

Mechanical and electro-mechanical analysis in differently stabilized GdBCO coated conductor tapes with stainless steel substrate

Arman R. Nisay and Hyung-Seop Shin *

Department of Mechanical Design Engineering, Andong National University, Andong, Korea

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Abstract

The understanding of the strain dependence of critical current, I_c , in the reversible region is important for the evaluation of the performance of coated conductor (CC) tapes in practical applications. In this study, the stress/strain tolerance of I_c in GdBCO CC tapes with stainless steel substrate stabilized by additional Cu and brass laminate was analyzed quantitatively through I_c -strain measurement at 77 K under self-field. The variation in irreversible strain limits of CC tapes by the addition of stabilizing layers was analyzed through the consideration of the pre-strain induced on the GdBCO coating film. The results were then compared with the ones previously reported for GdBCO CC tapes with Hastelloy substrate. As a result, GdBCO CC tapes with stainless steel substrate showed much higher strain tolerance of I_c as compared with those adopting Hastelloy substrate.

Keywords: coated conductor, critical current, GdBCO, irreversible strain limit, stainless steel substrate, stabilizing layer, pre-strain

1. INTRODUCTION

REBCO coated conductor (CC) tapes have been recently used in practical applications such as power cables, rotating machines, coil windings, and magnets [1-6] since these CC tapes have shown superior superconducting properties at external magnetic fields and have good mechanical strength [7-9]. Among REBCO CC tapes, GdBCO CC tape showed better electrical properties under external magnetic fields as compared to those of YBCO or SmBCO CC tapes [10-12].

Evaluation of electro-mechanical properties in coated conductors is important because various kinds of stresses and strains can be induced during manufacturing and operation due to extreme conditions. It was noted that significant degradation of I_c occurred when the applied strain exceeds the irreversible strain limit and cannot be reversibly recovered due to the formation of crack on the superconducting coating film [13-18]. To suppress the initiation of crack, Cu layer protection is added to the CC tape thus enhancing the reversibility of I_c and providing further thermal and electrical stability [15-18]. From the previous report of author's group, it was found that different stabilizers such as Cu or stainless steel provided different extent of enhancement in reversible strain limit of YBCO CC tape [17]. Moreover, a strong substrate material is expected to enhance the axial strain performance and to promote good mechanical support to the CC tape such as Ni alloy which is used in RABiTS process and Hastelloy for IBAD process. It is of great concern to fabricate CC tapes with inexpensive substrate having good mechanical properties comparable to commercially available CC tapes with Hastelloy substrate.

In this study, the mechanical and electro-mechanical properties of the GdBCO CC tapes adopting stainless steel substrate with additional Cu stabilizer and brass laminate were measured at 77 K under self-field and quantitatively analyzed. The thermal contraction and coefficient of thermal expansion (CTE) of CC tapes of each constituent layers were measured and used to determine the residual strain induced in the GdBCO coating film. The results are then compared with that of GdBCO CC tapes with Hastelloy substrate [18].

2. EXPERIMENTAL PROCEDURE

2.1. Samples

In order to investigate the influence of stabilizing layer on the electro-mechanical property, three kinds of GdBCO CC samples, Ag-stabilized, Cu-stabilized and Brass laminated CC samples, were supplied by SuNAM Co., Ltd. for this study.

Fig. 1 shows the architecture of RCE-DR GdBCO CC tapes. The coating film was deposited on the stainless steel substrate using reactive co-evaporation by deposition and reaction (RCE-DR) process. Ag layer was sputtered onto the coating film which serves as protection layer. Then, copper was electroplated which surrounds the CC tape. Additional reinforcement of brass laminates were soldered on both sides of the tape.

The bare stainless steel substrate was also obtained by removing the Ag and GdBCO film from Ag-stabilized CC tape through the etching process.

The specifications of the samples tested were shown in Table I.

2.2. Measurement of mechanical properties

Tensile tests of each GdBCO CC tape samples and bare stainless steel substrate were carried out at 77 K using a

* Corresponding author: hsshin@andong.ac.kr

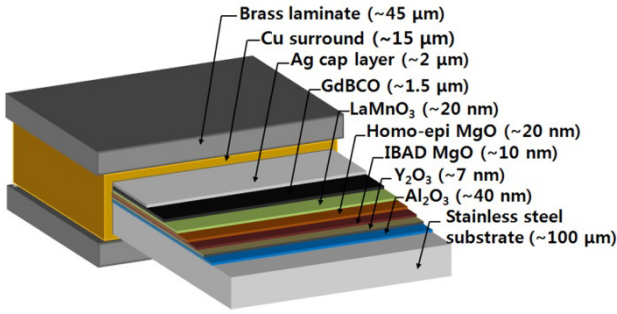


Fig. 1. Architecture of RCE-DR GdBCO CC tape with stainless steel substrate. It shows the component layers and each thickness.

