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Variation of the Transport Property in Lap-Jointed YBCO Coated Conductor Tapes with Tension and Bending Deformation

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***Abstract*-- In practical applications of HTS tapes for electric devices such as coils and power cables, the jointing of HTS tapes is inevitable even though long length tapes have recently been achieved. The critical current, I_c, degradation behaviors with tensile and bending deformations were investigated in commercially available YBCO coated conductor tapes. When the V-I relationship was measured at the jointed section of the lap-jointed YBCO CC tapes, the resistance at the joint decreased with increasing joint length. The critical load for 95% I_c retention were determined for the IBAD and RABiTS YBCO tapes and they were 175 and 355 N, respectively. Fracture occurred at the unjointed part which represents strong copper lamination and solder jointing. The electro-mechanical properties of lap-jointed CC tapes depended on the properties of single tapes. The V-I behavior under bending strain was similar with the tensile case.**

1. INTRODUCTION

Recent advances in the fabrication technology of ReBCO coated conductors (CC) have widened their application fields to electric power devices especially power cables. Long length YBCO CC tapes over 100m with high current density, J_c, over 1 MA/cm^2, have been achieved through the rolling-assisted biaxially textured substrate (RABiTS) and ion beam assisted deposition (IBAD) substrate [1-3].

For superconducting devices including coils and cables, several kilometers in length of CC tapes are needed. This means that joining of CC tapes is essential in order to meet this need. Several research works have been conducted on the joining of CC tapes [4-5]. High joint resistance could be obtained when non-superconducting joints were made, and this resistance could be decreased tremendously when diffusion joint is made [4]. The design of jointed part considering the resistance and mechanical property is necessary. The electromechanical characteristics of these joints are therefore needed to be investigated. Recently, Sugano et al investigated the load dependence of I_c in solder-jointed CC tapes with no stabilizers. The I_c degradation behavior under an applied axial load was observed. And that overall fracture took place at the interface between YBCO and buffer layer [5].

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In practical applications to electrical devices, HTS wires/tapes will be subjected to various kinds of stresses/strains. Among the various types of stresses occurring in superconducting wires or tapes in practical applications, tensile and bending stresses/strains are two of the most common when they are fabricated into cables or wound in a coil shape for magnet construction [6-12].

In this paper, I_c degradation behaviors under tensile and bending deformations in lap-jointed YBCO CC tapes have been investigated.

2. EXPERIMENTAL PROCEDURE

Two commercially available YBCO CC tapes with RABiTS and IBAD substrates were supplied for the tests. Table 1 summarizes their properties. The RABiTS tape was reinforced externally at both sides by the lamination of copper stabilizers, while the IBAD tape was surround-stabilized by the electroplating of copper.

The joining and voltage tap configuration of CC tapes are shown schematically in Fig. 1, one tape overlaps another tape and soldering was done manually. The length of the jointed region (J.L.) was varied from 10 to 40 mm, consequently, the sample length (S.L.) was varied from 90 to 120 mm accordingly.

TABLE I
SPECIFICATION OF YBCO COATED CONDUCTOR SAMPLES.

	RABiTS/YBCO	IBAD/YBCO
Structure	Ag/YBCO/CeO_2/YSZ / Y_2O_3/Ni-5at.%W	Ag/YBCO/LMO/Homo-epi MgO/IBADMgO/Hastelloy
YBCO film thickness	~1 μm	~1 μm
I_c	97 A	95 A
Dimension, T x W	0.21 x 4.32 mm	0.09 x 4.34 mm
Substrate	Ni-5at.%W	Hastelloy
Substrate thickness	80 μm	50 μm
Stabilizer	Hardened copper	Copper
Stabilizing technique	Lamination (solder)	Copper electroplating
Stabilizer thickness	40 μm	20 μm

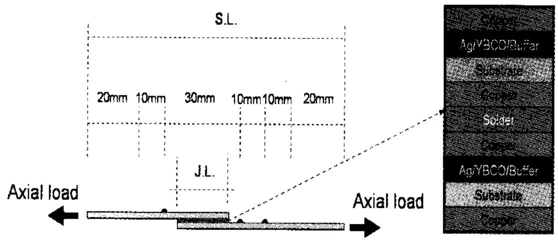


Fig. 1. Schematic view of the jointing and voltage tap configurations of YBCO CC tapes.

