dependence of T_c and J_c the each axis for a wide strain range experimentally.

In case of (Y, Gd)BCO single crystal, the twin boundary can be disappeared by annealing under the strain [8]. We have tried to control the twin boundaries and residual strain by the strain-annealing for the REBCO coated conductors using a bending jig [9], [10]. However, this method is not enough to remove twin boundaries for coated conductors completely, because of a formation of cracks. In this study, we succeeded in preparing the completely detwined REBCO coated conductors by a newly developed in-situ tensile apparatus at high temperature. We also investigate the single-crystal-like uniaxial strain dependence of superconducting properties of REBCO coated conductors. The applied strain effects on T_c and J_c for detwinned (Y, Gd)BCO coated conductors at 77 K are reported in this paper.

II. Experimental Detail

Samples used in this study were a commercially available (Y, Gd)BCO coated conductor without an artificial pinning center made by the SuperPower Inc [11]. The substrate is a biaxially textured buffer made by the ion beam assisted deposition (IBAD) of MgO on a high-strength Hastelloy tape with a thickness of 100 μm. The (Y, Gd)BCO layer was grown by Metal Organic Chemical Vapor Deposition (MOCVD). The annealing under the strain is carried out by a newly developed in-situ tensile apparatus which tensile device is set in the image furnace. The samples were annealed at 300 °C for 3 hours in air with an external stress/strain. The tensile stress was gradually applied after the sample temperature reached to 300 °C and

Manuscript received August 12, 2014; accepted November 25, 2014. Date of publication December 4, 2014; date of current version February 6, 2015. This work was supported in part by the Japan Science and Technology Agency (JST): Advanced Low Carbon Technology Research and Development Program (ALCA), and Grants for Excellent Graduate Schools, MEXT, Japan.

The authors are with the Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan (e-mail: takumi-s@imr.tohoku.ac.jp).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TASC.2014.2377577

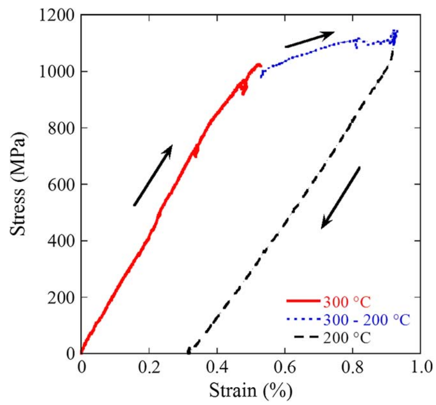

Fig. 1. Strain-stress curve for (Y, Gd)BCO coated conductors during the detwin process.

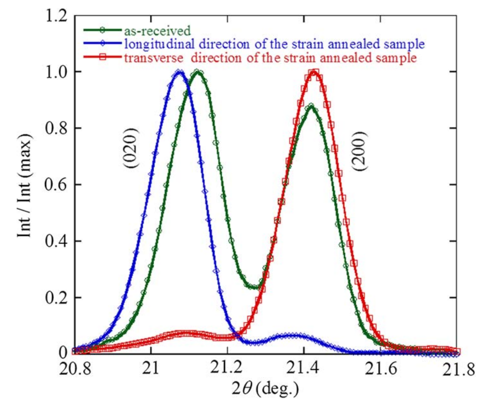

Fig. 2. (200) and (020) reflections along the longitudinal and transverse directions after the annealing under the strains in the (Y, Gd)BCO coated conductors. The longitudinal direction data of the as-received sample are also shown for comparison. Intensities are normalized by the maximum values.

kept a constant displacement during annealing. However, the stress and strain increase when temperature decreases due to the thermal contraction. We controlled the applied strain less than about 0.9 % as shown Fig. 1, because an expansion of about 0.85 % is expected by the alignments of all the b-axis. Then the applied strain was released at 200 °C. The stress and strain were measured using a load cell and a strain gauge, respectively.

The lattice constants and crystal alignments of the a- and b-axes along the longitudinal and transverse directions of the (Y, Gd)BCO coated conductors were measured at room temperature (RT) by a transmission X-ray diffraction using MoKα X-ray. The strain dependence of T_c and J_c were measured using a CuBe beam placed in a four-point bending apparatus [12]. The J_c measurements under the strain were performed at 77 K in liquid N_2. The samples were soldered onto the surface of the beam. The transport properties were measured by a four probe method under the applied strain from a compressive to a tensile strain. We define a compressive strain as a negative value in this study. A micro-bridge with about 100, 200 or 500 μm wide and 1 mm long was made by a photolithography. The J_c was determined using the criterion of $E = 1$ μV/cm. Strains were measured using a strain gauge on the samples.

