

# Preliminary investigation of $I_c$ homogeneity along the longitudinal direction of YBCO coated conductor tape under tensile loading

J. R. C. Dizon<sup>a, c</sup>, S. S. Oh<sup>b</sup>, K. D. Sim<sup>b</sup>, and H. S. Shin<sup>\*, a</sup>

<sup>a</sup> Department of Mechanical Design Engineering, Andong National University, Andong, Kyungbuk, 760-749 Korea

<sup>b</sup> Korea Electrotechnology Research Institute, Changwon, 641-120 Korea

<sup>c</sup> College of Engineering and Architecture, Bataan Peninsula State University, Balanga, Bataan, 2100 Philippines

(Received 22 May 2013; revised or reviewed 24 June 2013; accepted 25 June 2013)

## Abstract

In this study, the homogeneity of critical current,  $I_c$ , along the lengthwise direction in the coated conductor (CC) tape under uniaxial tension was investigated using a multiple voltage tap configuration. Initially, a gradual and homogeneous  $I_c$  degradation occurred in all subsections of the tape up to a certain strain value. This was followed by an abrupt  $I_c$  degradation in some subsections, which caused scattering in  $I_c$  values along the length with increasing tension strain. The  $I_c$  degradation behaviour was also explained through  $n$ -value as well as microstructure analyses. Subsections showed  $I_c$  scattering corresponding to damaged areas of the CC tape revealed that transverse cracks were distributed throughout the gauge length. This homogeneous  $I_c$  degradation behaviour under tension is similar with the case under torsion strain but different with the case under hard bending which were previously reported. This behaviour is also different with the case using Bi-2223 HTS tapes under tension strain.

*Keywords:* Coated Conductor, REBCO, Critical Current, Homogeneity, Mechanical Properties, Tension

## 1. INTRODUCTION

The recent development of long-length 2G HTS REBCO coated conductor (CC) tapes with high critical current density,  $J_c$ , even under magnetic field has widened their application to various electric devices such as power cables, motors and magnets [1-7]. For design and fabrication of such devices, stress and strain tolerance of the critical current,  $I_c$ , in the CC tapes has to be understood [8-10]. Therefore, the evaluation of the electromechanical properties of CC tapes is important in the design of superconducting devices.

Several groups have already investigated the strain dependence of  $I_c$  in YBCO CC tapes under tensile, compressive, bending and torsion strain modes respectively [9-18]. It was observed that the  $I_c$  behaves reversibly up to an irreversible strain limit,  $\epsilon_{irr}$  [11, 15]. Under bending, the  $I_c$  was still reversible even after bending to a diameter of  $\sim 12$  mm, corresponding to  $\sim 0.4\%$  bending strain at the YBCO superconducting coating film [16]. Also, the lamination of stabilizers to enhance the mechanical properties and stability of these CC tapes resulted in the increase in  $\epsilon_{irr}$  [14].

Previously, the  $I_c$  degradation behaviour in CC tapes under hard bending and torsional strains have been reported using multiple voltage tap configuration [16, 17].

Under hard bending, initially, all subsections showed no

degradation and little variation of  $I_c$ , which represented that no damage was induced in the YBCO coating film. When the bending strain exceeded a critical strain limit ( $\sim 0.6\%$ ), the  $I_c$  abruptly dropped in one subsection which caused the overall  $I_c$  to also irreversibly decrease when the bending strain applied was released [16]. On the other hand, a characteristic behaviour under torsion strain was described by a gradual  $I_c$  degradation occurred gradually with increasing torsion strain. A homogeneous torsional deformation was induced in the YBCO coating film demonstrated by the consistent  $I_c$  degradation behavior in all subsections and along the longitudinal direction of the tape. Even with this degradation, the reversible behavior of the  $I_c$  under torsional loading was found up to an irreversible limit ( $\sim 1.6\%$  torsion strain) [17].

Under an applied uniaxial tension stress/strain, it is expected that the homogeneity of the  $I_c$  degradation behaviour in CC tapes along the lengthwise direction of the tape could follow either the case under hard bending or torsion strains. The  $I_c$  degradation behaviour in CC tapes under uniaxial tension strain, which could depend on several factors such as the intrinsic fragile characteristic of the YBCO coating film which influences the local critical current in each subsection.