For the tensile test of CC tapes at 77 K and self-field, a universal testing machine (loadcell capacity: 5 kN) was used. The jointed specimen was fixed at both ends to the upper and lower gripping holders. The upper gripping holder was attached to the loadcell through a universal joint and the lower one was set on the 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 the thermal contraction which occurs during cooling and to prevent any bending or twisting loads expected during specimen fixing. The test-set up could be found in Reference [7].

The test fixture including the specimen was slowly cooled down to 77 K taking about 10 min. The strain applied to the CC samples was measured using the double extensometers developed by Nyilas with a gauge length of 12.5 mm, which were directly attached to the lower unjointed part of the specimen [7].

The I_c measurement was performed at two sections, namely, the jointed part (J.L.) and unjointed part (10 mm). GFRP sheets were inserted between the specimen and the gripping holders for electrical insulation. The copper gripping holders serve as current terminals. A V-I curve was measured using the four-probe method at 77 K under self-field, and the I_c was defined by a 1 μV/cm criterion. The I_c was normalized by the I_{c0} value obtained at the as-cooled state.

For the bending test, Fig. 2 shows the bending mandrels each of which consists of a curved cover plate (female die) and a curved base plate (male die) which were devised for the Mini-RRT for VAMAS TWA16 [13]. The cover and the base plates have identical curvature. The bending strain was applied to the tapes at room temperature (RT), depressing the cover plate to sandwich the sample between the two plates and mechanically fixing both ends of the tape to the Cu current terminals installed to the base plate, and measuring the I_c after cooling down to 77 K. The total length and the separation of voltage taps of the tape were 70 and 30 mm, respectively. Fig. 3 shows a sample bent at 1.0 % bending strain where the jointed section of 20 mm is located at the central region of the holder.

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 strains on the tape are given by [11-12].

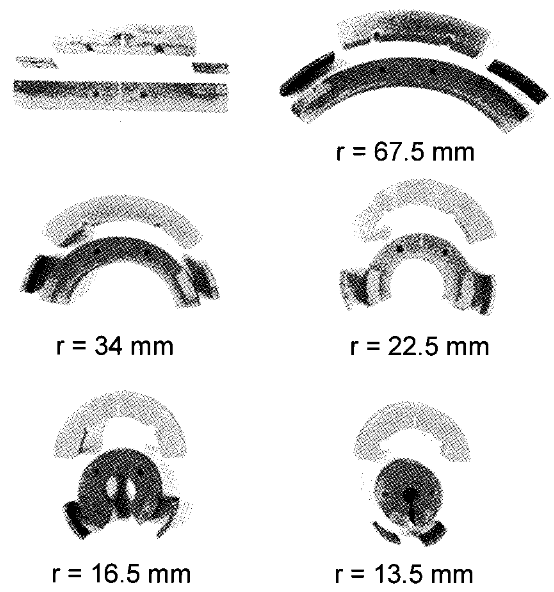


Fig. 2. Views of a series of FRP sample holders with mechanical fixing in the easy bending mode.

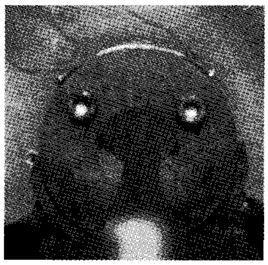


Fig. 3. View of the sample (J.L.: 20 mm) mounted on the bending mandrel ($\varepsilon_b \sim 1.0\%$).

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

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

where r is the radius of sample holder; t is the thickness of the sample, t_s is the thickness of the substrate.

3. RESULTS AND DISCUSSION

Fig. 4 shows the tensile stress-strain relationship in jointed YBCO CC tapes at 77 K. The strain measured at the unjointed part was adopted. Similar stress-strain behaviors (of jointed tapes) were obtained in both samples regardless of the joint length. Up to the failure, the jointed part did not show any shear deformation or delamination among layers. The final fracture occurred at the unjointed section of the tapes. From this result, it is evidence that good and uniform soldering was achieved at the jointed part of the CC tapes.

