Artificial Pinning Centers-doped RE-based Coated Conductors

Wataru HIRATA,[1] Shogo MUTO,[1] Yutaka ADACHI,[1] Tomo YOSHIDA,[1] Shinji FUJITA,[1] Kazuomi KAKIMOTO,[1] Yasuhiro IIJIMA,[1] Masanori DAIBO,[1] and Satoshi AWAJI[2]

RE-based coated conductors (CCs) have high critical current characteristics in high temperatures/magnetic fields and are expected to be applied to various superconducting systems. It is known that the critical currents in the magnetic fields are improved by introducing some kind of impurities called artificial pinning centers (APCs) into a superconducting layer of the RE-based CC.

We have been developing high-quality APC-doped RE-based CCs using our original manufacture apparatus. In this work, we report on the results of fabrication and evaluation of APC-doped RE-based CCs aiming for mass production.

1. Introduction

1.1 RE-based Coated Conductors

RE-based Coated Conductors, which are represented in $REBa_2Cu_3O_{7-\delta}$ (REBCO, RE = Rare Earth element such as Gd, Eu, Sm, etc.), are expected to be the next-generation superconducting wires because they can exhibit the higher critical current densities under high temperatures and high magnetic fields compared to the conventional metal-based superconducting wires and the Bismuth-based superconducting wires.

Fig. 1 shows the structure of RE-based CCs of Fujikura.

We deposited a buffer layer, a superconducting layer, a protection layer and a stabilizer in this order on a Hastelloy™ tape substrate.

Finally, we provided an insulation on the tape by wrapping polyimide tapes.

The techniques to deposit a thin film such as IBAD, PLD which enables the control of the crystalline orientation are important for CCs to show high critical current (I_c) characteristics.

IBAD method enables the fabrication of an oriented intermediate layer on a non-textured metal substrate by irradiating ion beams during the deposition.

The superconducting layer is deposited on the intermediate layer by PLD method, which is a technique for depositing a thin film by irradiating a sintered target with a strong pulsed laser.

1.2 Artificial Pinning Centers doped RE-based CCs

In order to improve the performance of some applications such as MRI, NMR, and accelerators, further improvement of in-field I_c is required.

It is known that the improvement of in-field I_c is achieved by the introduction of APCs which act as magnetic flux pinning centers.

By using a sintered REBCO target which contains $BaMO_3$ (M = Zr, Hf, Sn, etc.) in the PLD process, $BaMO_3$ nano-rod structures with diameters of several nanometers are formed in the REBCO layer [1].

We confirmed that the doping of $BaZrO_3$ or $BaHfO_3$ in the GdBCO or EuBCO layer improved the in-field I_c [2].

For the mass production of APC-doped CCs, the improvement of the production speed is one of the challenges.

2. Deposition and evaluation method of APC-doped CCs

2.1 Hot-wall heating PLD system

We have developed the original PLD system called as "Hot-wall heating PLD system" with highly stable temperature environment like an electric furnace, as

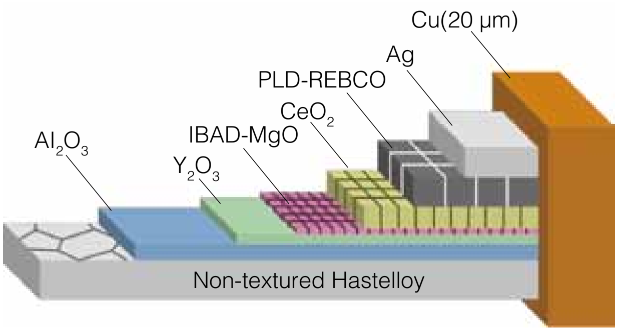

Fig. 1. The structure of RE-based coated conductors.

1 Superconductor Research Department, Advanced Technology Laboratory
2 High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University

Panel 1. Abbreviations, Acronyms, and Terms.

Critical temperature, T_c
Maximum temperature that can keep a superconducting state.

Critical current, I_c
Critical current (I_c) is the maximum current value that can flow in a superconducting state.
It depends on temperatures and magnetic fields.

