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Delamination behaviors of GdBCO CC tapes under different transverse loading conditions

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Abstract

In superconducting coil applications particularly in wet wound coils, coated conductor (CC) tapes are subjected to different type of stresses. These include hoop stress acting along the length of the CC tape and the Lorentz force acting perpendicular to the CC tape's surface. Since the latter is commonly associated with delamination problem of multi-layered CC tapes, more understanding and attention on the delamination phenomena induced in the case of coil applications are needed. Difference on the coefficient of thermal expansion (CTE) of each constituent layer of the CC tape, the bobbin, and the impregnating materials is the main causes of delamination in CC tapes when subjected to thermal cycling. The CC tape might also experience cyclic loading due to the energizing scheme (on - off) during operation. In the design of degradation-free superconducting coils, therefore, characterization of the delamination behaviors including mechanism and strength in REBCO CC tapes becomes critical. In this study, transverse tensile tests were conducted under different loading conditions using different size of upper anvils on the GdBCO CC tapes. The mechanical and electromechanical delamination strength behaviors of the CC tapes under transverse tensile loading were examined and a two-parameter Weibull distribution analysis was conducted in statistical aspects. As a result, the CC tape showed similar range of mechanical delamination strength regardless of cross-head speed adopted. On the other hand, cyclic loading might have affected the CC tape in both upper anvil sizes adopted.

Keywords: coated conductor, transverse tension, delamination, I_c degradation superconducting coil, cyclic loading, Weibull analysis

1. INTRODUCTION

In superconducting coil applications, high temperature superconductor (HTS) coated conductor (CC) tapes exhibited the greatest potentials due to its high critical current density (J_c) and superior mechanical properties. However, when they are used in impregnated coil applications, CC tapes might experience various mechanical stresses and deformation acting on different direction. The radial tensile stress acting transversely on the surface of the CC tape is one in the list. This stress /strain induced by mismatch of the coefficient of thermal expansion among each constituent layers present on the CC tape causes the degradation of its electromechanical properties particularly the critical current (I_c) through the occurrence of delamination. Furthermore, in some device applications, by repeated loading due to rotational stresses, applications that utilize alternating current, random loads and mobile system, and thermal cycling (repetitive cool down and removal from cryogen), might worsen this delamination issue [1]. As reported elsewhere, the I_c of an epoxy impregnated double pancake coil degraded due to at almost 5 thermal cycles [2].

In order to improve the structure and capabilities of the CC tape in regards with this delamination issues, many research groups have been conducting delamination tests with their preferred methods (*i.e.* anvil, pin-pull, cleavage, and peel test methods) [3-7]. In spite of this, only limited information or in worst case, none is available regarding the effect of cyclic transverse load on the mechanical and electromechanical delamination strength of CC tapes.

Characterization of the delamination behavior of CC tapes is essentially needed for the fabrication of delamination-free superconducting coil. Therefore, the effect of transversely applied cyclic loading to the CC tapes should also be considered for the coil fabrication.

In this study, we attempted to investigate the I_c response of $GdBa_2Cu_3O_y$ (GdBCO) CC tapes fabricated through the reactive co-evaporation by deposition and reaction (RCE-DR) and metal-organic chemical vapor deposition (MOCVD) processes under different transverse loading conditions using the anvil test method. A two-parameter Weibull analysis was conducted in order to analyze the intrinsic delamination strength of the CC tape samples.

2. EXPERIMENTAL PROCEDURES

2.1. Samples

Two kinds of CC tapes which are commercially-available were used. Table 1 shows the specifications of the CC tape samples. Both CC tapes were fabricated by the ion beam assisted deposition (IBAD) technique. The first sample was fabricated through the RCE-DR process which

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TABLE I
PROPERTIES OF CC TAPE SAMPLES.

