磁場中 REBCO CC テープの臨界電流へのひずみ効果評価
Evaluation of Strain Effect on Critical Current under Magnetic field in REBCO Coated Conductor Tapes

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1. Introduction

Due to the remarkable development of HTS fabrication and properties, it is being considered now to be applied to the many power device applications such as motors, power cables, transformers and magnets. Long CC tapes with higher J_c about a kilometer in length, improvement of electrical performance through densification of the BSCCO layers, and adding some impurities to HTS films in the case of coated conductor tapes to improve its performance under magnetic field have been achieved [1-4]. In most of the applications, HTS tapes are usually subjected to different mechanical stresses/strain during manufacturing and operations therefore electromechanical property evaluation is one of the foremost tasks to do [5-8]. Specifically in rotating machines and magnets in which HTS tapes will be subjected to external magnetic field, the behavior of current carrying capacity response on strain under magnetic field should be understood. In Table 1, conductors' requirement for some electric power applications is presented [9].

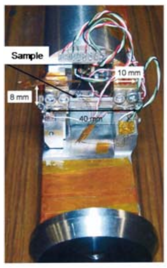
Among HTS tapes usually between BSCCO and REBCO CC tapes, coated conductor tapes received much attention nowadays due to its promising potentials. It has advantages in terms of mechanical strength, has lower AC loss, and lower magnetic susceptibility against the 1G BSCCO and other superconductors and is also expected to have a lower production cost due to development in its fabrication processes.

In this study we measured the strain effect on I_c in REBCO CC tapes under magnetic fields which was applied perpendicular to the tapes surface.

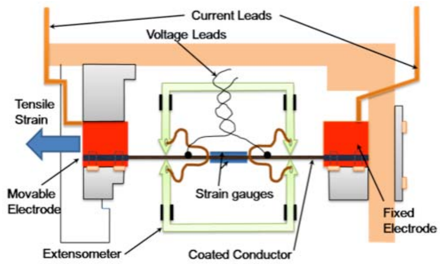
2. Experimental Procedure

Differently processed coated conductor (CC) tapes with different superconducting layer of YBCO, and SmBCO were supplied as samples for the test. Commercially available YBCO CC tapes were supplied from Superpower. Two kinds of SmBCO CC tapes were fabricated by the batch type EDDC process (evaporation on dual drum chamber) and reel to reel RCE-DR process (reactive co-evaporation by deposition and reaction), respectively [10]. All samples have Hastelloy substrate, and adopted IBAD process for grain alignment of the buffer layer and were Cu surround stabilized. Geometry of the different layers and electrical properties are tabulated in Table 2.

For the evaluation of the electromechanical property under magnetic field, a Katagiri type loading frame was used. The tensile load is applied to the sample by moving the pull rod actuated by a stepping motor. This vertical motion was translated to horizontal one by a combination of the upper and lower cam which was shown in detail similarly in [11,12]. Consequently, the end of the lower cam pushes the movable current terminal as shown by the arrow in Fig. 1(b). Strain was measured using strain gauge and Nyilas-type extensometer simultaneously. Two strain sensing devices were adopted for comparison and to ease the burden in case one will not function properly. In this test, strain gauges used have



(a)



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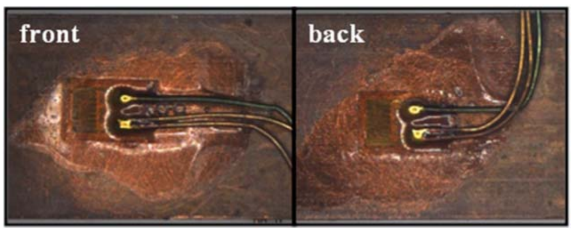


(c)

Fig. 1. Bottom part of the test rig (a) showing the mounted sample, sample length and grip length (b) schematic showing the strain sensing devices (not to scale). (c) Strain gauges attached to the front (HTS side) and back (substrate side) surfaces of the CC tape.

