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Influence of External Reinforcement on Strain Characteristics of Critical Current in BSCCO Superconducting Tapes

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Abstract-- **For the purpose of standardization of the critical current measurement, it is meaningful to describe how I_c will behave as the stress/strain level changes. In this study, strain dependencies of the critical current I_c in Ag-alloy sheathed multifilamentary Bi(2212) and Bi(2223) superconducting tapes were evaluated at 77K, 0T. The external reinforcement was accomplished by soldering AgMgNi alloy tapes onto single or both sides of the sample. With the external reinforcement to the Bi(2212) tape, the strength of the tapes increased but the critical current at the strain free state, I_{c0} decreased in some cases. The strain for onset of the I_c degradation, $\varepsilon_{irr.}$, increased with an increase of the reinforcing volume and then saturated to a certain value. The effect of external reinforcement on the degradation of I_c due to the bending strain in the Bi(2223) tape was also examined. Contrary to the expectation, it showed a significant I_c degradation even at a small strain of 0.4 %. The observations of damage morphologies gave a good explanation to the I_c behavior.**

Keywords : External reinforcement, Strain effect, Critical current, BSSCO tapes, Bending

1. INTRODUCTION

Recently, there has been much activity in the area of standardization of testing and measurement methods of various high temperature superconductors, such as critical current, mechanical properties, AC loss, etc. With increased application of high T_c superconductors to high field magnets and electric power industries, the standardized method for evaluating stress/strain effects on I_c is necessary and it will be one of the most urgent areas to be studied in the near future.

Ag/BSCCO superconducting tapes were used for high-field magnets because of its high upper critical field and high I_c at 4.2 K. During their operation, the windings are subjected to a high electromagnetic force and a bending strain. The I_c degrades irreversibly when the mechanical damage occurred at oxide superconductors. Various efforts have been made to suppress the degradation of superconducting properties due to forces applied or the bending strain. One of them was to reinforce the superconductor with the tape having a high strength in order to improve the strength property and the stress/strain characteristic of I_c in the superconducting tapes, which is known as the external reinforcement method. The strain characteristics of I_c in short samples is liable to vary in certain cases depending on the parameters such as wire construction, quality of the superconductor, measuring condition and criterion of critical current [1]. Therefore, it is important to clarify the influence of external reinforcement on the strain effects of I_c using short samples at 77 K.

This paper describes the strain dependencies of I_c in both Bi(2212) and Bi(2223) tapes by applying the external reinforcement to them, at 77 K and 0 T. Morphologies of damage induced in the superconductors due to mechanical strain were also examined.

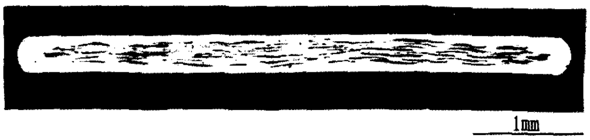
2. EXPERIMENTAL PROCEDURE

2.1. Samples

Two kinds of Ag/BSSCO samples were used; Bi(2212) 54 filament superconducting tapes with Ag/Ag-0.025wt% Mg-0.0125 wt%Ni alloy sheath, and Bi(2223) 57 filament tapes with Ag alloy sheath (supplied as VAM-1 for VAMAS bending RRT). They were prepared by a powder in-tube method. The dimensions were 4.8x0.3x40 mm for the Bi(2212) tape and 3.7x0.27x80 mm for the Bi(2223) one. Fig. 1 shows cross sectional views of samples supplied. They had Ag alloy/Ag/S.C. volume ratio of 45/35/20 for the Bi(2212) tape and sheath/SC ratio of 2.3 for the Bi(2223) one, respectively. In the case of tensile testing with the Bi(2212) tape, tapes of AgMgNi in the size of 4.8x0.1x40 mm were soldered on one or both sides of the sample. In the case of bending test with Bi(2223) tape, the AgMgNi tape was soldered on one side only; the tension or the compression side of the sample under bending.