In the case of multifilamentary Bi-2223 tapes, the damage is localized in the weakest subsection, causing reduction in  $I_c$  and  $n$ -values in the measured subsection, while all other subsections retained their original unstrained values. Interestingly, it was observed that the value of the overall  $I_c$  was similar with the damaged subsection. At higher strains,

---

\* Corresponding author: [hsshin@andong.ac.kr](mailto:hsshin@andong.ac.kr)

and after almost all filaments have been damaged in the weakest subsection, damage then propagated to neighboring filaments causing  $I_c$  and n-value reduction [19, 20].

In this paper, the homogeneity of the  $I_c$  along the tape length under tensile loading was investigated, particularly comparing the local  $I_c$  and overall  $I_c$  degradation behaviours as a function of applied tension strain. Additionally, the  $I_c$  degradation behaviours are discussed based on n-value and microstructural analysis. Results have been compared with the case of CC tapes under torsion and hard bending. Additionally, comparisons with the case using multifilamentary Bi-2223 tapes have been made.

## 2. EXPERIMENTAL PROCEDURES

A commercially available YBCO CC tape manufactured by the IBAD/MOCVD process was supplied for the test. Fig. 1 shows the cross-sectional view and the properties are tabulated in Table 1. The sample was electroplated with copper for mechanical and electrical stability.

For the tensile test of the CC tape at 77 K and self-field, a universal testing machine was used. The total length of the sample was 120 mm, and the gauge length subjected to deformation was 80 mm. The sample was fixed at both ends by the upper and lower gripping holders shown in Fig. 2. The upper gripping holder was connected to the load cell through a universal joint and the lower one was set on the

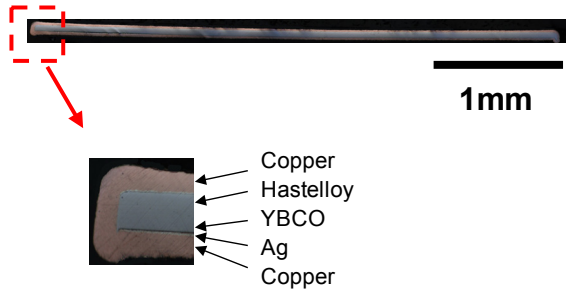


Fig. 1. Cross-sectional view of YBCO CC tape used for the study.

TABLE I.  
SPECIFICATIONS OF YBCO CC TAPE SAMPLE.

	IBAD/MOCVD
Structure	Ag/YBCO/LMO/Homo-epi MgO/ IBADMgO/Hastelloy
YBCO film thickness	~ 1 $\mu$ m
$I_c$ , A	95
Dimension, T x W	0.09 x 4.04 mm
Substrate	Hastelloy
Substrate thickness	50 $\mu$ m
Stabilizer	Copper
Stabilizing technique	Copper electroplating
Stabilizer thickness	15 $\mu$ m

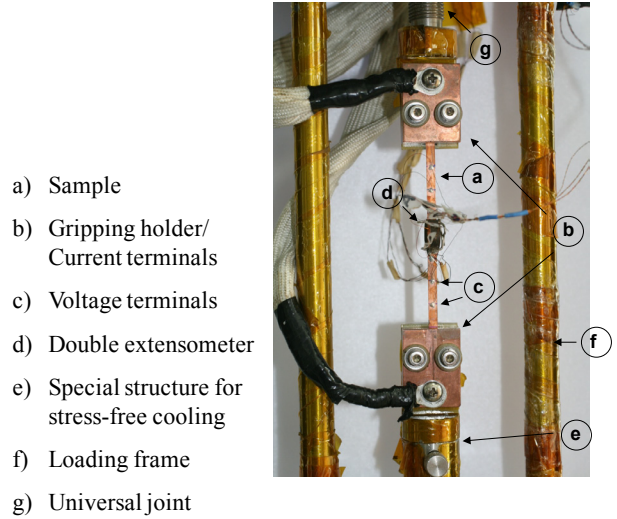


Fig. 2. Set-up for  $I_c$  homogeneity test under tensile loading.

