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Influences of Bending Temperature on the I_c Degradation Behavior of Bi-2223 tapes under Bending

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Abstract-- **The I_c degradation behavior of Bi-2223 tapes bent at RT and 77K were investigated using the bending device invented by Goldacker. Test results on fixing the tape at RT and 77K showed no difference. At 77K and RT bending, the critical strain was 0.67 and 0.50%, respectively, for the VAM-1 tape. For the AMSC tape, it was 0.94 and 0.88%, respectively. These results show that there is additional residual stress in the superconducting filaments to be bent at 77K which shifts the formation of cracks into smaller bending radii. This was proved by computational analysis based on the mixture rule of composites. For the VAM-1 tape, the I_c degradation behavior using the Goldacker type device shifted to higher strain levels at about 0.5%, as compared with the FRP sample holders which have a critical bending strain of about 0.24%. Also, for the externally reinforced AMSC tape, I_c degradation using the Goldacker type device begins at a higher strain level, at 0.88% as compared with using FRP sample holders, at 0.74%. The difference between both cases can be explained by the tensile and thermal stresses that the tapes were subjected to during fixing (soldering) when the FRP sample holders were used.**

1. INTRODUCTION

In applications such as coils, motors, power cables, and magnets, HTS tapes are subjected to various stresses and strains. The effects of stress and strain on the transport properties, especially the strain tolerance of the critical current, I_c, in BSCCO tapes have been studied because of their importance in practical aspects [1-5].

It has been established that I_c degradation mechanism in HTS tapes is due to crack formation in the superconducting filaments which irreversibly lowers the transport critical current. In BSCCO tapes, usually, the onset of I_c degradation is caused by the initiation of cracks in the superconducting filaments and the degradation characteristic of I_c with strain is influenced by the subsequent growth of cracks [5].

The improvement of the mechanical property, critical current density and critical tolerance strain of BSCCO tapes have been achieved by adopting multi-filaments [5], and by alloying the sheath material such as Ag-Mg alloy or reinforcing the BSCCO tapes externally with metallic foils such as stainless steel [6,7].

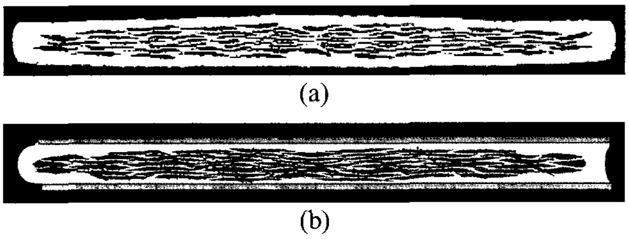
In order to determine a standard test method for the bending strain effect measurement, bending strain dependencies of HTS tapes were investigated using FRP sample holders adopting a series of bending radii in the framework of VAMAS round robin test (RRT) [8]. Recently, Goldacker et al [9] have developed a test rig which can change the bending radius of HTS samples continuously, and measure I_c without any additional thermal damage implicated during soldering or cooling down of the tapes used in the conventional testing procedure. Some studies regarding the application of the new test rig have already been reported in [9-11].

When the data obtained by the newly developed testing procedure are used, it is necessary to consider the real application situations of HTS tapes and compare it with the conventional test procedures. Therefore in this study, the I_c degradation behaviors of Bi-2223 tapes were investigated using the Goldacker type continuous bending test apparatus, and they were compared with the results obtained using the conventional method which uses FRP sample holders. Initially, influences of sample fixing and bending temperature on the I_c degradation behavior were examined to understand the characteristic of the Goldacker type testing apparatus during the I_c measurement at 77K. And then, a computational approach was also carried out to discuss the influence due to the difference of the thermal contraction coefficients of the test rig and sample.

2. EXPERIMENTAL PROCEDURE

Two commercial multifilamentary Bi-2223 superconducting tape samples were used for the tests. These tapes were fabricated using the powder-in-tube (PIT) method. Fig. 1 shows the cross sectional views of VAM-1 and AMSC tapes. The superconducting filaments are wrapped by the inner sheath of pure silver, and the outer sheaths are silver alloy for VAM-1 tapes. On the other hand, for the case of AMSC tapes, the top and bottom surfaces were reinforced with thin stainless steel foils. Table 1 shows characteristics of the samples used.

For the bending tests of Bi-2223 tapes in this study, a Goldacker-type device allowing a continuous change of the bending radius of the sample was used. Fig. 2 shows the Goldacker-type bending test rig, the details are given in [11]. Also, the conventional bending test using FRP sample holders was used for comparison.


