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Investigation on the electromechanical properties of RCE-DR GdBCO CC tapes under transversely applied load

Alking B. Gorospe[a, b] **and Hyung-Seop Shin**[*, a]

[a]*Department of Mechanical Design Engieering, Andong National University, Andong, 760-749 Korea*
[b]*Department of Engineering, Aurora State College of Technology, Baler, Philippines 3200*

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Abstract

REBCO coated conductor (CC) tapes with superior mechanical and electromechanical properties are preferable in applications such as superconducting coils and magnets. The CC tapes should withstand factors that can affect their performance during fabrication and operation of its applications. In coil applications, CC tapes experience different mechanical constraints such as tensile or compressive stresses. Recently, the critical current (I_c) degradation of CC tapes used in coil applications due to delamination were already reported. Thermal cycling, coefficient of thermal expansion mismatch among constituent layers, screening current, etc. can induce excessive transverse tensile stresses that might lead to the degradation of I_c in the CC tapes. Also, CC tapes might be subjected to very high magnetic fields that induce strong Lorentz force which possibly affects its performance in coil applications. Hence, investigation on the delamination mechanism of the CC tapes is very important in coiling, cooling, operation and design of prospect applications. In this study, the electromechanical properties of REBCO CC tapes fabricated by reactive co-evaporation by deposition and reaction (RCE-DR) under transversely applied loading were investigated. Delamination strength of the CC tape was determined using the anvil test. The I_c degraded earlier under transverse tensile stress as compared to that under compressive one.

Keywords: *Coated conductor, I_c degradation, transverse tension, compression, delamination strength, superconducting coil*

1. INTRODUCTION

High temperature superconductor (HTS) 2G coated conductor (CC) tapes have promising potentials in a wide range of application fields such as energy saving, transportation, high energy physics, *etc*. However, in coil applications, CC tapes experience different mechanical stress/strain that can affect their performance especially their current carrying capability. Particularly, the difference in the coefficient of thermal expansion (CTE) of its component materials can cause delamination to the CC tape when subjected to thermal cycling during operation. Such factor can cause significant degradation on its critical current, I_c similar to the one reported elsewhere when the CC tapes were used for an epoxy (wet wound) impregnated double pancake coil [1]. The I_c degradation was a result of the cool down (thermal cycling process - 5 cycles) effect that was done on the CC tape.

In coil application, compressive stress and tensile stress are generated by Lorentz force. Excessive Lorentz force can be converted into hoop stress on the coil and acts as an in-plane stress on the CC tape. The hoop stress produced by the Lorentz force then induces a compressive radial stress on the overlapping CC tapes in the coil. Several research groups have carried out evaluation tests to investigate the properties of these CC tapes under transverse tensile stress delamination conditions in order to improve its structure and enhance its operating performance. Experimental procedures such as the pin-pull and anvil tests have been adopted to evaluate transverse tensile properties of different HTS CC tape sample types [2-5]. Also, transverse compressive properties of the CC tapes were reported elsewhere [6, 7]. In the case of compression for CC tapes, high yield-strength substrate material can enhance the tolerance of critical current density, J_c to transverse stress by preventing in-plane yielding [6]. In addition, a so called “Bennie ten Haken’s press” was used by the University of Twente group in order to investigate the compressive property of the CC tapes. Using the press, it was found that I_c degraded at a lower compressive stress when the pushing anvil was located on the substrate side of the CC tape rather than when located on the superconducting side [7]. Still, delamination mechanism in CC tapes is not yet well understood. Therefore, characterization of the delamination behavior of the CC tapes is a great challenge due to the the wide variety of HTS CC tapes; different fabrication processes, architecture including thickness of constituent layers, and inhomogeneity within the tape.