Fabrication/ REBCO	RCE-DR	MOCVD
Superconducting film	GdBCO (~ 1 μm)	
Substrate	Stainless steel (~104 μm)	Hastelloy (~50 μm)
I_c	~ 150 A	~ 100 A
Dimension, t x w	0.137 mm x 4.08 mm	0.089 mm x 4.04 mm
Stabilizer	Electroplated Copper (~15 μm)	(~20 μm)
Manufacturer	SuNAM	Superpower

adopts a 104 μm thick stainless steel substrate material. It also has GdBCO film of 1 μm thick with I_c of approximately 150 A at 77 K and self field conditions. It was slitted from a 12 mm wide original CC tape and was surround-electroplated by 15 μm thick copper. The second CC tape sample fabricated by the MOCVD process also adopts a 1 μm thick GdBCO superconducting coating film with I_c of 100 A at similar conditions with the former sample. In this case, the CC tape sample adopted a stabilizer with 20 μm thick Cu material for additional protection and electrical stability. Also, artificial pinning centers were introduced in the CC tape sample.

2.2. Transverse tension test

For the delamination testing sample preparation, a soldering technique was used to attach the sample into the upper and lower Cu anvils. A flux ($ZnCl_2$) was applied for easy soldering and in order to equally distribute the In-Bi solder material on the effective contact area of the sample to both anvils. Two different upper anvil sizes were used; a smaller 3 mm x 8 mm (width x length) upper anvil and a wider 4.5 mm x 8 mm upper anvil. The wider one covers the whole CC tape's width representing its actual condition when impregnated in the case of superconducting coil applications. A sample holder was utilized to ensure complete alignment of the anvils and CC tape sample during the soldering process for sample mounting. Pressure was applied uniformly on the contact area by applying dead load which also enhances the adhesion of sample to the anvils. Soldering was done at ~120°C and sample mounting preparation was similarly conducted with the one reported elsewhere [5].

After soldering, the attached sample/anvil assembly (with 50 mm length CC tape sample) was mounted on a delamination testing apparatus [5, 8]. The mechanical delamination strength of each CC tape samples was determined from the load-displacement curves obtained at the cross-head speed (ram rate) of 0.1 and 0.5 mm/min.

On the other hand, electromechanical delamination properties of the CC tape samples were investigated using the setup shown in Fig. 1. In this case, the CC tape sample has a total length of 120 mm with 25 mm Cu block grip part at both ends and 70 mm gauge length for a 20 mm voltage tap separation. The setup features universal joint, wire rope, eyebolt, and pull rod to maintain a good load-axis alignment during the testing. A common voltage criterion of 1 μV/cm was adopted for I_c measurements. It took 10 min of pre-cooling time when the sample/anvils assembly was submerged in liquid nitrogen bath and held for 15 min (holding time).

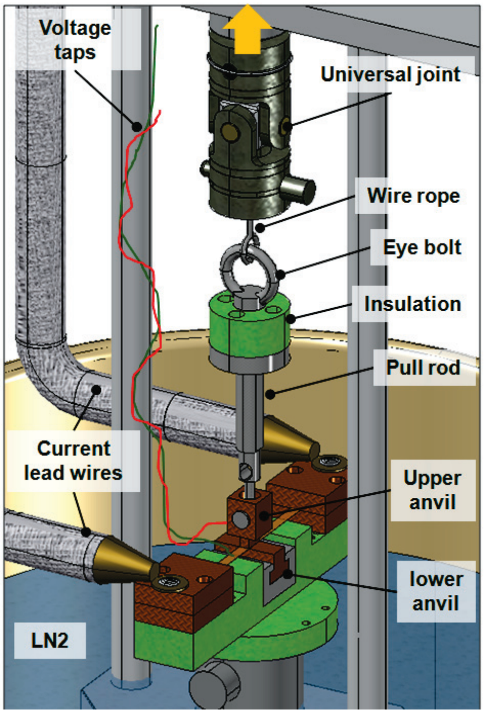


Fig.1. Set-up for electro-mechanical test under transverse tension loading.

