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Proof tests of REBCO coated conductor tapes for device applications through electromechanical property assessment at 77 K

Mark Angelo Diaz[a], Michael De Leon[a], Hyung-Seop Shin[a,*], Ho-Sang Jung[b], and Jaehun Lee[b]

[a] *Department of Mechanical Design Engineering, Andong National University, Andong, 36729 Korea*
[b] *SuNAM Co. Ltd., Anseong, Gyunggi-do, 17554, Korea*

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Abstract

The practical application of REBCO coated conductor (CC) tapes, vital for energy transmission (*e.g.,* cable application) and high-field magnets (*e.g.,* coil application), necessitates efficient and simple quality assessment procedures. This study introduces a systematic approach to assess the electromechanical properties of REBCO CC tapes under 77 K and self-field conditions. The approach involves customized tensile and bending tests that clarify the critical current (I_c) response of the CC tapes under mechanical loads induced by tension and bending. This study measures the retained I_c values of commercially available GdBCO CC tapes under 250 MPa tensile stress and 40 mm bending diameter. Through experimentation, the study demonstrates the resilience of these tapes and their suitability for applications. By presenting a simplified stress-based analysis and a bending test of the tapes, the study contributes to effective quality assessment methods for the development of practical superconducting products.

Keywords: proof test, electromechanical property, critical current, REBCO tape, uniaxial tensile test, bending test

1. INTRODUCTION

Rare-earth barium copper oxide (REBCO) coated conductor (CC) tapes have exhibited high critical current (I_c) characteristics and superior mechanical properties, making them indispensable for applications in power cables and high-field magnets. However, the practical utilization of these tapes introduces challenges related to mechanical stresses encountered in device applications. Particularly, the deployment of REBCO CC tapes in cable systems demands resilience against tension-induced load, while their incorporation into coil structures necessitates endurance against tensile stress and bending deformation. These mechanical load and deformation scenarios pose a substantial risk to the I_c degradation of the CC tapes. As a consequence, a comprehensive investigation into the electromechanical behaviors, including electromechanical properties (EMP) of REBCO CC tapes under uniaxial tension and bending deformation, has been carried out [1-7].

Several measurement-related internation standards for HTS wires were established by IEC-TC90 [8-10]. However, these standards are fundamental ones and still difficult to implement in practical devices. Additonally, manufacturers may require a more specific assessment of stress and strain effects on I_c and other related EMPs.

This study aims to simplifiy the quality assessment process for manufactures by adopting a stress-based analysis that evaluate the impact of tensile stress on the I_c behavior of REBCO CC tapes including responses to bending deformation. Notably, the study provides a targeted and efficient approach to assess the tapes' behavior under tension and bending, potentially streamlining quality assessment processes in the industry.

*Corresponding author: hsshin@anu.ac.kr

To comprehensively address the distinct mechanical stress scenarios in cable and coil applications, this study employs two practical testing methods: the tensile test [1] for cable application and the bending test [3] for coil application. The specific stress requirement of 250 MPa for the tensile testing and the use of a 40 mm bending diameter for the bending testing are selected to simulate real-world stress conditions experienced by these tapes in cable and coil applications, respectively. In this investigation, brass-laminated Cu-stablized CC samples were employed with a focus on their application in superconducting cables. Meanwhile, the Cu-stabilized CC tape was specifically designed for coil use.

2. EXPERIMENTAL PROCEDURES

2.1. Samples specifications.

For this study, commercially available REBCO CC tapes were supplied by SuNAM. The tapes were fabricated using the RCE-DR process and featured distinctive specifications, as detailed in Table 1. Sample 1 comprised of single-side brass laminated to the Cu-stabilized CC tape (Sample 1-a) and double-side brass laminated CC tape (Sample 1-b), while Sample 2 consisted of Cu-stabilized CC tape with different widths of 4 mm (Sample 2-a and 2-b) and 12 mm (Sample 2-c, 2-d, and 2-e). The brass lamination in Sample 1 provided enhanced electrical stability and protection.

2.2. Tensile and bending test methods.

Two practical testing methods were employed to evaluate the I_c response of commercially available GdBCO CC tapes. Figure 1(a) illustrates the setup for the tensile test, where a UTM (Shimadzu AG-IS; load cell capacity, 5

TABLE 1
SPECIFICATIONS OF THE CC TAPE SAMPLES.

