

Bending Strain Dependence of the Transport Property in Jointed BSCCO Tapes

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Abstract-- In this study, the effect of bending strain on the transport property and critical current of lap and butt-jointed (non-laminated) BSCCO tapes has been investigated. The samples were joined using a mechanically controlled jointing procedure. To achieve a uniform thickness at the joint a single point loading contact has been devised. GFRP mandrels with different bending radii which support the sample during bending have been used. I_c have been measured at 77 K and self field. In the case of easy bending test for jointed BSCCO tapes, sudden degradation of I_c is caused by the local strain concentration due to non uniform deformation at the edge parts of the joint. In the case of hard bending test of jointed BSCCO tapes transverse macroscopic crack at specific subsection caused a large I_c degradation. The transport property of jointed BSCCO tapes in each bending mode was discussed with the damage morphology occurred.

1. INTRODUCTION

Application of superconducting tapes such as BSCCO tapes to electric devices made it possible to achieve a clean and efficient utilization of energy. However, in order to utilize its full potentials in practical applications, thorough investigations to ensure its superconducting characteristics should be done. In electric device applications BSCCO tapes will be subjected to various stresses/strains and therefore, electromechanical property evaluation should be examined in order to ensure its current carrying capacity as well as the performance of the device with mechanical deformation. In the past years, different issues on the improvement of HTS current carrying capability, strength, length and production cost have been addressed by developing new materials, manufacturing methods and techniques. Regarding the improvement of BSCCO tape's current carrying capacity, the process called "CT-OP (controlled temperature over pressure)" has been developed and resulted to a quite higher J_c [1, 2] due to much denser superconducting core by applying HIP process. Aside from this high J_c , a long length tape of around 1 km has been also produced. For practical applications, on the other hand, jointing of tapes is necessary in power cables and superconducting coils which require several kilometers in length. From the previous studies on joint between BSCCO tapes, different

joint configurations have been tried and classified as superconducting or resistive joint, respectively [3, 4]. The former is a direct contact of the superconducting cores by removing the Ag sheath and stabilizing layer by etching process and the latter is using solder material to join the HTS tapes. In the case of superconducting joint, Jeong et al investigated the mechanical properties of BSCCO joints and found out that the reason for the earlier decrease of I_c compared to normal single tape is due to the defect such as micro crack caused by the weak connection of cores [5]. For resistive joints, Gu et al reported that the influence of the joint on the critical current could be ignored when the overlapped length is larger than 4.5 cm based on the obtained critical current ratio (CCR) curves [4]. In this study a resistive joint by simple soldering method of over-lapped BSCCO tapes employing mechanically controlled jointing is adopted. The transport property of solder jointed BSCCO tapes under different bending modes namely easy and hard bending have been investigated.

2. EXPERIMENTAL PROCEDURE

Commercially available Bi-2223 tapes with no lamination have been used as sample and its specifications are listed in Table 1. It has an average thickness and width of 0.22 and 4.1 mm, respectively. Lap- and butt-joint types have been adopted. Different joint lengths have been tried to check the joint length-joint resistance relation behavior just in the cases of YBCO tapes in Ref [6]. Jointed tapes have been made by employing a mechanically controlled jointing with an applied pressure of 1 MPa devising a single point loading to ensure the uniform pressure application on the joint part. Details of the jointing process

TABLE I
SPECIFICATIONS OF BSCCO SAMPLE.

High I_c	BSCCO-2223
Dimension, t x w (mm)	0.22 x 4.1
I_c at 77K (A)	172 A (ave)
Sheath material	Ag alloy
Type	Type H
Reinforcement	None
Manufacturer	Sumitomo

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are described in Ref [7]. Samples with 20 mm joint length were used in the easy bending test while with 10 mm joint length were used in the hard bending test. Bending deformation to jointed samples was given using mandrels with different bending radii employing mechanical contact for current terminals as shown in Fig. 1. Bending conditions employed in the jointed tapes are the same with the case of single tapes [8]. Bending strains under easy and hard bending modes are calculated at the outer surface/edge of the tape as described in [9]

$$\varepsilon_b = t/(2r + t)$$

where t is the sample thickness (in easy bending mode) or width (in hard bending mode) and r is the bending radius of mandrel used. In the case of jointed tape, the continuous bending test rig devised by Goldacker [10] is not applicable since jointed tape has different stiffness at the jointed and unjointed parts, therefore FRP mandrels which support the sample to provide uniform radius is used in the test. These mandrels have been also used in the VAMAS-RRT for BSCCO tapes [11]. Mandrels used for the hard bending test are shown in Fig. 1. Critical current behaviors of the jointed tapes under bending strains have been investigated. Critical current was measured using $1 \mu\text{V}/\text{cm}$ criterion for the unjointed part/single tape while $1 \mu\text{V}/\text{cm}$ offset criterion was used to measure the I_c at the jointed part [7]. In the case of hard bending test, multiple voltage taps has been adopted to check the behavior of I_c degradation along the gage length. The separations of the six (A to F) voltage taps in that case were 5 mm (subsections AB, BC, DE and EF) at the unjointed part, but subsection CD at the jointed part was 20 mm.

