B//c-axis 磁場中 GdBCO CC テープの Ic のひずみ依存性
Strain effect on critical current, I_c in GdBCO CC tapes under B//c-axis magnetic field

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1. Introduction

The remarkable development in the fabrication technology of REBCO CC tapes and their superior properties made it potentially attractive to power device applications such as power cables, motors, generators and SMES [1, 2]. The CC tapes have received much attention on magnetic applications due to their promising potentials particularly their lower magnetic susceptibility as compared with the BSCCO tapes. Regarding to the issue of electromechanical properties, specifically in rotating machines, SMES and magnets where CC tapes will be subjected to external magnetic field, to understand the behavior of current carrying capacity response with the strain induced under magnetic field is essential to ensure their performance under operation. In most of the device applications such as coils and magnets, it is expected that the CC tapes will experience different modes of electromechanical stress/strain during fabrication, cool-down and operation. Differences in the thermal expansion coefficient between the turns and the adjacent material may cause thermo-mechanical stress and strain in the coated conductor. Coils will experience hoop stress when energized. The conductor will then be subjected to different strains which originated from the bending during winding, the thermal mismatch during cool-down and the Lorentz force during operation. Since the strain of a magnitude can cause large degradation on the current density and when it exceeded the critical strain, the current carrying capacity is irreversibly reduced [3, 4]. The design process of coils requires the understanding of the strain dependence of the critical current in the conductor and the ability to predict the strain state of the conductors in the coil. To ensure the performance of coated conductors in coil application, the evaluation of the electromechanical property under magnetic field is necessary and is one of the foremost things to do prior to device designing [5-7]. Under magnetic field, normalized I_c changed more gradually with increasing magnetic field up to 2-3 T while it degrades more rapidly under higher magnetic fields for MOD-YBCO CC tape [8], Also, the variation of I_c with applied strain becomes more pronounced at high temperatures and magnetic fields [9]. Recently, Sugano et al and van der Laan et al analyzed the I_c and J_c behavior in YBCO CC under magnetic field and systematic magnetic field dependence of I_c (ε, B) had been reported [5-7]. When the magnetic field is oriented parallel to c-axis (B//c-axis), shifting of the strain corresponding to the I_c peaks with magnetic field was observed. This observation implies that the location of the peak in I_c or J_c with strain cannot be entirely determined by the initial strain state on the YBCO coating layer. Van der Laan et al also noted that different pinning mechanisms in the YBCO CC tapes are affected differently by the strain. But the I_c degradation or variation mechanism against strain or stress is not yet fully understood.

In this study, the uniaxial strain effect on I_c under magnetic field (B//c-axis) in RCE-DR GdBCO CC tapes was investigated.

2. Experimental Procedure

Commercially-available Cu-stabilized GdBCO CC tapes fabricated by the reactive co-evaporation by deposition and reaction (RCE-DR) were supplied for the test. Samples have different substrate materials of Hastelloy and stainless steel, respectively. In addition, the Cu-stabilized samples were externally reinforced by laminating brass foils at both sides called the brass laminated samples. Specifications of the CC tapes including their dimensions are presented in Table 1.

Under magnetic field, a Katagiri-type loading fixture was used to evaluate the electromechanical properties of GdBCO CC tapes [5, 10]. Figure 1 shows the sample mounted on the loading frame located at the bottom part of the testing probe. External magnetic field was applied perpendicular to the CC tape's surface (B//c-axis) using the 10 T cryo-cooled superconducting magnet at HFLSM, IMR at Tohoku

TABLE 1
SPECIFICATIONS OF RCE-DR-GdBCO CC TAPES

Fabrication process	IBAD-RCE-DR	
Structure	Ag/GdBCO/$LaMnO_3$/ IBAD MgO/Y_2O_3/Al_2O_3/ Substrate	
GdBCO film thickness	~ 1.5 μm	~ 1.5 μm
I_c , A	~ 170 A	~ 170 A
Dimension, t x w		
Cu-stabilized	0.136 x 4.07	0.092 x 4.01
Brass laminated	0.232 x 4.20	0.175 x 4.16
Substrate	Stainless steel	Hastelloy
thickness	~100 μm	~57 μm
Stabilizer	Copper	
technique	Electroplating	
thickness	15 μm	15 μm
Laminate	Brass	
thickness	45 μm	
Manufacturer	SuNAM	

