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Effect of Bending Test Procedure on the Degradation Behavior of Critical Current in ReBCO Coated Conductor Tapes

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Abstract-- **The I_c degradation behavior of critical current in differently processed YBCO and SmBCO CC tapes with IBAD template has been investigated. It has been known that the residual strain in the CC tape will influence the shape of the I_c-strain window; I_c may show a peak value if there exist a residual strain induced in the tape during manufacturing. The difference of residual strain may be resulted from the adopted different deposition techniques. In this study, bending test of CC tapes has been done using the Goldacker bending test rig which can produce both compressive and tensile bending strain continuously or alternately to the sample. For SmBCO CC tapes, in continuous compressive bending test, I_c showed a minimal increase and did not degrade up to the largest strain that can be applied using the bending rig equivalent to 1.15% based on the sample thickness. However, in the case of alternate application of compressive and tensile bending strain, I_c showed a larger degradation and a lower reversible limit when compared with the case of continuous application of the bending strain. When I_c started to degrade significantly at the tension side, the reversibility ended, also at the compression side which is resulted from the permanent deformation like delamination or cracks that was induced due to tensile bending strain.**

1. INTRODUCTION

The continuous efforts on the development of HTS fabrication to achieve superior transport and electromechanical property have opened to the many possible practical applications for superconductors. At this point in time, many electric device prototypes such as cable, SFCL, motors and magnets are now being tested and developed [1, 2]. However, in most applications the HTS tapes are required to be manufactured as a shape of coiling. Therefore, bending strain characterization is one of the foremost procedures to be done in order to ensure the current carrying capacity of HTS tapes as well as the performance of the device. Also, aside from being wound into coil, HTS tapes will experience and must withstand mechanical stresses during handling, fabrication into cables or device operation without significant decrease of its transport property [3].

The CAST has been developing a new fabrication process of CC tapes of IBAD/EDDC-processed SmBCO CC tapes through the DAPAS program in Korea which almost reached to commercialization of SmBCO CC tapes.

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C. Park et al have first investigated bend strain tolerance of critical currents for YBCO films deposited on rolled-textured (001)Ni [4]. Many researches on bending strain characterization of HTS tapes, aside from the influences of bending strain on critical currents [5, 6], they also found out that I_c also showed reversibility which was also observed in uniaxial tensile loading [7, 8]. In our previous study, we investigated the degradation behavior of I_c in Bi-2223 under tension-bending mode and the bending strain effects on the critical current in Cu-stabilized IBAD/EDDC processed SmBCO coated conductor tapes. We found out that I_c showed reversibility and when repeated bending strains were applied, at first it degraded with the application of strain but no more further degradation occurred when it was subjected to cyclic bending up to 100 cycles [8, 9].

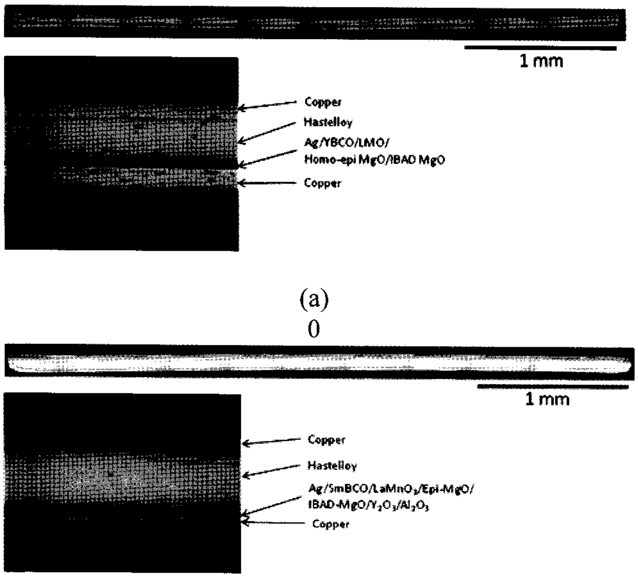
In this present study, the effect of bending strain on the degradation behavior of critical current depending on the application procedures named as continuous and fully reversed bending tests was investigated.

2. EXPERIMENTAL PROCEDURE

Commercially available YBCO CC tape (SCS4050) and SmBCO tape manufactured by KERI have been used as samples. Both of the tapes have IBAD template with substrate thickness of 50 and 80 μm, respectively and Cu stabilizer with thickness of 20 μm. Fig. 1 shows the cross sectional views of the samples and their properties are tabulated in Table 1. The bending strain dependence of I_c has been investigated using the Goldacker bending test rig as in [8].

