Superconductivity and Cryogenics
Vol.12, No.4, (2010), pp.20~23

Electro-mechanical Property Evaluation of REBCO Coated Conductor Tape with Stainless Steel Substrate

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Received 9 November 2010; accepted 17 November 2010

Abstract-- **In this study, the electromechanical property of REBCO coated conductor (CC) tape adopting a stainless steel substrate has been investigated. Sample was subjected to uniaxial tension and measured its mechanical properties at RT and 77 K. I_c-ε_t relations was also studied in which the strain and stress corresponding to the 95% I_c retention and reversible strain limit were measured. In addition, these results were compared to the case of conventional REBCO CC tape adopting a Hastelloy substrate. As a result, by adopting a stainless steel substrate comparable strength and good electromechanical property to Hastelloy one could be achieved.**

1. INTRODUCTION

Development of 2G coated conductors such as achieving longer length tape with higher mechanical and electrical properties and with higher susceptibility to magnetic field [1-4] made CC tapes potentially applicable to different device applications such as motors, generators, power cables and magnets [5-8]. In Korea, under the DAPAS program, continuous efforts to improve the performance of coated conductors including its response to different mechanical stress/strains to further achieve a good performance under operating conditions are being done. The EDDC technique developed from KERI showed a good potential in producing coated conductor with higher J_c with good magnetic susceptibility [9-10]. Also, the reel to reel reactive co-evaporation (RCE) process which was currently developed to produce long length commercial CC tapes is underway.

The coated conductors are composed of superconducting film, diffusion barriers, strengthening component usually the substrate which acts as a backbone of the whole composite and the stabilizer. Understanding the mechanical response of each component is essential to predict its service life. In our previous reports on the strain effect on the critical current in YBCO CC tapes with different stabilizing layer, it was found that the additional lamination of Cu or stainless steel stabilizer resulted in the enhancement of reversible strain limit [11]. In addition, the degree of enhancement also depends on the kind of stabilizer used such as Cu or stainless steel. For substrate material, commercially available MOCVD-YBCO CC tapes use Ni alloy substrate in the case of RABiTS process. Currently, Hastelloy is commonly used in the case of IBAD process even though it is expensive and difficult in handling. Therefore, there are many efforts to find other cheap substrate materials instead of Hastelloy.

In this study, the mechanical properties of GdBCO CC tape with stainless steel substrate at RT and 77 K were evaluated. The reversible strain limits of I_c under uniaxial tension was determined and compared it with other REBCO CC tapes with Hastelloy substrate.

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2. EXPERIMENTAL PROCEDURE

In this study, two REBCO CC tapes with different superconducting films, namely SmBCO and GdBCO adopting different substrates have been evaluated. SmBCO CC tape was deposited on the IBAD substrate system with Hastelloy, Al_2O_3, Y_2O_3, MgO, and $LaMnO_3$ (LMO). On the other hand, GdBCO was deposited on a simpler IBAD substrate system with stainless steel, Al_2O_3, MgO, and LMO omitting the Y_2O_3 layer. Both the superconducting films were deposited by reactive co-evaporation technique which was developed by SuNAM Co. Properties and specifications of samples are shown in Table 1.

REBCO CC tapes have been subjected to uniaxial tension. Sample length and gauge length were 90 and 40 mm, respectively. Sample was mounted on the loading frame fixing it to the Cu grips which also serve as current lead terminals. Nyilas type extensometer with gauge length of 14.5 mm was used to measure the induced strain during tensile loading and it was mounted at the central region of

TABLE I
SPECIFICATIONS OF REBCO CC SAMPLES.

	SmBCO CC	GdBCO CC
Fabrication process	RCE	RCE
Structure	Ag/SmBCO/ $LaMnO_3$/IBAD MgO/Y_2O_3/Al_2O_3/ Hastelloy	Ag/GdBCO/$LaMnO_3$/ IBAD MgO/Al_2O_3/ SUS
Film thickness	~ 1 μm	~ 2 μm
I_c	~110 A	~160 A
Dimension, t x w	0.094 x 4.12 mm	0.186 x 4.04 mm
Substrate	Hastelloy	SUS310
Substrate thickness	45 μm	100 μm
Stabilizer	Copper	Copper
Stabilizing technique	Copper Electroplating	Copper Electroplating
Stabilizer thickness	15 μm	20 μm
Manufacturer	SuNAM	SuNAM

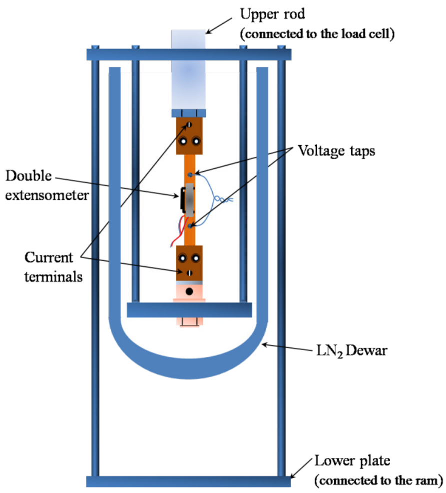


Fig. 1. Schematic of the loading frame.

the sample within the voltage taps separation of 20 mm. Schematic of the loading frame is shown in Fig. 1. For the I_c measurement at 77 K, sample was slowly cooled down for about 10 mins and immersed for about 15 mins before measuring the I_c. I-V curves were measured using the four-probe method at 77 K and in self field, and I_c was defined by a 1 μV cm^{-1} criterion. Reversibility of I_c was measured by the repeated loading and unloading scheme by which the reversible strain limit of I_c, ε_{rev}, was defined as "99% I_c recovery strain".