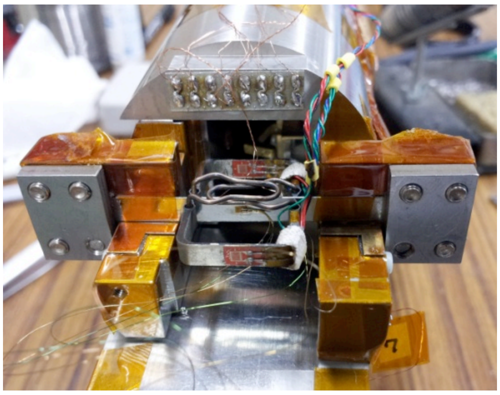


Fig. 1. RCE-DR GdBCO CC sample mounted at the Katagiri-type tensile loading rig showing the extensometer and the strain gauges attached to the CC samples as strain sensing devices.

University [10]. In this case, the sample length, gauge length and voltage tap separation were 40, 20 and 10 mm, respectively. Details of this test procedure were published elsewhere [10]. Critical current, I_c was measured by four-probe method using the electric field criterion of 1 μV/cm.

3. Results and Discussion

3.1 Magnetic field dependence of I_c (J_c) with magnetic field (B//c-axis) in RCE-DR GdBCO CC tapes

Figure 2 shows the I_c/I_{c0}-magnetic field dependence at unstrained state (ε=0%) subjected to an external magnetic field oriented perpendicular to the tape surface (B//c-axis) at 77 K in RCE-DR GdBCO CC tapes. Since all samples tested have no artificial pinning centers, it can be found that the I_c degraded by 90% of I_{c0} at 1 T for both samples having Hastelloy and stainless steel substrates, respectively. In Fig. 3, almost similar J_c-B relation has been observed for both samples with Hastelloy and stainless steel

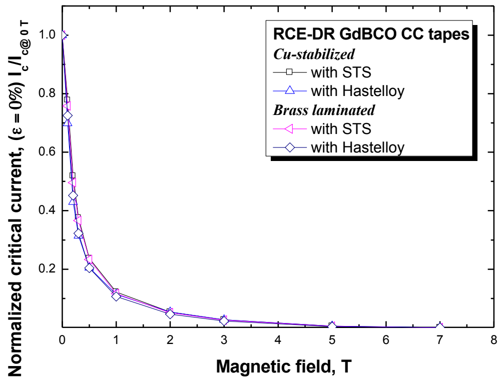


Fig. 2 Magnetic field dependence of I_c/I_{c0} in RCE-DR GdBCO CC samples at 77 K and at unstrained state (ε = 0%) under B//c-axis.

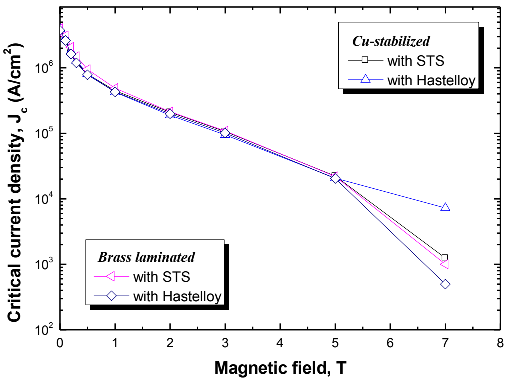
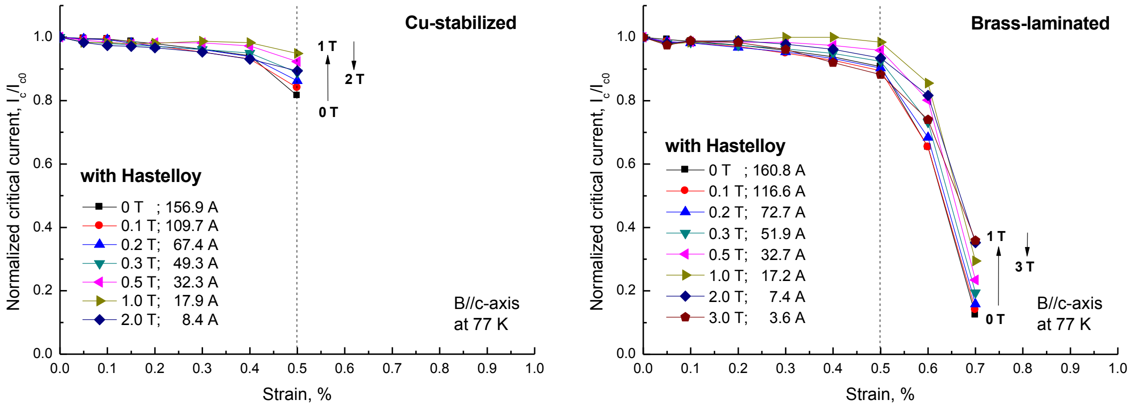


