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Investigation of I_c Degradation Behavior in Bent Bi-2223 Tapes under Pressurized Liquid Nitrogen using a ρ-shaped Sample Holder

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Abstract-- **The degradation behavior of the critical current (I_c) of Bi-2223 superconducting tapes under pressurized liquid nitrogen were investigated using a newly developed ρ–shaped sample holder which gives a series of bending strains to a sample. Three kinds of commercially available multi-filamentary Bi-2223 superconducting tapes were used. At atmospheric pressure, the I_c degradation behavior depended on the manufacturing process undergone by each tape. The tapes externally reinforced or densified by over pressure showed better bending strain tolerance than the Ag alloy-sheathed Bi-2223 tape. But these tapes showed a significant I_c degradation when pressurized to 1 MPa in liquid nitrogen. For all samples, after depressurization to atmospheric pressure from 1 MPa, the I_c was completely recovered to its initial values at atmospheric pressure. When the samples were subjected to a thermal cycle wherein the tape was warmed up to room temperature after being depressurized from 1 MPa, it was found that the larger degradation of I_c occurred at the regions where significant ballooning occurred, such as 0% and 0.2%. However, an improved ballooning damage tolerance was observed in the highly-densified tape.**

1. INTRODUCTION

The evaluation of endurance and reliability of high temperature superconducting (HTS) tapes are necessary for practical applications such as power transmission cables, motors, magnets and coils adopting $Bi_2Sr_2Ca_2Cu_3Ox$ (BSCCO) and coated conductor (CC) tapes. These HTS tapes are subjected to various stresses and strains during fabrication, cooling down and operation. The effects of stress and strain on the transport properties in BSCCO tapes have been mainly studied at atmospheric conditions [1-5]. Among the various types of stresses occurring in superconductors in practical applications, the stress/strain under bending occurs most commonly in superconducting wires or tapes when they are wound in a coil shape for magnet construction [2, 6]. Therefore, the bending strain effect on critical current, I_c, has been studied widely.

It is also necessary to consider its environmental operating conditions, the influence of pressurization due to vaporization of liquid nitrogen (LN_2) on the transport property of Bi-2223 tapes, which is expected in a closed cryostat system.

In addition, when the BSCCO tapes were warmed up after cooling to 77K, ballooning of the cross section due to the rapid vaporization of LN_2 which diffused into the pores and cracks in the filaments through the defects in the sheath materials resulted in the I_c degradation [7].

The improvement of the mechanical property, critical current density and critical tolerance strain of BSCCO tapes have been achieved by adopting multi-filaments [5], by alloying the sheath material such as Ag-Mg alloy, by reinforcing the Bi-2223 tapes externally with metallic foils such as stainless steel [8, 9], and by adopting a sintering process under high pressure to achieve full densification of the ceramic core [7]. Therefore, it is interesting to investigate how the fabrication and the reinforcement processes adopted in the Bi-2223 tapes influence on the ballooning characteristics of these tapes.

In order to determine a standard test method for the bending strain effect measurement, bending strain dependencies of I_c in HTS tapes were investigated using FRP sample holders in the framework of VAMAS round robin test (RRT) [10]. Recently, Goldacker et al [11] have developed a test rig which can change the bending radius of HTS samples continuously at RT and 77K. However, the currently available test methods are not suitable for bending test under pressurized LN_2. Therefore, the development of a new test procedure which facilitates the mounting of the sample and lessens the testing time is still needed.

In this study, in order to investigate the transport property of Bi-2223 tapes at bent state under pressurized LN_2, a ρ-shaped sample holder was devised which gives a series of bending strains to a tape in just single mounting and a cryostat incorporating a stainless steel dewar was set-up which allows to pressurize LN_2 up to 1 MPa. In addition, the effects of pressurization of LN_2 on the I_c degradation behavior with bending strain were investigated. The effects of thermal cycle on the I_c degradation and ballooning damage in Bi-2223 tapes were examined.

2. EXPERIMENTAL PROCEDURE

In this study, three different kinds of commercially available Bi-2223 tapes were supplied. Fig. 1 shows the cross-sectional view of the tape samples.