The CC tapes were subjected to monotonic and cyclic loading under transverse tension at a cross-head speed of 0.5 mm/min. Initial I_c of the CC tapes were determined at zero stress/strain. In the case of monotonic transverse tensile loading, I_c was measured at each 60 N interval until delamination of the CC tape occurred. On the other hand, in the case of cyclic transverse tensile loading, 10 cycles were applied before I_c was measured at each 120 N loading interval [9].

3. RESULTS AND DISCUSSION

3.1. Mechanical delamination strength

Mechanical delamination strengths of both differently fabricated GdBCO CC tapes under different loading conditions were plotted in Fig. 2. It can be observed that mechanical delamination strength of the RCE-DR CC tape exhibited no significant difference between 0.1 and 0.5 mm/min cross-head speed for both samples. However, a significant increase of mechanical delamination strength value was observed in the case of the 3 mm x 8 mm upper anvil at the cross-head speed of 0.1 mm/min as compared to the gathered value using the 4.5 mm x 8 mm upper anvil. The significant low value of the mechanical delamination strength in the particular CC tapes is addressed to the defects present on its edges. These include sharp burrs formed on the substrate and micro cracks on the superconducting film as a result of the slitting process [3, 5]. On the other hand, at a cross-head speed of 0.5 mm/min, the MOCVD CC tape exhibited similar mechanical delamination strength in both anvil cases with wide scattered values.

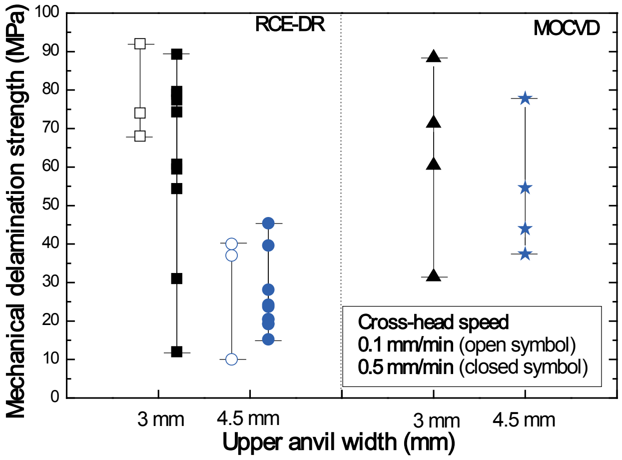


Fig. 2. Mechanical delamination strength of GdBCO CC tapes under different anvil sizes and cross-head speed conditions.

In order to clarify the large variation of mechanical delamination strength values observed in the case of RCE-DR CC tape under the 3 mm x 8 mm upper anvil, a two-parameter Weibull distribution analysis was performed. The Weibull analysis can provide reasonable probability analysis and be used to analyze fracture strength and other properties of composite materials [10-11]. This is also meaningful to statistically analyze the effect of cross-head speed used on the mechanical delamination strength of the CC tape.

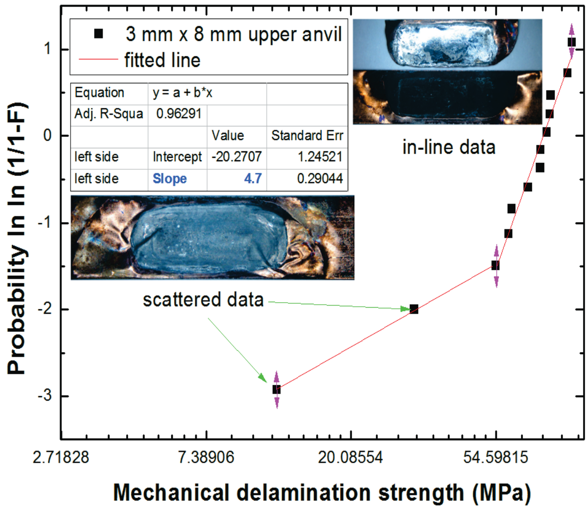
In each upper anvil size cases, the mechanical delamination strength values taken at both 0.1 and 0.5 mm/min cross-head speed denoted by x were combined together and were systematically arranged from the lowest to the highest value. The total number of tests were denoted as n (where $n = 13$ for each anvil cases) while the number of test or the ordinal number were denoted as i (*i.e.* 1,2,3,4…n). The equation for X and Y (*double logarithm of the median rank*) - values were given in Eqs. (1) and (2), respectively [12, 13]. In this case, the *F(x)*, which denotes the cumulative fraction of the mechanical delamination strength values, was accurately estimated by Bernard's median rank shown in Eq. (3) [14].