Critical current density, J_c
Critical current density (J_c) equals the critical current (I_c) divided by the cross-section area of a superconducting layer.

Ion beam assisted deposition, IBAD
Ion beam assisted deposition (IBAD) is the key original technology when fabricating RE-based coated conductors, and is a method by which the crystalline orientation depending on the superconducting characteristics is highly controlled. This is applied to a buffer layer which is located between a metal tape and a superconducting layer. Fujikura has basic patents of IBAD in Japan, USA, Europe, and it is widely used for fabricating RE-based coated conductors with high characteristics.

Pulsed laser deposition, PLD
Pulsed laser deposition (PLD) is a method when fabricating RE-based coated conductors. This is applied to a superconducting layer in a vacuum by focusing a beam of ultraviolet laser radiation.

n-value
I-*V* characteristics of a superconducting wire around the critical current are expressed as $V = V_c (I/I_c)^n$ (V_c: Voltage criterion for critical current). This expression is referred to as an *n*-value model and the index is called *n*-value.

shown in Fig. 2.

This system have realized high quality CCs with a quite uniform I_c distribution, because the quality of the superconducting layer strongly depends on the temperature during the deposition [3].

2.2 Sample preparation

The buffer layer including the IBAD-MgO layer was deposited on a Hastelloy™ substrate.

In order to improve the critical current densities per cross section of the CC, 50 μm thick substrates were applied for the APC-doped CC samples, instead of the 75 μm thick one applied to the conventional non-doped CCs.

We selected Eu as a Rare-Earth element, $BaHfO_3$ as artificial pinning centers, because it is known that J_c keeps high as the film thickness increases [4].

We prepared several samples by the different PLD deposition conditions.

For the evaluation of mechanical properties, a Cu stabilizer with a thickness of 20 μm was formed around the 4 mm-wide CC by electroplating.

2.3 Evaluation method

The critical current I_c of the samples was measured by the conventional DC four-probe method with an electric-field criterion of 1 μV/cm. In addition, Tapestar™ was used for magnetization measurements which enable the evaluation of the I_c distribution in the longitudinal direction of the CC. A standard deviation of I_c divided by average I_c was used to evaluate the uniformity of the CC.

For the in-field I_c measurements, a micro-bridge was formed on the sample by wet-etching as shown in Fig. 3 in order to limit a transport current. The width

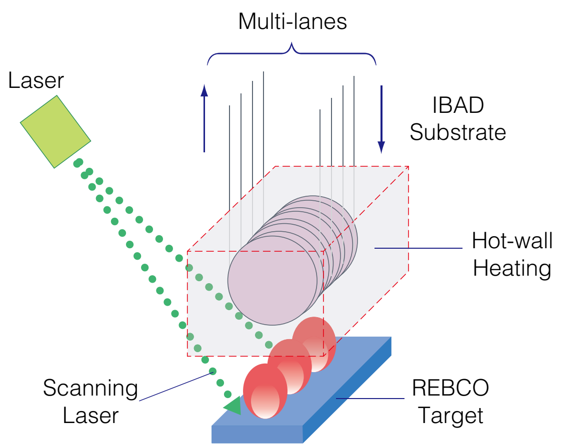

Fig. 2. The schematic of Hot-wall heating PLD system.

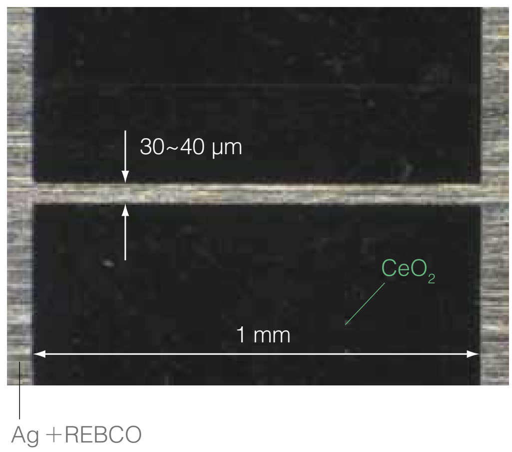

Fig. 3. The photograph of the micro-bridge fabricated by wet etching.

and length of the micro-bridge are 30-40 μm and 1 mm respectively.

