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Evaluation of electromechanical properties in REBCO CC tapes under transverse compression using anvil test method

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Abstract

One of the major applications of REBCO coated conductor (CC) tapes is in superconducting magnets or coils that are designed for high magnet fields. For such applications, the CC tapes were exposed to a high level of stresses which includes uniaxial tensile or transverse compressive stresses resulting from a large magnetic field. Thus, CC tapes should endure such mechanical load or deformation that can influence their electromechanical performance during manufacturing, cool-down, and operation. It has been reported that the main cause of critical current (I_c) degradation in CC tapes utilized in coil windings for superconducting magnets was the delamination due to transversely applied stresses. In most high-magnetic-field applications, the operating limits of the CC tapes will likely be imposed by the electromechanical properties together with its I_c dependence on temperature and magnetic field. In this study, we examined the influence of the transverse compressive stress on the I_c degradation behaviors in various commercially available CC tapes which is important for magnet design Four differently processed REBCO CC tapes were adopted to examine their I_c degradation behaviors under transverse compression using an anvil test method and a newly developed instantaneous I_c measurement system. As a result, all REBCO CC tapes adopted showed robustness against transverse compressive stresses for REBCO coils, notably at transverse compressive stresses until 250 MPa. When the applied stress further increased, different Ic degradation behaviors were observed depending on the sample. Among them, the one that was fabricated by the IBAD/MOCVD process showed the highest compressive stress tolerance.

Keywords: electromechanical property, transverse compressive stress, REBCO tapes, critical current, anvil test method

1. INTRODUCTION

Extensive improvements of high-temperature superconductor (HTS) second-generation REBCO coated conductor (CC) tapes enable it to have superior performance in high magnetic field applications. As such, it was mainly utilized in manufacturing superconducting coils for high magnetic field applications [1]. However, in these applications, the CC tapes were exposed to large mechanical stress or strain that affects their electro-mechanical properties. In particular, the multiple-layer structured CC tapes in the coil winding due to the mismatch of coefficient of thermal expansion among its layers during thermal cycling as well as Lorentz force induced can induce transversely applied stresses that significantly affect the electrical performance of the CC tape [2, 3].

In CC coil windings, uniaxial tensile stress and transverse compressive stress are inevitable: These stresses by Lorentz force cause a hoops stress with the radial compressive stress on the CC tapes in the wound coils. Various types of research have been done to investigate and improve the CC tapes under transverse stress, especially at tensile state [4-6]. Most of them are about delamination phenomena which is the most common problem on coil windings especially epoxy impregnated (wet wound) pancake coil [7]. In the case of transverse compressive stress, on the other hand, little data are available which can prove that it somehow affects the current-carrying capabilities of REBCO CC tapes [8-10]. Manufacturers used to produce 12-mm wide CC tapes, and then slit them to various width depending on the request of the customers which is typicaly 4 mm wide. However, mechanically slitted REBCO tapes have premature cracks along the edges of the ceramic REBCO layer which may cause degradation of the transport property of those CC tapes. Also, the burrs at the slit edge of the substrate layers reduce the delamination strength significantly under transverse tension [11]. One way of investigating the effect of this premature crack caused by mechanical slitting is the use of fatigue cycling under transverse compressive stress [8]. Moreover, some studies revealed that having high yield-strength substrate material can improve the resilience of the critical current density (J_c) to the transverse compressive stress by limiting in-plane yielding [12]. The effect of transverse stress on the critical current (I_c) of the CC tapes is a critical design parameter for devices especially those used in a high magnetic field.