(a)

(b)

Fig. 1. Cross-sectional views of (a) VAM-1 tape and (b) AMSC tape.

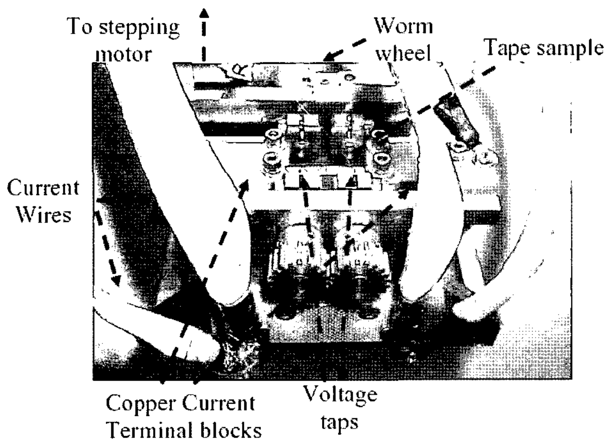


Fig. 2. The Goldacker-type bending strain rig which gives continuous change of the bending radius at RT and 77K.

TABLE I
SPECIFICATIONS OF BI-2223 TAPES.

Sample	VAM-1	AMSC
Width & Thickness (mm)	3.7 x 0.27	4.1 x 0.3
I_c (A)	50	115
Filament No.	57	55

The nominal bending strain of the tape, ε_b, is simply defined as the strain at the outer surface of the sample,

$$\varepsilon_b = t/2R \times 100(\%), \qquad (1)$$

where t is thickness, R is the radius of bending [8, 10, 12].

In the Goldacker type device, the tape is mechanically connected to the current terminal blocks instead of soldering in the cases using FRP sample holders. Therefore, it is possible to make some variations in the sample installation and bending procedures, such as fixing or bending temperature of the tape, to the sample. In the tests conducted using the Goldacker-type device, the total length of the tape sample, and the separation of voltage taps were 80mm, and 20mm, respectively.

Bending tests under 3 different test procedures were conducted to investigate the influence of bending temperature on the I_c degradation behavior and to find the possibility of adopting this to be a standard test method for the measurement of bending strain effects.

Room-temperature bending test procedures (designated as "RT bending" afterwards)

Test (1) One side of the sample was fixed at RT; The sample was cooled down to 77K in straight position together with the device; The cooling rate was about 10 °C/min; The other end was fixed after the device was cooled enough; I_{c0} was measured; The sample was warmed to RT; The sample was bent at RT; The sample was cooled down again to 77K; I_c was measured at a specified bending strain; The last four steps were repeated down to R_{min} (the minimum radius allowed to the tape by the device).

Low-temperature bending test procedure (designated as "77K bending" afterwards)

Test (2) One side of the sample was fixed at RT; The sample was cooled to 77K in straight position; The other end was fixed at 77K; I_{c0} was measured; The sample was then bent; I_c was measured at a specified bending strain; The last two steps were repeated down to R_{min}.

Test (3) Both sides of the sample were fixed at RT; The sample was cooled to 77K in straight position; I_{c0} was measured; The sample was bent at 77K ; I_c was measured at a specified bending strain; The last two steps were repeated down to R_{min}.

In the cases of FRP sample holders, the bending strain was applied to the tapes at RT, fixing the tape in a bent position on a curved sample holder and measuring the I_c after cooling down to 77K. This method was used in the VAMAS RRT [8]. In this case, the bending strain is also given in (1). The total length and the separation of voltage taps of the tape were 70 and 30mm, respectively.

Voltage-Current measurements were performed using the four-probe technique at 77K under self-field. I_c was determined by a 1 μV cm^{-1} criterion.

3. RESULTS AND DISCUSSION

3.1. Influences of sample-fixing temperature on I_c degradation behavior of Bi-2223 tapes.

In the case of 77K bending, initially, the fixing temperature of the Bi-2223 tape to the current terminal blocks of the Goldacker type device was varied at RT and 77K. According to the procedures of test (2) and (3) mentioned, the influences of sample fixing temperature on the I_c degradation during bending tests were investigated. Figs. 3 and 4 show the behavior of I_c as a function of bending strain, ε_b, for VAM-1 and AMSC tapes

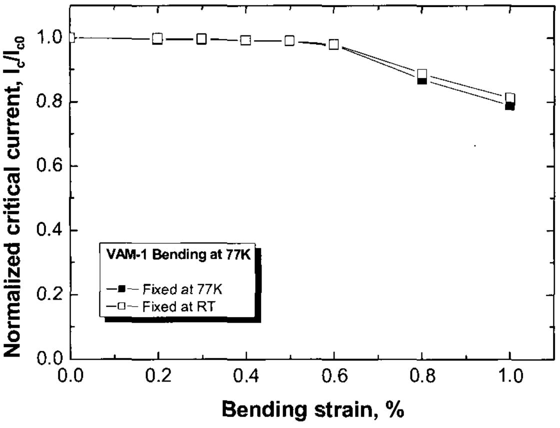


Fig. 3. Initial fixing temperature dependence of I_c degradation behavior for the VAM-1 tape.

