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Transport Property of Externally Reinforced Bi-2223 Superconducting Tape under Axial Fatigue Loading

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Abstract--**For practical applications, the evaluation of reliability or endurance of HTS conductors is necessary. The mechanical properties and the critical current, I_c, of multifilamentary Bi-2223 superconducting tapes, externally reinforced with stainless steel foils, subjected to high cycle fatigue loading in the longitudinal direction were investigated at 77K. The S-N curves were obtained and its transport property was evaluated with the increase of repeated cycles at different stress amplitudes. The effect of the stress ratio, R, on the I_c degradation behavior under fatigue loading was also examined considering the practical application situation of HTS tapes. Microstructure observation was conducted in order to understand the I_c degradation mechanism in fatigued Bi-2223 tapes.**

1. INTRODUCTION

In the application fields such as coils, motors, power cables and magnets, HTS tapes are subjected to various kinds of stresses. The effects of stress/strain on the superconducting properties, the strain tolerance of the critical current, I_c, in the Ag sheathed BSCCO(Bi(Pb)-Sr-Ca-Cu-O) tapes, have mostly been studied because of the importance in the superconducting device design aspects [1-3]. It is also well established that the 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 the I_c with strain is influenced by the subsequent growth of cracks.

The improvement of the mechanical property, critical current density and critical tolerance strain of BSCCO tapes have been achieved by adopting multi-filaments [4], and by alloying the sheath or reinforcing the BSCCO tapes externally with metallic foils such as stainless steel [5,6].

During the service life of electric devices using superconducting tapes, the components will be subjected to cyclic loading which are caused by various reasons such as thermal cycling, variation in Lorentz forces due to changes in coil current, and alternating centrifugal forces during motor operation. Therefore, in order to apply HTS tapes to practical superconducting devices such as magnets, power transmission cables and motors, the reliability evaluation of the tapes which includes the mechanical and electrical reliability are necessary. Although the mechanical property tests of Bi-2223 tapes have already been performed in many laboratories, available information or data on the mechanical and electrical properties of these HTS tapes under fatigue loading are still insufficient [7-10]. Therefore the investigation of fatigue behaviors of BSCCO tapes will be of great significance in the design of superconducting devices, especially in the aspect of their reliability [11].

In this study, the mechanical properties and the critical current. I_c, of multifilamentary Bi-2223 superconducting tapes, externally reinforced with stainless steel foils, subjected to high cycle fatigue loading were investigated at 77K. Especially, the influence of the stress ratio on the electrical property of Bi-2223 tape under fatigue loading was examined. In addition, microstructure examination was performed in order to understand the damage mechanism which occurred under fatigue loading.

2. EXPERIMENTAL PROCEDURE

A commercially available Ag-sheathed Bi-2223 multifilamentary superconducting tape was supplied for the experiments (manufacturer: AMSC; high strength reinforced wire). The tape was fabricated by the powder-in-tube (PIT) method and reinforced with stainless steel foils by soldering on both sides. Fig. 1 shows the cross-sectional view of the sample. Tape width and thickness are 4.2mm and 0.3mm, respectively. The I_c at 77K is about 150A.

Monotonic tensile and high cycle fatigue tests of the Bi-2223 tape were conducted at RT and 77K using a hydraulic-servo material testing machine (Instron type 8516, loadcell capacity: 5 kN). The total length of the specimen and the gage length between the gripping holders were 80mm and 40mm, respectively. The specimen was fixed at both ends to the upper and lower gripping holders, shown in Fig. 2. The upper gripping holder was attached to the loadcell and the lower one was set on the fixture of the loading frame which was connected to the actuator of the testing machine. For testing at 77K, the test fixture including the specimen was slowly cooled down to 77K taking about 10 min. The thermal contraction of the specimen which occurred during cooling was released by the clearance put between the lower gripping holder and the fixture.

In order to evaluate the mechanical properties of the Bi-2223 tapes supplied, monotonic tensile tests were

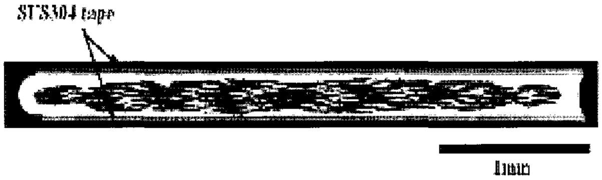


Fig. 1. Cross-sectional view of the sample supplied.