Table 1. Conductor Requirements for Electric Power Applications

Applications	J_c (A/cm^2)	Field (T)	Temp$_{op}$ (K)	Ic (A) for 4-5 mm tape width	Axial Strain (%)	Axial Stress (MPa)	Transverse Stress (MPa)	Fatigue (<5% Ic deg.)	Bend Radius (m)
Fault-current limiter	NA	Low	70-77	500+A/cm; 1-4 cm wide; Thick, stainless steel stabilizer		10 N (4.4mm tape)		> 100's thermal	0.1
Generator (300+MVA)	J_e> 10,000	1.5-2 (5)	>30	>120 at T_{op}, B_{op}	From 0.2 to +/- 0.4-0.5	350	>20/30 (tension/ compress)	10^4 (-0.1% to +0.3%) 100 thermal	0.1
Transmission Cable	NA	<0.1	67-77	~200 A, 77K, sf	0.4	300			~0.2 cable
Transformer	$J_c>10^6$ J_e>12,500	<0.3	70-77	>100 at T_{op}, B_{op}	~0.3	200			0.05
MRI	$J_c>10^6$ J_e>10,000	>3	20-30	>120 at T_{op}, B_{op}	~0.2	200		10 thermal	0.05

Table 2. Specification and Properties of REBCO CC Tapes

	IBAD/SmBCO CC		IBAD/YBCO CC
Fabrication process	EDDC	RCE	MOCVD
Structure	Ag/SmBCO/$LaMnO_3$/ IBAD MgO/Y_2O_3/Al_2O_3/ Hastelloy		Ag/YBCO/ $LaMnO_3$/Homo-epi MgO/ IBAD MgO/Hastelloy
ReBCO film thickness	~ 2 μm	~ 1 μm	~ 1 μm
Critical current , I_c	~100 A	~110 A	~87 A
Dimension, t x w	0.12 x 4.13 mm (ave)	0.094 x 4.12 mm	0.115 x 4.19 mm (ave)
Substrate	Hastelloy		Hastelloy
Substrate thickness	80 μm	45 μm	50 μm
Stabilizer	Copper		Copper
Stabilizing technique	Copper Electroplating		Copper Electroplating
Stabilizer thickness	20 μm	15 μm	20 μm
Manufacturer	KERI	SuNAM	Superpower

0.2 mm gauge length and gauge factors of 1.88± 1.5% and 2.02± 1.5%. Twin extensometers have gauge lengths of 12.5 and 14.5 mm, respectively. Strain gauges were attached axially with the load directions at both HTS and substrate surfaces as shown in Fig. 1(c). On the other hand, twin extensometer was clipped to the sample. Measurement of the strain effect on I_c under magnetic field in coated conductors was carried out at 77 K by using 15 T cryo-cooled superconducting magnet of HFSLM, IMR at Tohoku University. Critical current was measured using 1 μV cm^{-1} criterion. Sample length, gauge length and voltage tap separation were 40, 20 and 10 mm, respectively. Reversibility test was done by loading and unloading scheme. Magnetic field was applied to the sample parallel to the c-axis/perpendicular to the tape surface. Stress-free cooling was considered to prevent the contraction effect of different materials of the rig during cool-down from RT to 77K.

3. Results and Discussion

Fig. 2 shows the magnetic field dependence of I_c. At 0.3T, I_c of YBCO and RCE-SmBCO CC tapes degraded to 20 A and showed almost the same value with increasing magnetic field while EDDC-SmBCO maintained its I_c of about 40 A at this magnetic field level. Fig. 3 depicts that all CC tapes showed a significant I_c/I_{c0} degradation curve up to 3 T in which EDDC-SmBCO exhibits a much better magnetic tolerance of I_c. This shows that CC tape has a potential to be adopted in electrical devices especially in