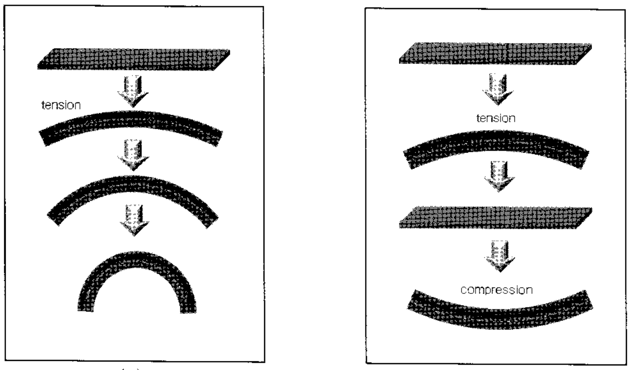
TABLE I
SPECIFICATIONS OF ReBCO CC SAMPLES.

	IBAD/EDDC/SmBCO	IBAD/MOCVD/YBCO
Structure	Ag/SmBCO/$LaMnO_3$/Epi-MgO/ IBAD-MgO/Y_2O_3/Al_2O_3/ Hastelloy	Ag/YBCO/LMO/Homo-epi MgO/IBAD MgO/Hastelloy
ReBCO film thickness	~ 2μm	~ 1μm
I_c	~ 100 A	87 A (ave)
Dimension, t x w	0.127 mm x 4.0 mm	0.114 mm x 4.19 mm
Substrate	Hastelloy	Hastelloy
Substrate thickness	80 μm	50 μm
Stabilizer	Copper	Copper
Stabilizing technique	Electroplating process	Electroplating process
Stabilizer thickness	20 μm	20 μm
Manufacturer	KERI	Superpower



(b)

Fig. 1. Cross sectional views of the samples (a) SmBCO and (b) YBCO CC tapes.



(a) (b)

Fig. 2. Illustration of bending test procedures (a) continuous bending; tension (b) fully reversed bending (alternately applied).

Fig. 2 shows the illustration of bending procedures adopted in this study. (a) shows a continuous bending procedure, one end of the sample was fixed to a Cu current terminal by mechanical contact at straight position at RT, the other side was fixed at 77 K to avoid the thermal stress induced during cool-down, then I_{c0} measurement was done at 77K. The bending strain was increased with a certain strain interval and I_c measurement was carried out at each strain level. In this case, the ReBCO film was placed in the position wherein it would be subjected under tensile/compressive strain against bending. When I_c started to degrade from I_{c0}, the bending strain applied was released by recovering to straight position at 77K, then I_c was measured to check its reversibility. Continue to increase the strain after each reversal up to the maximum bending strain that can be applied using the bending rig. (b) is different from the first; fully reversed procedure is alternately applying both tensile and compressive bending strain with increasing strain up to its maximum value. For both tapes, ε_b and $\varepsilon_{b,ReBCO}$ bending strains at the outer stabilizer surface of the tape and at the ReBCO coating film were defined and calculated as following respectively [10, 11];

$$\varepsilon_b = \frac{t}{2r+t} \times 100\,\% \tag{1}$$

$$\varepsilon_{b\,ReBCO} = \frac{t_s}{2r+t} \times 100\,\% \tag{2}$$

where t and t_s are the thickness of sample tape and substrate, respectively, and r is the corresponding radius of a circular shape (part) formed by the sample. I_c measurement was done at 77 K and self field using a four probe method with voltage tap separation of 10 mm and at an electric field criterion of 1 μV/cm. Other test conditions are described in [8].

3. RESULTS AND DISCUSSION

Fig. 3 shows the I_c dependence of bending strain under continuous tensile and compressive bending for SmBCO CC tapes. In the case of continuous tensile bending, no peak I_c was observed and I_c monotonically decreased with increasing bending strain but showed reversibility up to 0.6% when the strain is relieved. When induced tensile strain is calculated at the SmBCO coating film, it is 0.34% which is comparable to the behavior under the uniaxial strain case. I_c degradation at the applicable minimum bending diameter (~11.9 mm) was ~20%. On the other hand, in the case of compressive bending I_c continuously increased with increasing bending strain and showed reversibility up to the largest strain (1.15%) applicable to the tape by using Goldacker type bending test rig.