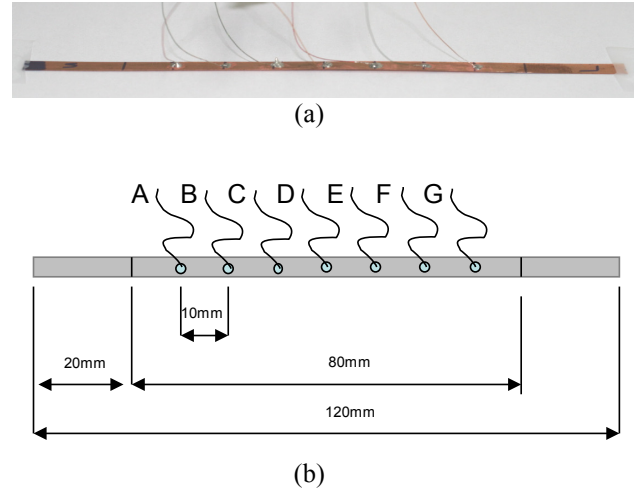


Fig. 3. a) YBCO CC tape sample with seven voltage taps; b) Schematic representation of the sample with multiple voltage taps.

loading frame fixed to the testing machine. A connecting structure which gives a clearance of 2 mm was inserted on the lower part to release possible stresses expected during cooling. For testing at 77 K, the test fixture including the sample was slowly cooled down to 77 K taking about 10 min. The strain applied to the CC samples was measured using the Nyilas-type double extensometers, with a gauge length of 12.5 mm, which were directly attached to the sample. From the obtained stress-strain curves, the mechanical properties of CC tape such as the Young's modulus and yield stress could be determined.

On the other hand, for the  $I_c$  measurement during tensile tests, GFRP sheets were inserted between the sample and the gripping holders (which also serve as current terminals) for electrical insulation. To check the homogeneity of deformation along the tape's longitudinal direction, multiple voltage taps were soldered to the CC tape sample

as shown in Fig. 3 (a). Seven voltage taps were used and the distance between each tap, called as subsection, was 10 mm. Fig. 3 (b) shows a schematic representation of the multiple voltage tap configuration. The  $I_c$  was measured at each subsection and also at the overall section of 60 mm.

The I-V curves for each subsection were measured by the four-probe method at 77 K under self-field. The  $I_c$  was defined by a  $1 \mu\text{V}/\text{cm}$  criterion. During tensile testing, the  $I_c$  was measured at specified strain levels. The  $I_c$  was normalized by the  $I_{c0}$  value obtained at the as-cooled state. From the I-V curve obtained, the n-value at the transition region was also derived by a linear fitting in the voltage range of  $0.2 \sim 5.0 \mu\text{V}/\text{cm}$  [21].

To observe the crack morphology which was induced on the YBCO coating film along the longitudinal direction of the CC tape, the copper and silver layers were removed through etching. To remove the copper layer, the sample was immersed in the solution of 30% vol.  $\text{HNO}_3 + 70\%$  vol.  $\text{H}_2\text{O}$ . To etch the silver layer, the sample was immersed in the solution of 25% vol.  $\text{H}_2\text{O}_2 + 25\%$  vol.  $\text{NH}_4\text{OH} + 50\%$  vol.  $\text{H}_2\text{O}$ . Then, the sample was rinsed with water after each etching procedure. The samples were then observed under SEM (Scanning Electron Microscopy).

Fig. 4 shows the tensile stress-strain curve of YBCO CC tape sample obtained from the tensile test at 77 K. The Young's modulus,  $E$ , and the 0.2% offset yield stress,  $\sigma_y$ , could be determined were 114 GPa and 657 MPa, respectively.

### 3. RESULTS AND DISCUSSION

Fig. 4 also shows the  $I_c/I_{c0}-\varepsilon_t$  relationships at each subsection of the YBCO CC tape sample adopting multiple voltage taps. The small solid symbols represent each of the subsection (voltage tap separation: 10 mm), while the large square represents the overall  $I_c$  (60 mm). Up to  $\varepsilon_t = 0.45\%$ , a monotonic but small degradation in  $I_c$  occurred. The  $I_c$  degradations of all subsections were similar with the 60-mm section (AG). This value and behaviour is similar with the simple  $I_c/I_{c0}-\varepsilon_t$  test conducted with shorter samples