$$X = \ln(x) \tag{1}$$

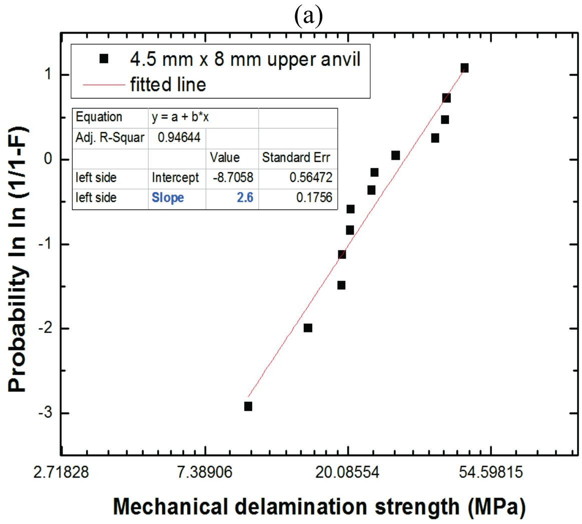
$$Y = \ln \ln\left[\frac{1}{1-F(x)}\right] \tag{2}$$

$$F(x) = \frac{i-0.3}{n+0.4} \tag{3}$$

With good soldering implied by the morphology of the CC tape sample, mechanical delamination strength values of the RCE-DR CC tape in the case of 3 mm x 8 mm upper anvil lies in an almost straight line excepting two points on the left of the graph as shown in Fig. 3 (a). The scattered points is part of the data obtained at the 0.5 mm/min cross-head speed condition and was due to poor soldering. In addition, it might also imply that misalignment, and other external factors might have occurred during the particular



(a)



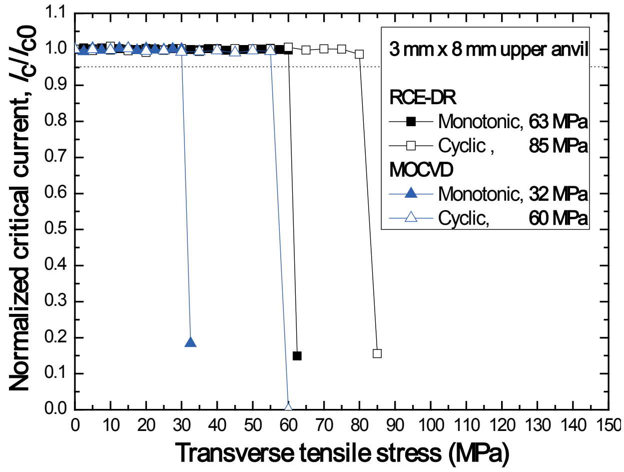
(b)

Fig. 3. Two-parameter Weibull distribution of mechanical delamination strength in RCE-DR CC tapes for (a) 3 mm x 8 mm and (b) 4.5 mm x 8 mm upper anvils.

