Journal of the Korea Institute of Applied Superconductivity and Cryogenics
Vol.9, No.2, (2007), pp.11~14

Influence of bending strain on I_c Degradation Behavior in YBCO Coated Conductor Tapes processed using RABiTS/MOD

Hyung-Seop Shin *, John Ryan C. Dizon, Rolly Bonifacio and Jeong-Soo Park

School of Mechanical Engineering, Andong National University, Andong, Kyungbuk 760-749, Korea

Abstract-- **The critical current, I_c, degradation behaviors with bending strain were investigated in a commercially available YBCO coated conductor tape. In particular, the strain reversibility of I_c and the influence of repeated bending on I_c have been studied. Also, repeated bending at 77 K was done in order to understand the I_c behavior under cyclic bending strains. A reversible behavior of I_c has been found up to a high bending strain of 1.60% for the RABiTS/MOD processed CC sample with copper reinforcement. Under repeated bending, the I_c showed a 95% I_c retention up to 100 cycles for bending strains of 1.0% or less. The n-value behavior showed a good agreement with the I_c degradation behavior, representing that any cracking did not occur on the YBCO film resulting from the reinforcement provided by the copper stabilizers.**

1. INTRODUCTION

Recent advances in the fabrication technology of ReBCO coated conductors (CC) have widened their application fields to electric power cables, motors, magnets, etc. Long length YBCO CC tapes with high current density, J_c, over 1 MA/cm^2, have been achieved through the rolling-assisted biaxially textured substrates (RABiTS) and ion beam assisted deposition (IBAD) substrates [1-3].

The I_c-strain/stress relations in YBCO CC tapes will be of great significance in the design of superconducting devices. For YBCO CC tapes, some electro-mechanical properties have already been investigated by many research groups including tensile and bending strain dependencies of the critical current, I_c [4-8]. Under tensile stress, it was observed that the I_c can increase or decrease reversibly with strain up to an irreversible strain limit, ε_{irr}. [5-7]. Also, the lamination of stabilizers which enhances the mechanical properties of these tapes resulted in the increase in ε_{irr}. [5]. A peak value of I_c was also observed before decreasing at higher strain values [5,7]. When a bending strain was over 0.5%, cracking was observed. The generation of the crack appears to be the primary reason for the I_c degradation [4,8].

In practical applications to electrical devices, HTS wires/tapes will be subjected to various kinds of stress/strain. Among the various types of stresses occurring in superconductors in practical applications, bending stress/strain is most common in superconducting wires or tapes when they are fabricated into cables or wound in a coil shape for magnet construction [4, 9-13]. Also, during the service life of these tapes, they will be subjected to cyclic/repeated loading which are caused by various reasons such as re-coiling, thermal cycling, Lorentz force variations due to change in coil current, and alternating centrifugal forces during motor operation. Therefore, in order to apply HTS tapes to practical applications, the endurance evaluation of the tapes which includes mechanical and electrical stability and reliability is needed [14].

Since thin CC tapes have now become available commercially, testing the bending strain tolerance of CC tapes would require the use of much smaller diameters of bending mandrels as compared with those used for BSCCO tapes [9-13]. For this reason, a small-scale Goldacker type test rig to apply bending strain of up to ~1.6% to 0.2 mm thick CC tapes was used.

In this paper, we have investigated the I_c degradation behaviors with bending strain in a YBCO CC tape. The reversibility of I_c under bending strain, and the effects of repeated bending on the I_c degradation have been discussed.

2. EXPERIMENTAL PROCEDURE

A commercially available YBCO CC tape which was manufactured by the RABiTS/MOD process was supplied for the bending tests. Fig. 1 shows its cross-sectional view

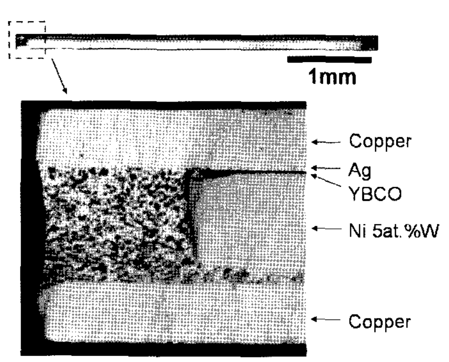


Fig. 1. Cross-sectional view of copper-stabilized YBCO CC tape processed by the RABiTS/MOD method.