TABLE I
SPECIFICATIONS OF GdBCO CC SAMPLES.

	IBAD/GdBCO CC
Fabrication process	RCE-DR
Structure	Ag/GdBCO/LaMnO ₃ / Homo-epi MgO/IBAD MgO/ Y ₂ O ₃ /Al ₂ O ₃ /Stainless steel
Dimension, t x w (mm)	
Ag-stabilized	0.105 x 3.98
Cu-stabilized	0.139 x 4.02
Brass laminated	0.234 x 4.19
Manufacturer	SuNAM

universal tensile testing machine (Shimadzu AG-IS, 5 kN load cell) at a constant cross-head speed of 1 mm/min [12]. A 15 mm gauge length Nyilas-type double extensometer was directly attached at the central part of the sample to measure the induced strain during uniaxial tension. The sample gauge length for tensile test was 40 mm. Elastic modulus and yield strength were determined.

The measured elastic moduli of GdBCO CC tapes were then compared with the estimation of elastic modulus using the rule of mixture described by the following equations [18, 19]:

$$E_{Ag-stab.} = E_{Ag}V_{Ag} + E_{STS}V_{STS} \quad (1)$$

$$E_{Cu-stab.} = E_{Cu}V_{Cu} + E_{Ag}V_{Ag} + E_{STS}V_{STS} \quad (2)$$

$$E_{Brass lam.} = E_{Brass}V_{Brass} + E_{Cu}V_{Cu} + E_{Ag}V_{Ag} + E_{STS}V_{STS} \quad (3)$$

where E_i and V_i correspond to the elastic modulus and volume fraction of each constituent layer i , respectively.

The thermal contraction and coefficient of thermal expansion (CTE) of three kinds of GdBCO CC tapes and constituent layers such as stainless steel substrate, Cu stabilizer, and brass laminate were measured using double extensometer. The measuring procedure is described in detail in [20].

The thermal contraction and CTE of each sample are calculated by the following equations:

$$\frac{\Delta L}{L} = \frac{\Delta V_{sample} - V_{ext.}}{(CF_{@77K})(GL_{ext.})} \quad (4)$$

$$\alpha = \frac{\frac{\Delta L}{L}}{\Delta T} \quad (5)$$

where $\Delta L/L$ is the thermal contraction of the sample; ΔV_{sample} corresponds to the difference in voltage reading of the sample in cooling from RT to 77 K; $V_{ext.}$ is the initial voltage reading of the double extensometer; $CF_{@77K}$ is the calibration factor at 77 K which is 1.82 in this study; $GL_{ext.}$ is the gauge length of the double extensometer, 15 mm; α is the coefficient of thermal expansion (CTE); and ΔT represents the temperature difference from RT to 77 K.

2.3. Measurement of I_c under uniaxial tension

The response of I_c depending on uniaxial strain/stress was measured at 77 K under self-field for the CC sample mounted to a loading frame installed on the universal tensile test machine. Both ends of the sample were fixed by copper grips which serve as electric contacts to current leads. The gauge length of the sample was 40 mm and voltage taps were soldered at the middle part of the sample with a separation distance of 20 mm. The strain induced to the sample due to the application of tensile load was measured by double extensometer attached between both voltage taps. I_c was measured at a voltage criterion of 1 $\mu V/cm$ for every 0.05% interval of applied uniaxial strain on the sample. When an I_c degradation of about 5% occurred, the applied tensile load was released to check the reversible behavior of I_c against strain. The sample was loaded and unloaded periodically to determine its irreversible strain and stress limits, ϵ_{irr} and σ_{irr} respectively, which have been defined in this study as 99% I_c recovery during unloading.

3. RESULTS AND DISCUSSION

3.1. Mechanical properties

Stress-strain curves of GdBCO CC tapes and bare stainless steel substrate obtained at 77 K are shown in Fig. 2. Elastic modulus was determined from the initial linear slope of each curves and the yield strength was obtained from 0.2% offset strain. From the results, it can be found that additional Cu and brass lamination have caused the decrease in the elastic modulus and yield strength of the samples.

As a reference, the results of GdBCO CC tapes with stainless steel substrate were compared with the GdBCO CC tapes adopting Hastelloy substrate [18]. As can be observed in Table II, all CC tapes with Hastelloy substrate showed higher mechanical properties than those with stainless steel substrate.

When using Eq. (1) for Ag-stabilized CC tape, it resulted to an estimated E value of 205 GPa which is almost similar with the measured value of 207 GPa. The calculated E value of 187 GPa for Cu-stabilized CC tape using Eq. (2) also showed similarity with the measured one of 186 GPa. But in the case of Brass laminated using Eq. (3), the calculated E value of 155 GPa showed a small difference from the measured one of 141 GPa. This indicates that disregarding the solder layer in the calculation will result to the difference between the measured and calculated E values.