Thus, this study focused on the investigation of the influence of the transverse compressive stress on the electromechanical properties of REBCO CC tapes using the anvil test method. Unlike a transverse tension test wherein the application of the tensile loads can directly influence the failure features of the CC tapes usually (e.g. delamination of layers, bulging, etc.), the transverse compressive stress is different. Under transverse compression, it is impossible to obtain any variation in

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TABLE 1
SPECIFICATIONS OF REBCO CC TAPE SAMPLES

Fabrication process	**IBAD/RCE-DR (Sample 1)**	**IBAD/MOCVD (Sample 2)**	**ISD/RCE (Sample 3)**	**IBAD/PLD (Sample 4)**
	Ag/GdBCO/$LaMnO_3$/ IBAD-MgO/ Y_2O_3/Al_2O_3/ Stainless steel	Ag/YBCO/LaMO Homo-epi MgO/IBAD MgO/Hastelloy	Ag/GdBCO/ISD-MgO/Hastelloy	Ag/GdBCO/EuBCO/MgO/ Hastelloy
REBCO film thickness	~ 1.5 μm	~1.6 μm	~3 μm	~4.5 μm
Critical current, I_c	~270 A	~110 A	~190 A	~250 A
Dimension, t x w	0.134 mm x 4.05 mm	0.085 mm x 4.06 mm	0.147 mm x 4.07 mm	0.100 mm x 4.04 mm
Substrate/ thickness	~100 μm	~50 μm	~100 μm	~50 μm
Stabilizer/technique	Cu electroplated, surround (~15 μm)	Cu electroplated, surround (~20 μm)	Cu electroplated, surround (~43 μm)	Cu electroplated, surround (~20 μm)

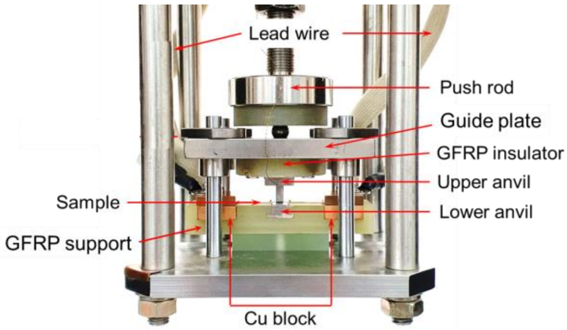
characteristic mechanical properties or failure. No obvious damages induced in the CC tapes could be observed under transverse compressive stress, unless directly observing the REBCO layer microscopically, typically through SEM. The occurrence of damages or defects in the REBCO layer could only be manifested by the change in the I_c degradation behavior. That is why a simultaneous I_c measurement system was adopted in this study to continuously observe the I_c degradation behavior while compressive stress is being applied. A comparison among four CC tapes was made to analyze whether the constituent layers especially the substrate may alter the I_c degradation behavior under transverse compression.

2. EXPERIMENTAL PROCEDURES

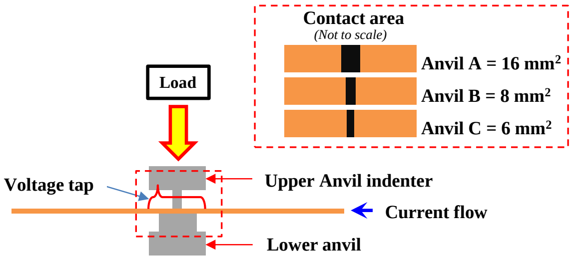
2.1. Samples

Four commercially available CC tapes were used in this study and their specifications are listed in Table 1. The first sample is from SuNAM, ion beam assisted deposition, (IBAD/*GdBCO* CC) tape, fabricated by the RCE-DR process [13]. $LaMnO_3$-buffered IBAD-MgO were used as buffer layers on the templates for the GdBCO layer atop a stainless-steel (STS) substrate. A ~1 μm silver (Ag) layer was used to protect the GdBCO CC tape with a Cu stabilizer using an electroplating process. Second, SuperPower CC tape, architecture was comprised of a superconducting layer, based on the YBCO, fabricated by metal-organic chemical vapor deposition (MOCVD). The bi-axially textured stack of buffer layers was deposited via IBAD or sputtering atop a Hastelloy substrate that acts as a template for the introduction of the REBCO material. The third sample is from THEVA, fabricated by the inclined substrate deposition (ISD). The REBCO layer was epitaxially grown on biaxially textured ISD-MgO-buffered and non-magnetic Hastelloy substrate. Lastly, Fujikura was fabricated by advanced IBAD for biaxially textured buffer layers and a large PLD system with hot wall heating for depositing the superconducting layer. Silver (Ag) and Cu stabilizers were sputtered and electroplated to the CC tape completely, to provide good electrical stability.