Fig. 3 Magnetic field dependence of J_c in RCE-DR GdBCO CC samples with different substrates at 77 K and under B//c-axis.

substrates. Similar behavior for both the Cu-stabilized and brass laminated samples were also observed. From these graph, it can be found that the magnetic field dependence of I_c and J_c in RCE-DR GdBCO CC tapes is independent on the substrate material adopted both in the Cu-stabilized and brass-laminated samples. Variation in critical current density at higher magnetic field is due to the difficulty in determining the I_c which is almost zero using the electron field criterion as can be seen in Fig. 2 [11]. It can be inferred that similar deposition conditions used in the RCE-DR process will produce similar microstructure which eventually determine its flux pinning characteristics [7]. However, the effect of strain on the flux pinning behavior should also be investigated and will be discuss in the following sections.

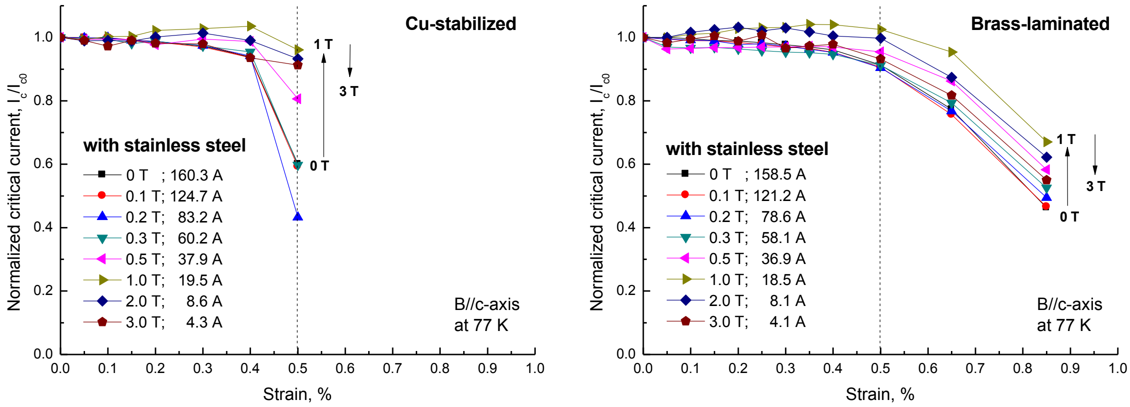
3.2 Strain effect on I_c under magnetic field (B//c-axis) in RCE-DR GdBCO CC tapes

Figures 4 and 5 show the uniaxial strain response of I_c at each applied magnetic field in RCE-DR GdBCO CC tapes. I_{c0} values at each magnetic field were also shown in the graph. (a) and (b) represent the results for Cu-stabilized and brass laminated GdBCO CC



(a) (b)

Fig. 4. Strain response of I_c/I_{c0} under magnetic field in (a) Cu-stabilized and (b) brass laminated RCE-DR GdBCO CC tapes with Hastelloy substrate at 77 K.



(a) (b)

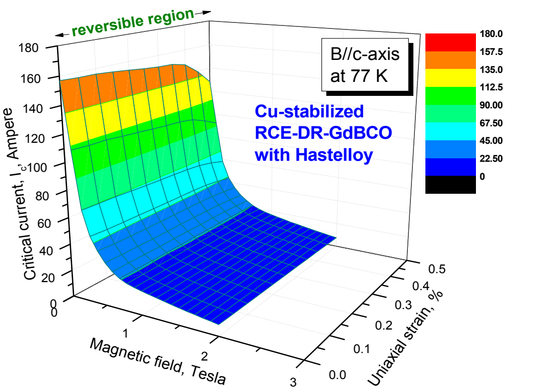
Fig. 5. Strain response of I_c/I_{c0} under magnetic field in (a) Cu-stabilized and (b) brass laminated RCE-DR GdBCO CC tapes with Stainless steel substrate at 77 K.