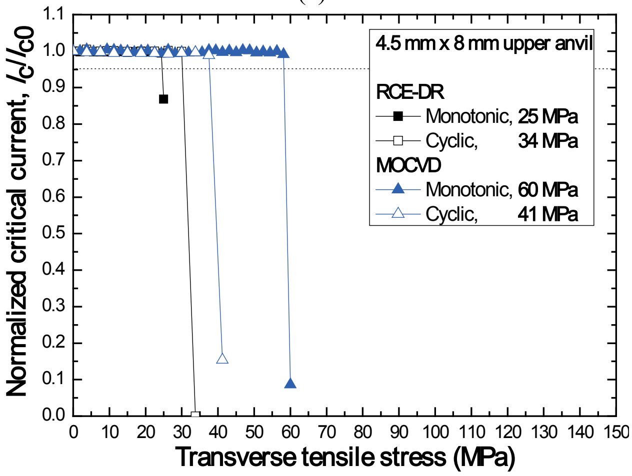
test [5]. The slope of the fitted line for the 3 mm x 8 mm upper anvil is 4.7, which is higher than the 2.6 value in the case of 4.5 mm x 8 mm. However, the mixed data included on the straight line formation in both 3 mm x 8mm and 4.5 mm x 8 mm anvil cases further suggest that different cross-head speed has no significant effect on the delamination strength of the CC tape as shown in Fig. 3 (a) and (b). This finding is very important in the succeeding transverse tension test.

3.2. I_c behavior under monotonic and cyclic transverse tensile loading

Since the cross-head speed has no significant effect on the delamination strength of the CC tapes, the 0.5 mm/min was adopted in the monotonic and cyclic test under the transverse tensile loading. This is corresponding to a practical and reasonable time needed for a single test during the cyclic testing without load over shooting. The I_c degradation behavior of the GdBCO CC tape samples under monotonic and cyclic loading for both anvil size cases were shown in Fig. 4. In the case of 3 mm x 8 mm



(a)



(b)

Fig. 4. Critical current, I_c behavior of GdBCO CC tapes under monotonic and cyclic loading conditions for (a) 3 mm x 8 mm, and (b) 4.5 mm x 8 mm upper anvils.

upper anvil as shown in Fig. 4 (a), both RCE-DR and MOCVD CC tape samples undergone transverse cyclic loading exhibited small increase in electromechanical delamination strength as compared with the case of monotonic loading. Though both values are in the range of the mechanical delamination strength for each respective CC tape sample, one should also consider the difference of delamination processes used. Previously, mechanical delamination strength of the CC tape was taken in a dynamic way (continuous) while I_c was measured with load intervals. It is also possible that work hardening of the Cu stabilizer might have occurred. In this anvil configuration, stress concentration is greatest on the Cu stabilizer among the CC tape constituent layers [15]. On the other hand, the stress distribution changes and the maximum transverse tensile stress shifted to the superconducting film in the case of wide upper anvil (4 mm x 8 mm) which covers the whole width of the CC tape [15]. As shown in Fig. 4 (b), cyclic transverse tensile loading still showed no significant effect on the electromechanical delamination strength of the sample particularly in RCE-DR CC tape. However, a small decrease on the delamination value was observed in the case of the MOCVD CC tape sample. The transverse cyclic loading scheme possibly affected the electromechanical delamination strength of the CC tape sample. It is possible since the stress is concentrated on the superconducting film made of brittle ceramic material and work hardening did not occur. This made the CC tape sample weaker under such upper anvil size condition as compared to monotonic loading. In both anvil sizes and loading cases, both the RCE-DR and MOCVD CC tape samples exhibited an abrupt I_c degradation behavior [5].

4. SUMMARY

In this study, mechanical and electromechanical delamination behaviors of GdBCO CC tapes fabricated by RCE-DR and MOCVD process under monotonic and cyclic transverse loading were investigated. Both CC tape sample exhibited similar mechanical delamination strength values in the case of 3 mm x 8 mm upper anvil. However, in the case of the 4.5 mm x 8 mm upper anvil, the CC tape samples exhibited different values. Cross-head speed adopted during loading did not show any significant effect on the mechanical delamination strength of both CC tape sample as depicted by the two-parameter Weibull analysis. Finally, CC tape samples might have been affected by transverse tensile cyclic loading in both anvil size cases and exhibited abrupt I_c degradation behavior. Further investigation, however, is needed to clarify the effect of the transverse cyclic tensile load on the CC tapes which are commercially available.