The in-field I_c measurements under various temperatures, magnetic fields and field angles were conducted with the cooperation of High Field Laboratory for Superconducting Materials Institute for Materials Research, Tohoku University.

The observation of micro structure of the REBCO layer was conducted by transmission electron microscope (TEM). The cross-sectional TEM images were obtained from the thin samples prepared by focused ion beam milling technique.

For the evaluation of the mechanical properties, tensile and bending tests in liquid nitrogen were conducted and the difference of the properties between APC-doped and non-doped CCs was examined.

3. Results

3.1 Deposition rate dependence

We examined the difference of the critical current properties due to the deposition rate of EuBCO layer.

We fabricated the samples with different thickness of EuBCO layer by using two deposition rates.

The deposition rate of Condition A is 5-7 nm/sec (slow), and that of B is 20-30 nm/sec (fast).

Fig. 4 shows the angular dependence of in-field I_c (I_c-θ) at 30 K, 7 T.

In the slow condition samples, a peak structure around 0 degree was found.

As the thickness increased, the peak structure was suppressed. This suggests that the microstructure of the EuBCO layers is changed.

In the fast condition samples, the peak structure around 0 degree was not observed.

When comparing samples with similar thickness, the minimum I_c values are almost the same.

It is thought that the fast condition is more practical in terms of productivity.

Fig. 5 shows the cross-sectional TEM images of the EuBCO layer.

In the slow condition sample, $BaHfO_3$ nano-rods with a diameter about 4 nm grown straight along with *c*-axis direction of the EuBCO crystal were observed.

It suggests that those nano-rods work as strong pinning centers against external magnetic field parallel to *c*-axis and induce the peak structure in I_c-θ profiles.

In the fast condition sample, nano-rods were short and tilted from *c*-axis.

3.2 Evaluation of critical current properties under high magnetic field

We investigated the critical current properties under high magnetic fields for the APC-doped EuBCO CCs fabricated by two deposition conditions and the non-doped GdBCO CCs.

Table 1 shows the specifications of the samples we investigated.

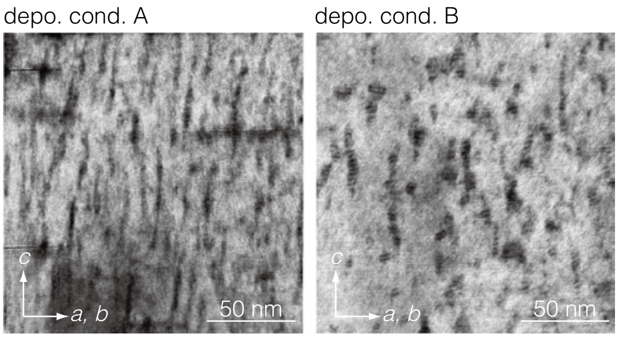

Fig. 5. The cross-sectional TEM images of the EuBCO layer.

Table 1. Specifications of the samples used for evaluation of the in-field characteristics.

Sample Index	REBCO layer	Deposition rate [nm/sec]	REBCO thickness [μm]	I_c(77.3 K, s. f.) [A/cm-w]	T_c [K]
FAST	EuBCO-BHO	20-30	2.2	387	91.2
SLOW	EuBCO-BHO	5-15	1.1	250	91.8
Pure	GdBCO	10-20	1.9	575	93.1

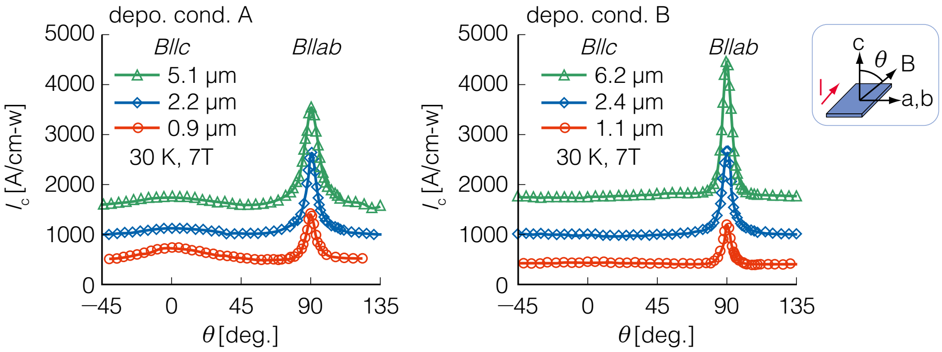

Fig. 4. Angular dependence of I_c with different deposition rates and thicknesses of the EuBCO layer (30 K, 7 T).

