pISSN 1229-3008 eISSN 2287-6251
Progress in Superconductivity and Cryogenics
Vol.18, No.3, (2016), pp.6~ 9
http://dx.doi.org/10.9714/psac.2016.18.3.006

# Influence of brass laminate volume fraction on electromechanical properties of externally laminated coated conductor tapes

**Zhierwinjay M. Bautista[a], Hyung-Seop Shin[*,a], Jae-Hun Lee[b], Hunju Lee[b], and Seung-Hyun Moon[b]**

[a] *Department of Mechanical Design Engineering, Andong National University, Andong,760-749, Korea*
[b] *SuNAM Co Ltd. Anseong, Gyunggi-do 456-812, Korea*

(Received 23 August 2016; revised or reviewed 22 September 2016; accepted 23 September 2016)

**Abstract**

The enhancement of mechanical properties of coated conductor (CC) tapes in practical application are usually achieved by reinforcing through lamination or electroplating metal layers on either sides of the CC tape. Mechanical or electromechanical properties of the CC tapes have been largely affected by the lamination structure under various loading modes such as tension, bending or even cyclic. In this study, the influence of brass laminate volume fraction on electromechanical properties of RCE-DR processed Gadolinium-barium-copper-oxide (GdBCO) CC tapes was investigated. The samples used were composed of single-side and both-side laminate of brass layer to the Cu-stabilized CC tape and their $I_c$ behaviors were compared to those of the Cu-stabilized CC tape without external lamination. The stress/strain dependences of $I_c$ in laminated CC tapes under uniaxial tension were analyzed and the irreversible stress/strain limits were determined. As a result, the increase of brass laminate volume fraction initially increased the irreversible strain limit and became gradual. The corresponding irreversible stress limit, however, showed no difference even though the brass laminate volume fraction increased to 3.4. But the irreversible load limit linearly increased with the brass laminate volume fraction.

*Keywords*: coated conductor, mechanical properties, electromechanical properties, brass laminate volume fraction, irreversible strain/stress limit

## 1. INTRODUCTION

Nowadays, the mechanical and electromechanical properties of 2G Rare-earth-barium-copper-oxide (REBCO) coated conductor (CC) tapes have been widely studied in practical applications [1-3]. Since the CC tapes can be used under various loading conditions such as uniaxial tension, bending and torsion, the characterization of their mechanical and electromechanical properties is inevitable [4-6].

To further enhance their mechanical properties and to achieve thermal and electrical stability, REBCO CC tapes are usually reinforced by electroplating metal layers and externally laminating metallic foils such as copper, brass, and stainless steel on both or single sides of the CC tapes [7]. Some research results from our group have already reported that one key to improve the mechanical and electromechanical property of CC tapes is adding brass laminate to Cu-stabilized CC tapes [8-10].

The addition of copper and brass layer will also provide further electrical and thermal stability [11]. Usually, the stress characteristics of brass laminated Cu-stabilized CC tape decreased with increasing brass laminate volume fraction because the brass laminate is softer than the substrate layer. Thus, it is necessary to investigate the influence of brass laminate volume fraction not only on the mechanical stress, but also on the strain tolerance of the critical current.

In this study, the influence of brass laminate volume fraction on electromechanical properties of the externally laminated RCE-DR processed CC tapes was analyzed. The stress/strain tolerances of transport property in RCE-DR processed CC tapes were measured at 77 K and self-field. The mechanical properties of the major constituent layers were also measured and used in the calculation of strain tolerance.

* Corresponding author: hsshin@andong.ac.kr

## 2. EXPERIMENTAL PROCEDURES

2.1. Samples

The CC tape samples used are fabricated by reactive co-evaporation by deposition and reaction (RCE-DR) process. The Superconducting film (1.5 μm) was deposited on bi-axial textures ceramic layer coated stainless steel substrate of 100 μm in thickness by ion-beam assisted deposition (IBAD)/RCE-DR process. The buffer layers served as a diffusion barrier during the deposition of superconducting film. The Ag cap layer was sputtered onto the superconducting film as protection layer. Copper of ~15 μm thick was electroplated surrounding the whole CC tape for additional thermal and electrical stability. An external brass laminate reinforcement was done to the Cu-stabilized CC tape. The laminated CC tapes were made with different configurations such as single and both-side