Fabrication process	IBAD/RCE-DR						
Sample designation	**Sample 1** *(for tension test)*		**Sample 2** *(for bending test)*				
	$Ag/GdBCO/LaMnO_3/IBAD\text{-}MgO/\ Y_2O_3/Al_2O_3$/Stainless steel						
REBCO film thickness	~ 1.5 µm						
Substrate/ thickness	~100 µm						
(Sample designation)	*a (single-side laminated)*	*b (double-side laminated)*	*a*	*b*	*c*	*d*	*e*
Critical current, I_c (A)	~260	~304	~220	~280	~670	~860	>900
Dimension, *t* x *w*	0.275 mm × 4.30 mm	0.29 mm × 4.30 mm	0.134 mm × 4.01 mm		0.134 mm × 12.01 mm		
Stabilizer/technique	Brass laminated Cu stabilized (Brass: H)		Cu electroplated, surround (~15μmm)				

kN) was utilized. Figure 1(b) depicts the Goldacker-type bending test rig used for bending tests [2-3]. Sample 1 used for the tensile test has a total length of 120 mm and a gauge length of 60 mm. The sample was securely mounted on gripping fixtures and aligned carefully to ensure uniform load distribution. The tensile proof test was conducted as follows: initially, I_{c0} was measured at 77 K and self-field. Subsequently, I_c was measured after applying the 250 MPa tensile stress. Finally, the retained I_c was measured after releasing the stress from 250 MPa to 0 MPa.

The selected proof stress of 250 MPa is significantly lower than the sample's irreversible stress limit, as depicted in Figure 2. This deliberate margin was incorporated as a safety buffer in order to determine the conditions for a superconducting cable. With a higher safety factor, the CC tape can withstand stress levels beyond the proof stress, providing an additional layer of safety against potential variations in material properties.

For the bending proof test, Sample 2 was used with a total length of 90 mm and a gauge length of 32 mm. The bending strain calculation, taking into account the bending radius, was based on previous works [1-2]. The sample was secured at both ends with rotatable components, which served as current blocks. A rotating rod connected to a stepping motor allowed continuous adjustment of the angle between the two parts from 0° to 180° [11]. The bending diameter for this test was fixed at 40 mm and under tension bending, which is equivalent to 0.25% of bending strain (ε_b). This diameter was chosen based on the CC tapes' bending integrity related to the minimum inner diameter required for winding coils [7, 12]. The bending behavior ensured that the sample retained a circular shape throughout the bending process.

The I_c response was evaluated using the four-probe method, with a set criterion of 1 µV/cm. For the tensile test, we used voltage tap separations of 20 mm, and for the bending test we used 10 mm. The voltage clip method [13] was adopted for the tensile proof test, which facilitated I_c measurement during tensile testing. The initial I_c (I_{c0}) were measured without applied stress for both methods, serving as a reference for normalized I_c assessment. By comparing I_c values under stress conditions with I_{c0}, potential I_c. degradation was evaluated. Additionally, I_c measurements were carried out after unloading (removal of applied stress) to determine the reversibility of I_c.

3. RESULTS AND DISCUSSION

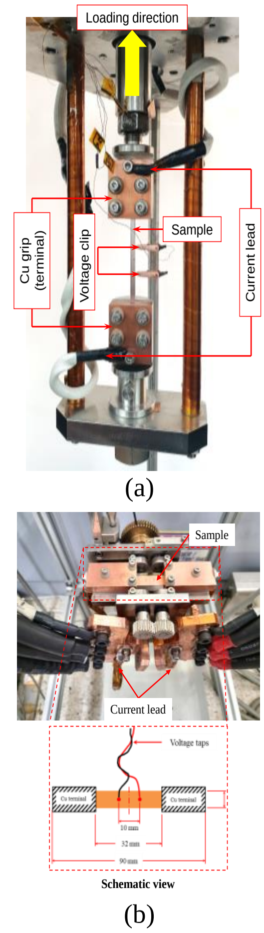

Fig. 1. Proof test setups under (a) tension and (b) bending conditions.