2.2. Anvil test method for the transverse compressive test at 77 K



(a)



(b)

Fig. 1. (a) Test setup for transverse compressive loading at 77 K, and (b) schematic diagram of the anvil/sample assembly.

In evaluating the influence of the transverse compressive stress on the electro-mechanical properties of REBCO tape samples, we modified our current transverse loading setup for the transverse tensile test (see Fig. 1 (a)) using the anvil test method reported elsewhere [2, 9]. It uses a guide plate associated with the four linear bearings and guide shafts, this ensures uniform distribution of transverse compressive stress over the anvil contacting surface of the sample during the test. By doing this, it will minimize the stress concentration to occur at both edges of the upper anvil indenter. The upper anvil indenter and the lower anvil are made of stainless-steel which ensures the application of high compressive load to the CC samples without any deformation on both anvils. The ball bearing acts as a universal joint between the push rod and the guide plate which maintains the alignment of the setup from sudden or unwanted movement of the push rod as it applies the compressive load to the sample via the indenter To electrically isolate the CC sample during I_c measurement, GFRP insulator is embedded between the guide plate and the anvil/sample assembly. Figure 1 (b) shows the schematic diagram of how we assembled both anvils to the sample. The CC sample was held by the Cu blocks which serve as the current terminals for flowing the current to the sample. Moreover, we used three different upper anvil indenter; anvil A (4 mm width x 8 mm length), anvil B (2 mm width x 8 mm length), and anvil C (1.5 mm width x 8 mm length), respectively. When applying the compressive stress to the sample, the effective contact area (see Fig. 1(b)) for this study was 16 mm^2, 8 mm^{2,} and 6 mm^2, respectively. Compressive stress (σ_{comp}) was applied monotonically at a constant ramp rate of 0.1 mm/min with a maximum limit of ~4,800 N which corresponds to the capacity load of the load cell used. The initial and retained I_c was defined by the 1µV/cm electric field criterion which corresponds to the voltage tap separation of 10 mm.

2.3. Continuous I$_c$ measurement system under transverse compression

Recently, we have developed an I_c measurement system that can control continuously and simultaneously the transport current corresponding to its I_c of the CC sample under tensile loading during testing [14-15]. We adopted it in this study so we can observe the I_c variation as the transversely applied compressive load gradually increased. The entire system can effectively characterize I_c degradation behaviors in CC tapes under transverse compression by combining into I_c-stress curves.

In a conventional I_c measurement procedure, we deal with manually applying the load in a specific stress/load-interval accompanied by multiple I_c measurements concerning the applied stress/load [9]. In such transverse compressive tests wherein we cannot define the stress level `that the CC tape will fail mechanically or electromechanically, and it is a time-consuming work. Moreover, the continuous I_c measurement system will not only reduce the test time significantly but will also eliminate human error during load application considering that we can apply a specified load simultaneously with applying the current to the CC tape. Through this test procedure, the I_c degradation behavior and the electrical transverse compressive stress limit can be determined efficiently.

3. RESULTS AND DISCUSSION

3.1. Electromechanical properties of REBCO CC tapes under transverse compression

Fig. 2 shows the I_c degradation behavior of commercially available REBCO CC tapes under different contact area using (a) anvil A, (b) anvil B, and (c) anvil C subjected to transverse compressive stress. As the transverse compressive stress increased, each CC tape showed a different behavior of I_c depending on its manufacturing process.

At a wider anvil, there's no significant degradation could be found until 250 MPa (see Fig. 2(a)). Since the contact area is large, the compressive stress applied did not cause significant damage to the REBCO film of the CC tapes.