TABLE I
SPECIFICATIONS OF BI-2223 SUPERCONDUCTING TAPES

Sample designation	Dimension	I_c at (77K)	Filament No.	Reinforcement	Yield stress at 77K (MPa)	Manufacturer
KERI	4.0 x 0.2	70	55	Ag alloy sheath	135	Nexans Korea
ERT	4.1 x 0.3	150	55	Stainless steel foils	360	AMSC
OPT	4.1 x 0.2	100	61	Densification of filaments (HIP)	200	Sumitomo

TABLE II
PROPERTIES OF THE COMPONENTS OF KERI TAPES

	Filament	Ag	Ag/Mn
Young's modulus (GPa)	106	83	83
Volume fraction	0.256	0.317	.427
Coefficient of thermal expansion (K^{-1})	14.4×10^{-6}	19.5×10^{-6}	18×10^{-6}

TABLE III
PROPERTIES OF THE COMPONENTS OF AMSC TAPE

	Filament	Ag	SUS foils
Young's modulus (GPa)	106	83	193.6
Volume fraction	0.326	0.438	0.236
Coefficient of thermal expansion (K^{-1})	14.4×10^{-6}	19.5×10^{-6}	18×10^{-6}


(a) KERI tape

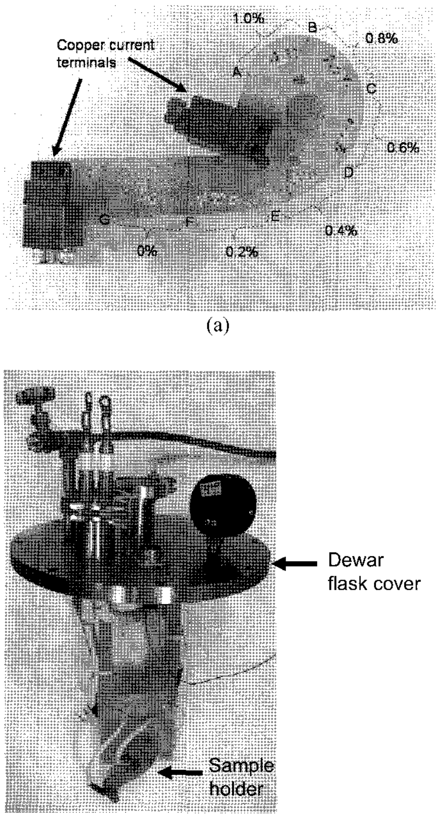

(b) ERT tape


(c) OPT tape

Fig. 1. Cross-sectional views of Bi-2223 tape samples used.

Their specifications and properties are listed in Tables I, II and III. All the samples were fabricated by the powder-in-tube (PIT) process. They have different reinforcement geometries. The KERI tape was reinforced by an outer Ag alloy sheath. The ERT tape was reinforced externally by soldering stainless steel foils on both sides of the tape. The OPT tape which has an outer sheath of Ag alloy was densified by the over-pressure treatment.

For bending tests under pressurized liquid nitrogen, a newly designed ρ–shaped sample holder (called as mandrel afterwards) and a cryostat for pressurization were used as shown in Figs. 2 (a) and (b). The mandrel gives nominal bending strains corresponding to approximately 0%, 0.2%, 0.4%, 0.6%, 0.8% and 1.0%. Unlike the conventional sample holder used in the VAMAS round robin test which needed to successively change bending mandrels with increasing bending strain [10], this sample holder produces the same desired effect with a significantly lesser test procedure. The cover assembly of the cryostat for pressurization test includes a pressure gauge, a relief valve, voltage tap and current wire connectors, LN_2 inlet, and a N_2 gas outlet shown in Fig. 2 (b).



(b)

Fig. 2. Devices used to measure I_c -ε_b relationship under pressurized LN_2. (a) A sample holder which gives a series of bending strains to Bi-2223 tapes, (b) view of the cover assembly of cryostat for pressurization.