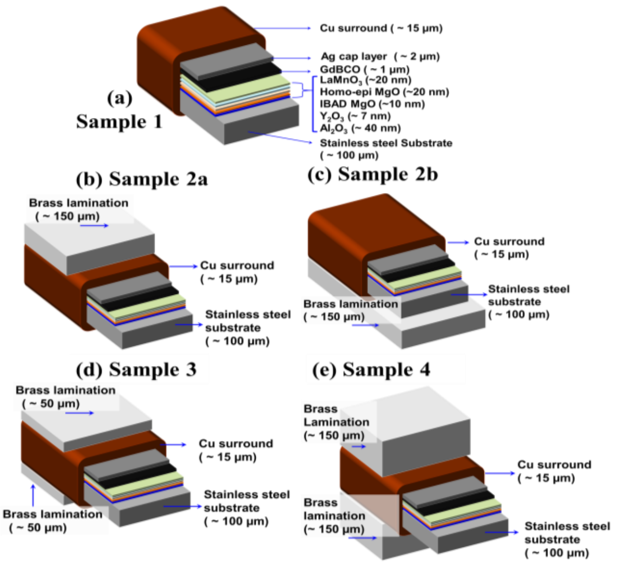


Fig. 1. Structures of (a) Cu-stabilized CC tape (b) Single-side brass laminated at superconducting layer (c) Single-side brass laminated at substrate layer (d) both-side brass laminated (~50 μm) (e) both-side brass laminated (~150 μm) CC tape samples.

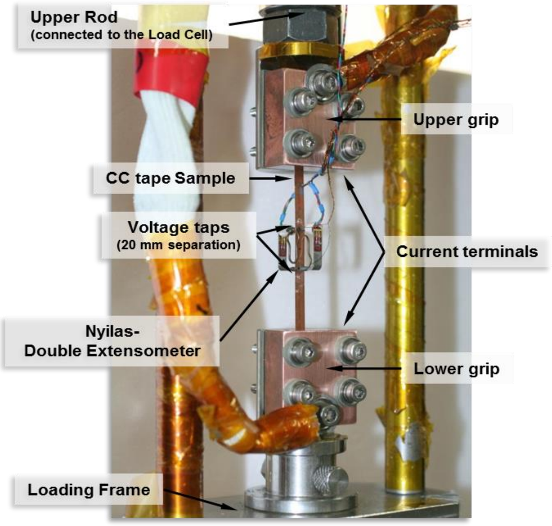


Fig. 2. Set-up for uniaxial tension test.

lamination. The single-side brass laminated CC tape samples with a thickness of ~150 μm have two different types, the one is designated as Sample 2a where the brass laminate is located on the superconducting side and the other is Sample 2b where the brass laminate is on the substrate layer side. In the case of both-side brass laminated ones, different thickness brass laminate of ~50 μm and ~150 μm were used and designated as thin brass laminate and thick brass laminate, respectively.

Fig. 1 shows the sample designation and Table I shows the sample specifications of different brass laminate and Cu-stabilized CC tapes. The relative volume fraction of the brass laminate in the adopted CC tapes was calculated using the formula,

$$V_f = \frac{V_{Cu} + V_{lam}}{V_{Cu}} \qquad (1)$$

where $V_f$ is the relative volume fraction of the laminated CC tape, $V_{Cu}$ and $V_{lam}$ are the volume of Cu-stabilized CC tape without brass lamination and with brass lamination, respectively.

## 2.2. Uniaxial tension test

In order to evaluate the mechanical properties of the laminated CC tapes with different volume fraction, uniaxial tensile load was continuously applied until fracture using a universal testing machine (Shimadzu AG-IS, loadcell 5 kN) at a ram rate of a 1mm/min. The Nyilas-type double extensometers with 25mm length connected to signal conditioner were attached to the sample to obtain the displacement (strain) induced during loading. The samples have a total length of 120 mm and a gauge length of 60 mm. It was fixed on the lower and upper grips at both ends as shown in Fig. 2. The upper grip was connected to the load cell and the lower grip was set on the fixture of the loading frame. Emery sand paper of #800 was inserted between the sample and the gripped part to prevent the slippage of the sample during testing.