Compared with the GdBCO CC, the EuBCO CCs had lower I_c at 77 K and lower T_c.

This suggests that the disorder in the REBCO layer increases due to the APCs doping.

Fig. 6 shows the magnetic field dependence of I_c.

The GdBCO CCs showed high I_c values in a high temperature and low magnetic field range.

In a low temperature and high magnetic field range, I_c values of the EuBCO CCs increased due to the APCs doping.

In terms of the I_c values which are obtained in the same deposition time, the fast condition EuBCO sample has higher performance than other samples.

Fig. 7 shows the angular dependence of in-field I_c.

In the slow condition sample, the peak structure around 0 degree was observed at a high temperature and low magnetic field range, and it was suppressed at a low temperature and high magnetic field range.

In the fast condition sample, the peak structure was not observed, and high I_c values were obtained over a wide angle range.

3.3 Fabrication of long length CCs

We fabricated long length CCs by using the fast deposition condition.

Fig. 8 shows the longitudinal I_c distribution of the 4 mm-wide and over 600 m-long CC obtained by the magnetization measurement and the DC four-probe measurement.

In the magnetization measurement, the value of I_c standard deviation divided by average I_c was 2.9%, and it was comparable to the non-doped mass-produced CCs.

In the DC four-probe measurement, it was confirmed that I_c values were higher than 150 A and *n*-values were higher than 20 over the entire length.

Additionally, we have successfully fabricated an APC-doped CC longer than 1 km as shown in Fig. 9.

Although the uniformity value was a little larger, no noticeable I_c degradation was observed.

The prospect for producing APC-doped CCs with length and uniformity comparable to mass-produced non-doped CCs was obtained.

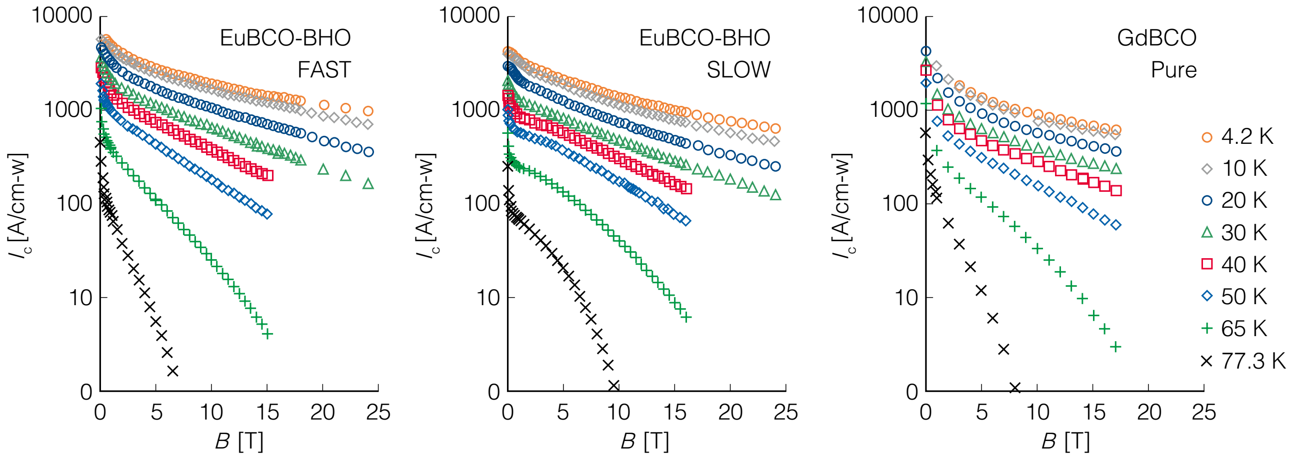

Fig. 6. Magnetic field dependence of I_c (*B*//*c*).