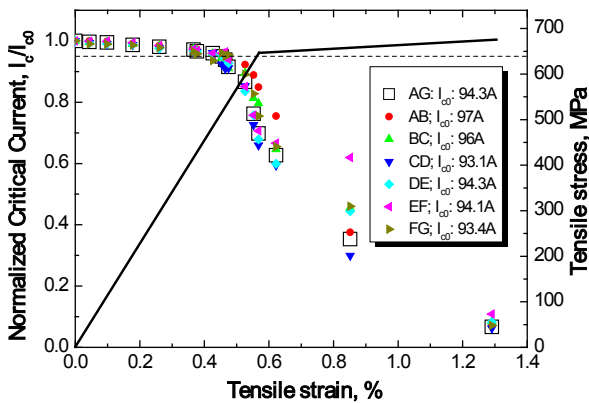


Fig. 4. Tensile stress-strain curve (solid line) and  $I_c/I_{c0}-\varepsilon_t$  curves at each subsection (10 mm) and overall length (60 mm) measured in IBAD/MOCVD YBCO CC tape sample using multiple voltage taps.

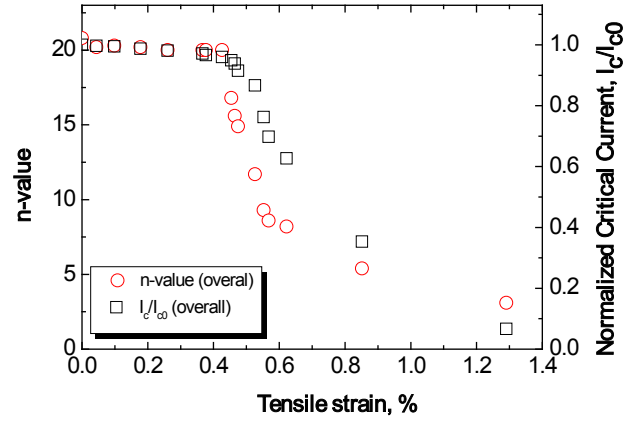


Fig. 5. n-value versus tensile strain relationship in IBAD/MOCVD YBCO CC tape sample.

[15]. From  $\varepsilon_t = 0.52\%$ , some scattering of the  $I_c$  values in each subsection could be observed. At  $\varepsilon_t = 0.55\%$ , a rapid drop in  $I_c$  could be observed. This strain value is close to the proportional strain limit when the whole CC tape yielded which is  $\varepsilon_t = 0.56\%$ .

With increase of strain, the scattering of  $I_c$  in subsections increased. Significant scattering of  $I_c$  occurred at  $\varepsilon_t = 0.85\%$ . But eventually, at  $\varepsilon_t = 1.3\%$ ,  $I_c$  values in all subsections decreased to below 10% of  $I_{c0}$ . This behaviour is similar to the case under torsion strain [17] but different with the case under hard bending strain [16]. Further, this is different with the case in Bi-2223 tapes wherein the damage of the Bi-2223 filaments arose first locally in the weakest subsection, resulting in the reduction of the  $I_c$  only in that subsection, even though the other subsections almost retained their original  $I_c$  values [19].

The n-value, which refers to the sharpness of the transition from super- to normal conducting state has been used to explain the transport property in the CC tape sample under tensile strain. The variation in n-values means some change in the transport property had occurred due to the introduction of damage like cracks. In Fig. 5, the n-value- $\varepsilon_t$  relation showed a similar behaviour with the  $I_c/I_{c0}-\varepsilon_t$  under tensile strain for the overall length, which could represent that no damage within the YBCO coating film occurred up to 0.52%. Additionally, it was also observed that the  $I_c$  and n-values for the overall length were lower than the average values of the subsections, and interestingly they were close to the lowest  $I_c$  and n-value among the subsections. This is similar to the Bi-2223 case, wherein the overall  $I_c$  and n-values were almost determined by the values at the weakest subsection [19].

For YBCO CC tapes without stabilizers, it was reported that annealed Hastelloy showed discontinuous yielding [13]. However, the  $I_c$  degradation shown for the stabilized YBCO CC tape tested in this study, represented that the surround copper stabilizer may have contributed in the homogeneous  $I_c$  degradation even with such behaviour of the Hastelloy substrate. Or the Hastelloy may have yielded discontinuously and the cracks were concentrated locally

near the grips before spreading into the whole tape as can be observed from the similar  $I_c$  values of all the subsections in the figure.