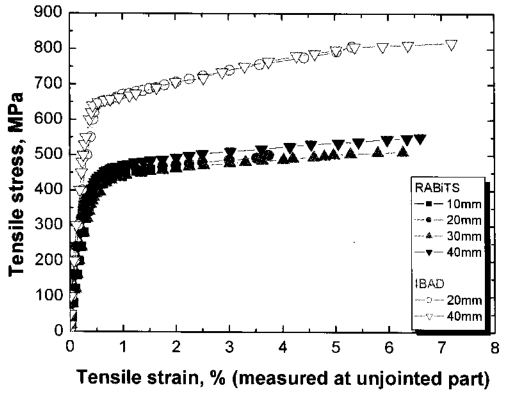
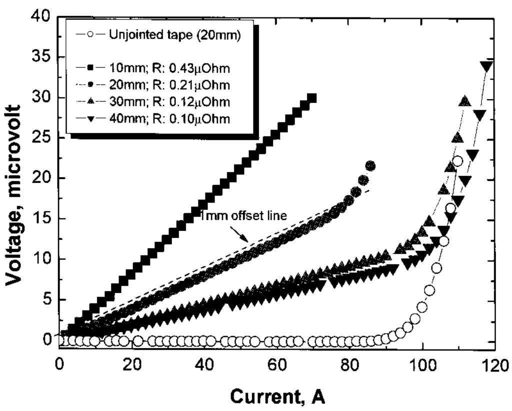
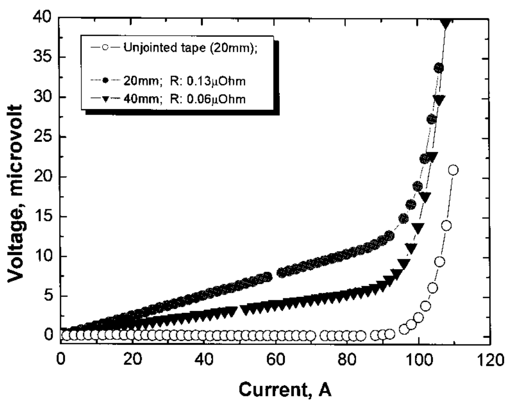


Fig. 4. Tensile stress-strain curves of YBCO CC tapes.

The V-I curves at the jointed and unjointed sections of the tapes were measured. Fig. 5 (a) and (b) show the V-I curves for both samples at the jointed and unjointed parts. Resistance could be measured at the jointed section. For the RABiTS sample, joint resistances have been measured for 10, 20, 30 and 40 mm joints, and they were, 0.43, 0.21, 0.12 and 0.1 μ Ohm, respectively. For the IBAD sample, it was 0.13 and 0.06 μ Ohm for the 20 and 40 mm joints, respectively. Resistance in longer joint lengths could be negligible and is believed to approach the V-I curve in unjointed tapes. Estimation of I_c was done using a 1 μV offset line.



(a) RABiTS/YBCO



(b) IBAD/YBCO

Fig. 5. V-I curves in jointed RABiTS and IBAD YBCO CC tapes.

To check if the direction of current flow had any influence on V-I behavior, the polarity of current connections were exchanged. Fig. 6 shows the comparison of V-I curves in IBAD YBCO CC tapes with different polarity. The graph shows that changing the polarity did not affect the V-I curves in both the jointed and unjointed sections of the sample. Fig. 7 (a) and (b) shows the variation of V-I curves of samples with 20 mm joint length with the increase of tensile load.

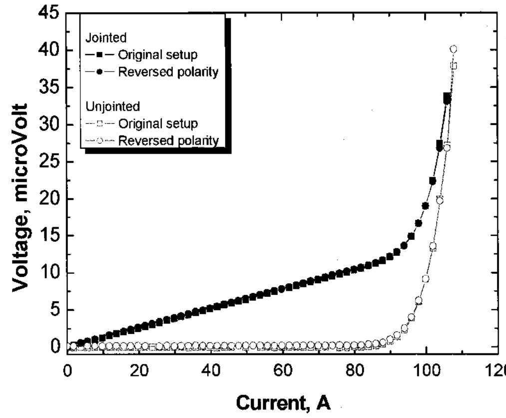
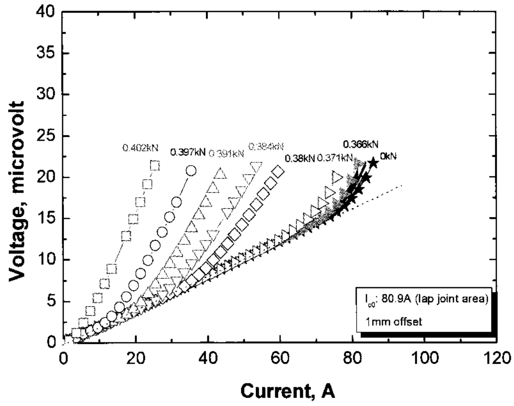
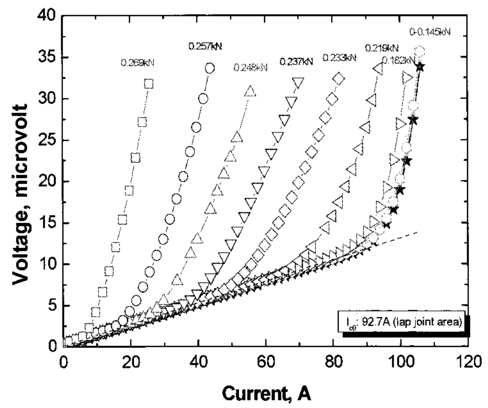