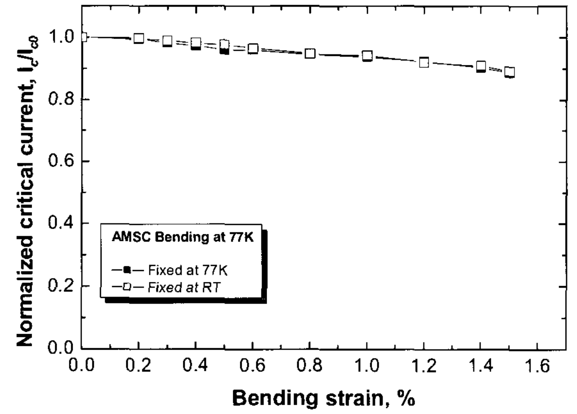


Fig. 4. Initial fixing temperature dependence of I_c degradation behavior for the AMSC tape.

respectively. It can be seen that there is no appreciable difference in I_c degradation behaviors according to the fixing temperature in both tapes, although it was expected that the extent of thermal strain induced in the superconducting filaments would be different depending on the fixing temperature. This behavior in the bending mode was different from the one in the tensile mode. This might have resulted from the configuration of the Goldacker type device allowing contraction of the sample during bending without being shaped or mounted on any specific radius. In the aspect of establishment of a standard test method, it is important to investigate the influence of substrate (mandrel) to support the tape at a specific radius during bending testing.

From these results, it will be interesting to investigate the bending temperature effect on I_c degradation when the Goldacker type device, which applies bending to the tape without any substrate, is adopted for the measurement of bending strain effects.

3.2. Influences of bending temperature on the I_c degradation behaviors of Bi-2223 tapes

Fig. 5 shows the normalized critical current I_c/I_{c0} as a function of the bending strain for VAM-1 tape depending on the bending temperature. In these cases, tests were carried out according to the procedures of test (1) and (2). It can be seen that I_c degraded in an irreversible way with increasing bending strain. For VAM-1 tapes, I_c degraded gradually with bending strain but the RT bending case showed earlier degradation as compared with the case of the 77K bending. The irreversible strain, $\varepsilon_{irr.b.}$, defined by $I_c/I_{c0} = 0.95\%$ was 0.50% for the RT bending, but it was 0.67% for the 77K bending. There exists about 0.17% difference in tolerable bending strain, depending on the bending temperature. This difference might have resulted from the existence of additional pre-compressive strain induced in the superconducting filaments due to bending at 77K, which shifts the formation of cracks into smaller bending radii. In addition, repeated warming up to RT of the sample to provide the bending strain might have produced further degradation of I_c in the case of the RT bending. These results have been previously observed in [10, 11].

However, for the AMSC tape sample, the irreversible strain was 0.94 and 0.88% for the 77K and RT bending, respectively, showing an insignificant difference of about 0.06% as shown in Fig. 6. This was believed to have resulted from AMSC tape's better strain tolerance when evaluated based on 95% I_c retention. The fact that the external reinforcement of stainless steel foils, having high Young's modulus, occupied a quite large portion of the cross-section of the tape resulted in less influence of bending temperature on $\varepsilon_{irr.b}$.

The data obtained by using FRP sample holders, which bent the tape at RT, were plotted in Fig. 5 and compared with RT bending cases. For the VAM-1 tape, the I_c degradation behavior using the Goldacker type device shifted to an $\varepsilon_{irr.b.}$ of 0.5%, as compared with the FRP sample holder which has an $\varepsilon_{irr.b.}$ of about 0.24%. The

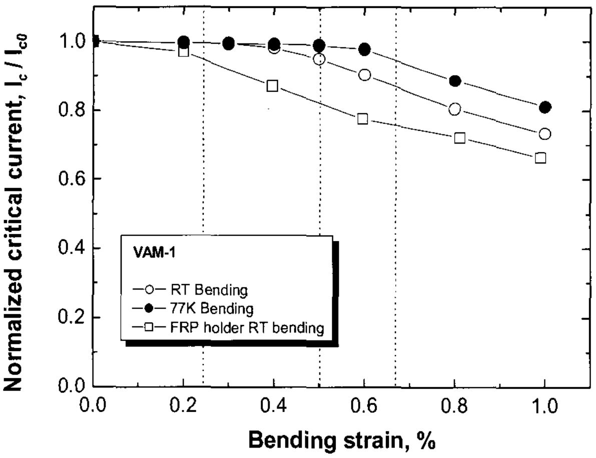


Fig. 5. Bending strain dependence of I_c bent at RT and 77K for VAM-1 tape sample using Goldacker and Conventional methods.