III. Experimental Result

Fig. 2 shows the X-ray diffraction patterns along the longitudinal and transverse directions of the (Y, Gd)BCO coated conductors. Both (020) and (200) reflections can be seen. The amount of the a- and b-axis domains in the longitudinal direction of the as-received (Y, Gd)BCO tape is about 50%, because the intensities of (020) and (200) peaks are similar to each other. However, the annealing under the strain changes the peak intensity and position at the same time. The (200) peak in the longitudinal direction disappears after annealing under the strain. It means that the coated conductors can be detwinned by annealing under the strain. From the changes of the intensity ratio, we found that the domain ratios for the longitudinal and transverse directions become $V_a : V_b = 94 : 6$ and $= 6 : 94$, respectively. Here we call the longitudinal and transverse directions of the strain-annealed samples A-domain and B-domain samples, respectively. Therefore, the A-domain and B-domain samples were taken out from the same sample with different direction.

From the changes of peak position, we calculated the effective residual strain along the longitudinal direction of the tapes. The relative change of residual strain was estimated using the difference of d-values from the as-received sample. Hence, the strain of the as-received sample was assumed to be zero. The relative residual strain can be defined as follows:

$$\varepsilon^*_{(hkl)} = \frac{d_{(hkl)} - d_{0(hkl)}}{d_{0(hkl)}} \quad (1)$$

where $\varepsilon^*_{(hkl)}$, $d_{(hkl)}$, and $d_{0(hkl)}$ are the effective residual lattice strain, the lattice spacing of the sample and the as-received sample in terms of the (hkl) reflection, respectively. The $\varepsilon^*_{(200)}$ of A-domain and $\varepsilon^*_{(020)}$ of B-domain samples becomes -0.066% and 0.227%, respectively.

Fig. 3 shows a typical example of the SEM surface images after the strain annealing with a maximum strain of about 0.9%. Many micro-cracks exist in the entirety of sample. The size of micro cracks is approximately 0.1×200 μm^2. Most of cracks align perpendicular to the applied strain direction, i.e., along the a-axis. Therefore the J_c was deteriorated due to the crack. The J_c values at 77 K without applied strain are 2.6, 0.79, and 0.013 MA/cm^2 for the as-received, the A-domain and the B-domain samples respectively.

The change in lattice strain was evaluated under uniaxial tensile loading of the B-domain sample. Fig. 4 shows the applied strain dependence of lattice strain along longitudinal direction of the B-domain sample. The lattice strain was determined from equation (1). In this case, the d_0 is the lattice spacing of the B-domain sample at 0%. The lattice strain increases along the b-axis of the B-domain sample with increasing applied strain. The lattice strain of the B-domain sample has linear applied strain dependence. The slope of the applied strain dependence of lattice strain (strain ratio) for (Y, Gd)BCO (020) and Hastelloy become 0.57 and 0.88 respectively. On the other hand, the difference between the lattice strain and the applied strain along the longitudinal direction of the REBCO coated conductor was reported [5], [13]. Although the strain ratio obtained in this study is smaller than the strain ratio reported for