* Corresponding author: hsshin@andong.ac.kr

TABLE I
SPECIFICATION OF YBCO COATED CONDUCTOR SAMPLES.

	RABiTS/MOD
Structure	Ag/YBCO/CeO_2/YSZ/ Y_2O_3
YBCO film thickness	~1 μm
I_c	86 A
Dimension, T x W	0.19 x 4.3 mm
Substrate	Ni-5at.%W
Substrate thickness	80 μm
Stabilizer	Hardened copper
Stabilizing technique	Lamination (solder)
Stabilizer thickness	40 μm
Manufacturer	AMSC

and the properties are tabulated in Table 1. The tape was reinforced externally at both sides by the lamination of copper stabilizers.

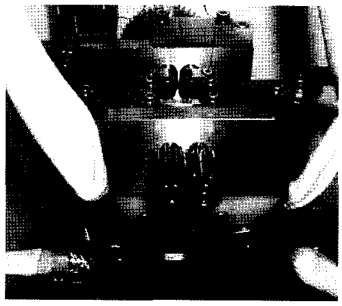
The bending strain dependence of I_c in Cu-stabilized YBCO tapes has been investigated. Fig. 2 (a) shows the small-scale Goldacker type test rig used for the bending tests [11-13]. The bending deformation was applied to the tape using the test rig which is suitable for the test of CC tapes in the easy bending mode [9]. The tape was mechanically connected to the current terminal blocks instead of soldering. The total sample length, voltage tap separation, the location of the turn axis, and gauge length subjected to bending deformation were 60, 10, 11.8 and 18.5 mm, respectively. Voltage taps were soldered on the edge of the tape to keep a homogeneous circular deformation of the tape. For the test procedure: One end of the sample was fixed at RT; the sample was cooled to 77 K in straight position; the other end was fixed at 77 K; the critical current at the as-cooled state, I_{c0}, was measured; The sample was bent; I_c was measured at a specific bending strain; the last two steps were repeated up to the specified bending strain.

The bending strains, ε_b, and $\varepsilon_{b,ybco}$ were defined as the strain at the outer surface of the tape and at the YBCO coating film, respectively. The nominal bending strain on the tape are given by [9, 10]

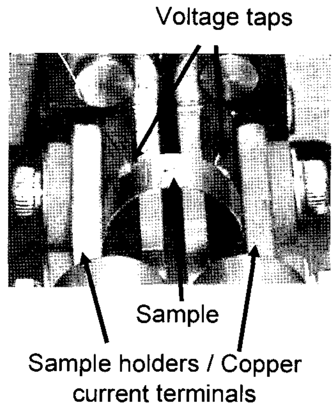
$$\varepsilon_b = \frac{t}{2r+t} \times 100\% \qquad (1)$$

$$\varepsilon_{b,ybco} = \frac{t_s}{2r+t} \times 100\% \qquad (2)$$

where r is the radius of sample holder; t is the thickness of the sample, t_s is the thickness of the substrate. The maximum bending strain, that can be given by the small-scale Goldacker type bending test rig to the RABiTS/MOD YBCO CC sample was ~1.60%. Fig. 2 (b) shows the sample bent at this bending strain. Repeated bending tests were carried out at specific bending strains such as ε_b = 0.8, 1.0 and 1.1%.



(a) at ε_b = 0%



(b) at ε_b = 1.6%

Fig. 2 View of the bending rig for electro-mechanical testing at 77K.

I_c measurements were carried out using the four probe method at 77 K and defined by a 1 μV/cm criterion. For the reversibility tests, the I_c was measured at specific bending strains and also after straightening. From the current-voltage (I-V) curve obtained, the n-value was also calculated by a linear fitting in the voltage range of 0.2-5.0 μV/cm. The voltage, V, in the transition range from the superconducting state to the normal state can be empirically approximated by $V=cI^n$ as a function of current, I, where c is a constant.