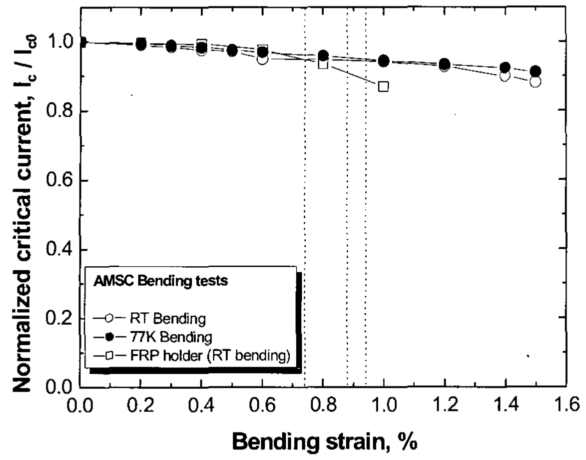


Fig. 6. Bending strain dependence of I_c bent at RT and 77K for AMSC tape sample using Goldacker and Conventional methods.

difference between both cases can be explained by the additional tensile and thermal stresses that the tapes were subjected to during soldering of the tapes when FRP sample holders were used. Similar results have been previously reported in [10, 11]. The data using AMSC tape were plotted in Fig. 6. I_c degradation using the Goldacker type device showed a slightly higher tolerable bending strain of 0.88% as compared with 0.74% for using FRP sample holders.

3.3. Computational Approach

The extent of the residual strain induced in the superconducting filaments of Bi-2223 tapes during cooling up to 77K can be calculated by considering the difference in the coefficients of thermal expansion, CTE, of their constituents and the applied temperature difference, ΔT. After cooling down from heat treatment temperature (1103K) to RT during fabrication of tapes, and further cooling to 77K for I_c measurement testing, the tape was assumed to have contracted with an average thermal expansion coefficient of the composite superconducting tape, α_c. Residual strain was induced in each component of Bi-2223 tapes: superconducting filament, Ag, and Ag alloy. Considering that the CTEs of Ag and Ag alloy are larger than those of the supeconducting filaments, it was assumed that the residual strain of Ag and Ag alloy will be tensile, while the residual strain of Bi-2223 filaments will be compressive. The yield stress of pure Ag is 13.2 MPa, and its strain hardening coefficient is 0.008. Therefore, it was believed that the Bi-2223 filament and the Ag alloy behaved elastically in the early stage of bending, while the pure Ag component behaved plastically when the thermal stress induced was greater than its yield stress. Table 2 and 3 provides the properties of constituents comprising the tapes. These values were cited from [13].

TABLE II
SAMPLE PROPERTIES OF VAM-1.

	Filament	Ag	Ag/Mg
Young's Modulus (GPa)	106	83	96
Volume Fraction	0.29	0.35	0.36
Coefficient of Thermal	14.4 x	19.5 x	19.4 x
Expansion (K-1)	10-6	10-6	10-6

TABLE III
SAMPLE PROPERTIES OF AMSC.

	Filament	Ag	SUS
Young's Modulus (GPa)	106	83	193.6
Volume Fraction	0.38	0.39	0.23
Coefficient of Thermal	14.4 x	19.5 x	9.6x
Expansion (K-1)	10-6	10-6	10-6

The computation of the residual strain was estimated from the CTE of the composite, superconducting filament, Ag, and Ag alloy. Applying the rule of mixture, the following equations can be used to calculate the residual strain (ε_{ri}) which was induced in the superconducting filaments during cooling.