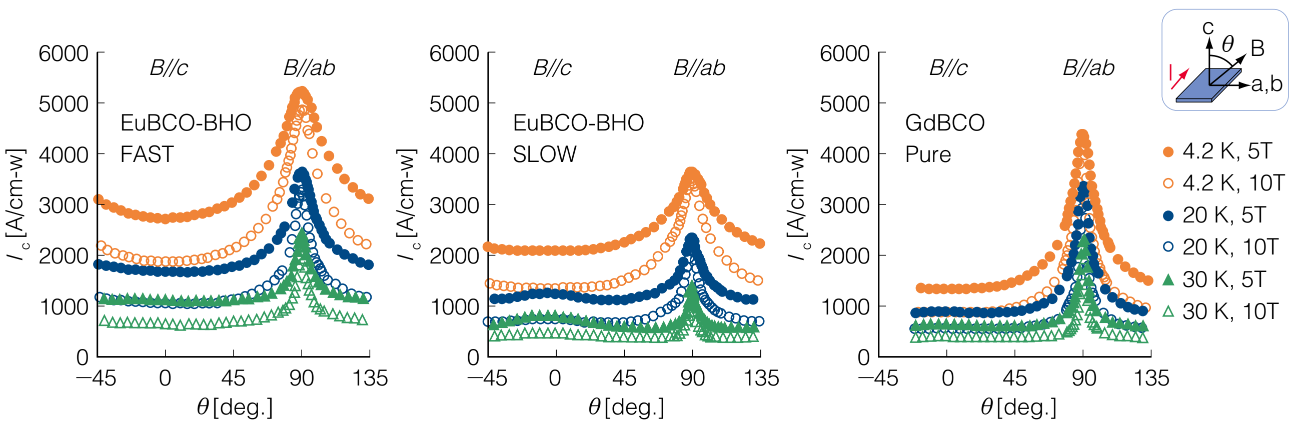

Fig. 7. Angular dependence of I_c.