Fig. 6. Comparison of polarity dependency of V-I curves in IBAD YBCO CC tapes.



(a) RABiTS/YBCO



(b) IBAD/YBCO

Fig. 7. Variation of V-I curves at the joint under tensile load.

The slopes of the linear region in V-I curves (i.e. intrinsic resistance at the joint) did not change even after significant I_c degradation occurred as the applied load increased. For the RABiTS sample (a) up to 366 N, the V-I curves were similar. And starting from 371 N, significant deviation from the original V-I curve occurred (resulting in the dropping of I_c). On the other hand, for the IBAD sample (b) up to 145 N, the V-I curves were similar. And from 182 N, large deviation from the original V-I curve occurred resulting in the dropping of I_c. Since the lap-joint between two tapes are strong enough to resist the shear stress which was induced at the solder part when the axial load was applied to the tapes, final fracture always occurred at the unjointed section of the samples.

The critical loads for 95% I_c retention were determined for the jointed and unjointed sections. The average tolerable tensile load was ~175 N and ~355 N for the jointed IBAD and RABiTS CC tapes, respectively. The figures were not shown for brevity.

Fig. 8 shows the variation of V-I curves at the joint in the RABiTS/YBCO tape under each bending strain corresponding to decreasing bending radii. The joint length was 20 mm. Similar with the case under tensile load, the slopes of the linear region in V-I curves (i.e. intrinsic resistance at the joint part) did not change even after large I_c degradation occurred which was caused by high bending strains applied on the tape. The 95% I_c retention strain was determined and it was $\varepsilon_{b,95\%} \sim 0.8\%$, which corresponds to a bending diameter of 45 mm.

With these results, for practical applications, long joint lengths should be made to reduce the resistance at the joint. It also reduces the shear stress induced at the joint. It was found out that fracture occurred at the unjointed part which further represents strong jointing and that the electro-mechanical properties of lap-jointed CC tapes depend upon the properties of single CC tapes.

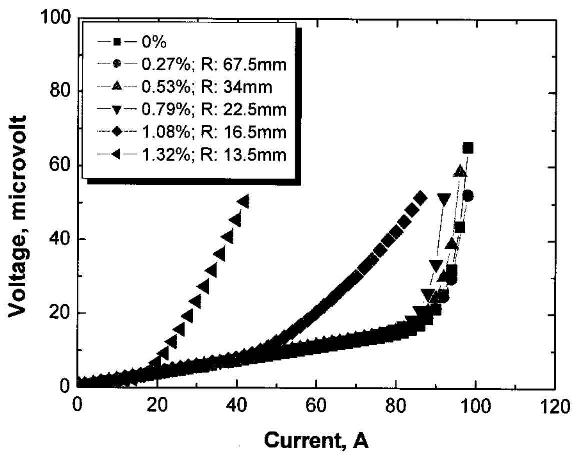


Fig. 8. Variation of V-I curves at the joint in RABiTS/YBCO tape at the joint under bending strain.

Furthermore investigation on the effect of solder used including its composition and melting temperature must be considered.

4. CONCLUSION

The V-I relationships were measured at the jointed section of lap-jointed YBCO CC tapes. The resistance at the joint decreased with increasing joint length. Under tensile load, the critical load for 95% I_c retention were determined for the IBAD and RABiTS YBCO tapes were 175 and 355 N, respectively. The unjointed part showed strong jointing and thus the electro-mechanical properties of lap-jointed CC tapes depended on the properties of single tapes. The V-I behavior under bending strain was similar with the tensile case.

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