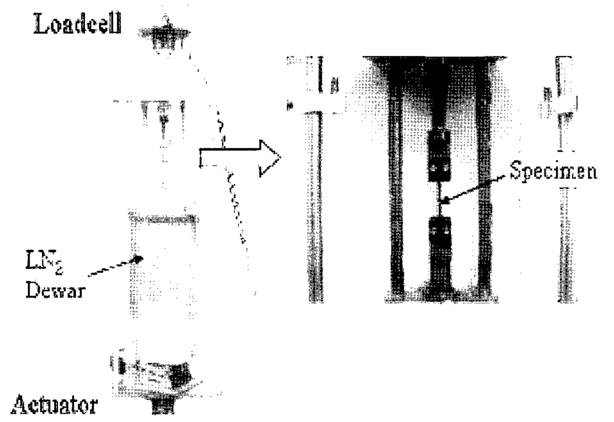


Fig. 2. Photos of apparatus and fixtures for tensile and fatigue tests of HTS tapes at RT and 77K.

initially performed at a ram rate of 1 mm/min. Based on the obtained yield stress, σ_y, the applied maximum stress levels were determined and they were in the range of 0.65 ~ 0.98 σ_y. The fatigue tests were carried out at constant stress amplitude at RT and 77K. The influence of the stress ratio on the fatigue behavior of Bi-2223tapes was investigated The stress ratio was defined as the ratio of the minimum to the maximum stress in each cycle. The stress ratios adopted in this study were 0.1 and 0.5. The frequency was 10 Hz, but it was 1 Hz up to 100 cycles.

For the I_c measurement during fatigue tests, GFRP sheets were inserted between the specimen and the gripping holders for electrical insulation. An I-V curve was measured using the four-probe method at 77K under self-field, and the I_c was defined by a 1 μV/cm criterion. Voltage taps were attached at the central region of the specimen with a separation of 20mm. During fatigue tests, the I_c was measured at the mean stress level of the stress amplitude at specific numbers of repeated cycles, N, such as 10, 100, 1,000, 10,000 and so on and normalized by the I_{c0} value obtained at the as-cooled state.

From the I-V curve obtained, the n-value was also calculated by a linear fitting in the voltage range of 0.2 ~ 5.0 μV/cm. The voltage, V, in the transition range from the superconducting state to the normal state can be empirically approximated by $V=cI^n$ as a function of current, I, where c is a constant. The behavior of the n-value with repeated fatigue cycles allows predicting the damage process which indirectly occurred in the Bi-2223 tapes under fatigue loading.

3. RESULTS AND DISCUSSION

Fig. 3 shows the stress-strain curves obtained by monotonic tensile tests of externally reinforced Bi-2223 tapes at RT and 77K. From the curve, some design parameters such as the Young's modulus and the 0.2% offset yield stress, σ_y, can be derived. At 77K, the externally reinforced Bi-2223 tapes showed significant hardening, therefore the yield stress increased to 460 MPa at 77K from 360 MPa at RT.

Fig. 4(a) indicates I_c/I_{c0}-ε_t relationships obtained by tension tests of the Bi-2223 tapes at 77K and 0T. The I_c measured at each tensile strain applied to the tape was normalized by the I_{c0} obtained at ε = 0% and 77K. Up to about 0.4%, the Bi-2223 tapes exhibited little degradation in I_c. After that, the I_c decreased rapidly as the tensile strain increased. The critical tensile strain for the onset of I_c degradation, $\varepsilon_{t.irr.}$, was defined as the strain for the I_c reduction to I_c/I_{c0}=0.95. It is about 0.48% for the Bi-2223 tape. The value was large since both sides of the tape are externally reinforced with stainless tapes. On the other hand, the critical tensile stress for the onset of I_c degradation, $\sigma_{t.irr.}$, is 340 MPa.