3. RESULTS AND DISCUSSION

Table 2 shows the result of tensile tests both at RT and 77 K. The elastic modulus was almost the same at RT and 77 K. The yield strength of the CC tape at 77 K showed 1.2 times higher at RT which significantly increased from 723MPa to 864 MPa.

As a reference, the result of SmBCO CC tape adopting Hastelloy substrate with the same manufacturing process has been compared to the current GdBCO CC tape adopting stainless steel substrate. Fig. 2 shows the stress-strain curves of both SmBCO and GdBCO CC tapes at 77 K obtained during the I_c measurement at different tensile load including the result of tension test of GdBCO CC tape at RT. As can be observed from the figure, GdBCO CC tape with stainless steel substrate showed a lower elastic modulus of 115.3 GPa compared to the SmBCO CC tape with Hastelloy substrate with 143.6 GPa. In addition, SmBCO CC tape with Hastelloy substrate showed quite

TABLE II

RESULT OF THE UNIAXIAL TENSION TEST AT RT AND 77 K.

	GdBCO/SUS @ RT	GdBCO/SUS @ 77K	*SmBCO/ Hastelloy @ 77K
Modulus of elasticity, E	119.7 GPa	116.4 GPa	143.6 GPa
Yield strength, σ_y	722.8 MPa	863.7 MPa	926 MPa
Load at yield point	543 N	649 N	358.6 N
Yield strain, ε_y	0.81 %	0.95 %	0.85 %
Fracture strength	767 MPa	Not fractured	-
Sample thickness, mm	0.186	0.186	0.094
Sample width, mm	4.04	4.04	4.12
Gauge length, mm	40	40	40

*Data of SmBCO CC tape was measured from the I_c measurement test.

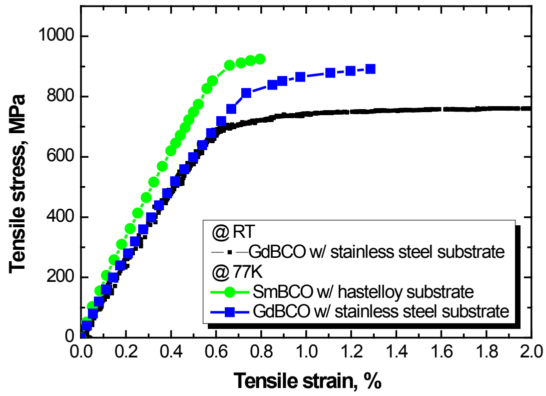
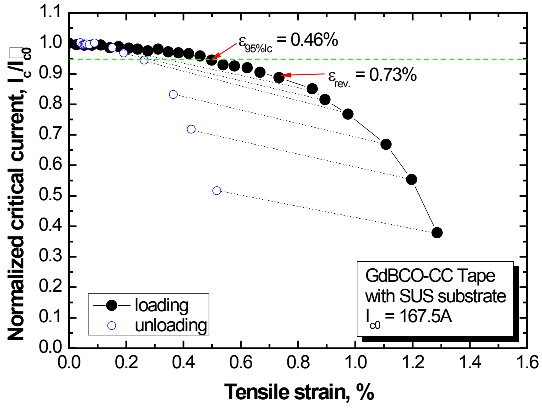
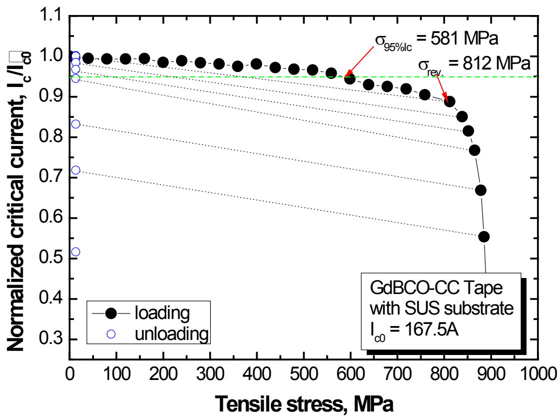


Fig. 2. Stress-strain curve of SmBCO and GdBCO CC tapes.