2.2. Testing apparatus

For Bi(2212) tapes, the stress-strain relation and the tensile stress/strain dependence of I_c were investigated at 77 K and 0 T using the tensile testing apparatus described elsewhere [1]. For Bi(2223) tapes, fixtures having specific radii of curvature were used to apply a bending strain to the tape (which were prepared for RRT). In the case of tensile test in Bi(2212) tapes, the gage length and the voltage monitoring length were 18 and 5 mm, respectively. In the testing of I_c in Bi(2223) tapes at a bending strain, the Voltage tap separation was 30 mm. The criterion for I_c was 1 μV/cm.



(a) AgMgNi/Bi(2212) tape (54-filaments)

(b) Ag alloy/Bi(2223) tape (57 filaments)

Fig. 1. Cross sectional views of samples supplied.

3. RESULTS AND DISCUSSION

3.1. Effect of external reinforcement on I_c behavior in Bi(2212) tape under tensile strain

Fig. 2 shows the stress-strain curves of the AgMgNi sheathed Bi(2212) tapes measured at 77 K and 0 T. They showed a nearly similar Young's modulus (36 GPa), regardless of the existence of external reinforcement. When the Bi(2212) tape was reinforced externally by the AgMgNi tape at one side, the proof strength increased to 256 MPa from 108 MPa for the tape without the external reinforcement. In the case with the tape reinforcement at both sides of sample, more increase in the proof strength was achieved. With an increase in the amount of the external reinforcement, the mechanical properties at 77 K improved.

Strain dependencies of I_c in Bi(2212) tapes are shown *in Fig. 3. With an increase in the amount of the external* reinforcement, $\varepsilon_{irr.}$ increases, but the I_{c0} drastically decreases. The value of $\varepsilon_{irr.}$ for each case was shown in Table 1. The degradation in I_{c0} was due mainly to the damage induced into the superconductors by the thermal influence during soldering. The residual strain, $\varepsilon_{irr.}$, corresponding to the strain for onset of the I_c degradation could be deduced from I_c/I_{c0}-ε curve. The rough estimation of the residual stress using the law of mixture was performed to predict the residual strain induced in the oxide conductor. The calculated one was also shown in the same table. In the present study, it saturates to a value of 0.53 %. It can be seen that there exists a relation in a

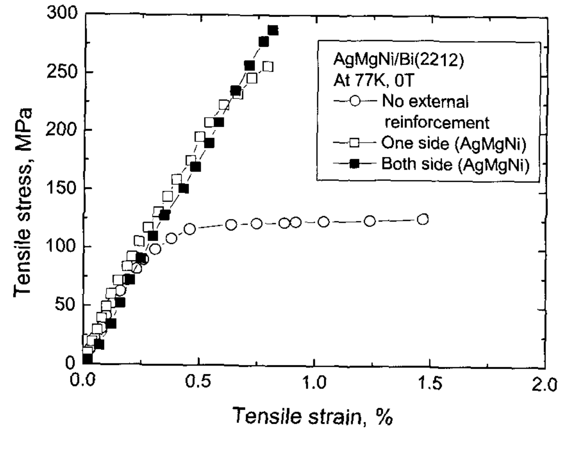


Fig. 2. Stress-strain curves of AgMgNi/Bi(2212) tapes at 77 K and 0 T.

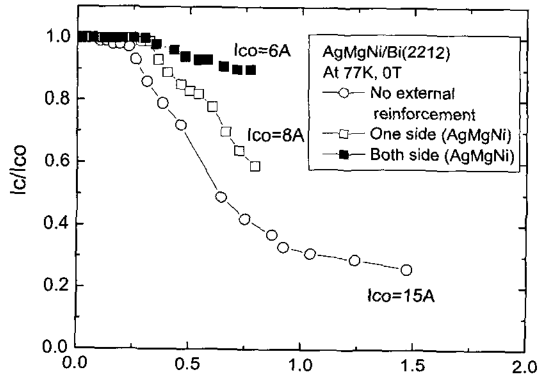
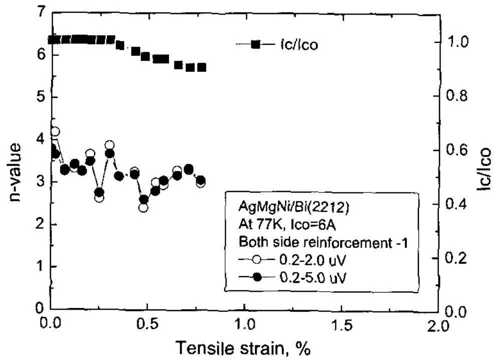
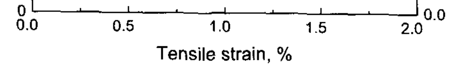