tapes, respectively for samples having Hastelloy and stainless steel substrate. In Fig. 4 for both samples with Hastelloy substrate, the I_c/I_{c0}-strain behavior was initially improved (became less strain sensitive) as the magnetic field applied increases from 0 T up to 1 T showing a reduced strain sensitivity. However, it was followed then with increasing strain sensitivity behavior when magnetic field was further increased to 3 T. At magnetic field over 1 T, a minimal I_c/I_{c0} peak strain existed. Although it showed improved strain sensitivity up to 1 T, the I_c was highly affected by the applied external magnetic field as can be seen in Fig. 2. This current carrying capacity of CC tapes under magnetic field can be eventually improved by further decreasing the operation temperature and/or by improving the intrinsic flux pinning characteristics of the CC tapes through the introduction of APC's [5]. Cu-stabilized and brass laminated samples were tested within their reversible strain limit. However, in the case of brass laminated sample, the significant decrease of Ic both at 0.6% and 0.7% strain was due to the increase in the strain value during increasing of magnetic field from 0 T [12]. And since the sample is just gripped at both ends, upon the application of load beyond the elastic limit may result to continuous increase in strain value due to almost perfect plastic deformation of the sample. Therefore, the significant degradation of I_c at 0.7% strain might be attributed to the local deformation site within the voltage tap separation.

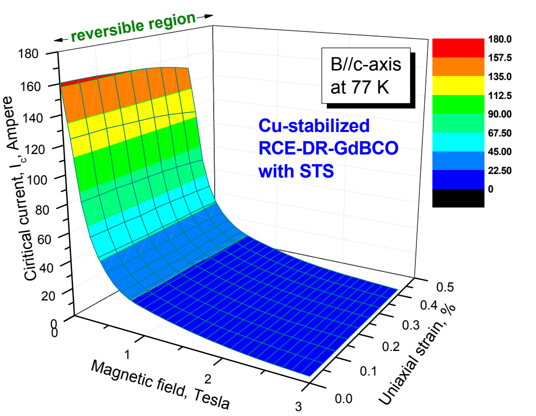
In Fig. 5, for both RCE-DR GdBCO CC samples with stainless steel substrate, similar behavior to those with Hastelloy substrate has been observed showing improved I_c/I_{c0}-strain sensitivity up to 1 T. From these results, it can be found that the behavior of strain effect on I_c under magnetic field was not dependent on the substrate material adopted. It can be inferred that the similar deposition condition of the RCE-DR process used produced similar microstructure which determine its flux pinning characteristics and therefore its electromechanical property behavior under magnetic field. On the other hand, significant degradation of I_c was observed at 0.5% strain close to the yield stress in the case of Cu-stabilized samples which was due to the simultaneous increase of strain from the set value (specified strain) during increasing of the magnetic field strength [12]. However, in the case of brass-laminated CC sample, the degradation was less as compared with the cases of Cu-stabilized one due to its relatively less stiffness and at 0,5% strain it did not enter the plastic region. These significant drops of I_c were observed in all samples that exhibits continuous increase in strain value during testing and entered the plastic deformation region. And after unloading, I_c was not recovered anymore and might be attributed to permanent damage in the GdBCO film such as cracks.

4. Summary

In Figs. 6(a) and (b), we can observe an abrupt I_c degradation from 0 T to 0.5 T in both CC tapes with different substrate material. I_c strongly depends on the magnetic field especially when it is oriented parallel to the c-axis (B//c-axis). The I_c-B-ε behavior under B//c-axis will be useful to predict the CC tapes



(a)



(b)

Fig. 6 I_c-B-ε relation at 77 K in Cu-stabilized RCE-DR GdBCO CC tapes with (a) Hastelloy substrate (B//c-axis).

performance under operating environment. For most applications, the magnetic field characteristics at a fixed temperature is the primary engineering curve used to set the operating current of superconducting coils. If the operating conditions will be set at 77 K for an electric device, for magnet in particular, the results showed that the magnetic field oriented normal to the tapes surface will be very detrimental on the current carrying capacity of the CC tapes. Since the current RCE-DR GdBCO has no artificial pinning sites included, the pinning sites might be the small precipitates and defects. In most of the coated conductors with no artificial pinning sites, the effect of external magnetic field is maximum when it is oriented parallel to the c-axis.

Acknowledgement

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