2. EXPERIMENTAL PROCEDURES

2.1. Samples

Two commercially-available CC tapes were supplied in this study; both fabricated by the ion beam assisted deposition (IBAD) technique. Table 1 shows the specifications

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* Corresponding author: hsshin@anu.ac.kr

TABLE I
SPECIFICATIONS OF CC TAPE SAMPLES

Fabrication/ REBCO	RCE-DR	MOCVD
Superconducting film	GdBCO (~ 1.5 - 2.0 μm)	GdBCO (~ 1 μm)
Substrate	Hastelloy (~57 μm)/ STS (~104 μm)	Hastelloy (~50 μm) -
I_c	~ 170 A/ > 200A	~ 116 A
Dimension, t x w	0.092 mm x 4.01 mm 0.132 mm x 4.08 mm	0.091 mm x 3.95 mm -
Stabilizer	Electroplated Copper (15 μm)	Electroplated Copper (20 μm)
Manufacturer	SuNAM	Superpower

of the CC tape samples used. Samples fabricated by RCE-DR process have two variants, one adopting Hastelloy substrate material and the other one with stainless steel (STS). Both RCE-DR CC tapes have $GdBa_2Cu_3O_y$ (GdBCO) coating film around 1.5~2.0 μm thick with I_c of approximately 170 A (for Hastelloy) and >200 A (for STS) and were surround- electroplated by 15 μm thick copper. The thinner RCE-DR CC tape sample has approximately 57 μm thick Hastelloy substrate while the thicker one adopts a 104 μm thick stainless steel substrate material.

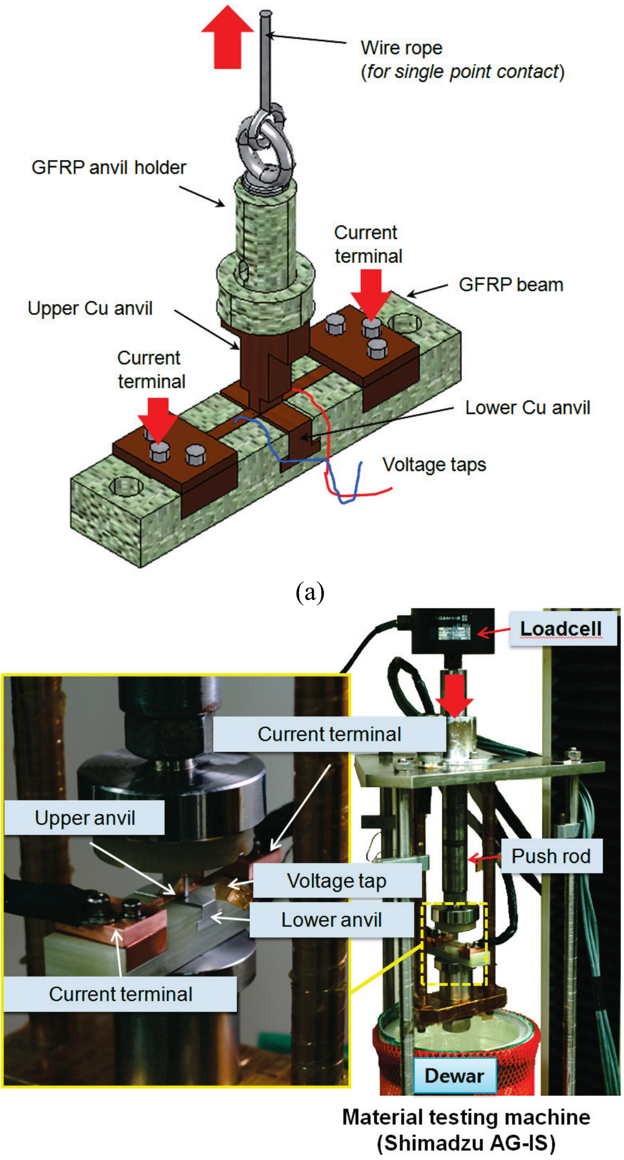
On the other hand, the CC tape sample fabricated by the metal organic chemical vapor deposition (MOCVD) process has around 1 μm thick GdBCO coating film with I_c of 116 A. The CC tape sample adopted a 50 μm thick Hastelloy substrate and was surround copper stabilized by electroplating a little thicker Cu of 20 μm for additional protection and electrical stability.