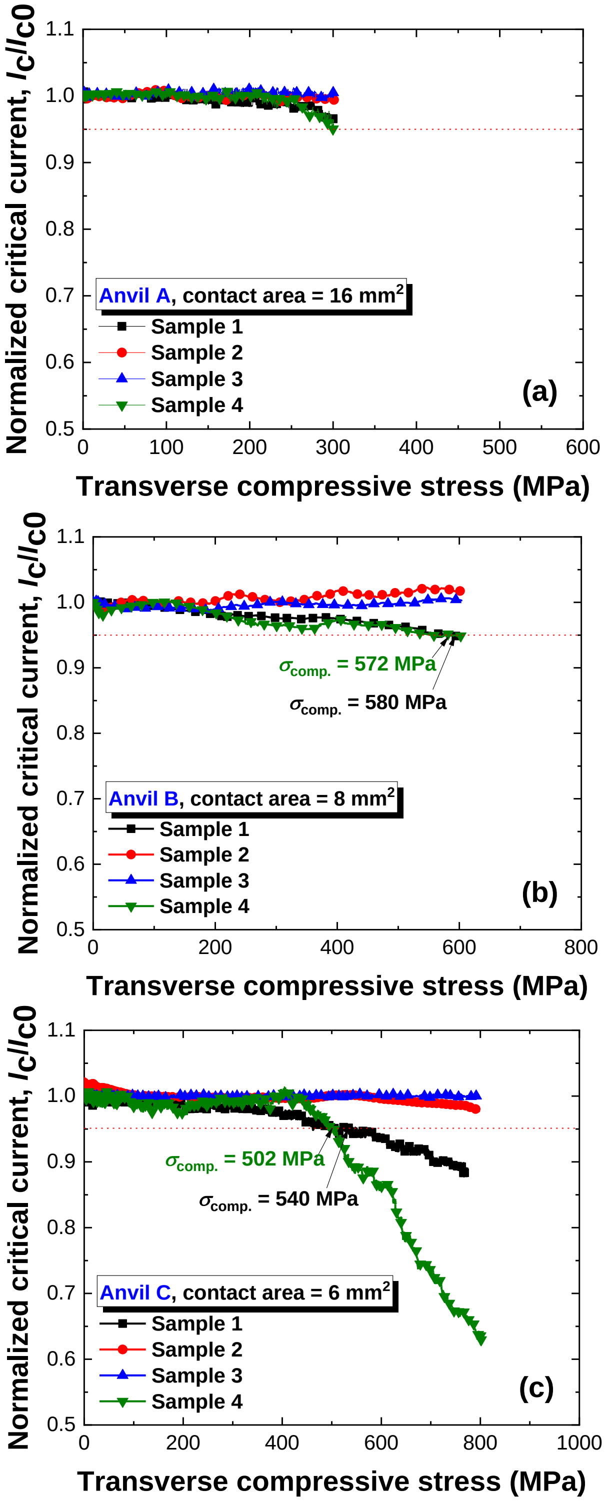


Fig. 2. I_c degradation behavior of commercially available REBCO CC tapes under different contact area using (a) anvil A, (b) anvil B, and (c) anvil C subjected to transverse compressive stress.

However, at narrow anvils shown in Fig. 2 (b) and (c), the stress concentration becomes more pronounced which caused a significant drop in I_c for some samples, but not for others. With narrow upper anvils of Fig. 2 (b) and (c), it can be found that Samples 1 and 4 exhibited a gradual but