Fig. 3 shows the bending strain dependence of the I_c degradation in the RABiTS/MOD processed YBCO CC tape. A gradual and small I_c degradation with the increase of the bending strain was observed. No peak I_c was observed unlike the I_c-tensile strain previously reported [5]. At ε_b = 1.6%, which was the applicable maximum bending strain using the test rig, the I_c degradation was ~10% for the RABiTS/MOD sample. At this bending strain, the I_c still showed a reversible behavior. The bending strain corresponding to 95% I_c retention, i.e., $\varepsilon_{b,95\%}$, was about 1.1%. As compared with Bi-2223 tapes, this bending strain tolerance of I_c in YBCO CC tapes are much higher [9-10]. When compared with the ReBCO tapes previously reported [8], the reinforcement of Cu layers to YBCO CC tapes enhanced the resistance to the initiation of cracking on the YBCO film, which resulted from the difference of thermal contraction between Cu layers and other components and acted as a crack arrester [5,7].

3. RESULTS AND DISCUSSION

The I_c was also plotted against the bending strain calculated on the YBCO layer using Eq. (2). The I_c degradation curve significantly moved towards the left side, and the bending strain corresponding to 95% I_c retention was $\varepsilon_{b,\ YBCO,\ 95\%}$ ~ 0.45%. This large difference in $\varepsilon_{b,\ 95\%}$ resulted from the bending strain characteristics. It can be found that the 95% I_c retention strain limit for this tape under easy bending is similar with the case under uniaxial tensile strain which was ~0.43% [15].

The results of the reversibility tests by I_c measurements after the straight state are also plotted in Fig. 3. The I_c degradation behavior was reversible up to ε_b ~ 1.6%.

For the repeated bending test, three bending strain levels were selected from the I_c-ε_b relationship; ε_b = 0.8, 1.0 and 1.1%. Fig. 4 shows the results of the repeated bending tests of the CC samples.

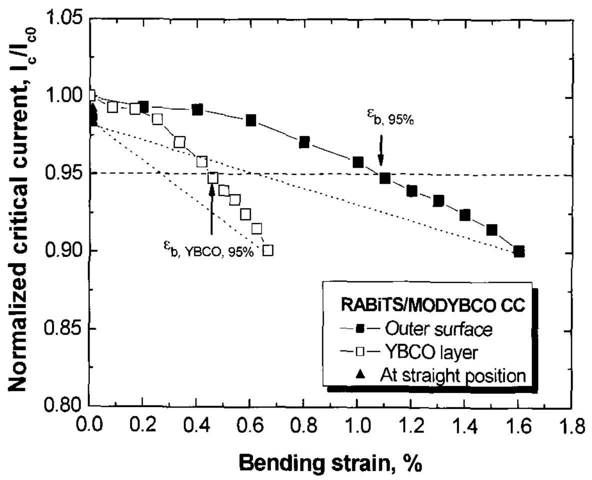


Fig 3. I_c-ε_b, $\varepsilon_{b,YBCO}$ characteristics of the RABiTS/MOD YBCO CC tape.

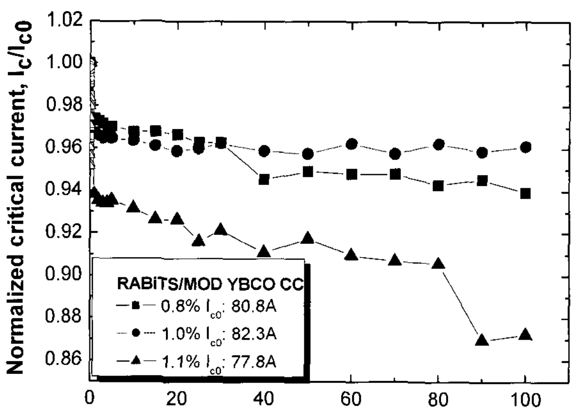


Fig. 4. I_c/I_{c0}-N relationship of the RABiTS/MOD YBCO CC tape.