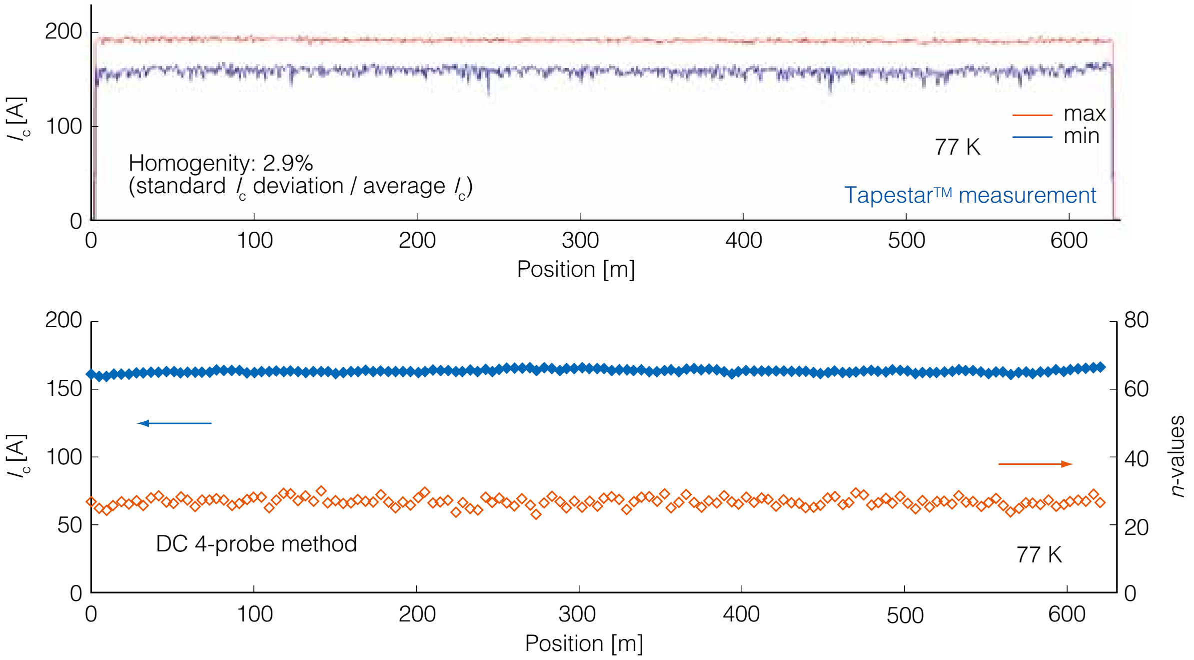

Fig. 8. Longitudinal I_c distribution of over 600 m-long coated conductor.

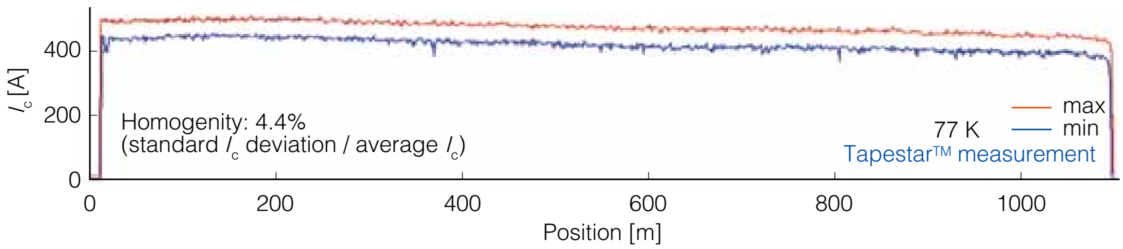

Fig. 9. Longitudinal I_c distribution of over 1 km-long coated conductor.

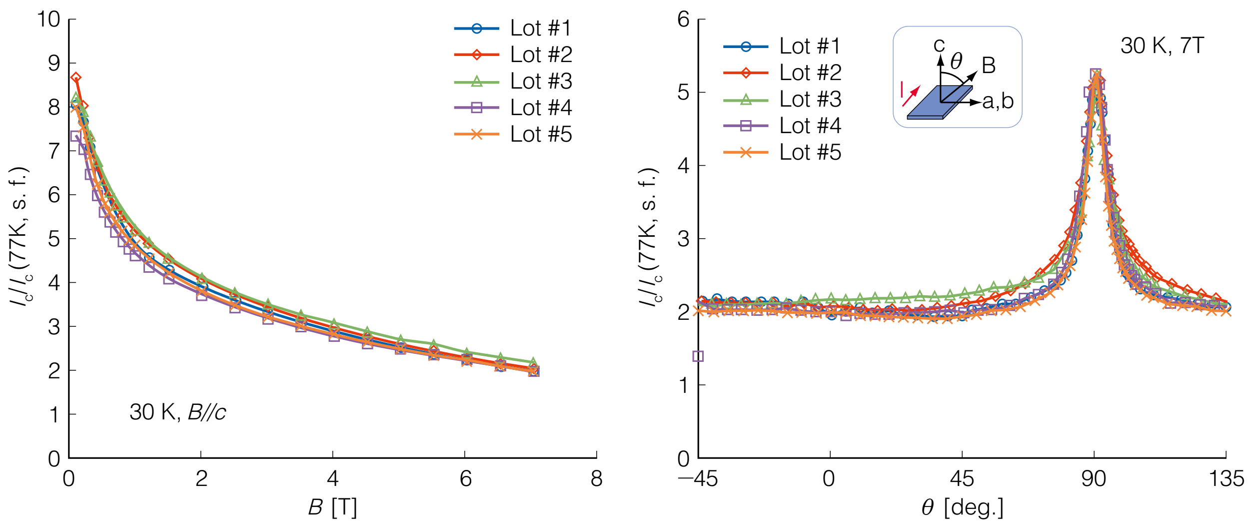

Fig. 10. In-field characteristics of the samples.

3.4 Evaluation of the in-field I_c variation

Because the increase of I_c variation between lots due to APC doping is concerned, we evaluated the in-field I_c variation for several APC-doped CC samples fabricated by the fast deposition condition.

