pISSN 1229-3008 eISSN 2287-6251
Progress in Superconductivity and Cryogenics
Vol. 19, No. 4, (2017), pp.26~30
https://doi.org/10.9714/psac.2017.19.4.026

Characterization of electromechanical properties of Sn-Cu double layer stabilized GdBCO coated conductor tapes at 77 K

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(Received 24 November 2017; revised 18 December 2017; accepted 19 December 2017)

Abstract

The promising characteristics of 2G high-temperature superconductor (HTS) coated conductor (CC) tapes have made it possible to apply to various electrical device applications. In this study, the mechanical and electromechanical properties of Sn-Cu double layer stabilized GdBCO CC tapes have been characterized. The stress and strain tolerances of I_c in GdBCO CC tapes adopting stainless steel substrate were evaluated using I_c-strain measurement at 77 K under both uniaxial tension and monotonic bending conditions. The results were compared to the conventional single Cu layer stabilized CC tape. As a result, the Sn-Cu double layer stabilized GdBCO CC tapes showed somehow lower or comparable electromechanical properties as compared to the Cu stabilized CC tape ones.

Keywords: mechanical properties, electromechanical properties, double layer stabilizer, uniaxial tension, monotonic bending

1. INTRODUCTION

The improvements in the properties of 2G REBCO CC tapes have widened the opportunities for the power and magnet applications [1-3]. In these applications, the CC tapes will subject to various loading conditions during fabrications, cool-down and operation, such as uniaxial tension, transverse tension, bending and torsion, etc. These loading conditions opened up a major topic; on the development of the long length 2G CC tapes with much reliable mechanical and electromechanical properties that are susceptible to magnetic field [4-6]. Under respective loading conditions, the characterization of the mechanical and electromechanical properties of 2G CC tapes is inevitable [7, 8].

It has been confirmed that when the strain induced to the CC tape exceeded a critical value, the critical current, I_c, significantly degraded [9, 10]. To suppress the initiation of damages and cracks on the superconducting layer, consequently which further improves the electro-mechanical properties, reinforcing the CC tape by electroplating metal layers and externally laminating metallic foils of copper and stainless steel as a stabilizer has been performed [11, 12]. The addition of brass lamination and copper layer also further enhance the performance of the CC tape such as electrical and thermal stability [13, 14]. Understanding the stress/strain dependence of the I_c degradation behavior in stabilized and/or externally laminated CC tapes under various loading conditions such as bending and uniaxial tension is indispensable to design the performance of power devices.

Compared with the Cu layer stabilized CC tapes, the additional Sn layer electroplating to the Cu-stabilized CC tapes has many advantages in shortening the electroplating time which improving the CC manufacturing process, as well as reducing the oxide film formation on the surface of the CC tape which may improve the lamination process and the interface resistance of the soldered CC joints.

In this study, the effect of Sn-Cu double-layered stabilizer on the electromechanical properties of the RCE-DR processed GdBCO CC tapes adopting a stainless steel substrate were investigated at 77 K and self-field. The stress and strain tolerances of I_c in the double-layer stabilized CC tapes were measured. The irreversible strain limits could be obtained by both the uniaxial tension and the monotonic bending tests, respectively. The results were then compared with the cases of single Cu layer stabilized GdBCO CC tapes.

2. EXPERIMENTAL PROCEDURES

2.1. Samples

In this study, Sn and Cu were electroplated as stabilizing

TABLE I
SPECIFICATIONS OF CC TAPE SAMPLE

Fabrication process	IBAD/RCE-DR
Structure	Sn-Cu stabilized Ag/GdBCO/$LaMnO_3$/ IBAD-MgO/ Y_2O_3/Al_2O_3/Stainless steel
REBCO film thickness	~ 1 μm
Critical current, I_c	~227 A
Dimension, t x w	0.137 mm x 4.07 mm
Substrate/ thickness	~90 μm
Stabilizer/technique,	Cu electroplated, surround (~15 μm) /Sn electroplated, surround (~10 μm)
Manufacturer	SuNAM.

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layer of the CC tapes adopting stainless steel substrate, and it is called as a Sn-Cu double layer stabilized CC tape to distinguish it from Cu layer plated ones. The specifications of the CC samples used are shown in Table 1. The GdBCO superconducting layer was deposited on the ion-beam assisted deposition (IBAD) processed template of ~90 µm stainless steel substrate. The superconducting film, on the other hand, was deposited using reactive co-evaporation by deposition and reaction (RCE-DR) process. An additional ~2 µm Ag layer was sputtered onto the superconducting film which serves as a protection layer. Firstly, a copper (Cu) layer was electroplated surrounding the whole CC tape with a thickness of ~15 µm. Then a tin (Sn) layer was similarly electroplated on the Cu-stabilized CC tape surrounding the whole tape, eventually making Sn-Cu double layer stabilized CC tapes.