In order to obtain the S-N curves of externally reinforced Bi-2223 tapes, fatigue tests were performed under constant stress amplitude with R=0.1 at RT and 77K. The results are shown in Fig. 5. In this study, the fatigue lives of specimens tested were located in the range of $4\times10^4 \sim 10^6$cycles. Although some scattering of data existed, a relatively good S-N curve was obtained at both temperatures, which are similar to the cases of structural materials [13].

It was observed that almost all specimens failed near or on the edge of the gauge length in the place where the specimen was in contact with the gripping holders. It is believed that the contact damage which occurred between the specimen and the holders during the fatigue test might have caused the failure of the specimen. At 77K and at the maximum stress of 300 MPa corresponding to $0.65\sigma_y$, the specimen did not fail until 10^6 cycles representing the increase of a fatigue tolerance stress (called the mechanical fatigue limit), as compared with that at RT. The mechanical fatigue limit of the externally reinforced Bi-2223 tapes

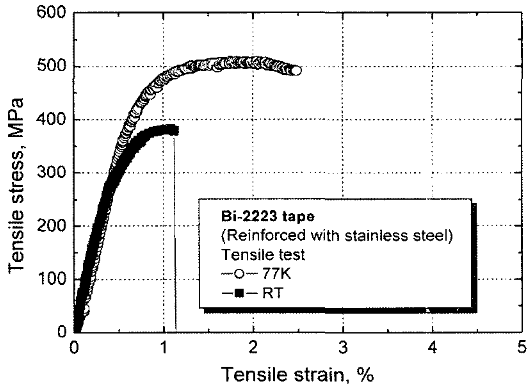
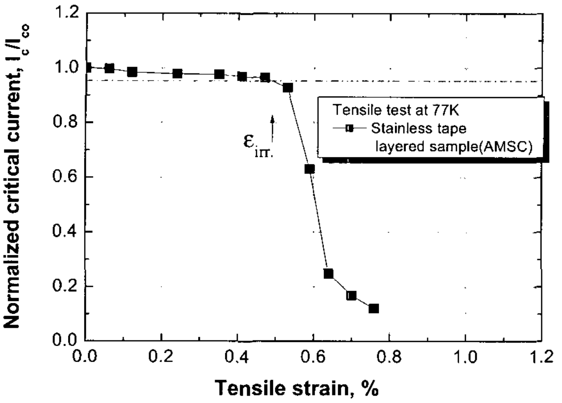
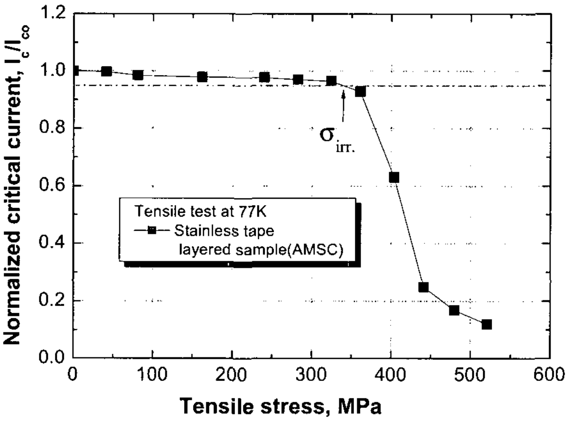


Fig. 3. Tensile stress-strain curves of stainless steel reinforced Bi-2223 tapes at RT and 77K.



(a) I_c/I_{c0}-strain relationship



(b) I_c/I_{c0}-stress relationship

Fig. 4. I_c/I_{c0}-stress/strain relationship of externally reinforced Bi-2223 tapes; $\sigma_{irr} = 340$MPa.

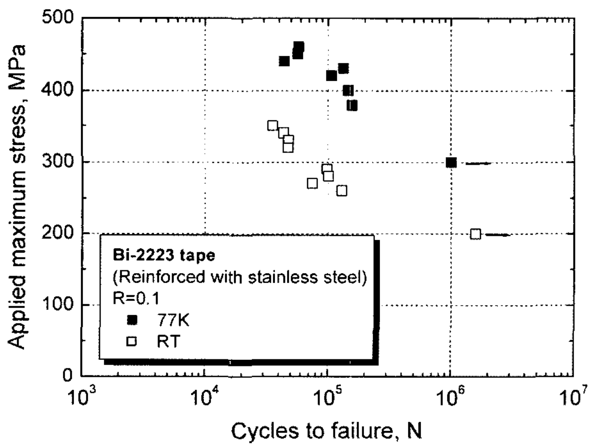


Fig. 5. S-N curves of externally reinforced Bi-2223 tapes obtained at R=0.1.