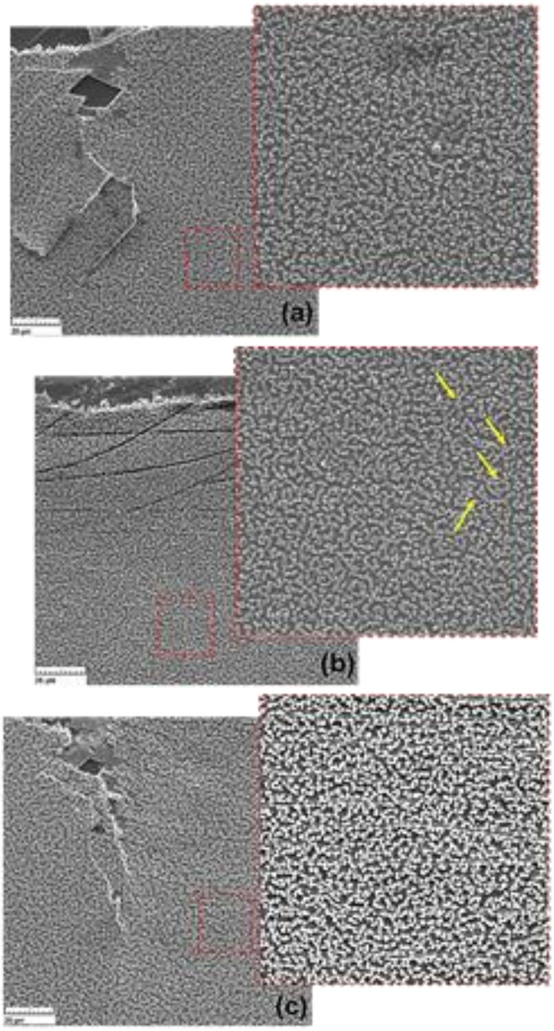


Fig. 3. SEM images of REBCO film observed at the indented parts of Sample 1 after transverse compression test using (a) anvil A (300 MPa), (b) anvil B (600 MPa), and (c) anving C (800 MPa).

nominal decrease of I_c with a 95% retention stress of 580 MPa and 572 MPa at 8 mm^2 (anvil B) contact area and 540 MPa and 502 MPa at 6 mm^2 (anvil C), respectively. These I_c degradation behaviors indicate that damage to the superconducting layer has occurred. On the other hand, Samples 2 and 3 did not show any significant decrease of I_c up to the applied maximum σ_{comp}.

Both Samples 1 and 4 have a small tolerance on the compressive stress for the three different anvil sizes. However, all commercially available CC tapes are not solely sensitive to transverse compressive stress with an engineering design of ~250 MPa as stated in [10]. This means that they are robust enough against the expected transverse compressive stresses for coil applications.

3.2. Observations of damage in REBCO layer after transverse compression test

Fig. 3 shows the SEM images of REBCO film observed at the indented parts of Sample 1 after transverse compression tests at (a) 300 MPa for anvil A, (b) 600 MPa for anvil B, and (c) 800 MPa for anvil C. For SEM observation, the Cu and Ag stabilizing layers of Sample 1 were chemically etched to expose the REBCO film and the effect of the compressive stress applied to the sample was observed. These images show some microcracks caused by the applied compressive stress, which both affect the I_c degradation behavior of the CC tapes. With a uniform distribution of transverse compressive stress at the indented surface of the CC tape, a stress concentration on the REBCO layer produced the I_c degradation. It was found that with a wide upper anvil (Fig. 3(a)), although cracks resulted from slitting of the sample, it does not significantly affect the I_c behavior among the CC tapes during the transverse compression (please see figure 2(a)). In the middle part of the compressed or indented area, the cracks did not initiate unlike in the case of the narrow anvils. The presence of microcracks was located in the middle part of the compressed area which could be the cause of the significant I_c degradation of Sample 1 at the narrow anvils (2- and 1.5-mm upper anvils). However, I_c degradation behaviors may vary according to the structure of the sample. High yield strength samples like Samples 2 and 3 did not show any I_c degradation up to 800 MPa. The presence of precipitate particles can also be seen on the surface of the REBCO layer. Under transverse compressive loading, these precipitate particles may also be accountable for the I_c degradation of the CC tape [16]. Since these particles are the current limiter of most commercially available REBCO CC tapes.

4. CONCLUSIONS

In this study, the I_c degradation behaviors of REBCO CC tapes under transverse compression were investigated and characterized using the anvil tests method with adopting a simultaneous I_c measurement system under loading. The IBAD/RCE-DR and IBAD/PLD processed REBCO CC tapes exhibited gradual I_c degradation behaviors with increasing transverse compression stress. On the other hand, IBAD/MOCVD CC tape showed significantly higher compressive stress tolerance among the commercially available samples tested. Moreover, all REBCO CC tapes showed robustness against transverse compressive stresses up to 250 MPa which is important for designing REBCO coils.

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