The experimental procedures for the bending tests under pressurized LN_2 were as follows: 1) The sample was mounted to the mandrel at RT. It was initially fixed on the current terminal near point A and then carefully mounted (bent) around the mandrel, and finally fixing it on to the current terminal near point G mechanically; 2) The cover assembly including the mandrel was slowly cooled down and was fixed to the dewar; 3) I_c was measured at atmospheric condition for all bending strain values; 4) The pressure was increased to the specified levels, such as 0.3. 0.5, 0.8 and 1 MPa, and I_c was measured after maintaining at each pressure level for 30 minutes. 5) The dewar was depressurized to atmospheric condition after I_c measurement test at 1 MPa; 6) I_c was measured again for all bending strain values; 7) The tape was warmed up to RT (waiting time was approximately 20mins) and cooled down to 77K again to give a thermal cycle; 8) I_c was measured for all bending strain values at atmospheric pressure; 9) Thickness of the Bi-2223 tape at each interval between voltage taps was measured at RT.

The bending strain of the tape in a bent position on the mandrel is given in Eqs. (1) and (2). The nominal bending strains of the tape, ε_b, were defined at the outer surface of the sample and at the outermost filament in the sample,

$$\varepsilon_b = \frac{t}{2R+t} \times 100\% \quad \text{(at outer surface)} \qquad (1)$$

$$\varepsilon_b = \frac{t_f}{2R+t} \times 100\% \quad \text{(at outermost filament)} \qquad (2)$$

where t is the sample thickness, R is the bending radius at each voltage separation [12,13], and t_f is the approximate thickness of the filament bundle layer on the cross-section. The total length of the specimen and the separation of voltage terminals were 160 and 20 mm, 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 criterion. In the case of I_c measurement, the test started from point A of the sample where the largest bending strain was applied.

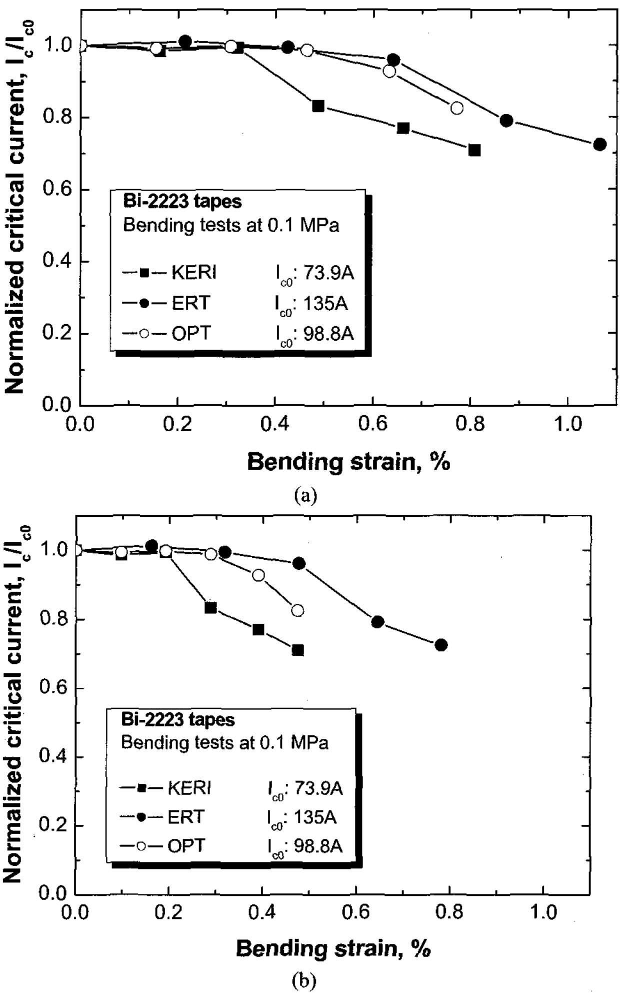
3. RESULTS AND DISCUSSION

A. I_c degradation behavior at atmospheric pressure

At atmospheric pressure and as-cooled state, the I_c degradation behaviors of 3 different samples with bending strain obtained using the newly developed mandrel are shown in Figs. 3 (a) and (b). The I_c degradation behavior depended on the manufacturing process undergone by each tape and can be classified into two. The Ag alloy-sheathed Bi-2223 (KERI) tape showed an early degradation of I_c with bending strain. The critical bending strain, $\varepsilon_{irr.}$, which was defined as the strain for 95% I_c retention is about 0.37%. While the tapes which underwent additional reinforcement or high densification by HIP process showed a good bending strain tolerance of I_c. The $\varepsilon_{irr.}$ for the OPT and ERT tapes were about 0.57% and 0.66%, respectively.