3.1. I_c response under a tensile stress of 250 MPa

The tensile proof test was conducted on single-side and double-side brass foil laminated Cu-stabilized REBCO CC tapes (Sample 1-a and 1-b) to understand the effects of tensile stress of 250 MPa on the I_c behavior. For comparison, the full-range EMP of a single-side brass foil laminated CC tape (Tape 1), represeting its I_c-strain/stress relationship (retrieved from [14]) is shown in Figure 2. Notably, two tapes originate from different batches, which accounts for the disparity in I_c values. However, it's worth noting that the stress level of 250 MPa applied in this proof test maintains a tensile factor of safety (FS_t) of 2.9 in relation to the 734 MPa irreversible stress limit (σ_{irr}.) depicted in Figure 2. This relationship is expressed by the

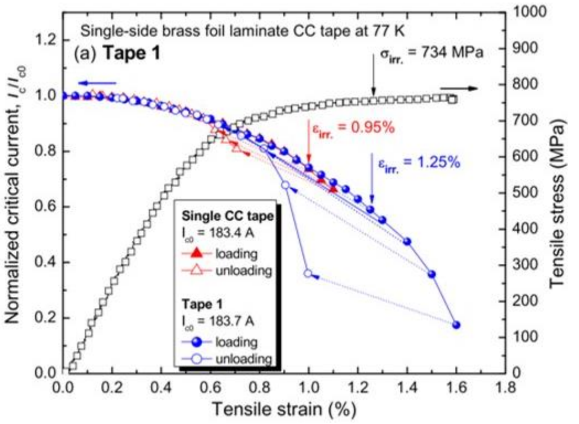

Fig. 2. Normalized critical currrent and tensile stress as a function of tensile strain in single-side brass laminated CC tape. Retrieved from Shin et al. Copyright 2016 by IEEE-Transactions on Applied Superconductivity [14].

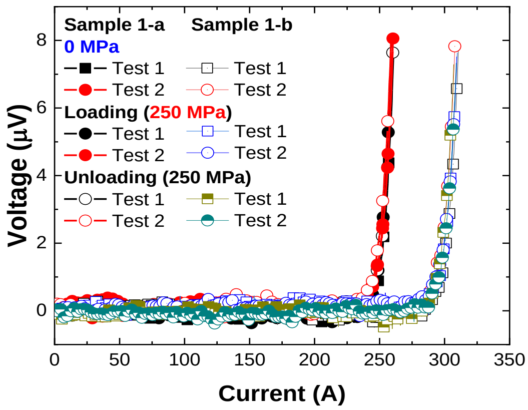

Fig. 3. Repesentative I_c behavior (I-V curves) of sample 1-a and 1-b under 250 MPa of tensile stress.

formula $FS_t = \sigma_{irr.}$/proof tensile stress = 734 MPa/250 MPa. Table 2 summarizes the results of Sample 1 subjected to a tensile stress of 250 MPa, while the representative current-voltage (*I-V*) curves are shown in Figure 3. Sample 1-a and -b show almost similar I_c behavior under 250 MPa with a less than ~1% decrease from its I_{c0}. Notably, the I_c values showed exceptional stability despite the considerable stress. Even after subjecting the samples to mechanical stress and subsequently unloading the applied stress, the retained I_c exhibited minimal alteration, indicating recovery to I_{c0}. This observation that the tensile stress applied along specific orientations did not cause any significant disruption to the alignment of superconducting layers, resulting in no I_c degradation.

The remarkable resilience of I_c values to mechanical stress underscores the effectiveness of the chosen quality assessment approach for externally laminated Cu-stabilized GdBCO CC tapes. The tapes' ability to maintain I_c values under substantial tensile stress highlights their aptitude for applications that might expose them to mechanical loadings, such as power transmission cables. This consistency in I_c values reinforces the promise of these tapes in real-world scenarios demanding both superconductivity and mechanical robustness.

TABLE 2
RESULTS FROM THE I_C MEASUREMENTS FOR EACH TAPE BY TENSILE PROOF TESTS.

Sample 1	Initial I_c (I_{c0})	I_c at 250 MPa	Retained I_c at 0 MPa
Sample 1-a	256 A	254 A	256A
Sample 1-b	303 A	301 A	302 A

TABLE 3
RESULTS FROM THE I_C MEASUREMENTS FOR EACH TAPE USING GOLDACKER-TYPE BENDING TEST RIG.

Sample 2	Initial I_c (I_{c0})	I_c at bent state	Retained I_c at unbent state
Sample 2-a	227 A	223 A	226 A
Sample 2-b	289 A	288 A	291 A
Sample 2-c	677 A	668 A	677 A
Sample 2-d	866 A	860 A	863 A
Sample 2-e	>900 A (920 A)	>900 A (911 A)	>900 A (919 A)

3.2. I_c response under bending proof test at 77 K

Table 3 summarizes the I_c results for all Sample 2 tapes subjected to bending deformation. Detailed analyses are presented in Figure 4, showing the *I-V* curves for each tape. The results present the impressive I_c retention of all Sample 2 tapes post-bending. Sample 2-a, for instance, exhibited a mere 1.8% decrease in I_c from 227 A to 223 A at the bent state to the 40 mm bending diameter.