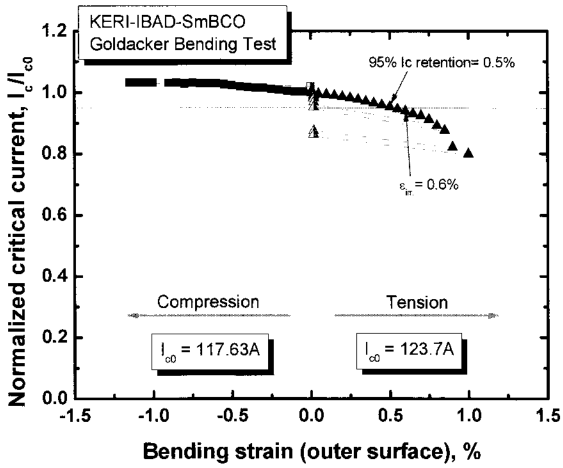


Fig. 3. Strain dependence of I_c under continuous compressive and tensile bending in SmBCO CC tapes.

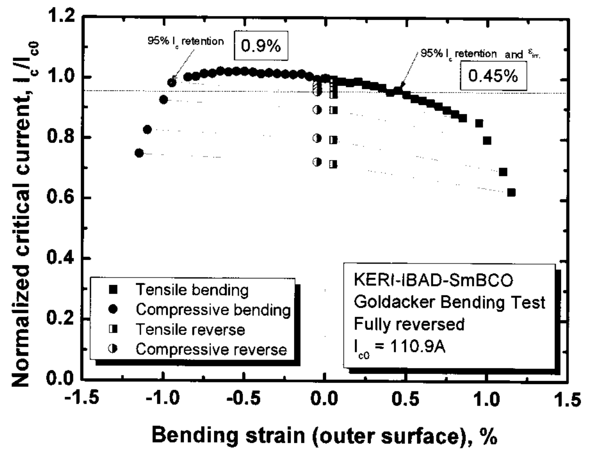


Fig. 4. Strain dependence of I_c under fully reversed bending procedure in SmBCO CC tapes.

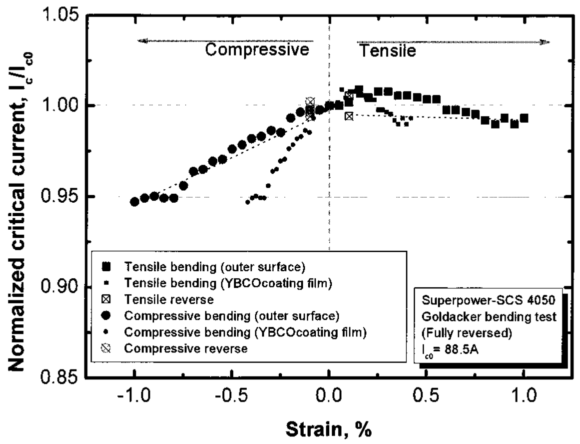


Fig. 6. Strain dependence of I_c under fully reversed bending procedure in YBCO CC tapes.

In the fully reversed bending, I_c behavior in tension side is almost the same with the continuous tensile bending while I_c behavior in compression side did not anymore continuously increase up to the minimum applicable strain rather it showed a peak and decreased thereafter. I_c decreased in compression side as the I_c in tension side started to degrade significantly as shown in Fig. 4. This might be caused by micro cracks or delamination of different layers and therefore micrographic observation should be done to clarify this behavior. At 0.45% strain in tension and compression side, reversibility stopped and I_c cannot be recovered anymore even when the strain is released. Although I_c can no longer be recovered, I_c

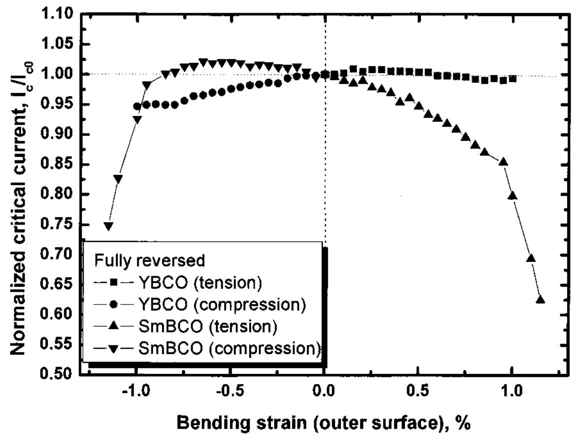


Fig. 7. Critical current behavior of YBCO and SmBCO CC tapes under bending strain.

TABLE II
MATERIAL PROPERTIES OF HASTELLOY AND COATING FILMS.