2.2. Mechanical properties measurement

Figure 1 shows the setup for the uniaxial tension test of CC tapes at 77 K and self-field. A sample with a total length of 100 mm was fixed by Cu gripping blocks to upper/lower grips at both ends. In order to prevent the slippage of the sample during the application of tensile load, a sand paper (#600) was inserted between the CC sample and the gripping fixture. The tensile load was applied by a universal material testing machine (Shimadzu AG-IS, load cell capacity: 5 kN) [15] at a constant cross-head speed of 1 mm/min. Nyilas-type double extensometers with a gauge length of 25 mm were placed at the central part of the sample to measure the strain induced during tension test [16]. The extensometer was directly connected to the signal conditioner (Kyowa, CDV-700, sampling rate: 500 kHz). For testing at 77 K, the sample was submerged in a liquid nitrogen (LN_2) bath and held for 10 min to obtain thermal equilibrium before applying the tensile load. The mechanical properties such as elastic modulus and yield strength were derived based on the stress-strain curves obtained using the double extensometers.

2.3. Electromechanical properties measurement

For the electromechanical properties evaluation of Sn-Cu stabilized CC tapes, the CC samples were subjected to both uniaxial tension and monotonic bending loading. For I_c measurement under uniaxial tension, the same setup shown in Fig. 1was used. During the I_c measurement, in order to keep electrical insulation between the CC tape sample and gripping fixture including the test system, a GFRP sheet was inserted between them. Voltage taps with 20 mm separation were soldered on the surface of the CC sample between the 25 mm gauge length of the double extensometers.

Figure 2 shows the photo of Goldacker type continuous bending test rig for the monotonic bending test. The same batch of CC sample was used in the bending test. The total length of the sample used in the monotonic bending test was 70 mm. It has a 10 mm voltage tap separation.

In both tests, the I_c was measured at an electric field criterion of 1 μV/cm in every 0.05% interval of the applied

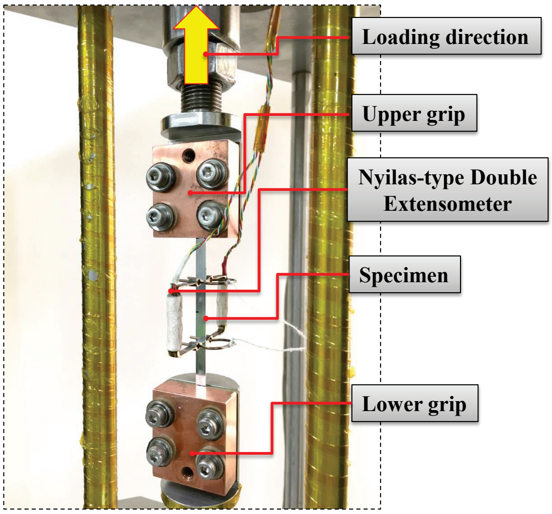

Fig. 1. Setup for uniaxial tension test of CC tape at 77 K.

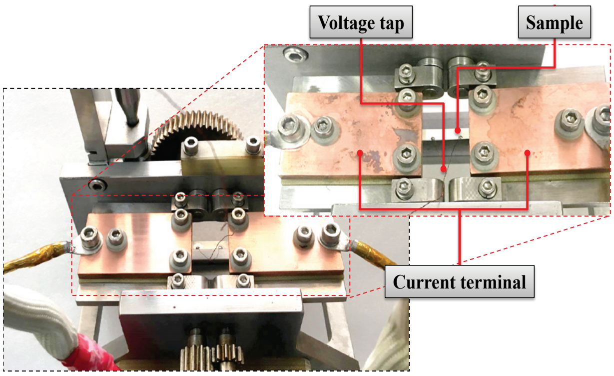

Fig. 2. Goldacker type continuous bending test rig CC tapes at 77 K under easy bending condition.

tensile strain and 0.03% interval of the applied bending strain, respectively. During both testing, when the I_c degraded to about 5% from its initial critical current, I_{c0}, the applied strain was then released to verify the reversibility of I_c in the CC tapes against the applied strain. The CC sample was subjected to loading and unloading repeatedly to determine the irreversible strain limit, ε_{irr} and stress limit, σ_{irr}, respectively. The strain induced on the superconducting layer was derived and discussed in details on [17].

3. RESULTS AND DISCUSSION

3.1. Mechanical properties of Sn-Cu Stabilized CC tapes

Figure 3 shows the stress-strain curves of differently stabilized RCE-DR processed CC tapes tested at 77 K. The elastic modulus was derived from the initial linear loading part of each curve and the yield strength was determined using 0.2 % strain offset slope method. The Sn-Cu double layer stabilized CC tapes exhibited a smaller elastic modulus and yield strength as compared to the Cu-stabilized ones.