$$\varepsilon_{ri} = [\alpha_{c(RT-77K)} - \alpha_{i(RT-77K)}]\,(T_{77K} - T_{RT}); \qquad (2)$$

$$\sigma_{r1} = \varepsilon_{r1}E_1 \qquad (3)$$

$$\sigma_{r2} = (1-\omega_2)\,\sigma_{y2} + \omega_2\varepsilon_{r2}E_2 \qquad (4)$$

$$\sigma_{r3} = \varepsilon_{r3}E_3 \qquad (5)$$

Subscripts 1, 2 and 3 refer to Bi-2223 filaments, Ag and Ag alloy, respectively. E_i, and α_i, are the Young's Modulus, and CTE, respectively, of each of the components. σ_{y2}, and ω_2, are Ag's yield stress and strain hardening coefficient, respectively. T_{RT} and T_{77K} are room temperature and liquid nitrogen temperature, respectively. The total stress in the composite is balanced from RT to 77K with the following: $\Sigma F_{ri} = 0$; $F_{ri} = \sigma_{ri}A_{ri}$. For all the components to be balanced, the following equation was used:

$$\sigma_{r1}A_1 + \sigma_{r2}A_2 + \sigma_{r3}A_3 = 0; \qquad (6)$$

where A_1, A_2 and A_3 are the cross-sectional areas of each component and can be represented by the volume fraction, V_i, in one dimensional tapes as follows:

$$\sigma_{r1}V_1 + \sigma_{r2}V_2 + \sigma_{r3}V_3 = 0; \qquad (7)$$

Substituting (2), (3), (4) and (5) in (7) will lead to (8) for the derivation of the CTE of the composite [12], and eventually, the pre-compressive strain in the filaments.

$$\alpha_C = \frac{(1-\omega_2)(\sigma_{y2})(V_2)}{[(T_{RT} - T_{77K})(E_1V_1 + \omega_2E_2V_2 + E_3V_3)]}$$

$$+\frac{(\alpha_1E_1V_1 + \omega_2\alpha_2E_2V_2 + \alpha_3E_3V_3)}{(E_1V_1 + \omega_2E_2V_2 + E_3V_3)} \qquad (8)$$

It was assumed that the CTE is constant in the region from RT to 77K. Therefore, for the VAM-1 tape, the overall CTE of VAM-1 tape would be:

$$\alpha_{c(VAM)} = 17.4 \times 10^{-6}\ K^{-1}$$

Then, from (2), the residual strain in the superconducting filaments would then be:

$$\varepsilon_{r1(VAM-1)} = -\ 0.38\%$$

But, in order to determine the real residual strain induced in the filaments, it is necessary to consider the constraints made by the Goldacker device to the tapes. Therefore, calculating for the actual residual strain in the superconducting filaments (during the bending test) by subtracting the thermal strain of the bending device to the residual strain of the VAM-1 tape would lead to:

$$\varepsilon_{r1(VAM-1,actual)} = \varepsilon_{r1(VAM)} - \varepsilon_{sus} = \alpha_c\Delta T - \alpha_{sus}\Delta T \qquad (9)$$

The calculated thermal strain of the sample holders made of stainless steel (SUS) during cooling to 77K is estimated to be $\varepsilon_{sus} = -\ 0.21\%$. Therefore,

$$\varepsilon_{r1(VAM-1,actual)} = -\ 0.17\%$$

For the AMSC tape, on the other hand, same calculations were carried out but SUS were substituted instead of Ag alloy in the above equations: $\alpha_{c(AMSC)} = 12.2 \times 10^{-6}\ K^{-1}$, $\varepsilon_{r1(AMSC)} = -\ 0.27\%$, $\varepsilon_{r1(AMSC,actual)} = -\ 0.06\%$.

For both the VAM-1 and the AMSC tapes, the calculated residual strains were similar to the measured ones of 0.17 and 0.06%, respectively. It can be observed that the AMSC tape has experienced less residual strain than the VAM-1 tape of which was caused by the lower CTE of externally reinforced SUS foils of the AMSC tape.

4. CONCLUSIONS

The I_c degradation behavior of Bi-2223 tapes bent at RT and 77K were investigated using the Goldacker type bending device. Test results on fixing the tape at RT and 77K showed no difference of I_c degradation behavior under bending. They have shown that the bending strain tolerance of I_c of the Bi-2223 tapes significantly depended on the bending temperature adopted for the VAM-1 tapes. At 77K and RT bending, the critical bending strain was 0.67 and 0.50%, respectively for the VAM-1 tape. For the AMSC tape, however, it was 0.94 and 0.88%, respectively. These results show that there is larger residual stress in the superconducting filaments to be bent at 77K which shifts the formation of cracks into smaller bending radii. These were also proved by the computational analysis based on the mixture rule of composites. Additionally, it was found that the I_c degradation behavior using the Goldacker type device shifted to higher strain levels as compared with the FRP sample holders.

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