Although similar in composition and structure, the additional strength of the OPT tape when compared with the Ag alloy sheathed KERI tape is due to the suppression of pores and cracks of the superconducting filaments which increased the mechanical strength of the tape significantly [7]. The higher strength of the ERT tape is due to the reinforcement of high-strength stainless steel foils. When the ERT tape was cooled down to 77K, the additional pre-compressive strain induced in the filaments resulted from the larger coefficient of thermal expansion of the stainless steel as compared with that of the Bi-2223 filaments as given in Table 3, and it resulted in a larger strain tolerance of I_c as compared with other tapes. Therefore, for the design of superconducting tapes and wires, it is important to consider the behavior of all the materials when cooled to cryogenic temperatures. Especially, the coefficient of thermal expansion of the sheath materials should be considered since this would play a major role in the irreversible strain of the current carrying performance of the superconducting filaments.

The bending strain at the outermost filament in each sample was also calculated, and the I_c degradation behavior with bending strain at the outermost filament was plotted in Fig 3 (b), making it possible to estimate the strain level at the filament part causing I_c degradation. No significant differences can be seen in the I_c degradation behavior for all samples when compared with Fig. 3 (a), except that the irreversible strain for I_c degradation became less than for those where the bending strain was computed at the outer surface of the tape.



(a)

(b)

Fig. 3. Bending strain dependence of I_c for each tape at atmospheric pressure state. (a) the bending strain measured at the outer surface and (b) the bending strain measured at the outermost filament of each Bi-2223 tape.

B. Effects of pressurization and ballooning on the I_c of

Bi-2223 tapes

Fig. 4 shows the I_c degradation behavior with bending strain at LN_2 pressurized to 1 MPa for each tape. It was observed that the I_{c0} values at 1 MPa for each sample were decreased by about 20-32% when compared with the case at atmospheric conditions. Depending upon the sample geometry supplied, they showed different I_c degradation behavior. The KERI tape showed pressure-independent behavior of I_c even though I_{c0} decreased with the increase of the applied pressure. The OPT and ERT tapes showed a pressure-dependent I_c degradation behavior. The higher pressure applied produced larger degradation of Ic with bending strain. This lowering of I_c values in Bi-2223 tapes under pressurized liquid nitrogen was mainly caused by the increase in temperature of LN_2 due to pressurization.

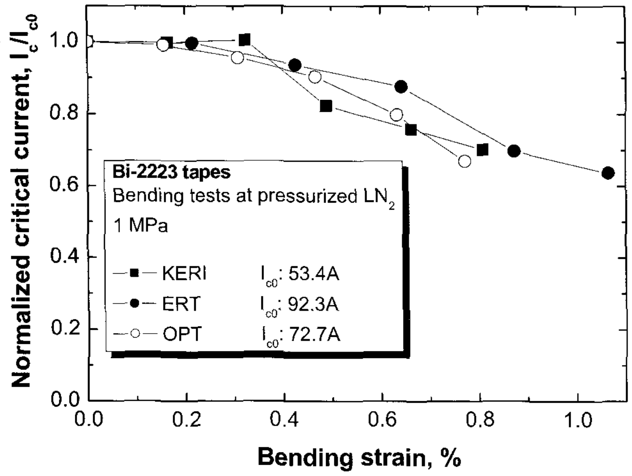
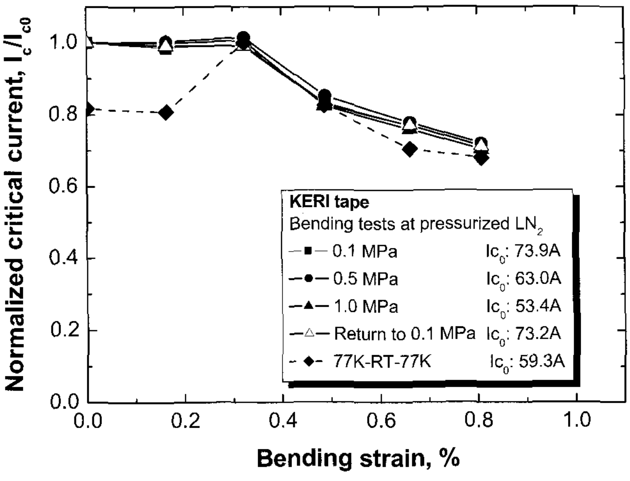