2.2. Transverse tension test

For the I_c measurement test under transverse tensile loading, the CC tape sample was placed on the GFRP beam with the substrate side facing the lower anvil and the superconducting side to the upper one. The samples were soldered on a 4 mm x 8 mm upper Cu anvil using an In-Bi solder and corrosive soldering flux $ZnCl_2$. Using a sample holder described elsewhere, the CC tape was held and alignment on the sample-anvil assembly was ensured while a dead weight was put at the top of the upper anvil holder [3-5]. Soldering of sample to the upper/lower Cu anvils was done at a temperature range of 120~130 ^{o}C using a heat blower. Similar soldering method was used and was elaborated elsewhere [3-5]. In Fig. 1(a), a pair of voltage taps was attached on the superconducting layer side of the CC tape sample with 20 mm separation distance. The sample/anvil assembly was pre-cooled for 10 min and submerged for 15 min (holding time) in a liquid nitrogen bath. After then, critical current at zero stress, I_{c0} was measured using typical voltage criterion of 1 μV/cm to check if damage occurred on the CC tape sample due to the sample preparation process including cutting, soldering and cool down of samples.

2.3. Transverse compression test

For the I_c measurement under transverse compression test, an upper anvil indenter and the flat lower anvil made of stainless steel material was used as shown in Fig. 1(b). This allows imparting a high compressive load to the sample without any deformation on the upper anvil indenter.

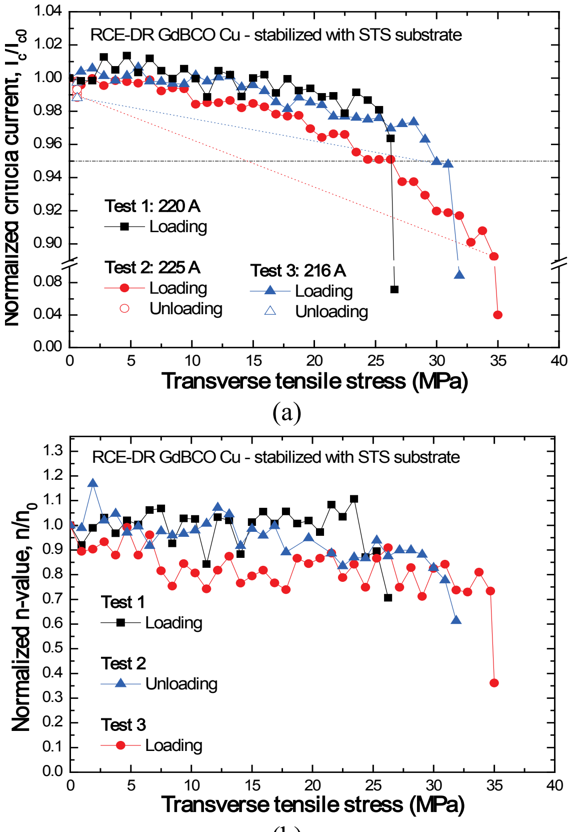


(a)

(b)

Fig. 1. Set-up for electro-mechanical test under (a) transverse tensile loading and (b) compressive loading.