TABLE I
SPECIFICATIONS OF VARIOUS BRASS LAMINATED CC TAPES.

| GdBCO CC Tape | (Cu-stabilized) | Single-side brass laminated | | Both-side brass laminated | |
|---|---|---|---|---|---|
| Designation | Sample 1 | Sample 2a | Sample 2b | Sample 3 | Sample 4 |
| Brass Lamination (thickness) | none | Brass laminated at superconducting side (~150 μm ) | Brass laminated at Substrate side (~150 μm) | Brass laminated at both side (~50 μm) | Brass laminated at both side (~150 μm) |
| Critical current, $I_c$ (A) | ~ 150 | 160 ~ 190 | | ~ 220 | ~ 225 |
| Relative volume fraction of brass Laminate ($V_f$) | 1.0 | 2.098 | | 1.6764 | 3.3305 |
| Dimension, t x w (mm) | 0.136 x 4.07 | 0.280 x 4.05 | | 0.280 x 4.05 | 0.443 x 4.3 |

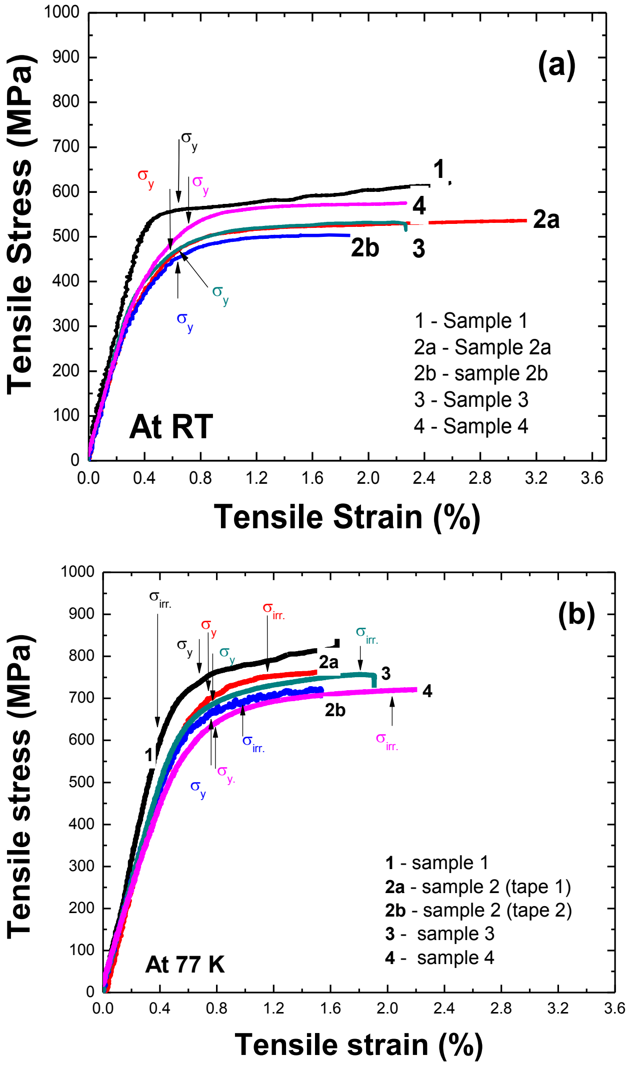


Fig. 3. Mechanical properties of different brass laminated CC tape at (a) RT and (b) 77 K.

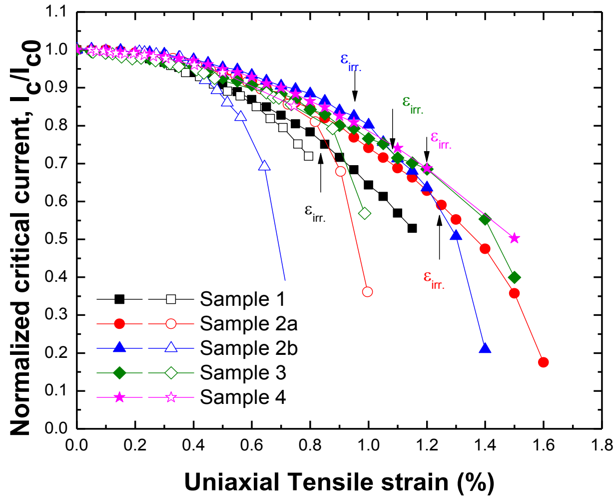


Fig. 4. $I_c/I_{c0}$ vs tensile strain relation in various laminated CC tapes.

TABLE II
MECHANICAL AND ELECTROMECHANICAL PROPERTIES OF LAMINATED CC TAPES AT 77 K.

| CC Tape | E (GPa) | $\sigma_y$ (MPa | $\varepsilon_{irr.}$ (%) | $\sigma_{irr.}$ (MPa) | $F_{irr.}$ (N) | $V_f$ |
|---|---|---|---|---|---|---|
| Sample 1 | 173 | 741 | 0.85 | 701 | 394 | 1.0 |
| Sample 2a | 125 | 704 | 1.25 | 734 | 832 | 2.098 |
| Sample 2b | 125 | 657 | 1.10 | 676 | 767 | 2.098 |
| Sample 3 | 128 | 683 | 1.00 | 625 | 587 | 1.676 |
| Sample 4 | 112 | 633 | 1.20 | 689 | 1,316 | 3.331 |

In the electromechanical property evaluation test, the same sample setup was also used. Cu-blocks were used in gripping the sample and they served as current terminal blocks during the $I_c$ measurement. For the electrical insulation, a 2 mm thick GFRP sheet was inserted between the sample and the grip holder at both ends of the sample to ensure that no current would flow in the entire set-up. A 20 mm separated voltage taps were soldered on the sample which was located within the Nyilas extensometers.