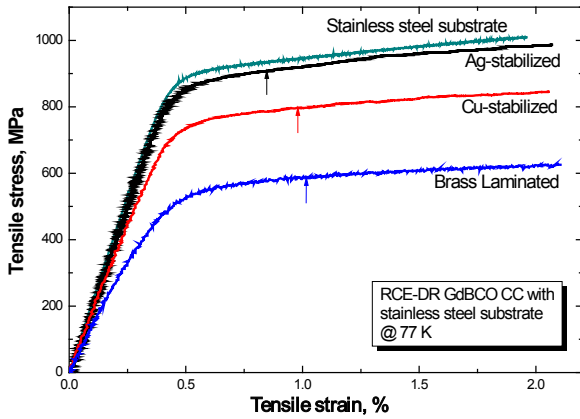


Fig. 2. Stress-strain curves of GdBCO CC samples and bare stainless steel substrate obtained through uniaxial tensile tests.

TABLE II
MECHANICAL PROPERTIES OF GdBCO CC TAPES.

	Elastic modulus, E (GPa)	Yield strength, σ_y (MPa)	Yield strain, ϵ_y (%)
Stainless steel substrate	212	914	0.62
Ag-stabilized	207	885	0.64
Cu-stabilized	186	764	0.61
Brass laminated	141	548	0.59
Hastelloy substrate*	232	1285	0.73
Ag-stabilized*	237	1244	0.75
Cu-stabilized*	191	887	0.71
Brass laminated*	148	626	0.65

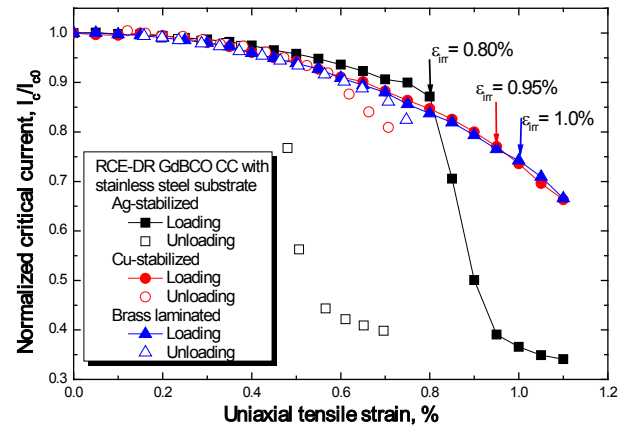
*[18]

3.2. I_c -strain response of GdBCO CC tapes under uniaxial tension

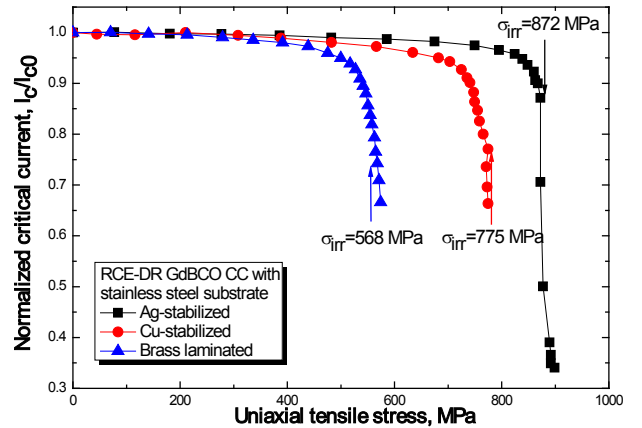
Fig. 3 shows the response of I_c under the application of uniaxial tensile strain/stress in GdBCO CC tapes with stainless steel substrate. From Fig. 3(a), Ag-stabilized sample showed less strain sensitivity of I_c at lower strain values than the other CC samples. However, when the strain was further increased over 0.80%, Ag-stabilized sample showed sudden I_c degradation to about 30% of the original I_c value. On the other hand, Cu-stabilized and Brass laminated samples showed continuous gradual I_c degradation behavior up to higher strain values. In addition, both samples showed almost similar I_c degradation behavior and had higher irreversible strain limits of 0.95% and 1.0%, respectively. This behavior for both Cu-stabilized and Brass laminated samples may be attributed to similar thermal contraction between major constituent layers resulting in an even pre-compression strain induced to the GdBCO coating film which will be discussed more in the following subsection.

Although the Cu-stabilized and Brass laminated samples showed higher tolerant strain limit, both have lower irreversible stress limits of 775 MPa and 568 MPa, respectively, than that of the Ag-stabilized sample with 872 MPa. This resulted from the additional copper and brass layers which decreased the apparent elastic modulus and yield strength of the whole CC tapes.