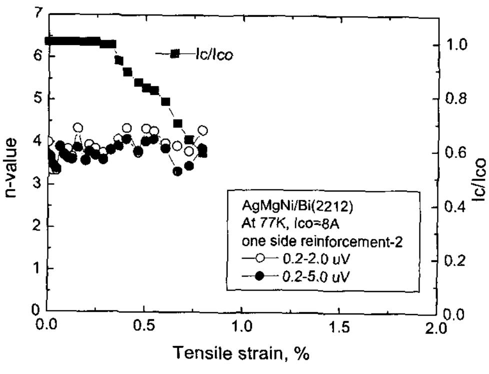
Fig. 3. Strain dependence on I_c/I_{c0} in AgMgNi /Bi(2212) tapes at 77 K and 0 T.



(a) No reinforcement



(b) One side reinforcement



(c) Both side reinforcement

Fig. 4. Tensile strain dependence of both I_c/I_{c0} and the n-value in Bi(2212) superconducting tapes.

TABLE I
RESIDUAL STRAIN PREDICTED BY I_c MEASUREMENT AND CALCULATION AND n-VALUE

Sample	I_{c0} (A)	$\varepsilon_{irr.}$ (%)		n-value*	
		Experimental	Calculated	0.2-2.0μV	0.2-5.0μV
Without reinforcement	15	0.28	0.51	5.5	4.8
With one side reinforcement	8	0.39	0.52	3.9	3.6
With both side reinforcement	6	0.77	0.53	3.5	3.2

qualitative sense between the experimental and calculated ones, excepting the case of both side reinforcement. In the case of both sides reinforcement, there existed a large difference between them because it had initially low I_{c0}. Therefore, any more degradation of I_c did not occur, even if a larger tensile strain was applied to the superconductor. According to the result by ten Haken [2], I_c decreases linearly to 80 % of peak value with a compressive strain up to 0.6 % and this cannot fully explain the present result.

From the I-V curves, the n-value for each condition was derived under different voltage range criteria. Fig. 3 shows the strain dependency of the n-value according to the external reinforcement. With an increase in the amount of reinforcement, the n-value decreased. That appeared to have been resulted from the current transfer through the AgMgNi reinforcement tape. It was also found that the averaged n-value within a region up to $\varepsilon_{irr.}$ was linearly related with the critical current at the applied strain free state (I_{c0}).

In the case without the external reinforcement (Fig. 4(a)), the strain dependency of both n-value and I_c showed a similar behavior. It means that the weak contacts in the oxide superconductor caused by the initiation and propagation of cracks produced the decrease in I_c and the corresponding n-value. On the other hand, in the cases with the external reinforcement of AgMgNi tape (Fig. 4 (b) and (c)), the n-value held a nearly constant value in spite of the decrease of I_c. The external reinforcement had a role to distribute the strain uniformly into the oxide conductor in the sample. It was different from the case without reinforcement (Fig. 4(a)) which the concentration of local strain occurred at the place where the crack initiated (Fig. 5). Due to the current distribution through the sheath layer when a local damage occurred, the n-value showed no appreciable change. At 77 K, further studies including the variation of n-value depending upon the cracking location were necessary for correct measurement of I_c degradation behavior in reinforced short sample due to mechanical deformation. Fig. 5 shows morphology of cracks induced in the oxide superconductor of Bi(2212) tape after tensile test. Some locally developed cracks aligning in a cross section of the superconductor can be seen.