The irreversibility limits of laminated CC tapes were measured to evaluate its electro- mechanical properties.

## 3. RESULTS AND DISCUSSION

### 3.1. Mechanical properties of laminated CC tapes

Fig. 3(a) and (b) show the mechanical properties of differently laminated CC tapes under uniaxial tension. As compared with the Cu-stabilized one (Sample 1), they showed a smaller elastic modulus, $E$ and yield strength, $\sigma_y$ at RT and 77 K. In the single-side and both-side brass laminated CC tapes, $\sigma_y$ of laminated CC tapes decreased with increase of the relative volume fraction, $V_f$.

Fig. 4 shows the normalized $I_c$ against the tensile strain applied and the irreversible strain limit of laminated CC tapes can be determined through loading–unloading process [9]. It showed that the brass laminated CC tapes have the higher irreversible strain limits from 1.00% - 1.25% as compared to the Cu-stabilized CC tapes without brass lamination of 0.85%. It has a good agreement to the previous report that the brass lamination can enhance the irreversible strain limit of the Cu-stabilized CC tapes [6]. However, the corresponding irreversible stress limit for only single-side brass lamination (Sample 2a) shown in Fig. 3(b) has the higher value as compared with the CC tape without brass lamination and the rest has a lower value. This behavior can be resulted from the supply of unusually strong brass laminate batch which is under consideration. On the other hand, the irreversible stress limit could be obtained from the equivalent irreversible strain limit on the stress/strain curves. Also the irreversible load limit can be calculated from the stress limit. The mechanical and electromechanical properties of laminated CC tapes are listed in Table II. The CC tapes with a thick brass laminate or larger Vf exhibited higher irreversible strain and load limit values.

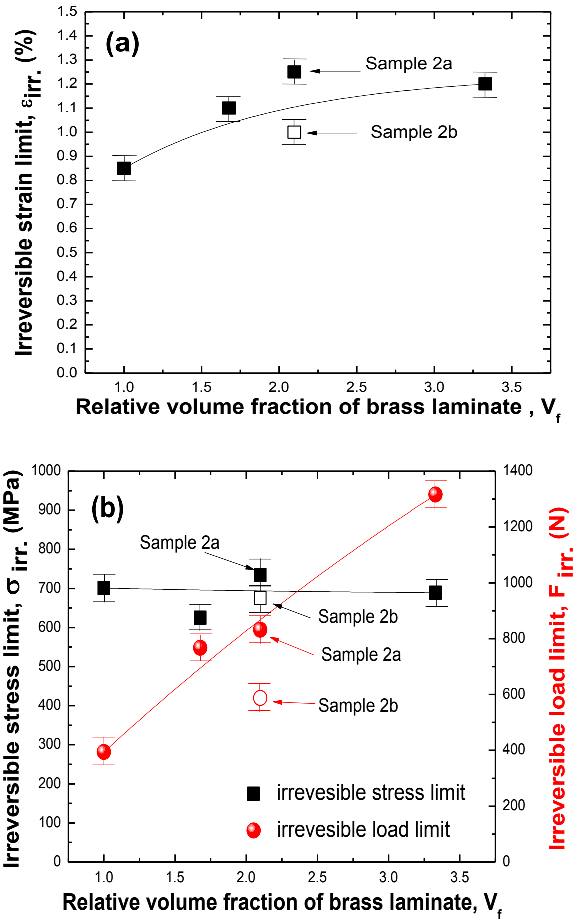


Fig. 5. Relation between (a) irreversible strain limit and, (b) irreversible stress limit and irreversible load limit as a function of relative volume fraction of brass laminate to Cu-stabilized CC tape at 77 K and self-field

Fig. 5 (a) and (b) show the relation between the relative volume fraction of brass laminate and irreversible strain limit and the irreversible stress/load limit, respectively. As Vf increases, the irreversible strain limit of laminated CC tapes increased until Vf =2.0 but held the limit up to Vf =3.4. The sample 2a and 2b shows different mechanical properties due to the different batch of brass laminate as previously mentioned. On the other hand, the corresponding irreversible stress limit showed almost the same value due to the hardening of brass laminate at 77 K, even though the brass laminate is getting thicker. But the equivalent irreversible load limit linearly increased up to 1.3 kN at Vf = 3.4 as the volume fraction increased.