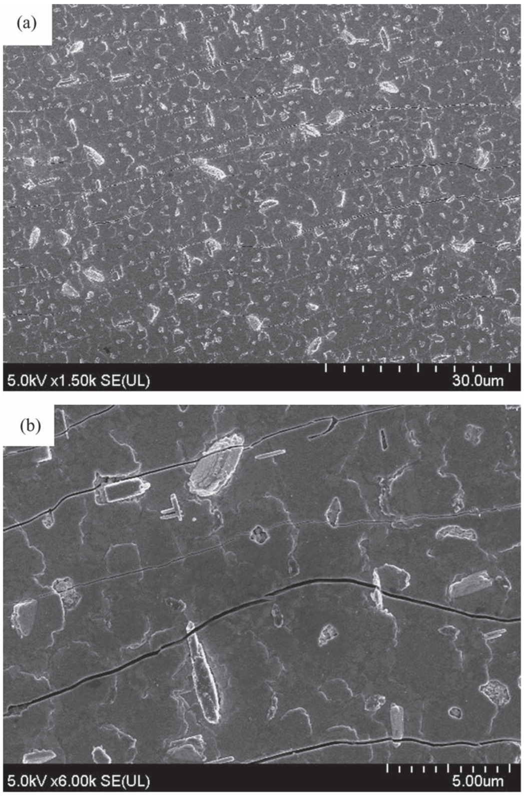

Fig. 3. SEM surface image of (Y, Gd)BCO layer after the annealing under the strains. (a) low magnification, (b) high magnification.

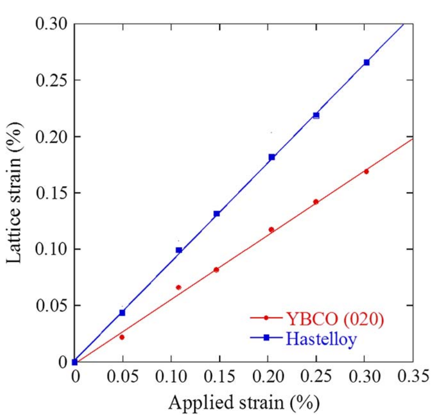

Fig. 4. Applied strain dependence of lattice strain after annealing under the strains in the (Y, Gd)BCO coated conductors along longitudinal direction.

the similar REBCO coated conductors made by the SuperPower in ref. [14], the linear applied strain dependence of lattice strain is observed. Therefore, it can be considered that the effect of the micro-cracks on the strain dependence is related to only the strain ratio.

Fig. 5 shows the strain dependences of T_c. The T_c for the B-domain (b-axis) decreases, but for the A-domain (a-axis) increases when the applied strain increases. The strain dependence of T_c for the A-domain (a-axis) can be well fitted by a power-law function whereas the single crystal behavior is linear [6], [7]. It was impossible to measure the pressure effect with a wide pressure region, since a brittle single crystal is easily fractured by the high pressure. Actually, the maximum pressure reported in ref. [7] corresponds to about 0.07%,

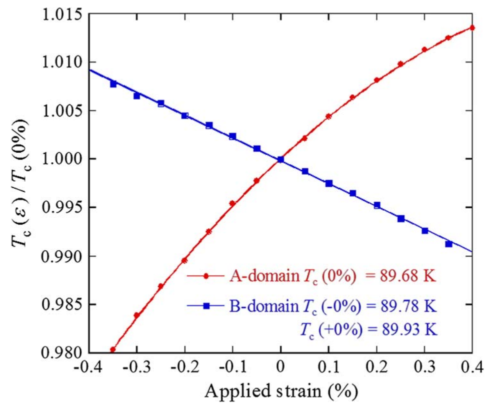

Fig. 5. Strain dependence of $T_c(\varepsilon)/T_c(\varepsilon = 0\%)$ after annealing under the strains in the (Y, Gd)BCO coated conductors. The A-domain and B-domain mean the applied strain along a-axis and b-axis directions, respectively. $T_c(+0\%)$ and $T_c(-0\%)$ is T_c (0%) for measurement of tensile region and compressive region respectively.

which is calculated using a Young's modulus of 162.7 GPa for a-axis [14]. Therefore we found that the strain dependence of T_c for A-domain shows the power-law behavior from the strain dependence measurement for a wide strain region, which was about 10 times wider than that reported in the single crystal. On the other hand, the strain dependence of T_c for the A-domain was analyzed by using the following empirical function:

$$\frac{T_c(\varepsilon)}{T_c(0\%)} = \frac{T_{c,\max}}{T_c(0\%;)} - a'(\varepsilon - \varepsilon_p)^2 \tag{2}$$

where a' is a strain sensitivity for the T_c. The maximum strain ε_p, where the T_c becomes a maximum, is estimated to be 0.77%. In addition, the additional thermal strain caused from the difference of thermal expansion between (Y, Gd)BCO and Cu-Be induces the compression strain of about 0.15% to the (Y, Gd)BCO. Hence, the strain at the maximum of T_c is shifted to a tensile strain side by the thermal strain. However, the ε_p value is much higher than the residual strain of 0.15%. Hence, the physical meaning of the ε_p is not clear yet. It should be discussed on the basis of the mechanism of high-T_c superconductors.