Fig. 6 shows the microstructure of an unstrained sample as the reference. The reference sample was not subjected to any test, and therefore no cracks can be observed on the YBCO coating film. Fig. 7 shows the microstructure of an YBCO coating film at subsection FG where a significant  $I_c$  degradation occurred which has been subjected to straining by uniaxial tension test. The cracks initiated and propagated normal to the direction of the applied strain. Some cracks that are longer in length are observed. Cracks are distributed almost uniformly throughout the gage length. The initiation of cracks caused the  $I_c$  to drop rapidly. Relatively larger cracks than those located at the center of the tape width could be seen near the edge of the tape which means that cracks have originated from the edges and propagated towards the center of the width as the applied strain increased. Although it is expected that the orientation of cracks on the YBCO layer would follow that of the Hastelloy substrate (usually  $\sim 45$  degrees from the loading axis for ductile materials), but may have changed due to the buffer layers.

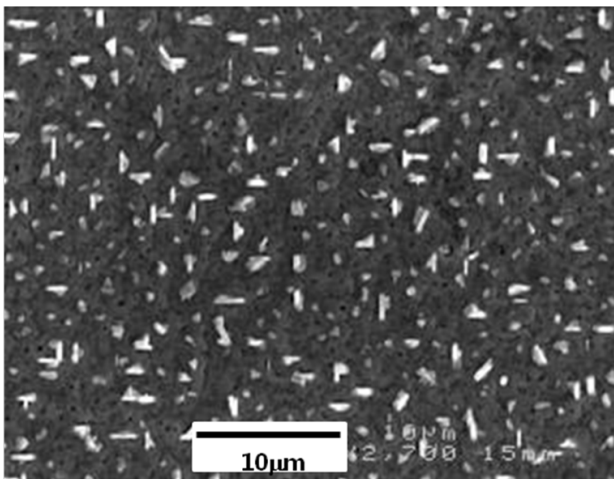


Fig. 6. Longitudinal section of the YBCO film as the reference unstrained IBAD/MOCVD YBCO CC tape sample.

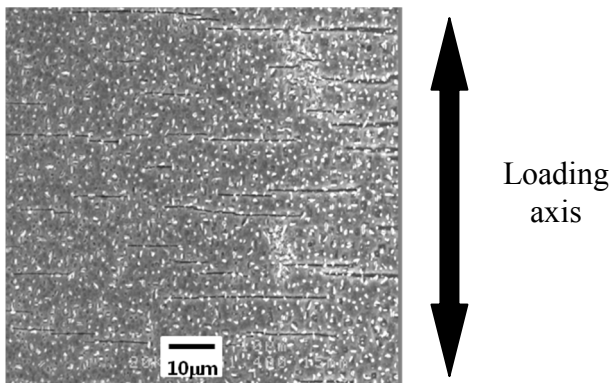


Fig. 7. Crack morphologies formed on subsection F-G after  $I_c$ - $\epsilon_t$  tests of the IBAD/MOCVD YBCO CC tape sample.

Crack initiation at multiple sites in the subsections caused a little scattered and gradual degradation of  $I_c$  along the length in YBCO CC tapes at the initial stage of straining. While during abrupt  $I_c$  degradation, variation in crack size along the width induced the large scattering of  $I_c$  values. This is unlike the case in multifilamentary Bi-2223 tapes wherein the crack initiated and propagated locally in just one site, and affecting neighboring elements after almost all filaments in the weakest element have been damaged [19, 22]. Various stabilizers used for CC tape reinforcement would contribute to higher strain/stress tolerances of the  $I_c$  than the yield point in CC tapes, however the maximum stress/strain that should be applied to the CC tape should be below the yield strength [18]. If the critical tolerance stress/strains of  $I_c$  in CC tapes depend on the mechanical properties such as the yield stress/strain or proportional stress/strain limit, then characterization would be easy. But there are cases when the irreversible strain limit could be located prior to yielding of the substrate material, especially in the case of Ag-coated CC tapes [12-13, 18]. What makes the characterization complicated is due to the multi-layered structure of the CC tapes. Depending on the substrate and reinforcement materials adopted, the stress/strain tolerance of the  $I_c$  in CC tapes will be different [10-18]. The thickness of each layer contributes to the large variation on electromechanical properties. The role of reinforcement of the copper stabilizer and external laminates on the deformation and damage mechanism of the whole CC tape should be further considered.