The ϵ_{irr} and σ_{irr} of GdBCO CC tapes with stainless steel substrate and those of Hastelloy substrate are shown in Table III. It can be apparently observed that samples with stainless steel substrate showed much higher ϵ_{irr} , but have lower σ_{irr} than that of samples with Hastelloy substrate. The Ag-stabilized, Cu-stabilized, and Brass laminated samples with stainless steel substrate have ϵ_{irr} differences of 0.35%, 0.40%, and 0.25–0.30%, respectively, from the samples adopting Hastelloy substrate. These only show that GdBCO CC tapes with stainless steel substrate are more strain tolerant than those with Hastelloy substrate.



(a)



(b)

Fig. 3. Degradation behavior of normalized critical current with uniaxial (a) tensile strain and (b) tensile stress in GdBCO CC tapes with stainless substrate at 77 K under self-field.

TABLE III
IRREVERSIBLE STRAIN AND STRESS LIMITS OF GdBCO DD TAPES.

GdBCO CC samples	With stainless steel substrate		With Hastelloy substrate*	
	ϵ_{irr} (%)	σ_{irr} (MPa)	ϵ_{irr} (%)	σ_{irr} (MPa)
Ag-stabilized	0.80	872	0.45	1,035
Cu-stabilized	0.95	775	0.55	800
Brass laminated	1.0	568	0.70-0.75	600

* [18]

As shown in Fig. 2, the irreversible strain limits of each GdBCO CC sample with stainless steel substrate were indicated as arrows and were located in the plastic region on the stress-strain curves. But, in the case of GdBCO CC tapes with Hastelloy substrate, the irreversible strain of Ag-stabilized sample was located in the elastic region before the onset of yielding [18].

3.3. Strain induced on the GdBCO coating film by the constituent layers

During cool down from RT to 77 K, the GdBCO coating film experiences additional pre-compression strain due to difference in the CTE among the constituent layers of each composite tape. In order to determine the additional pre-compression strain induced to the coating film, therefore, it is necessary to analyze the thermal contraction and CTE of each CC tape and its major constituent layers

Table IV shows the thermal contraction ($\Delta L/L$) and CTE of GdBCO CC tapes with stainless steel substrate and major constituent layers including the substrate, copper, and brass laminate. These values could be calculated using Eqs. (4) and (5). In the case of CC tapes with stainless steel substrate, it can be observed that the major constituent layers have almost similar thermal contraction that may be the reason of similar I_c degradation behavior of Cu-stabilized and Brass laminated samples.

To calculate the pre-compressive strain induced by these constituent layers on the GdBCO film, ε_{GdBCO} , after cooling from RT to 77 K, the following equation was used [15],

$$\varepsilon_{GdBCO} = \left(\frac{\Delta L}{L}\right)_{GdBCO} - \left(\frac{\Delta L}{L}\right)_{CC} \quad (6)$$

where $(\Delta L/L)_{GdBCO}$ is the thermal contraction of GdBCO film which is assumed as 0.14%, same as average thermal contraction of YBCO [7]; and $(\Delta L/L)_{CC}$ is the thermal contraction of the whole CC tape.

Using both Eq. (6) and thermal contractions of CC tapes from Table IV, the pre-strain values induced on the GdBCO film for Ag-stabilized, Cu-stabilized and Brass laminated CC tapes were calculated and they are 0.10%, 0.15%, and 0.16%, respectively. Almost similar pre-compression strain was induced to the GdBCO coating film of the Cu-stabilized and Brass laminated samples. Therefore, both samples have shown similar strain response of I_c and irreversible strain limits as demonstrated in Fig. 3(a).

TABLE IV
THERMAL CONTRACTION AND CTE MEASURED FOR GDBCO CC TAPES
AND CONSTITUENT LAYERS.

GdBCO CC tapes	$\Delta L/L$ (%)	CTE (10^{-6} K^{-1})
Ag-stabilized	-0.24 ± 0.03	11.25 ± 1.51
Cu-stabilized	-0.29 ± 0.04	13.17 ± 0.91
Brass laminated	-0.30 ± 0.05	13.97 ± 2.85
Constituent layers		
Stainless steel substrate	-0.32 ± 0.05	14.58 ± 2.29
Copper	-0.33 ± 0.01	15.21 ± 0.59
Brass laminate	-0.34 ± 0.01	15.62 ± 0.48

4. CONCLUSIONS

The mechanical and electro-mechanical properties of GdBCO CC tapes with stainless steel substrate were investigated through experimental measurement and analytical calculation. Results showed that these tapes have higher strain tolerance limits and have comparable mechanical strength to those GdBCO CC tapes with Hastelloy substrate. Improvement in irreversible strain limit was attained from the additional copper and brass layers to the CC tapes. Moreover, similar thermal contraction and CTE values between the layers of substrate and stabilizer materials have brought similar strain tolerance due to almost similar pre-compression strain induced to the superconducting film.

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