Fig. 6 shows the strain dependencies of normalized J_c at 77.3 K. The strain dependencies of J_c for the as-received and the A-domain samples behave as a power-law function similarly to that of T_c and the B-domain sample is linear. The strain dependency was analyzed by using the following empirical function [5]:

$$\frac{J_c(\varepsilon)}{J_c(0\%)} = \frac{J_{c,\max}}{J_c(0\%)} - a(\varepsilon - \varepsilon_p)^2 \tag{3a}$$

$$\frac{J_c(\varepsilon)}{J_c(0\%)} = b - a\varepsilon \tag{3b}$$

where a is a strain sensitivity for the J_c, b is a fitting parameter and ε_p is a maximum strain, at which the I_c/I_c (0%) becomes the maximum. The ε_p-values for the A-domain and the as-received samples are 0.249% and 0.006% respectively. It is noticed that the ε_p values are much different between T_c and J_c for the a-axis. The strain sensitivity a-values for the A-domain and

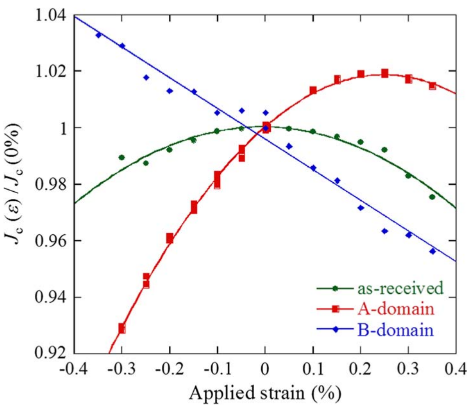

Fig. 6. Strain dependence of $J_c/J_c(\varepsilon = 0\%)$ after the annealing under the strains and as-received in the (Y, Gd)BCO coated conductors. The A-domain and B-domain are longitudinal and transverse direction respectively.

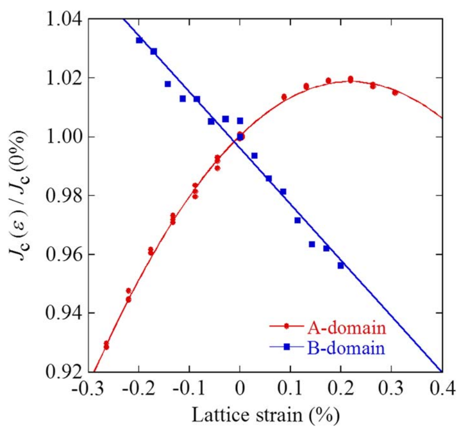

Fig. 7. Lattice strain dependence of $J_c/J_c(\varepsilon = 0\%)$ after the annealing under the strains and as-received in the (Y, Gd)BCO coated conductors. A-domain and B-domain are axial and lateral direction, respectively.

the as-received samples are 0.30 and 0.17 respectively. In case of the B-domain sample, however, the J_c linearly decreases with increasing applied strain. Therefore, it is considered the strain dependencies of J_c are related to those of T_c.

Fig. 7 shows the lattice strain dependence of $J_c(\varepsilon)/J_c$ (0%). The strain ratio of the b-axis for B-domain sample is 0.57. For the A-domain sample, because the applied strain direction is parallel to the micro-crack direction, it can be considered that the effect of micro-crack on the strain ratio is neglected for the a-axis. Hence, we use the strain ratio of 0.88 along the a-axis for the A-domain sample, which was reported in ref. 13. The lattice strain sensitivities for the a- and b-axes are 0.38 and 0.19, respectively from Fig. 7. It is concluded that the lattice strain sensitivity for each axis obtained in this study is an intrinsic strain sensitivity.