(a)



(b)

Fig. 3. Normalized critical current as a function of (a) tensile strain and (b) tensile stress in GdBCO CC tape.

higher yield strength of 926 MPa as compared to GdBCO CC tape with around 860 MPa. Fig. 3 shows the test results of the uniaxial strain/stress effect on I_c in GdBCO CC tape with stainless steel substrate. From 3(a), the I_c/I_{c0} decreased monotonically with strain and did not show any I_c peak like in the case of YBCO CC tapes [11]. During the experiment, when the I_c degraded about 5% at 0.46% strain which is corresponding to the 95% I_c retention, unloading was done to check its reversibility. The data measured at the unloaded state were also plotted in the figure and was connected by a dotted line. From this, the reversible strain limit was determined at 0.73%. Increasing further to 0.85%, the I_c can no longer be recovered, therefore it is considered as the reversible strain limit of the current CC tape. The stress corresponding to the 95% I_c retention was 581 MPa as can be seen in Fig. 3(b). The reversible stress limit was 812 MPa which was quite near the measured yield strength of 864 MPa in GdBCO CC tape. The reversibility test has been repeated to check the reproducibility of data using the present device and experimental procedures. In Fig. 4, the I_c/I_{co} curves in test-1 and -2 conform well showing almost the same strain values corresponding to the 95% I_c retention and reversible strain limits; Reversible strain limit measured was in the range of 0.73 % to 0.78% and the corresponding stress ranges from 812 MPa to 825 MPa.

On the contrary, even though the GdBCO CC tape represented a relatively lower elastic modulus and yield strength, it showed then a higher reversible strain limit of around 0.73% compared to SmBCO CC tape with 0.56% as can be seen in Fig. 5. It is also observed that in a short sample with 40 mm gauge length, the SmBCO CC tapes with Hastelloy substrate showed an abrupt decrease in I_c after the reversible limit. This can be attributed to the discontinuous yielding of Hastelloy substrate which may result from the local stress concentration due to occurrence

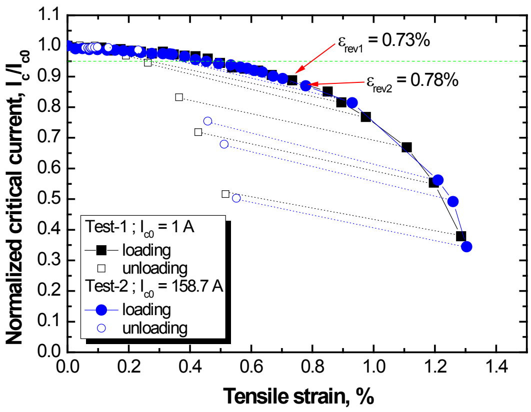


Fig. 4. Normalized critical current as a function of tensile strain in GdBCO CC tape.

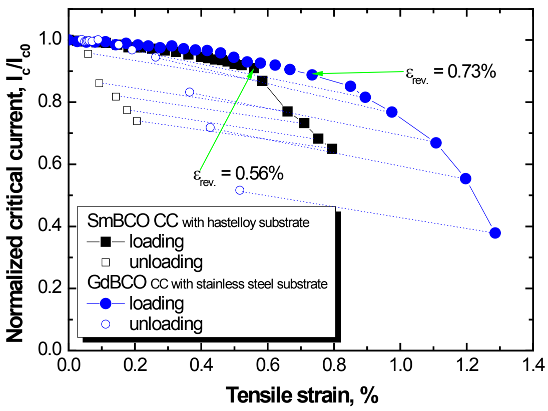


Fig. 5. Normalized critical current as a function of (a) tensile strain and (b) tensile stress in GdBCO CC tape.

of Luder's bands [12]. But in the case of GdBCO with stainless substrate, even after the reversible strain limit, the I_c degraded monotonically representing a homogeneous deformation within the gauge length thus showing a continuous yielding of the substrate as can be observed from the stress-strain curve in Fig. 2.

It should be noted that the samples evaluated here are currently under development and are nearly reaching to commercialization. By adopting stainless steel substrate, mechanical strength and electromechanical properties comparable to when Hastelloy substrate is adopted could be achieved. A clear understanding on the mechanical response of the composite conductors should be obtained to design a CC tape that can withstand a larger mechanical stress/strain during manufacturing and operation. Further investigation on the microscopic response of these materials is necessary to ensure a safe performance of the CC tapes in operating conditions.

Finally, to evaluate quantitatively the effect of substrate material on the I_c-ε_t behavior, it should be considered comparing CC tapes with the same superconducting coating film.

4. CONCLUSION

The GdBCO CC tape with stainless substrate showed relatively good mechanical and electro-mechanical properties under uniaxial tension. Strain tolerance limits of I_c are comparable and superior with those CC tapes adopting Hastelloy substrate. Although the I_c showed a good uniaxial strain tolerance in GdBCO CC tapes, further evaluation of its electromechanical properties under other loading mode such as bending, torsion and fatigue should be done including its response under magnetic field.

ACKNOWLEDGMENT

This work was supported by a Grant from the Center for Applied Superconductivity Technology under the DAPAS (Development of Advance Power System by Applied Superconductivity Technology) Program funded by the Ministry of Education, Science and Technology, Republic of Korea.

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