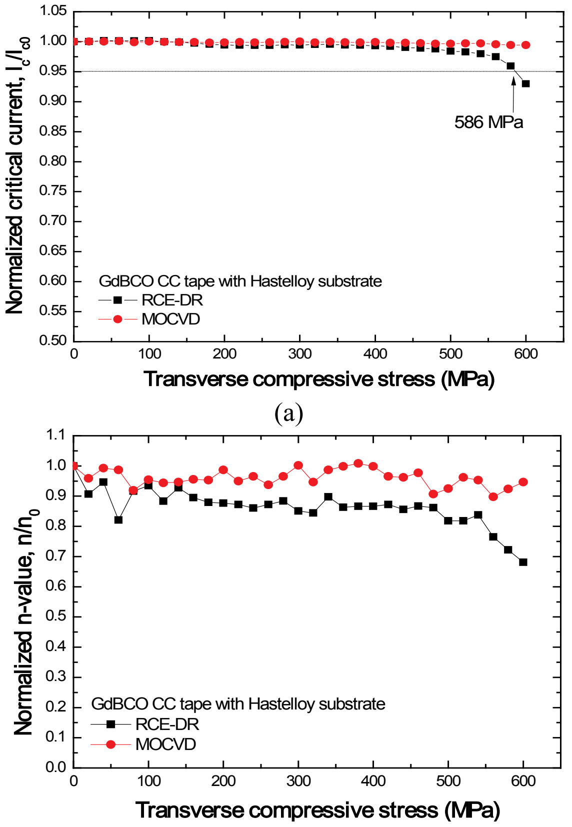
A GFRP (G10) was inserted between the holder and the indenter to isolate the sample during I_c measurement. The upper anvil indenter features a 16 mm^2 contact area (2 mm width x 8 mm length), where the length was oriented along the width of the CC tape sample. In this setup, an effective contact area of the indenter to induce compressive stress onto the CC tape would be 8 mm^2. Stress was applied in both monotonic and loading-unloading manner with an interval of 15 MPa and 30 MPa, respectively. After the holding time, I_c was measured at each load interval. In the case of monotonic loading, stress was applied gradually in an increasing manner without releasing the load between steps on the CC tape sample. However, in the case of loading - unloading manner, stress was applied to a certain value and was released before reapplying a higher stress value [6-8]. The test was continued up to 600 MPa stress value which corresponds to the capacity of load cell used.



(a)

(b)

Fig. 2. (a) I_c behavior, and (b) n-value behavior of RCE-DR GdBCO CC tape samples adopting STS substrate under transverse tensile loading using 4 mm x 8 mm upper Cu anvil.



(a)

(b)

Fig. 3. (a) I_c degradation behavior, and (b) *n-values* of RCE-DR and MOCVD CC tape with Hastelloy substrate under transverse compression loading (monotonic).

3. RESULTS AND DISCUSSION

3.1. I_c behavior under transverse tensile stress

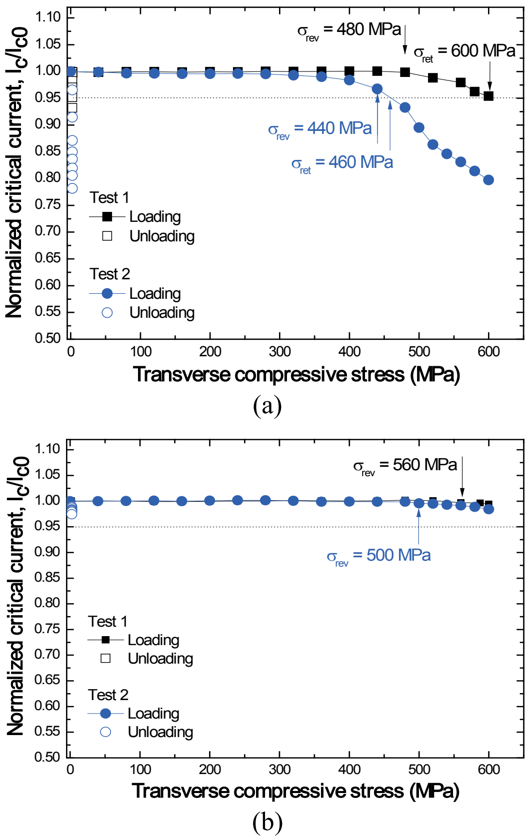
In Fig. 2 (a), I_c degraded with the increase of transverse tensile stress applied in a gradual and abrupt manner [3-5]. In Tests 1 and 3, I_c did not degrade below the 95 % I_c retention criterion, but was abruptly dropped due to delamination. However, in the case of Test 2, I_c decreased gradually beyond the criterion limit before it was completely delaminated. The variation of *n-values* with transverse tensile stress in Fig. 2 (b) showed good correlation with the I_c behavior. From the pressure dependence of I_c, it is not much affected along the c-axis. However, based on these results, it appears that I_c is also affected by stress at transverse loading direction (c-axis orientation) similar with the uniaxial tension test (*a-b* plane) [9, 10]. However, in regards to this study, further examinations on the occurrence of micro cracks, debonding zones and other I_c degradation related deformations are needed for better understanding of the mechanism.