Fig. 4. Bending strain dependence of I_c for each tape at pressurized LN_2 state.

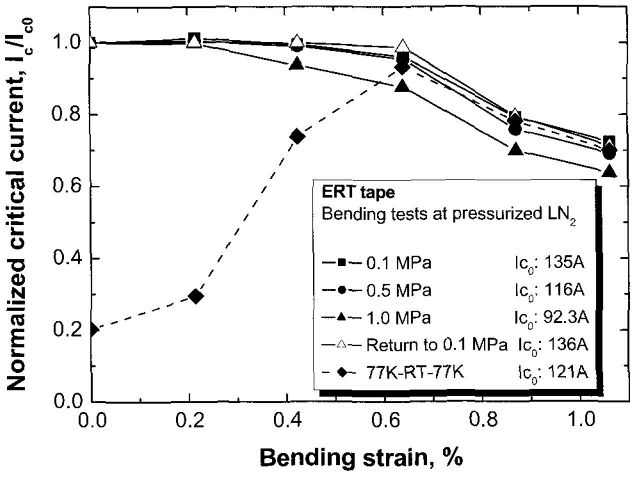
In the case of the KERI sample, no effects due to pressurization existed on the I_c degradation behavior, especially on the critical bending strains for I_c. But for the OPT and ERT tapes, there occurred a gradual decrease of I_c with the increase of the pressure applied. Eventually, the $\varepsilon_{irr.}$ for I_c degradation became similar to the case of the KERI tape. From this result, it can be found that the Bi-2223 tapes which have superior mechanical and electrical properties due to external reinforcement or densification showed a pressure-dependent behavior of I_c.

After pressurizing the tape up to 1 MPa, the pressure in the cryostat was depressurized down to atmospheric pressure and then the I_c was measured. For all samples, the I_c was recovered to its initial state at atmospheric pressure. These results show that the pressurization of LN_2 up to 1 MPa did not cause any permanent damage on to the superconducting filaments although some tapes showed pressure dependent behavior of I_c. This indirectly indicates that the application of higher hydrostatic pressure to Bi-2223 tapes reduced the pre-compressive strain induced on the filaments in ERT and OPT tapes.

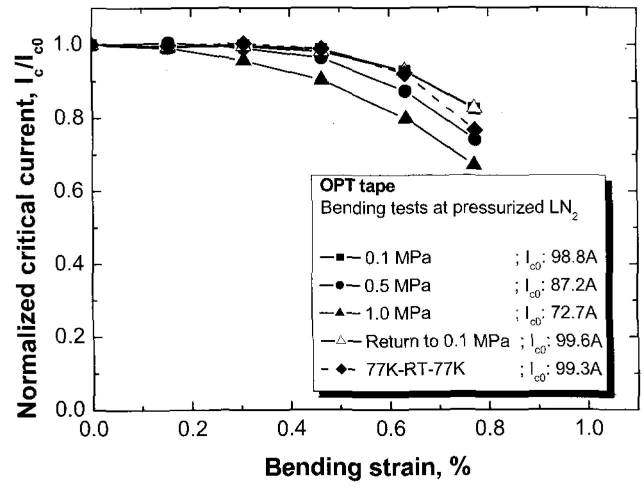
A thermal cycle (77K-RT-77K) was given to the samples after depressurization and its influence on I_c degradation behavior was examined. The result was added in Fig. 5 as a dotted line. By comparing the results with the