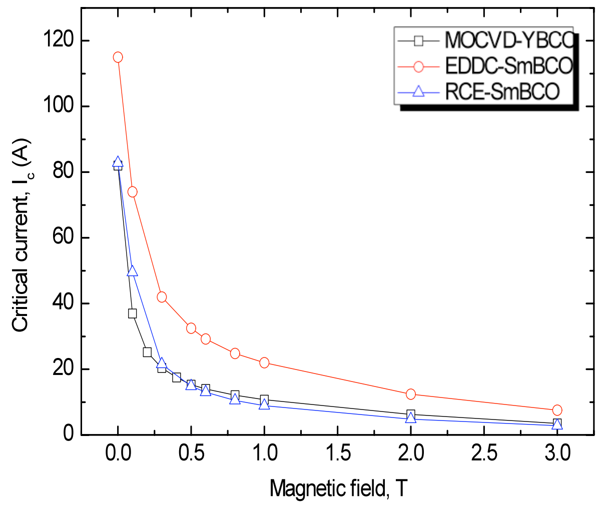


Fig. 2. Magnetic field dependence of I_c in REBCO coated conductor tapes.

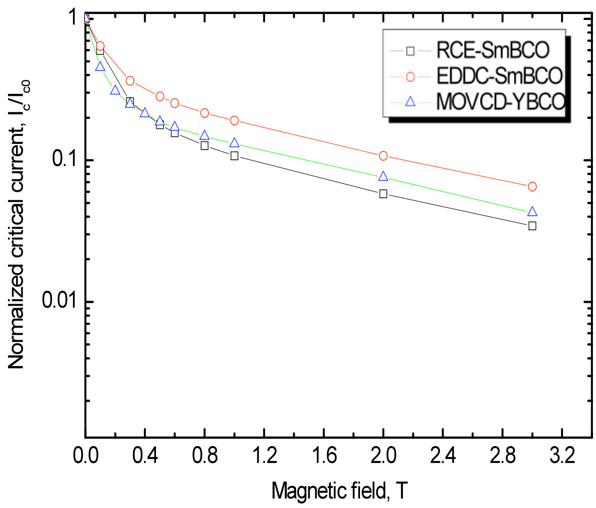
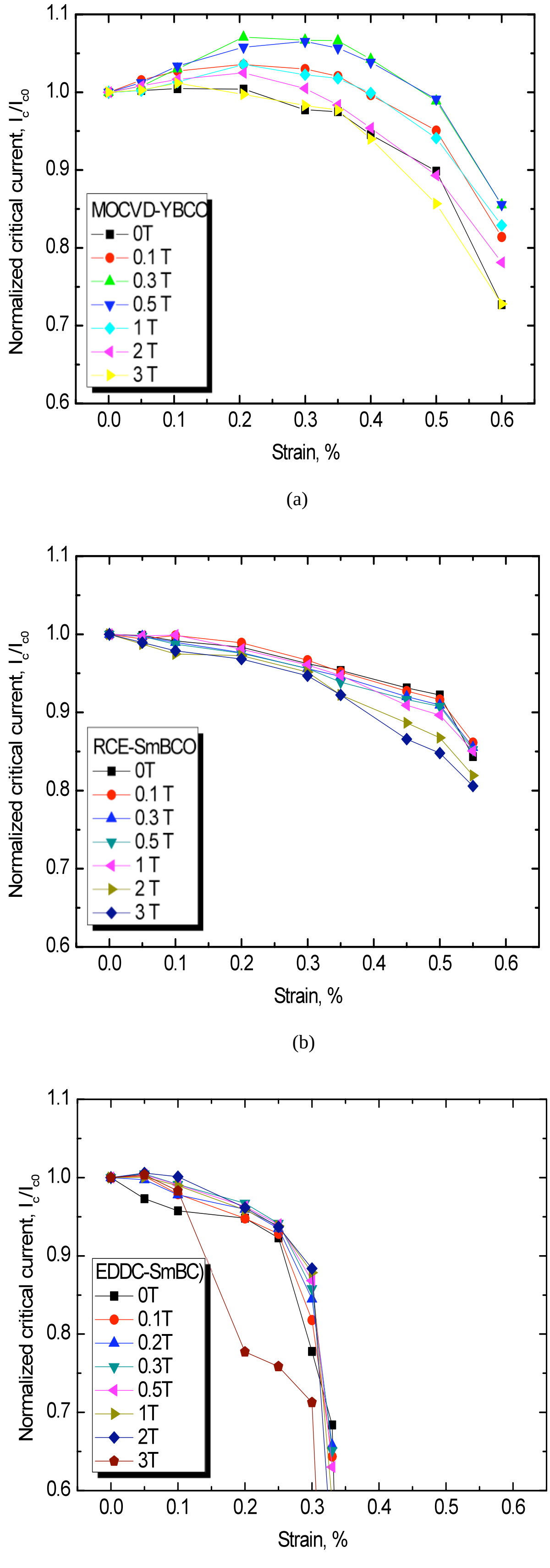