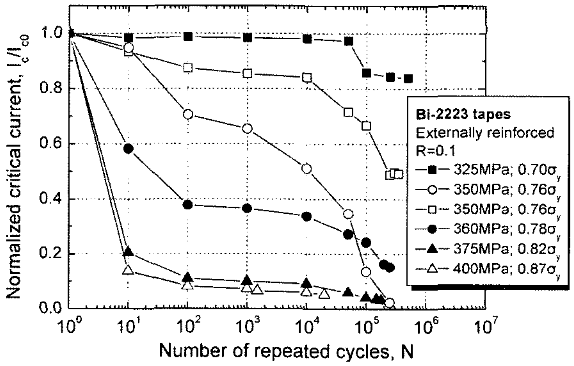
defined on 10^6 cycles was very high, about 320 MPa at 77K and 220 MPa at RT. On the other hand, in the case of R=0.5, even at a high maximum stress level of $0.98\sigma_y$, the specimen did not fail until 10^6 cycles. Therefore, a meaningful S-N curve could not be constructed in the same maximum stress range as in the case of R=0.1.

The degradation behavior of the I_c in the externally reinforced Bi-2223 tape as a function of the number of repeated cycles for various applied maximum stress levels are shown in Figs. 6 (a) and (b); (a) shows the result for the case of R=0.1 whereas (b) for R=0.5.

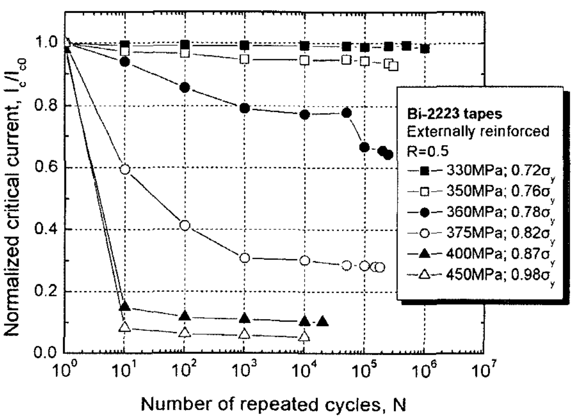
Firstly, in the case of R=0.1, the applied maximum stress level for the fatigue tests of externally reinforced Bi-2223 tapes at 77K was initially 0.98 σ_y, and then it was reduced by 3~10% in the succeeding tests.

The electro-mechanical fatigue tests were ended when the I_c degraded steeply and in one case, up to 10^6 cycles (for R=0.5) in order to determine the electric fatigue limit of the Bi-2223 tape, i.e., with 95% I_c retention [9].

Fatigue tests at maximum stress levels above 0.80 σ_y produced a significant I_c degradation up to 20% of I_{c0} even with just 10 cycles. For stress levels below 0.78 σ_y, the I_c degraded gradually with the increase of repeated cycles. In the range of 0.75~0.78 σ_y, a small difference of the applied stress produced large variations in the I_c behavior in the range of $10^3 \sim 10^5$ cycles. However, when



(a) at R=0.1



(b) at R=0.5

Fig. 6. I_c/I_{c0} - N relationship of externally reinforced Bi-2223 tapes.

the applied maximum stress decreased to 0.70 σ_y, the I_c kept a nearly constant value without any degradation up to 10^5cycles, after then it degraded gradually with repeated cycles. At maximum stress levels which are less than or equal to 0.65 σ_y, no significant I_c degradation occurred until 10^6 cycles, i.e., the I_c degradation was less than 5%, corresponding to the electric fatigue limit.