With this information, the introduction of employing a statistical analysis would be necessary, similar to the cases reported for BSCCO tapes [19, 23]. For statistical analysis of the  $I_c$  degradation behaviour, statistical analysis of  $I_c$  characteristics under various strain values should be considered in the electro-mechanical aspect, namely, the irreversible strain limit (or strain corresponding to the yield stress), the strain corresponding to the proportional limit, and the strain value where scattering of  $I_c$  initially occurred.

#### 4. CONCLUSION

The homogeneity in  $I_c$  behaviour along the longitudinal direction of the CC tape were investigated under uniaxial tension using multiple voltage tap configuration. A gradual and homogeneous  $I_c$  degradation occurred in the YBCO CC tape up to a certain strain value, and followed by an abrupt and scattered  $I_c$  degradation at almost all subsections, which is a characteristic feature under uniaxial tension. The  $I_c$  degradation behaviours could also be explained using both the  $n$ -value analysis and microstructural analysis. Longitudinal subsections of CC tapes after the tests revealed that transverse cracks were distributed over the entire gauge length. This homogeneous  $I_c$  degradation behaviour under tension is similar with the case under torsion strain but different with the case under hard bending. This behaviour is also different with the case using Bi-2223 HTS tapes under tension strain.

### ACKNOWLEDGMENT

This work was supported by a grant from National Research Foundation of Korea (NRF-2011-0015369) funded by the Ministry of Education, Science and Technology, Republic of Korea. John Ryan C. Dizon was supported by the National Research Foundation of Korea (NRF) under the auspices of the 2012 NRF Postdoctoral Fellowship Program for Foreign Researchers.