Fig. 3. Magnetic field dependence of I_c/I_{c0} in REBCO coated conductor tapes.

magnets. This also shows that the response of I_c with magnetic field depends not only on the kind of the superconducting layer but also on the fabrication process adopted. The difference may be attributed to the pinning mechanisms in each CC tapes.

Fig. 4 (a), (b), (c), show the I_c/I_{c0}-strain relation under magnetic field in YBCO, RCE-SmBCO and EDDC-SmBCO CC tapes, respectively. In the case of YBCO CC tape in (a), an interesting behavior can be observed showing shifting of the I_c peak location with magnetic fields as has been described in [11,13]. I_c peak shifted from 0.1% to around 0.3% from 0 T to 0.5 T, respectively which means that the location of these I_c peaks are not solely determined by the residual strain at the HTS film. The I_c/I_{c0}-strain curves deviate from the 0T curve in two ways. The curve



(c)

Fig. 4. Normalized critical current, I_c/I_{c0} as a function of

uniaxial strain under different magnetic field in (a) YBCO and (b) RCE-SmBCO (c) EDDC- SmBCO CC tapes.

moves upward up to about 0.5 T and then moves downward as the magnetic field increases. The magnetic field boundary of these two behaviors can be found between 0.3 and 0.5 T. Degradation of I_c/I_{c0} at 0 T and 3 T showed almost the same behavior.

On the other hand, in the cases of SmBCO CC tapes specifically in RCE-SmBCO, the I_c/I_{c0} showed different behavior. In both SmBCO CC tapes, no I_c peak was observed during tension showing a monotonic decrease of I_c/I_{c0} with strain in contrast to the case of YBCO CC tape. As can be seen in Fig. 4(b), I_c/I_{c0} decreased gradually with magnetic field. Degradation of I_c/I_{c0} became a little significant at higher magnetic field over 2 T. Fig. 4(c) shows the result for EDDC-SmBCO CC tapes. At 0.35% strain using strain gauge, I_c decreased abruptly. At this point, strain gauge did not function well and when the extensometer strain values were checked it showed that the abrupt I_c decrease was because the CC tape exceeded its yield strain. During the test, continuous increase in strain at high magnetic field was observed thus entering the plastic deformation region. Therefore, in the case of EDDC-SmBCO CC tapes, further test is necessary to check the influence of the substrate material and for a more reliable result as some scattering of data is observed.

For the reversibility test under magnetic field, all of the samples showed a reversible behavior up to some strain values around 0.5% which is comparable to the cases under self-field. We can infer that the reversibility strain tolerance of CC tapes here tested is independent on the magnetic field up to certain values considered in this test.

4. Summary

The magnitude of the strain effect on I_c depends on magnetic field. Results showed that the I_c/I_{co}-strain behavior was different in YBCO and SmBCO CC tapes. The difference is mainly due to the intrinsic properties of each superconducting layer namely YBCO and SmBCO although similar substrate material may also show a different degree of magnetic tolerance behavior as has been presented here.

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