3.2. I_c behavior under transverse compressive stress

Fig. 3 (a) shows the degradation behavior of I_c in CC tape adopting Hastelloy substrate on the monotonic loading manner. As can be seen, the RCE-DR CC tape sample exhibited a gradual but minimal decrease and 95 % I_c retention stress of 586 MPa wherein any damage on the HTS coating film might have occurred. On the other hand, the CC tape sample fabricated by MOCVD process adopting the same substrate material exhibits a higher I_c retention up to 600 MPa corresponding to the applicable stress limit by the current system. Also, the *n-values* in Fig. 3(b) showed similar behavior with I_c under transverse compressive stress. These data are still comparable with the transverse compressive stress value reported on a YBCO CC tape using 2 mm width stainless steel indenter which was greater than 518 MPa [7, 11].

3.3. Reversible I_c behavior under transverse compressive stress

Since it has been reported that the loading-unloading mode has a significant effect on the I_c degradation behavior of the CC tapes under transverse compressive stress, it is also necessary to investigate its effect on the CC tape itself [6, 7, 11]. Fig. 4 (a) shows the I_c degradation behavior in RCE-DR CC tapes adopting Hastelloy substrate under transverse compressive stress in a loading-unloading manner. Test 1 reached the 95 % I_c retention stress limit at 600 MPa. This critical stress value is much higher as compared to the one obtained in the monotonic loading mode for the same RCE-DR CC sample. However, it is observed that the I_c was already irreversible at a compressive stress higher than 480 MPa when evaluated based on the 99 % I_c recovery. In this case, the difference in load application interval for monotonic loading mode



(a)

(b)

Fig. 4. Critical current, I_c degradation behavior under transverse compression loading (loading-unloading) of (a) RCE-DR CC tape and, (b) MOCVD CC tape adopting Hastelloy substrate.

(15 MPa) and loading-unloading mode (30 MPa) might have an effect on the I_c degradation behavior. In the loading –unloading mode, the load interval was doubled that of the monotonic loading mode. In Test 2, the effect of the loading-unloading mode was significantly seen on the I_c degradation behavior of CC tape. The CC tape reached the I_c retention stress limit at a transverse compressive stress of 460 MPa. The reversibility I_c stress limit was lower as compared with the case of Test 1. This behavior was due to the frictional support induced by pressing the anvil. In a loading - unloading mode, releasing repeatedly the upper anvil indenter during unloading state might cause an in-plane expansion which may lead to the cracking on the REBCO coating film and buffer layer inside the CC tape. However in a monotonic loading mode, the pressing anvil indenter provides frictional support preventing a lateral expansion on the CC tape sample to occur [6, 11]. The difference in the behavior of two tests in RCE-DR CC samples might be resulted from the non-uniformity of the CC tape samples adopted.

In the case of the MOCVD CC tape sample, no significant effect of loading-unloading mode can be observed for two tests conducted as shown in Fig. 4 (b) wherein both tests showed a 95 % I_c stress limit greater than 600 MPa. However, reversibility limit was measured at 560 MPa and up to 500 MPa for Test 1 and Test 2, respectively.

The values obtained on both RCE-DR and MOCVD CC tape samples adopting Hastelloy substrate were indeed higher than that of the 100 MPa benchmark set for several superconducting device applications [6, 11]. This means that the currently adopted REBCO CC tapes are robust enough under transverse compressive stresses.

4. SUMMARY

In this study, critical transverse tensile and compressive stresses of REBCO CC tapes were measured and characterized using the anvil tests method. The IBAD REBCO CC tapes exhibited abrupt and gradual I_c degradation behaviors under transverse tensile loading. On the other hand, much higher irreversibility stress limit was measured under transverse compressive stress making the CC tape robust in this stress direction. Still, delamination strength including electro- mechanical property remained the main concern in coil applications.

ACKNOWLEDGMENT

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