3. RESULTS AND DISCUSSION

To investigate the transport property and the joint length-resistance behavior in jointed BSCCO tapes, samples with different joint lengths have been made and

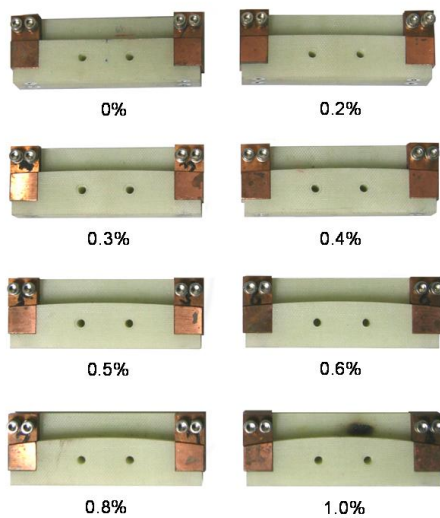


Fig. 1. Mandrels used for the hard bending test of jointed BSCCO tapes with different bending radii.

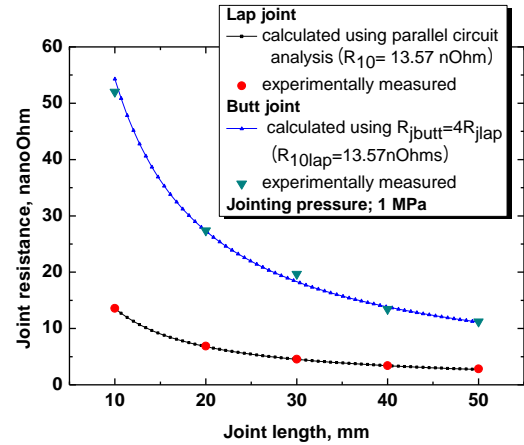


Fig. 2. Joint length-joint resistance behavior in lap- and butt-jointed BSCCO tapes.

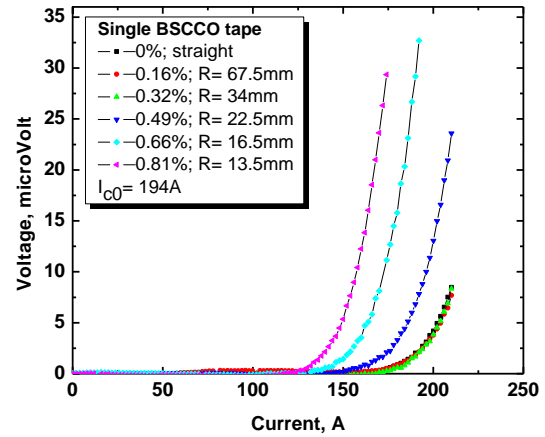
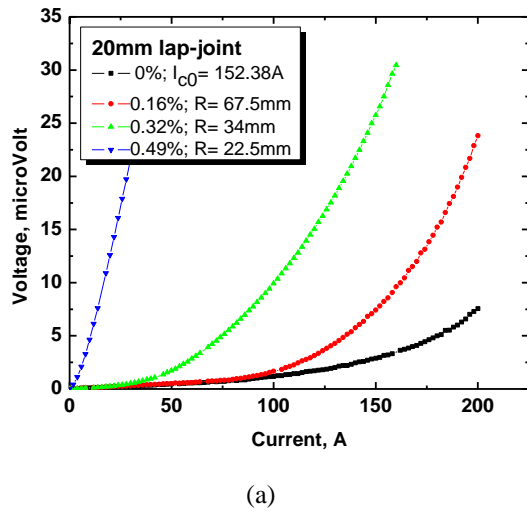