Fig. 10 shows the in-field I_c properties normalized by I_c at 77K self-field.

The results of five samples showed the good reproducibility and the in-field I_c variation was small.

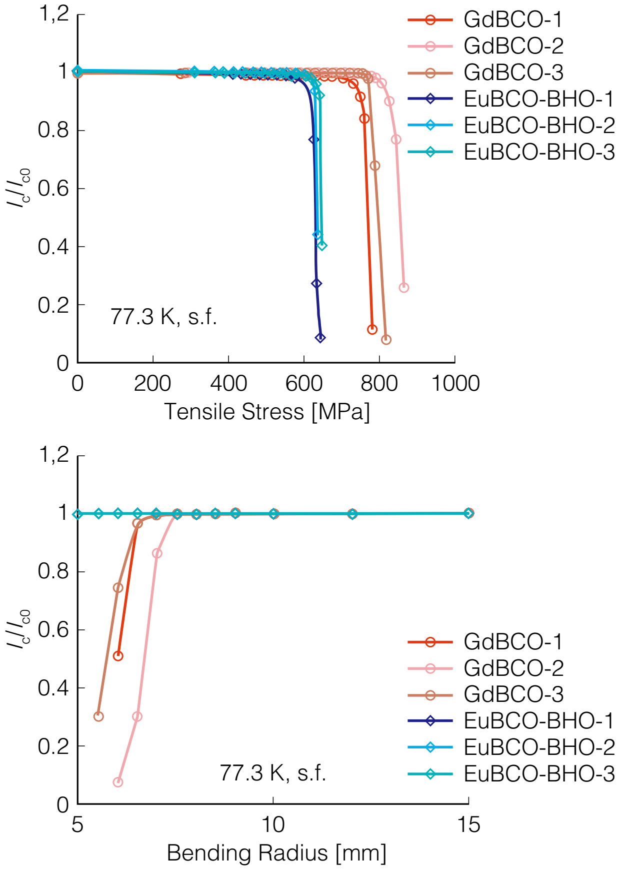

Fig. 11. Mechanical properties of the samples.

3.5 Evaluation of mechanical properties

Fig. 11 shows the results of tensile and bending tests in liquid nitrogen.

We examined I_c decrease from I_{c0} which represents the I_c before applying stress.

In the tensile test, I_c decrease was observed in the range over 700 MPa for the GdBCO samples, 600 MPa for the EuBCO samples.

In the bending test, I_c decrease was observed in the range below 7 mm of bending radius for the GdBCO samples, but no I_c decrease was observed even 5 mm for the EuBCO samples.

These results are thought to be due to the difference of substrate thickness.

It was confirmed that the APC-doped CCs have sufficient mechanical properties enough for practical use.

4. Conclusion

In this work, we fabricated APC-doped CCs by applying the fast deposition condition and evaluated their properties.

We succeeded in the development of APC-doped CCs which have high performance and high producibility compared with the conventional non-doped CCs.

We are plan to establish a mass production system of APC-doped CCs.

Acknowledgements

This work includes the results supported by New Energy and Industrial Technology Development Organization (NEDO).

We sincerely thank for the cooperation with the measurement of in-field characteristics to High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University.

References

1) H. Tobita et al., "Fabrication of $BaHfO_3$ doped $Gd_1Ba_2Cu_3O_{7-\delta}$ coated conductors with the high I_c of 85A/cm-w under 3 T at liquid nitrogen temperature (77 K),": Supercond. Sci. Technol., 25 (2012) 062002.
2) T. Yoshida et al., "Yttrium-based coated conductors with artifitial pinning centers,": Fujikura Technical Review, 47 (2017) 19-25.
3) Y. Iijima, "High-performance Y-based superconducting wire and their applications,": Fujikura Technical Review, 42 (2013) 117-121.
4) T. Yoshida et al., "Development of a 100-m-long $Eu_1Ba_2Cu_3O_{7-\delta}+BaHfO_3$-coated conductor with high in-field property using the IBAD/PLD method," J. Cryo. Super. Soc. Jpn., Vol. 49, No. 3, (2014) 163-168.