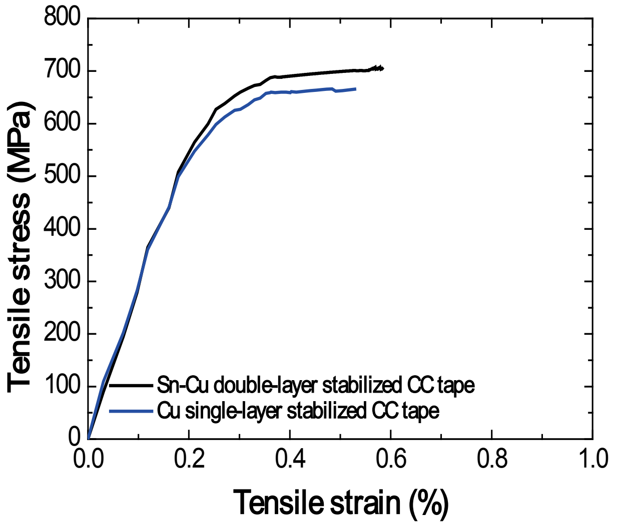

Fig. 3. Stress-strain curves of differently stabilized RCE-DR GdBCO CC tapes at 77 K.

Mechanical properties of the samples were summarized in Table 2. Three (3) tests were performed for each samples, the data presented in the table indicate their mean value. From the results, it can be found that additional Sn layer plating as a stabilizing layer on the Cu stabilized CC tape lowered the strength of the CC tapes from Cu-stabilized ones.

3.2. Stress/strain sensitivity of I_c under uniaxial tension

The representative I_c - strain sensitivity curves of both CC tapes under the uniaxial tension are illustrated in Fig. 4 (a). In the reversible I_c degradation region, both CC samples showed the same strain sensitivity of I_c. The Sn-Cu double layer stabilized samples exhibited almost the same limit of $\varepsilon_{irr} = 0.85\%$ with the Cu-stabilized CC tapes. It can be found that an additional soft Sn stabilizer to the Cu-stabilized CC tapes did not influence the critical strain value for I_c degradation. For both differently stabilized GdBCO CC tapes, adopted stainless steel substrate might be accountable for having a similar ε_{irr}. On the other hand, Fig. 4 (b) shows the relation between normalized critical current, I_c/I_{c0}, and uniaxial tensile stress applied. Both Cu-stabilized and Sn-Cu double layer stabilized CC tapes showed almost similar σ_{irr} of 687 MPa and 680 MPa, respectively. This indicates that the additional soft Sn stabilizing layer which decreased apparently the mechanical properties of the CC tapes but did not affect the electromechanical properties.

3.3. Stress/strain sensitivity of I_c under monotonic bending

In the case of monotonic easy bending condition at 77 K, for the tension bending where the GdBCO film of the CC tape is located at the tensile strain side, the irreversible bending strain limit, ε_{irr}, was determined by the 99% I_{c0} recovery criterion wherein at that strain the I_c can still be recovered. In compressive bending case, most of the CC samples showed no ε_{irr}, because the I_c was completely recovered to its I_{c0} after releasing the bending strain applied. Thus, in the case of compressive bending the reversible bending strain limit, ε_{rev} was defined by using