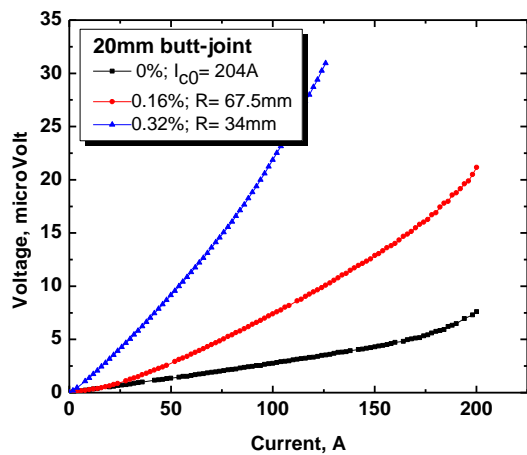
Fig. 3. I-V curves for single BSCCO tape in easy bending mode.

measured the resistance along the joints. Fig 2 shows both results for lap and butt joints. The experimentally measured resistances are well fitted with the estimated values based on R_{10} using parallel circuit analysis [7] where estimated values have been calculated by $R_{10n} = R_{10}/n$ formula derived from the parallel circuit analysis for lap joint configuration. And also by circuit analysis, the relation of the resistances in butt joint has been described as $R_{jbutt} = 4R_{jlap}$ [7]. By employing a mechanical controlled jointing which achieves an almost uniform thickness along the joint lengths this conformance of the experimental value to the estimated one was possible.

Fig. 3 shows the I-V curves in single BSCCO tape under easy bending mode. The bending radius and bending strain corresponding to the 95% I_c retention were 27 mm and 0.40%, respectively. On the other hand, the lap- and butt-jointed tapes in easy bending mode showed electrical resistivity across the joint of 9.34 and 24.7 nanoOhms, respectively. Joint resistance did not show enhancement with increasing bending strain. The joint thickness including solder layer is on the order of 0.46 mm. In the case of jointed tapes, in Fig. 4(a), I_c degraded significantly starting from bending radius of 67.5 mm for lap-jointed tape and similarly in Fig. 4(b) the I_c degradation has been



(a)



(b)

Fig. 4. I-V curves of (a) lap and (b) butt-jointed BSCCO tape measured at different bending radii in easy bending mode.

also observed for butt-jointed BSCCO tape. On the other hand, similarly with the single tape, the joint resistance did not change with increasing bending strain. The sudden degradation of I_c is caused by the local bending strain (or deformation) concentration due to non uniform deformation at the edge part of the joint as shown in Fig. 5(a) for lap joint. And the local bending concentration occurred both at the central region of the jointed tape and joint edges as shown in Fig. 5(b) for butt joint. The local bending deformation concentration is due to the difference in stiffness of the jointed and unjointed part which causes the strain to concentrate at the edges where the abrupt change in cross sectional area is present. The bending procedure adopted in this study is the same as the case for the single tape [8] in which bending strain is applied by depressing the cover die, which resulted in the occurrence of bending deformation concentration [7]. Therefore, the adoption of a careful and modified bending procedure and introduction of external lamination is necessary in order to lessen the local concentration of the bending deformation at the edges of the jointed tapes. In addition, a modification in the cutting angle of the tape or solder fillet finishing at the edge parts is also proposed to minimize the effect of

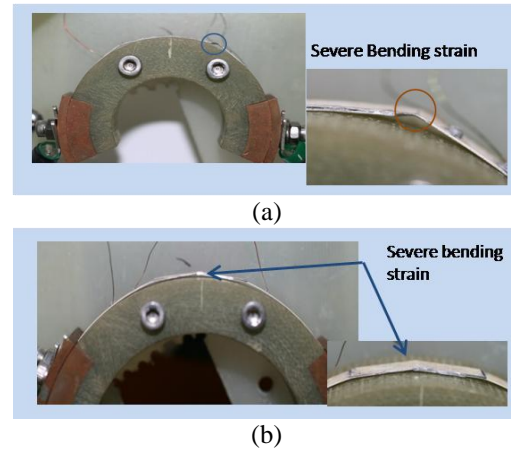


Fig. 5. Occurrence of severe and concentrated bending deformation (a) at joint edges in lap-joint and (b) both at the central part and joint edges in butt-joint.