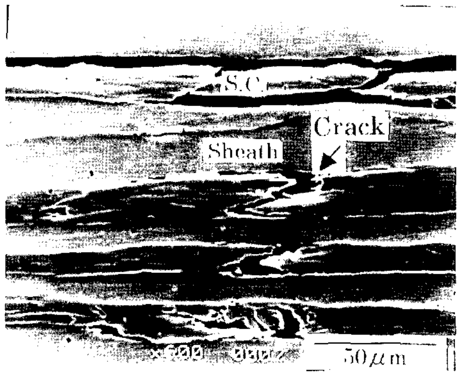


Fig. 5. Morphology of damage in Bi(2212) sample without any external reinforcement after the tensile test.

3.2. Effect of external reinforcement on I_c behavior in Bi(2223) tapes under bending strain

The Bi(2223) tapes supplied for VAMAS bending RRT (VAM-1) were used for investigating the influence of the external reinforcement on the I_c degradation behavior due to the bending strain effect. In this case, in order to apply the bending strain to the sample, GFRP fixtures having specific radii of curvature were used. The external reinforcement of AgMgNi tape was attached with Pb-Sn soldering on one side of the sample. The composite was

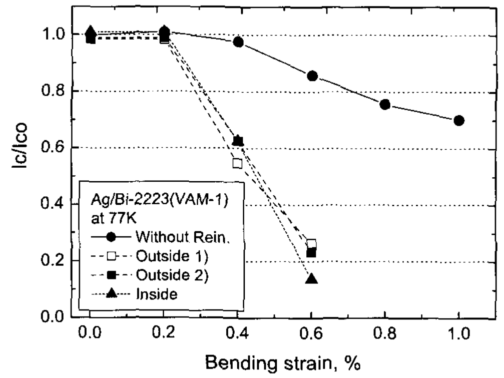


Fig. 6. Strain dependence of I_c/I_{c0} in Bi(2223) by external reinforcement of AgMgNi tape under bending strain.

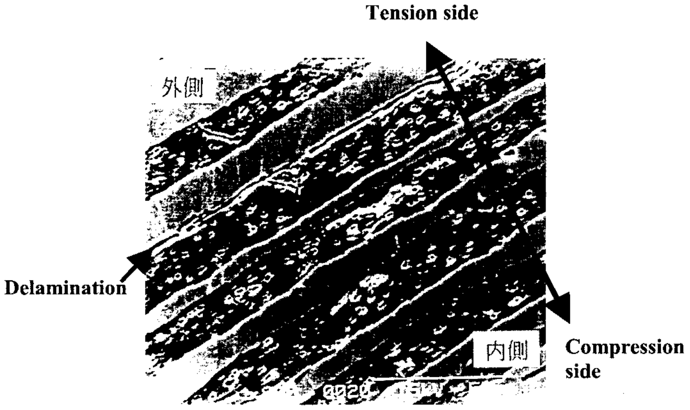
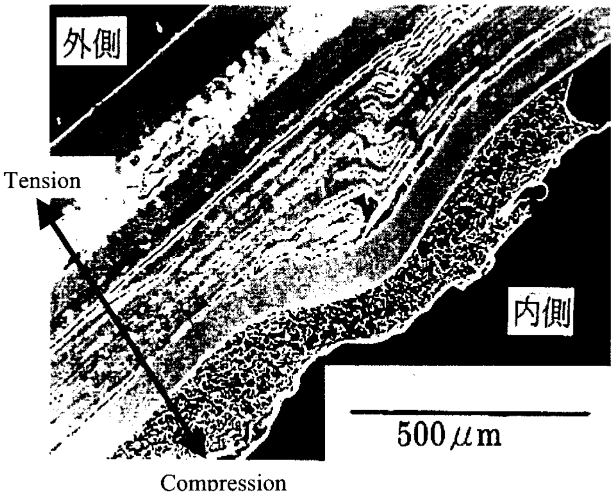
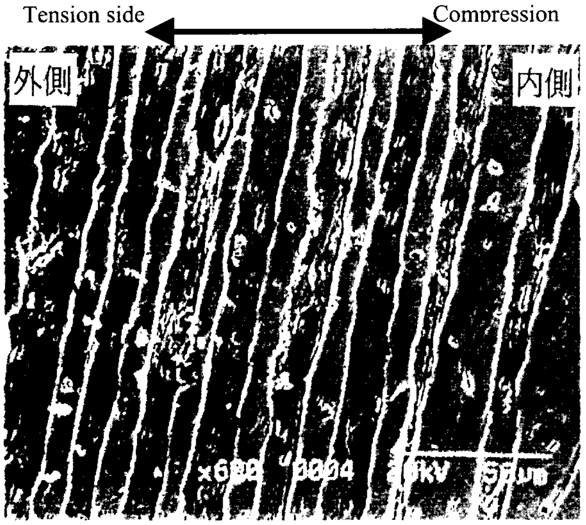