For the case of 0.8% bending strain, the I_c degraded slowly initially, but after 40 cycles the I_c degraded by 5% from the I_{c0} value. And then, the I_c saturated with cycles without further degradation up to 100 cycles. The I_c was recovered to the original value after straightening the sample after 100cycles.

For the case of 1.0% bending strain, the I_c degraded to about 4% at the bent state and maintained that level up to 100 cycles. But every time, the I_c recovered to I_{c0} when the sample was straighetened. For the case of 1.1%, the I_c dropped to 93% of the I_{c0} after bending, and to ~87% after 100 cycles, but after straightening the sample, it recovered to ~95% of the I_{c0}. From these results it can be thought that Cu-stabilized YBCO CC tapes represent high bending strain tolerance of I_c against repeated bending at 77 K.

In addition, thermal cycle tests at bent state and fully reversed (double bend) cyclic tests are further needed in order to assess the reliability of these YBCO CC tapes in bending mode for practical applications.

Finally, the n-value behaviors as a function of the applied strain, ε_b, was investigated and shown in Fig. 5. A gradual and small variation of n-value with the increase of bending strain could be seen. The curve shows a similar behavior with the I_c, shown in Fig. 3, representing that significant cracking did not occur on the YBCO film. This could explain the reversible strain effect in YBCO CC tape samples observed under bending strain, wherein the I_c behaved reversibly even though it degraded to almost 90% of I_{c0} for the RABiTS/MOD YBCO CC sample.

Under repeated bending shown in Fig. 6, the n-value showed a small variation with repeated cycles similar with the I_c, even though some scattering of n_o-value existed, which represents that any cracks did not form on the YBCO layer during repeated bending up to 100 cycles. As a whole, there was a good similarity between the n-value-ε_b and I_c/I_{c0}-ε_b behaviors.

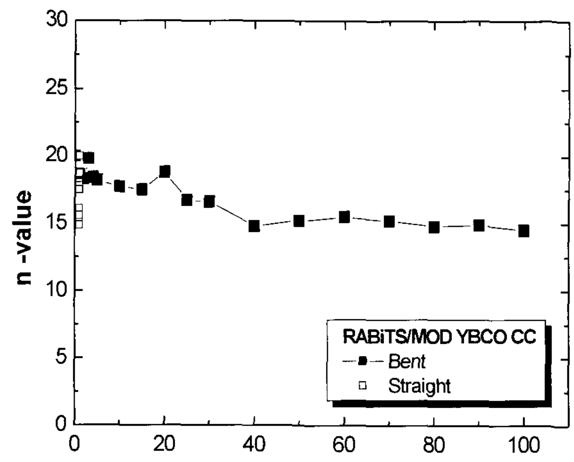


Fig. 5. n-value-ε_b relationship of the RABiTS/MOD YBCO CC tape.

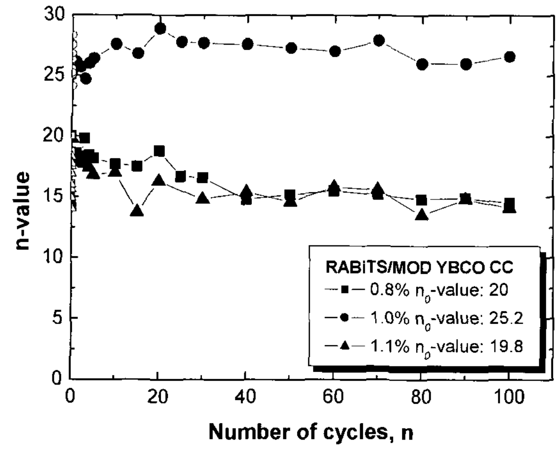


Fig. 6. n-value-N relationship of the RABiTS/MOD YBCO CC tape.

4. CONCLUSION

The influence of bending strain on the critical current, I_c, degradation behaviors in a commercially available YBCO coated conductor tape fabricated by the RABiTS/MOD process were investigated. The reversibility of I_c degradation and the influence of repeated bending on I_c have been discussed. Also, repeated bending at 77 K was done in order to understand the I_c behavior under cyclic bending strains. Due to the copper stabilizers used as reinforcement a reversible behavior of I_c was observed up to ε_b=1.6% in the RABiTS/MOD sample. Under repeated bending, at an applied maximum bending strain up to ~1.0%, the I_{c0} could be recovered up to 100 cycles. The n-value behaviors showed a good agreement with the I_c degradation behavior of the RABiTS/MOD tape.