IV. Conclusion

We succeeded in the preparation of completely detwinned (Y, Gd)BCO coated conductors using a newly developed high temperature tensile apparatus. Applied strain effects on T_c and J_c for the detwinned (Y, Gd)BCO coated conductors were also investigated. The intensities of (020) and (200) peaks along the longitudinal directions measured by XRD were similar to each other for (Y, Gd)BCO coated conductors before annealing. However, the (200) peak in the longitudinal direction disappears after annealing under the tensile stress. It means that the coated conductors are detwinned by annealing under the tensile stress. From the XRD for (020) and (200) peaks of (Y, Gd)BCO, we confirmed that the domain ratio of the a- and b-axes aligned along the longitudinal direction of the (Y, Gd)BCO tape becomes 94:6. Although the micro-cracks perpendicular to the longitudinal direction exist in the entirety of sample, we confirmed that internal strain increase with increasing applied strain by XRD. We found that T_c linearly decreases with increasing strain for the B-domain but obeys a power-law for the A-domain. The strain dependences of J_c are similar with those of T_c. This means that the strain dependence of J_c is closely related to that of T_c. The lattice strain sensitivities of J_c for a- and b-axes are estimated to be 0.38 and 0.19, respectively.

Acknowledgment

The strain dependency was measured using the Dr. Nishijima's 4 point bending apparatus. We thank Dr. Nishijima for a permission to use his equipment.

References

[1] H. Oguro *et al.*, "Strain dependence of superconducting properties for GdBCO coated conductor in high field under tensile load," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, Jun. 2012, Art. ID. 6600504.

[2] D. C. van der Laan and J. W. Ekin, "Large intrinsic effect of axial strain on the critical current of high-temperature superconductors for electric power applications," *Appl. Phys. Lett.*, vol. 90, no. 5, Jan. 2007, Art. ID. 052506.

[3] M. Sugano, K. Shikimacchi, N. hirano, and S. Nagya, "The reversible strain effect on critical current over a wide range of temperatures and magnetic fields for YBCO coated conductors," *Supercond. Sci. Technol.*, vol. 23, no. 8, Aug. 2010, Art. ID. 085013.

[4] D. C. van der Laan *et al.*, "Effect of strain, magnetic field and field angle on the critical current density of YBa2Cu3O7δ coated conductors," *Supercond. Sci. Technol.*, vol. 23, no. 7, Jul. 2010, Art. ID. 072001.

[5] M. Sugano *et al.*, "The effect of the 2D internal strain state on the critical current in GdBCO coated conductors," *Supercond. Sci. Technol.*, vol. 25, no. 5, May 2012, Art. ID. 054014.

[6] U. Welp *et al.*, "Effect of uniaxial stress on the superconducting transition in $YBa_2Cu_3O_7$," *Phys. Rev. Lett.*, vol. 69, no. 14, pp. 2130–2133, Oct. 1992.

[7] W. H. Fietz, K. P. Weiss, and S. I. Schlachter, "Influence of intrinsic strain on Tc and critical current of high-Tc superconductors," *Supercond. Sci. Technol.*, vol. 8, no. 12, S332–S337, Dec. 2005.

[8] J. Z. Liu, M. D. Lan, P. Klavis, and R. N. Shelton, "Meissner effect and magnetic critical current density in detwinned $YBa_2Cu_3O_{7-x}$ single crystals," *Phys. Lett. A*, vol. 144, no. 4/5, pp. 265–268, Mar. 1990.

[9] S. Awaji *et al.*, "Control of residual strain and twin boundary by annealing under strains," *Supercond. Sci. Technol.*, vol. 26, no. 6, Jun. 2013, Art. ID. 065013.

[10] T. Suzuki *et al.*, "Improvement of J_c for GdBCO coated conductors by annealing under strain," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, Jun. 2013, Art. ID. 8000104

[11] V. Selvamanickam *et al.*, "Progress in second-generation HTS wire development and manufacturing," *Phys. C, Supercond.*, vol. 468, no. 15–20, pp. 1504–1509, Sep. 2008.

[12] D. C. van der Laan *et al.*, "The effect of strain on grains and grain boundaries in $YBa_2Cu_3O_{7-\delta}$ coated conductors," *Supercond. Sci. Technol.*, vol. 23, no. 1, Jan. 2010, Art. ID. 014004.

[13] K. Osamura *et al.*, "Internal strain behavior exerted on YBCO layer in the YBCO coated conductor," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 3090–3093, Jun. 2011.

[14] H. Ledbetter and M. Lei, "Monocrystal elastic constants of orthotropic $Y_1Ba_2Cu_3O_7$ An estimate," *J. Mater. Res.*, vol. 6, no. 11, pp. 2253–2255, Nov. 1991.