### REFERENCES

- [1] K. Kakimoto, M. Igarashi, S. Hanyu, Y. Sutoh, T. Takemoto, T. Hayashida, Y. Hanada, N. Nakamura, R. Kikutake, H. Kutami, Y. Iijima, and T. Saitoh, "Long RE123 coated conductors with high critical current over 500 A/cm by IBAD/PLD technique," *Physica C*, vol. 471, pp. 929-931, 2011.
- [2] Y. Shiohara, M. Yoshizumi, Y. Takagi, and T. Izumi, "Future prospects of high  $T_c$  superconductors-coated conductors and their applications," *Physica C*, vol. 484, pp. 1-5, 2013.
- [3] M. Oomen, W. Herkert, D. Bayer, P. Kummeth, W. Nick, and T. Arndt, "Manufacturing and test of 2G-HTS coils for rotating machines: Challenges, conductor requirements, realization," *Physica C*, vol. 482, pp. 111-118, 2012.
- [4] J. K. Lee, S. H. Park, Y. Kim, S. Lee, H. G. Joo, W. S. Kim, K. Choi, and S. Y. Hahn, "Test results of a 5 kW fully superconducting homopolar motor," *Prog. Supercond. Cryo.*, vol. 15, no. 1, pp. 35-39, 2013.
- [5] T. Nakamura, "Progress of rotating machine development in Japan", *Superconductivity and Cryogenics*, vol. 13, no. 2, pp. 1-4, 2011.
- [6] M. C. Ahn and T. K. Ko, "Fault Current Limitation by a Superconducting Coil with a Reversely Magnetized Core for a Fault Current Controller," *Supercond. Cryo.*, vol. 14, no. 4, pp. 36-40, 2012.
- [7] S. J. Jung, G. H. Kim, K. M. Kim, M. W. Park and I. K. Yu, "Stability analysis of an insulationless HTS pancake coil under the magnitude of external magnetic field," *Supercond. Cryo.*, vol. 14, no. 4, pp. 41-45, 2012.
- [8] H. G. Lee, J. Bascunan and Y. Iwasa, "A high-temperature superconducting double-pancake insert for an NMR magnet," *IEEE Trans. Appl. Supercond.*, vol. 13, pp. 1546-1549, 2003.
- [9] Y. Iwasa, "Case studies in superconducting magnets," 2nd ed., Springer, 2009, pp. 1-218.
- [10] D. C. van der Laan, and J. W. Ekin, "Large intrinsic effect of axial strain on the critical current of high temperature superconductors for electric power applications," *Appl. Phys. Lett.*, vol. 90, pp. 052506-1 ~ 052506-3, 2007.
- [11] N. Cheggour, J. W. Ekin, C. L. H. Thieme, Y-Y Xie, V. Selvamanickam, and R. Feenstra, "Reversible axial-strain effect in Y-Ba-Cu-O coated conductors," *Supercond. Sci. Tech.*, vol. 18, pp. S319-S324, 2005.
- [12] M. Sugano, K. Osamura, W. Prusseit, R. Semerad, K. Itoh, and T. Kiyoshi, "Intrinsic strain effect on critical current and its reversibility for YBCO coated conductors with different buffer layers," *Supercond. Sci. Tech.*, vol. 18, pp. 369-372, 2005.
- [13] M. Sugano, K. Osamura, W. Prusseit, R. Semerad, K. Itoh and T. Kiyoshi, "Tensile fracture behaviour of RE-123 coated conductors induced by discontinuous yielding in Hastelloy C-276 substrate," *Supercond. Sci. Tech.*, vol. 18, pp. S344-S350, 2005.
- [14] H. S. Shin, K. H. Kim, J. R. C. Dizon, T. H. Kim, R. K. Ko, and S. S. Oh, "The strain effect on critical current in YBCO coated conductors with different stabilizing layers," *Supercond. Sci. Tech.*, vol. 18, pp. S364-S368, 2005.
- [15] H.S. Shin, J. R. C. Dizon, R. K. Ko, T. H. Kim, D. W. Ha, and S. S. Oh, "Reversible tensile strain dependence of the critical current in YBCO coated conductor tapes," *Physica C*, vol. 463-465, pp. 736-741, 2007.
- [16] H. S. Shin, M. J. Dedicatoria, J. R. C. Dizon, H.S. Ha, and S. S. Oh, "Bending strain characteristics of critical current in REBCO CC tapes in different modes," *Physica C*, vol. 469, pp. 1467-1471, 2009.
- [17] H. S. Shin, J. R. C. Dizon, T. H. Kim, D. W. Ha, and S. S. Oh, "Critical Current Degradation Behavior in YBCO Coated Conductors under Torsional Strain," *IEEE Trans. Appl. Supercond.*, vol. 17, pp. 3274-3277, 2007.
- [18] M. Dedicatoria and H. S. Shin, "Analysis on Stress/Strain Tolerances of  $I_c$  in Externally Laminated GdBCO CC Tapes," *submitted to IEEE Trans. Appl. Supercond.*, vol. 23, pp. 8400404, 2013.
- [19] S. Ochiai, T. Nagai, H. Okuda, S. S. Oh, M. Hojo, M. Tanaka, M. Sugano, K. Osamura, "Tensile damage and its influence on the critical current of Bi2223/Ag superconducting composite tape," *Supercond. Sci. Tech.*, vol. 16, pp. 988-994, 2003.
- [20] Y. Mukai, J.K. Shin, S. Ochiai, H. Okuda, M. Sugano, and K. Osamura, "The influence of tensile strain to critical current of Bi2223 composite tape", *Physica C*, vol. 468, pp. 1801-1804, 2008.
- [21] A. K. Ghosh, "V-I transition and n-value of multifilamentary LTS and HTS wires and cables," *Physica C*, vol. 401, pp. 15-21, 2004.
- [22] H. S. Shin and K. Katagiri, "Influence of external reinforcement on stress/strain characteristics of critical current, Ag/BSCCO superconducting tapes," *Proc. Int. Workshop on Mechano-electromagnetic property of composite superconductors*, pp. 31-34, 2001.
- [23] A. Mbaruku and J. Schwartz, "Statistical analysis of the electromechanical behavior of AgMg sheathed Bi2Sr2CaCu2O8+x superconducting tapes using Weibull distributions," *J. Appl. Physics*, vol. 101, p. 073913, 2007.