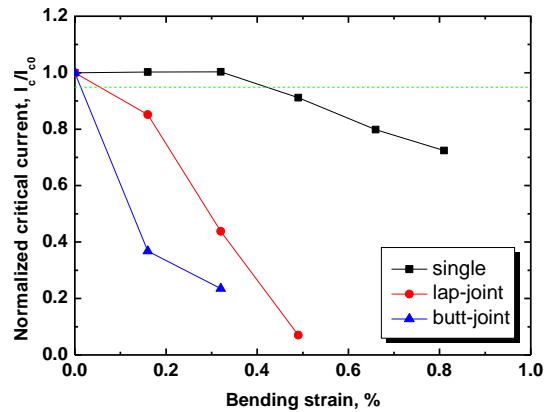


Fig. 6. Normalized critical current, I_c/I_{c0} as a function of bending strain in single and jointed BSCCO tapes in easy bending mode.

severe edge deformation concentration. Fig. 6 summarizes the results in easy bending mode showing the normalized critical current, I_c/I_{c0} as a function of bending strain in single and jointed BSCCO tapes. Butt-jointed tape degraded abruptly because it has more bending deformation concentrations occurred at the area with abrupt change in cross sectional area.

For hard bending test of lap-jointed BSCCO tapes in Fig. 7, for some subsections, I_c degraded as early as 0.2% bending strain application and degraded further with increasing strain. The critical current at 0.8% strain at subsection DE and the whole section AF almost reached to zero because of the transverse macroscopic crack at subsection DE as can be seen in Fig. 9(a). Similarly, in the case of butt-jointed tape I_c has almost reached to zero due to the transverse macroscopic crack at the subsection CD located at the central part of joint at overlapped single tape when bent with 0.4% bending strain as depicted in Fig. 8 and 9(b). Severe damage on the tape occurred at central region of the tape. The outer edges of the tape experienced high tensile stress which caused fracture to the tape. Fracture (cracked) locations for lap- and butt-jointed BSCCO tapes are shown in Fig. 9. For this reason, in coil

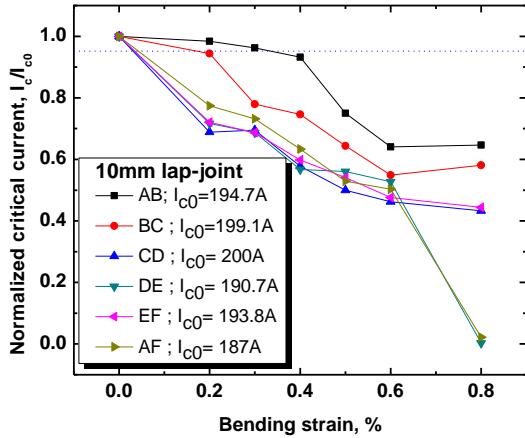


Fig. 7. Normalized critical current as a function of bending strain in lap-jointed BSCCO tape in hard bending mode.

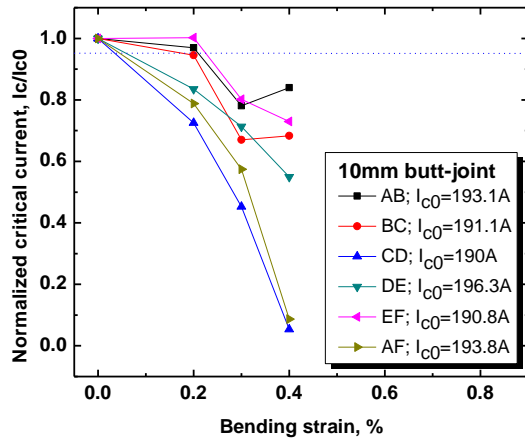


Fig. 8. Normalized critical current as a function of bending strain in butt-jointed BSCCO tape in hard bending mode.

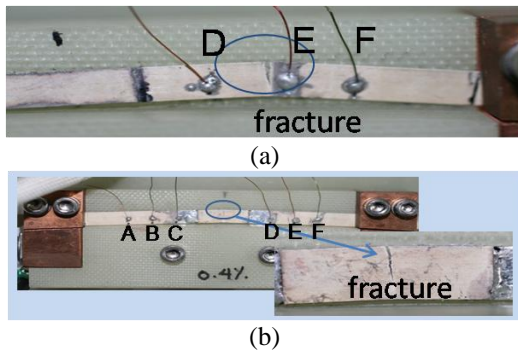


Fig. 9. Fracture locations in (a) lap- and (b) butt-jointed BSCCO tapes.

application it is suggested that joint should not be placed on the area where it will experience a considerable (hard) bending deformation.

4. CONCLUSION

In the case of jointed BSCCO tapes, the local bending deformations induced at the joint edge part of the tape or

central region of the jointed tape resulted to an early degradation of I_c as compared with the single tape case. A modification of the bending test procedure and the adoption of external reinforcement are necessary to lessen this effect. Also, electromechanical property of a single tape is important since the deformation principally occurred at the unjointed part, especially at the joint edges and central region of jointed tapes.

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