Fig. 7. Morphology of damage in Bi(2223) tape without any external reinforcement after the bending test at 1.0 %.



(a) Reinforced at tension side



(b) Reinforced at compression side

Fig. 8. Appearance of damage depending on reinforcement side after test at a bending strain of 0.6 %.

then bent and Indium soldered to the fixture setting the reinforcement either outside or inside of the sample. The external reinforcement of AgMgNi tape to the Bi(2223) tape will produce the movement of the neutral axis, a reference to define the bending strain. Especially, in the case of AgMgNi tape reinforcement to the tensile side, the neutral axis will move to the outward direction in the cross-section, and it will produce less tensile strain but larger compressive strain when compared with the case without reinforcement. It had been known that the I_c degradation of Bi(2223) tape under compressive strain region was less than that under tensile strain beyond the irreversible strain [2]. Therefore, it had been expected that some improvements in the I_c degradation characteristic could be achieved through the external reinforcement of high strength tape to the tension side of sample. Fig. 6 shows the results obtained from the bending effect test. Surprisingly, even at a small bending strain of 0.4 %, there occurred a significant degradation in I_c, irrespective of the reinforcement side. It was contrary to the expectation.

The SEM examinations of longitudinal cross-section of the samples after bending tests could explain the unexpected degradation behavior of I_c. Fig. 7 shows the micrograph of Bi(2223) tape without any external reinforcement after the bending test at 1.0 %. It can be seen that some cracks and delamination between sheath and superconductors were developed on the tension side of the sample, but no damage can be seen on the compression side. The cracks initiated at the tension region of the tape have developed into the compression region with the increasing of the bending strain applied. With regards to the influence of external reinforcement on the damage morphologies, Fig. 8 (a) shows a typical appearance of damage in the case of the tension side reinforcement after test at a bending strain of 0.6 %. In this case, at the compression side of the sample, extensively developed delamination and some failure of superconductors due to buckling can be seen. Maybe, these damages led to the significant degradation of I_c. The compressive stress concentrated at some irregularity in the filament during the bending test caused the buckling of superconductors. Fig. 8 (b) shows a typical damage appearance in the case of the compression side reinforcement after the test at a bending strain of 0.6 %. In this case, the cracking on the 5th layer of the filament from the outside of sample can be seen, although no appreciable damage can be seen in the samples without any external reinforcement. The damage including the cracks might have resulted in the significant degradation of I_c. In the case of the reinforcement of AgMgNi tape at the compression side, the increases in the tensile strain due to the expansion of the tension region resulting from the inward displacement of neutral axis have produced an interior bending strain-I_c characteristic.

4. CONCLUSIONS

1) With the external reinforcement of AgMgNi alloy tapes to the Bi(2212) tapes, the strength of the composite superconducting tapes increased but I_{c0} decreased in some cases. The strain for onset of the I_c degradation, $\varepsilon_{irr.}$, increased with an increase of the reinforcing volume and then saturated to a certain value.

2) The possibility of improvement in the degradation behavior of I_c by the external reinforcement of the AgMgNi alloy tape to the superconductor under bending was examined. Contrary to the expectation, it showed a significant I_c degradation even at a small strain of 0.4 %. The observations of damage morphologies gave a good explanation to the I_c behavior.

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