In the case of R=0.5 shown in Fig.6 (b), the externally reinforced Bi-2223 tapes showed a similar I_c degradation behavior as the repeated cycles increase. But in this case, the electric fatigue limit increased by about 25 MPa when compared with the case of R=0.1. This describes that when the Bi-2223 tapes are subjected to tension-tension fatigue loading along the longitudinal direction of the tape, the electric and mechanical fatigue limits evaluated through high cycle fatigue tests at R=0.1 can serve as a conservative side design data considering the influence of R on the I_c degradation behavior of externally reinforced Bi-2223 tapes. For design purposes, therefore, the maximum tensile stress that can be applied to the externally reinforced Bi-2223 tape, which is the electrically tolerable maximum stress, i.e., the electric fatigue limit, should be limited to 320 MPa for R=0.1 and 350 MPa for R=0.5, respectively, based on the 10^6 cycles and 95% I_c retention.

The n-values were derived from I-V curves measured at the maximum stress levels shown in Fig. 6. Fig. 7 shows the normalized n-value as a function of the number of repeated cycles at R=0.1. The n-value derived was normalized by n_o-value. The n_o-values measured at the unstrained state were between 7 and 25 according to the tested specimens. As the number of repeated cycles increased, the normalized n-value behaved differently depending upon the applied stress level, which quite well corresponds to the I_c degradation behavior shown in Fig. 6 (a). This indirectly explains the damage behavior in the superconducting filaments under fatigue loading. In the maximum stress range of 0.75 ~ 0.78 σ_y, the n-value gradually decreased with the increase of repeated cycles. In these cases, the cracks initiated transversely at an early stage of fatigue life and propagated toward adjacent filaments with the increase of repeated cycles, finally resulting in the ballooning of the cross-section due to a delamination which generated among the superconducting filaments shown in Fig. 9 (a). This damage process produced a gradual increase in voltage due to the current distribution into the Ag sheath, resulting in a distinct decrease in the n-value as repeated cycles increased.

Fig. 8 shows a representative example of the I-V curves before and after fatigue testing to externally reinforced Bi-2223 tapes. There exists some increase of voltage at the lower transport current(I) in the curve of fatigued specimen as compared with the case of the virgin specimen representing the occurrence of electrical resistance to superconducting filaments. These n-value behaviors under fatigue loading are slightly different from the behavior of Bi-2223 tapes by monotonic tensile tests where crack propagation occurs at a specific site in the tape due to the stress concentration and eventually a sudden drop of n-value [12]. However, at maximum stress levels above 0.80 σ_y, the breakage of superconducting filaments occurred even at few cycles resulting in the significant I_c degradation until 20% of I_{c0}. But the degradation was not significant although the repeated cycles increased, since the n_o-values in those cases were low. Further efforts to examine the damage morphology in filaments occurring under fatigue loading are required. The change of cross-section of the externally reinforced Bi-2223 tapes fatigued up to $5x10^5$ cycles for the I_c measurement test were checked. Fig. 9 (a) and (b) show polished cross-sectional views of deformed specimens after fatigue tests.

They showed different cross-sectional views depending on the applied maximum stress level. Most of the gage length part of the tapes tested at stress levels above 0.75 σ_y showed some ballooning, as shown in Fig. 10(a), while others have not. Especially, ballooning occurred mostly in specimens tested in the maximum stress range of 350 ~ 375 MPa which corresponds to the cases that the I_c degradation behaved transiently with the increase of repeated cycles for both cases of R=0.1 and 0.5. Ballooning of the tape might be caused by the increased pressure of N_2 gas evaporated within the tape by the heat generated during I_c measurement.

Specimens tested in the 350 ~ 375 MPa range were soaked in LN_2 for over 8 hrs. Several I_c measurements were also done, of which might be the reason of this balooning.