Even more noteworthy, Sample 2-b, 2-c, and 2-d show similar I_c retention of 0.3%, 1.3%, and 0.7% respectively. Remarkably, all these samples maintained I_c values above 95% of I_{c0}. In Sample 2-e, the I_c measurements were capped at 900 A due to testing constraints. Therefore, extrapolated values are denoted in parentheses in Table 3. Sample 2-e, despite using extrapolated values, sustained a slight I_c reduction of around 1% after bending. For comparative purposes, Figure 5 illustrates the irreversible bending strain ($\varepsilon_{irr.}$) of this tape at various bending diameters using the Goldacker bending test rig (extracted from [15]). Notably, with $\varepsilon_{irr.}$ = 0.62% and the proof bending strain = 0.25%, the bending factor of safety (FS_b = $\varepsilon_{irr.}$/proof bending strain = 0.62%/0.25%) stands at 2.48.

This consistent retention of I_c above 95% I_{c0} underscores the capacity of Sample 2 tapes to endure bending-induced strain while maintaining superconducting properties.

3.3. Implications for device applications

The robust results obtained from both the tensile and bending proof tests have implications for the viability of REBCO CC tapes in device applications.

The tensile proof test is an important tool for assessing the behavior of REBCO CC tapes in scenarios involving direct load deformation, such as in cable applications. By subjecting the tapes to controlled tensile stress, the method accurately simulates the conditions of cables.

On the other hand, the Goldacker-type bending test assesses the tapes' response to bending deformation, crucial for coil structures like those used in magnets. The automated rig simulates bending conditions by applying tension-induced bending strain which mirrors real-world situations where CC tapes within coils must endure bending deformation. The consistent I_c retention across

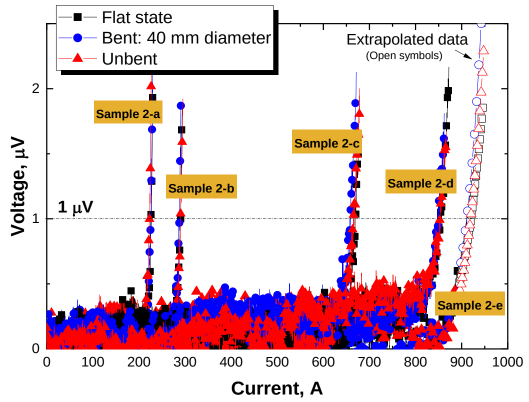

Fig. 4. Voltage-current curves for all I_c measurement sequences for Sample 2 tapes.

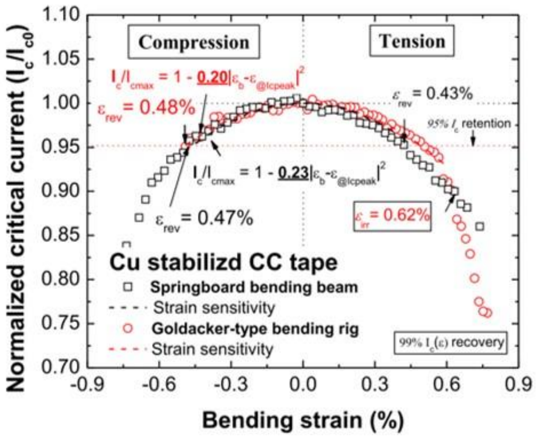

Fig. 5. Normalized critical current, I_c/I_{c0} as a function of monotonic bending strain. Retrieved from Diaz and Shin. Copyright 2019 by IEEE-Transactions on Applied Superconductivity [15].

various samples after bending demonstrates the reliability of these CC tapes under coil-like mechanical deformation.

Nevertheless, these findings significantly enhance the understanding of superconducting technologies and accelerate the advancements in energy transmission, medical imaging, transportation, and more. In general, the successful application of the stress/strain-based analysis approach and the robustness of the employed testing methods reaffirm the potential of REBCO CC tapes for practical applications.

4. CONCLUSION

This study evaluated the viability of tensile and bending proof tests by subjecting REBCO CC tapes to 250 MPa stress and 40 mm bending diameter. The results revealed that retained I_c remained stable under these mechanical stresses, suggesting recovery when operated below the tapes' irreversible limits. These findings underscore the efficacy of these proof test methods in assessing tape quality and reliability for diverse superconducting applications, ranging from power transmission to transportation. This study advances the understanding of superconducting technologies, showcasing the tapes' potential to harmonize mechanical durability and superconducting performance.

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