ACKNOWLEDGMENT

This work was supported by the Andong National University's Special Grant Program of 2006. JRC Dizon was supported by the Korea Research Foundation funded by the Korean Government (MOEHRD) (KRF-225-D00182).

REFERENCES

[1] R. A. Hawsey, and D. K. Christen, "Progress in research, development, and pre-commercial deployment of second generation HTS wires in the USA," *Physica C*, vol. 445-448, pp. 488-495, 2006.

[2] Y. Shiohara, Y. Kitoh, and T. Izumi, "Highlights in R&D for coated conductors in Japan ," Physica C, vol. 445-448, pp. 496-503, 2006.

[3] A.P. Malozemoff, D.T. Verebelyi, S. Fleshler, D. Aized, and D. Yu, "HTS Wire: status and prospects," *Physica C*, vol. 386, pp. 424-430, 2003.

[4] C. Park, D. P. Norton, J. D. Budai, D. K. Christen, D. Verebelyi, R. Feenstra, D. F. Lee, A. Goyal, D. M. Kroeger, and M. Paranthaman, "Bend strain tolerance of critical currents for $YBa_2Cu_3O_7$ films deposited on rolled-textured (001) Ni," *Appl. Phys. Lett.*, vol. 73, pp. 1904-1906, 1998.

[5] 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. 364-S368, 2005.

[6] M. Sugano, K. Osamura, W. Prusseit, R. Semerad, K. Itoh, and T. Kiyoshi, "Tensile fracture behavior of RE-123 coated conductors induced by discontinuous yielding in Hastelloy C-276 substrate," *Supercond Sci. Tech.*, vol. 18, pp. S344-S350, 2005.

[7] N. Cheggour, J. W. Ekin, C. L. H. Thieme, Y. Y. Xie, V. Selvamanickam, and R. Feenstra, "Reversible axial-strain effect in T-Ba-Cu-O coated conductors," *Supercond. Sci. Tech.*, vol. 18, pp. S319-S324, 2005.

[8] Y. Sutoh, K. Kakimoto, N. Kaneko, Y. Iijima, and T. Saitoh, "Mechanical bending property of YBCO coated conductor by IBAD/PLD ," *Physica C*, vol. 426-431, pp. 933-937, 2005.

[9] H. S. Shin, and Katagiri K, "Critical current degradation behavior in Bi-2223 superconducting tapes under bending and torsion strains," *Supercond. Sci. Tech.*, vol. 16, pp. 1012-1018, 2003.

[10] T. Kuroda, K. Katagiri, H. S. Shin, K. Itoh, K. Kumakura, and H. Wada, "Influence of test methods on critical current degradation of Bi-2223/Ag superconductor tapes by bending strain," *Supercond. Sci. Tech.*, vol. 18, pp. S383-S389, 2005.

[11] K. Katagiri, K. Hiroi, K. Kasaba, T. Asoh, T. Kuroda, K. Itoh, H. Wada, and H. S. Shin, "Bending strain characteristics of Ag/Bi(2223) tapes at liquid nitrogen temperature," *Physica C*, vol. 412-414, pp. 1101-1106, 2004.

[12] J. R. C. Dizon, Andong National University MS Thesis, 2005.

[13] W. Goldacker, S. I. Schlachter, R. Nast, H. Reiner, S. Zimmer, H Kiesel, A. Nyilas, "Bending strain investigations on BSCCO(2223) tapes at 77K applying a new bending technique," *Adv. Cryo. Eng.*, vol. 614, pp. 469-476, 2002.

[14] H. S. Shin, J. R. C. Dizon, K. H. Kim, S. S. Oh, and D. W. Ha, "Mechanical and transport properties of Ag alloy/Bi-2223 superconducting tapes under axial fatigue loading," *Physica C*, vol. 426-431, pp. 1188-1193, 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*, 2007 (in press).