ACKNOWLEDGMENT

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REFERENCES

[1] A. L. Mbaruku and J. Schwartz, "Fatigue behavior of Y-Ba-Cu-O/hastelloy-C coated conductor at 77 K," *IEEE Trans. Appl. Supercond.*, vol. 18, pp. 1743-1752, 2008.

[2] T. Takematsu *et al.*, "Degradation of the performance of a YBCO-coated conductor double pancake coil due to epoxy impregnation," *Physica C*, vol. 470, pp. 674-677, 2010.

[3] D. C. van der Laan, J. W. Ekin, C. C. Clickner, and T. C. Stauffer, "Delamination strength of YBCO coated conductors under transverse tensile stress," *Supercond. Sci. Technol.*, vol. 20, pp. 765-770, 2007.

[4] G. Majkic, E. Galstyan, Y. Zhang and V. Selvamanickam, "Investigation of delamination mechanisms in IBAD-MOCVD REBCO coated conductors," *IEEE Trans. Appl. Supercond.*, vol. 23, pp. 6600205, 2013.

[5] H. S. Shin and A. Gorospe, "Characterization of transverse tensile stress response of critical current and delamination behavior in GdBCO coated conductor tapes by anvil test," *Supercond. Sci. Technol.*, vol. 27, pp. 025001, 2014.

[6] N. Sakai, S. Lee, N. Chikumoto, T. Izumi, and K. Tanabe, "Delamination behavior of Gd123 coated conductor fabricated by PLD," *Physica C*, vol. 471, pp. 1075-1079, 2011.

[7] Y. Yanagisawa *et al.*, "Remarkable weakness against cleavage stress for YBCO-coated conductors and its effect on the YBCO coils performance," *Physica C*, vol. 471, pp. 480-485, 2011.

[8] A. Gorospe, A. Nisay, and H. S. Shin, "Delamination behaviour in differently copper laminated REBCO coated conductor tapes under transverse loading," *Physica C*, vol. 504, pp. 49–52, 2014.

[9] H. S. Shin, A. Gorospe, Z. Bautista, and M. Dedicatoria, "Evaluation of electromechanical properties in GdBCO coated conductor tapes under cyclic loading and bending," *Supercond. Sci. Technol.,* submitted for publication.

[10] E. Barbero, J. Fernandez-Saez, and C. Navarro, "Statistical analysis of the mechanical properties of composite materials," *Composites: Part B: Engineering*, vol. 31, pp. 375-381, 2000.

[11] M. H. Dirikolua, A. Aktas, and B. Birgoren, "Statistical analysis of fracture strength of composite materials uwing Weibull distribution," *Turkish J. Eng. Env. Sci*., vol. 26, pp. 45-48, 2000.

[12] R. V. Curtis and A. S. Juszczyk, "Analysis of strength data using two-and-three-parameter Weibull models," *J. Mater. Sci.*, vol. 33, pp. 1151-1157, 1998.

[13] A. J. Hallinan Jr., "A review of the Weibull distribution," *J. Qual. Technol.*, vol. 25, pp. 85-93, 1993.

[14] S. Ochiai *et al*., "Applicability of Weibull distribution of distributed normalized critical current of bent-damaged Bi2223 composite tape," *Mater. Trans*., vol. 51, pp. 1663-1670, 2010.

[15] J. R. Dizon, A. Gorospe, and H. S. Shin, "Numerical analysis of stress distribution in Cu-stabilized GdBCO CC tapes during anvil tests for the evaluation of transverse delamination strength," *Supercond. Sci. Technol*., vol. 27, pp. 055023, 2014.