(a) KERI tape



(b) ERT tape



(c) OPT tape

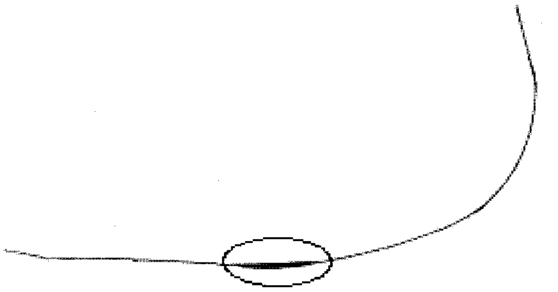
Fig. 5. shows the I_c degradation behaviors of Bi-2223 tapes at the pressurized and depressurized states.

ones at atmospheric pressure and at depressurized state, it can be found that the current carrying capacity of Bi-2223 tapes was affected by the thermal cycle produced by warming up to room temperature.

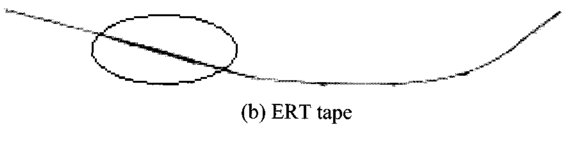
Except for the OPT tapes, I_c degradation occurred in other tapes, especially at smaller bending strain regions like 0% and 0.2%. The occurrence of ballooning was suppressed at larger bending strain regions where the tight contact of the tape to the mandrel gives a structural constraint to the tape under the bending.

Fig. 6 shows the ballooning which occurred to different tapes at differently bent regions after bending tests under pressurized LN_2. Comparing with Figs. 5 (a) and (b), the regions where I_c degradation occurred well corresponded to the regions where ballooning occurred. This ballooning damage was caused by the rapid vaporization of LN_2, which diffused during pressurized testing through the defects of the sheath, when it was warmed up to RT from 77K [7,13]. This ballooning damage resulted in the significant degradation of I_c because it produced a severe deformation or breakage of the filaments [7].

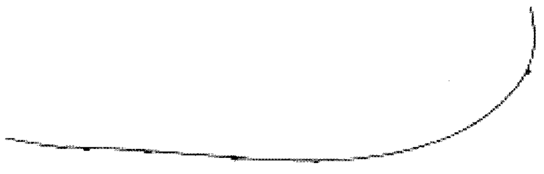
For the OPT tape, no ballooning was observed and therefore I_c did not degrade after a thermal cycle. As a result, it can be said that the high densification eliminated the pores and cracks in the filaments in the Bi-2223 tape and improved the I_c degradation behavior at pressurized state through the suppression of ballooning damage to Bi-2223 tapes [7].



(a) KERI tape



(b) ERT tape



(c) OPT tape

Fig. 6. Appearance of samples after a thermal cycle and I_c measurement test. Ballooning damage was encircled.

4. CONCLUSIONS

1) At atmospheric pressure, the Ag alloy-sheathed Bi-2223 tape showed an early degradation of I_c with bending strain. While the tapes which underwent additional reinforcement and densification showed a superior bending strain tolerance of I_c.

2) It was observed that the I_{c0} values at pressurized LN_2 to 1 MPa were decreased by about 20-32% when compared with the case at atmospheric conditions. It appeared significantly in ERT and OPT tapes.

3) The Ag alloy-sheathed Bi-2223 tape showed a pressure-independent behavior of I_c. The OPT and ERT tapes showed a pressure-dependent I_c degradation behavior. After depressurization from 1 MPa, for all tapes, the I_c was recovered to its initial state at atmospheric pressure, which represents that any permanent damage did not occur in the superconducting filaments.

4) Except for the highly-densified tape, a thermal cycle after pressurization affected the current carrying capacity of Bi-2223 tapes due to ballooning. The regions where significant I_c degradation occurred well corresponded to the regions where ballooning occurred.

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