## 4. SUMMARY

The volume fraction of brass laminate added to the Cu-stabilized CC tapes has significant effect on the mechanical and electromechanical properties. The addition of brass laminate to the CC tapes, either the single-side or both-side brass laminate, showed lower elastic modulus and yield strength at 77 K as compared with the case of Cu-stabilized ones under uniaxial tension. However, the increase of brass laminate volume fraction increased the irreversible strain and the irreversible load limit. When it was expressed as an irreversible stress limit, however, it showed almost the same value regardless of the brass laminate volume fraction adopted. Consequently, both-side laminated CC tapes with dissimilar materials having different electrical and thermal stability will be effective in the coil fabrication and are considered as a future work.

## ACKNOWLEDGMENT

This work was 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 (MTIE). (No. 20131010501800). This work was partially supported by a grant from National Research Foundation of Korea (No. 2014-002640) funded by the Ministry of Science, ICT and Future Planning (MSIP), Republic of Korea.

## REFERENCES

[1] N. Cheggour, J. W. Ekin, Y. -Y. Xie, V. Selvamanickam, C. L. H. Thieme, and D. T. Verebelyi, "Enhancement of the irreversible axial-strain limit of Y-Ba-Cu-O-coated conductors with the addition of a Cu layer," *Appl. Phys. Lett.*, vol. 87, p. 212505, 2005.

[2] H. S. Shin, and Marlon J. Dedicatoria, "Variation of the strain effect on the critical current due to external lamination in REBCO coated conductors," *Supercond. Sci. Technol.*, vol. 25, p. 054013, 2012.

[3] M. J. Dedicatoria and H. S. Shin, "Analysis on Stress/Strain Tolerances of Ic in Externally Laminated GdBCO CC Tapes," *IEEE Trans. Appl.*, vol. 23, p. 8400504, 2013.

[4] M. Sugano, T. Nakamura, T. Manabe, K. Shikimachi, N. Hirano, and S. Nagaya, "The intrinsic strain effect on critical current under magnetic field parallel to the c-axis for a MOCVD-YBCO-coated conductor," *Supercond. Sci. Technol.*, vol. 21, p. 115019, 2008.

[5] W. Goldacker, F. Grilli, E. Pardo, A. Kario, S. Schlachter and M. Vojenciak, "Roebel cables from REBCO coated conductors: a one-century-old concept for the superconductivity of the future," *Supercond. Sci. Technol.*, vol. 27, p. 093001, 2014.

[6] H. S. Shin, Z. Bautista, A. Gorospe, J. H. Lee, H. Lee and S. H. Moon, "Electro-Mechanical Properties of Single-Side Brass Foil Laminated Coated Conductor Tapes at 77 K Under Self-Field," *IEEE Trans. on Appl. Supercond.*, vol. 26, p. 8401805, 2016 .

[7] M. Sugano, S. Machiya, H. Oguro, M. Sato, T. Koganezawa, T. Watanabe, K. Shikimachi, N. Hirano, S. Nagaya, T. Izumi, and T. Saitoh, "The effect of the 2D internal strain state on the critical current in GdBCO coated conductors," *Supercond. Sci. Technol.*, vol. 25, p. 054014, 2012.

[8] A. R. Nisay, and H. S. Shin, "Mechanical and electro-mechanical analysis in differently stabilized GdBCO coated conductor tapes with stainless steel substrate," *Prog. Supercond. Cryog.*, vol. 15, pp. 29-33, 2013.

[9] H. S. Shin, M. Dedicatoria, A. Gorospe, J. R. Dizon, H. Oguro and S. Awaji, "Strain and Magnetic Field Response of Ic in Reinforced GdBCO Coated Conductor Tapes at 77 K," *AIP conference Proceedings*, vol. 1574, pp. 239-244, 2014.

[10] S. Ochiai, H. Okuda, T. Arai, M. Sugano, K. Osamura, and W. Prusseit, "Influence of Copper volume fraction in Tensile Strain/Stress tolerances of Critical Current in a Copper-Plated DyBCO-Coated Conductor," *The Japan Institute of Metals*, vol. 54 pp. 269-275, 2013.