Material Property	Hastelloy	YBCO	SmBCO
Elastic Modulus (GPa)	170-220	157	182
Thermal Expansion coefficient (10^{-6} K^{-1})	12.5	13.4	14
Poisson Ratio	-	0.3	0.14

From ref. [14] and [15]

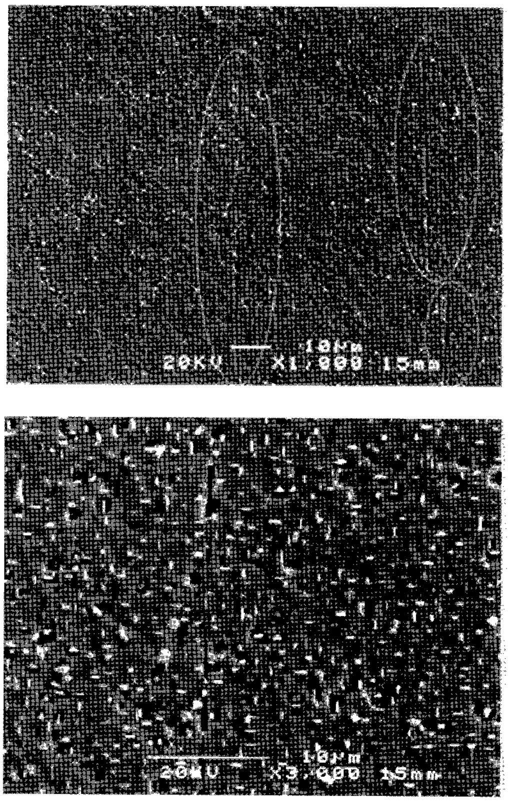


Fig. 5. SEM micrographs of SmBCO film showing transverse micro cracks.

continuously increased with further increase of strain in compression side and then decreased starting from -0.7% up to the largest strain (-1.15%). We can observe here that the behavior of I_c in tension and compression side after each reversal was different. In tension side I_c increases after each reversal and otherwise in compression side. The reason for this is that, as the crack has been supposedly initiated it is further opened upon application of tensile strain and causes a decrease in I_c due to the broken current path and closes upon the application of compressive strain resulting to a higher I_c as the crack closes and current path is reconnected. Furthermore, we can say that damage has already been induced to the tape since I_c can no longer be recovered after each reversal and continued to decrease with increasing strain. Fig. 5 shows SEM micrographs of SmBCO film with transverse cracks and these may be attributed to the 20% I_c degradation at ~1.0% tensile strain.

At this point, no delamination has been observed to the tape but further investigation should be done so that we can conclude that this behavior was purely resulted from crack damage and not from other causes.

For the YBCO CC tapes under fully reversed procedure it showed an I_c peak and then a monotonic decrease in tension side. I_c showed only around 5% decrease in compressive bending and a minimal decrease in tensile bending which means no permanent deformation has been induced on the YBCO film. This is due to the thin substrate thickness of the tape which makes it more strain tolerant even it is bent up to a minimum diameter of around 11.8 mm.

Fig. 7 shows the normalized critical current as a function of bending strain in fully reversed procedure for the SmBCO and YBCO CC tapes. Under tensile and compressive bending strain critical current of the two CC tapes behaves differently. I_c value of YBCO CC increases with increasing tensile strain up to peak I_c value afterwards decreases monotonically and it decreases with increasing compressive strain. On the other hand in SmBCO CC, I_c decreases with increasing tensile strain but increases with increasing compressive strain up to the peak I_c value afterwards decreases monotonically. It has been known that the residual strain in the CC tape will influence the shape of the I_c-strain window; I_c may show a peak value if there exist a residual strain induced in the tape during manufacturing. Negative residual strain will result to an I_c peak in tension side and otherwise in compression side. We may deduce that the reason for the different sign in the residual strain may be resulted from the different deposition techniques and manufacturing processes adopted in YBCO and SmBCO CC tapes. However, in the study of Sugano et al [12], even though fabricated through the same process, strain effects on I_c in SmBCO and YBCO CC tapes showed opposite signs. Therefore, the reason for the sign of residual strain is not only attributable with the fabrication process. In this case, we can infer that aside from the fabrication process, intrinsic properties shown in table 2 of the SmBCO and YBCO coating films such as CTE have influences on the behavior of I_c [13, 14].

Also, further investigation should be done on the influence of shear stress to be induced among layers of the tape due to alternate application of tensile and compressive strain which may result in delamination of different layers which also causes significant degradation of I_c.

4. CONCLUSION

For SmBCO CC tapes, I_c showed a higher strain tolerance on compression side compared to tension side during continuous bending. However in the case of fully reverse bending procedure, I_c decreased in compression side as the I_c in tension side started to degrade significantly. The I_c degradation can be attributed to micro cracks based on the observed micrographs. For YBCO CC tapes, I_c showed a high tolerance that can be attributed to its thin substrate. It did not show any significant degradation up to 1.0% bending strain but I_c decreased faster in compression than in tension. Most importantly, SmBCO and YBCO CC tapes showed different Ic behavior under bending strain due to the different sign of the intrinsic residual strain.

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