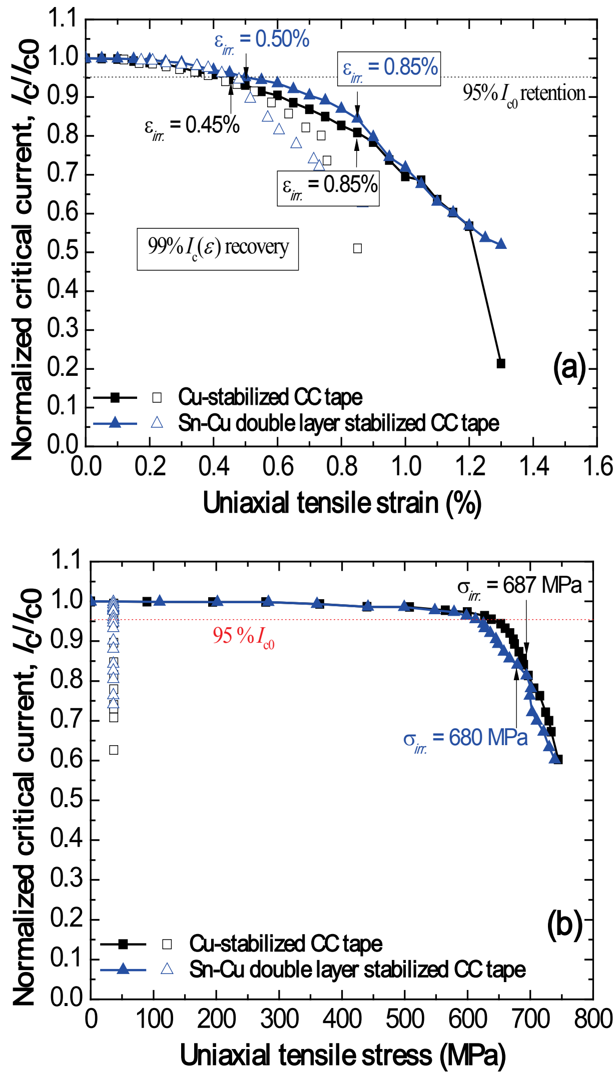

Fig. 4. (a) Normalized critical current, I_c/I_{c0} vs. uniaxial tensile strain and (b) vs. uniaxial tensile stress for differently stabilized CC tapes.

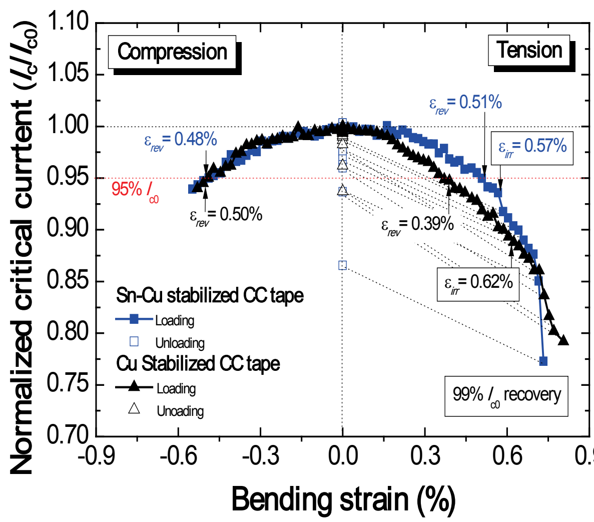

Fig. 5. Normalized critical current, I_c/I_{c0} vs. bending strain at GdBCO layer of differently stabilized CC tapes.

TABLE II
MECHANICAL AND ELECTROMECHANICAL PROPERTIES OBTAINED FROM DIFFERENTLY STABILIZED CC TAPES

Loading mode		Under uniaxial tension				Under monotonic bending	
Sample	Dimensions width/thicknes s (mm)	Young's modulus (GPa)	Yield strength (MPa)	Irreversible stress limit, σ_{irr} (MPa)	Irreversible strain limit, ε_{irr} (%) (99 % $I_c(\varepsilon)$ recovery)	Tensile bending $\varepsilon_{irr.}$ (%) (99 % I_{c0} recovery)	Compressive bending $\varepsilon_{rev.}$ (%) (95 % I_{c0} retention)
Sn-Cu double layer stabilized CC tapes	4.05/0.136	180	653	680	0.85	0.51	0.48
Cu layer stabilized CC tapes	4.07/0.136	181	724	687	0.85	0.62	0.50

the 95 % I_{c0} retention [18]. Fig. 5 shows the I_c degradation behaviors against the bending strain measured at the GdBCO layer for both differently stabilized CC tapes. It can be found that the Sn-Cu double layer stabilized CC tapes exhibited a little lower irreversible strain limit, ε_{irr} = 0.57 % compared to that of Cu-stabilized CC tapes ε_{irr} = 0.62 % on the tension bending using the 99 % I_{c0} recovery.

However, using the 95 % I_{c0} retention criteria, the results showed relatively good agreement in the ε_{irr} value obtained by the uniaxial tension test, shown in Fig. 4(a). On the other hand, on the compression bending, Sn-Cu double layer stabilized CC tape exhibited a reversible strain limit, ε_{rev} of 0.48%, which is similar to the Cu-stabilized ones.

The results showed that under the monotonic bending condition, it verified that additional soft Sn layer on the Cu-stabilized CC tape did not significantly affect the electromechanical properties of the CC tapes.

4. CONCLUSION

The mechanical and electromechanical properties of Sn-Cu double layer stabilized CC tapes were investigated and compared to the cases of Cu layer stabilized CC tapes. The results showed that although having Sn which served as an additional stabilizing layer on the Cu-stabilized CC tape did not exhibit any significant variation when compared to Cu single layer stabilized CC tape ones. The strain tolerance limit of Sn-Cu double layer stabilized CC tape is comparable to Cu stabilized ones. Further evaluation of Sn-Cu double layer stabilized CC tape including the I_c response under magnetic field application in order to fully understand the influence of Sn stabilizer is needed.

ACKNOWLEDGMENT

This work was supported by a grant from National Research Foundation of Korea (NRF-2017-001901) funded by the Ministry of Science, ICT and Future Planning (MSIP), Republic of Korea. This work was also partially supported by a grant from the Power Generation & Electricity Delivery Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) funded by the Ministry of Trade, Industry, and Energy. (No. 20131010501800)

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