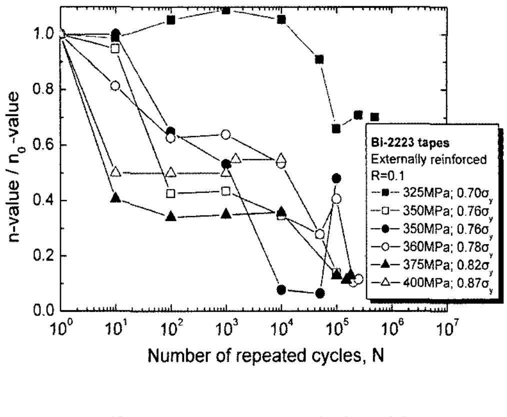


Fig. 7. Normalized n-value - N relationship in Bi-2223 tapes at R=0.1.

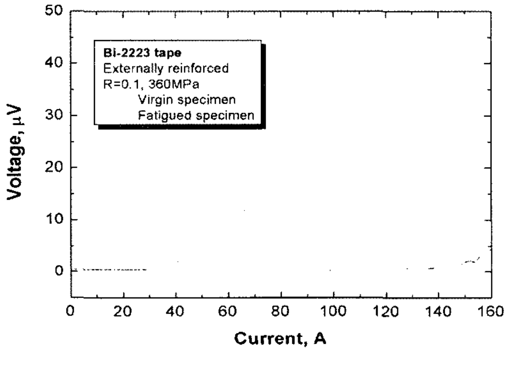


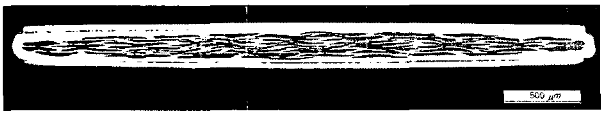
Fig. 8. Comparison of I-V curves before and after fatigue testing to Bi-2223 tapes.

However at stress levels below 330 MPa or above 400 MPa, it did not show any bulging, as shown in Fig. 9 (b). They resulted from that while the cases tested at low stress levels, any cracking did not occur within fatigue cycles tested, in the cases of high stress levels, the number of I_c measurement was few due to their shorter fatigue lives.

Another reason of this ballooning might be the warming-up from 77K to RT after the test. To explain these ballooning phenomena, a ballooning test was conducted wherein the specimen was immersed in LN_2 for 8hrs which corresponds to the total time of 250,000 cycles. The specimen changed in thickness from 0.31mm to 1.1mm as shown in Fig. 10(b). It was believed that the rapid expansion of N_2 within the wire when it was warmed to RT from 77K caused this ballooning damage to the tape.

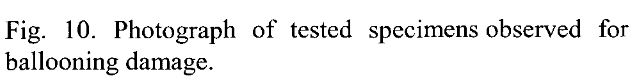
This warming up from LN_2 temperature to room temperature after several hours of operation might have caused this ballooning damage to the tape.

(a) σ_{max}= 350MPa
(Delamination among filaments and ballooning occurred).

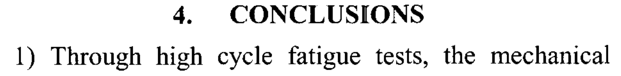


(b) σ_{max}= 300MPa
(no significant change occurred).

Fig. 9. Cross-sectional views after fatigue tests at 77K and R=0.1.



(a) specimen fatigued
(at R=0.1, σ_{max}=350MPa, N=2.5×10^5 cycles)



(b) specimen held at 77K for 8 hours

Fig. 10. Photograph of tested specimens observed for ballooning damage.

4. CONCLUSIONS

1) Through high cycle fatigue tests, the mechanical properties and the I_c degradation behavior in the externally reinforced multifilamentary Bi-2223 tape were investigated.

2) Under fatigue loading, the electric fatigue limit, i.e., the maximum stress at which has a 95% I_c retention up to 10^6 cycles, was decided. In externally reinforced Bi-2223 tapes, for the case of R=0.1, its value was 320 MPa and it was 350 MPa for R=0.5.

3) The effect of stress ratio on the I_c degradation behavior under fatigue loading of Bi-2223 tapes was examined. The increase in the electric and mechanical fatigue limits was observed when the stress ratio was increased to R=0.5 as compared with the case for R=0.1.

4) The n-value behavior of Bi-2223 tapes under fatigue loading was similar to the I_c/I_{c0} one depending upon the applied maximum stress levels, with the increase of repeated cycles. This indirectly indicates the damage process in the superconducting filaments under fatigue loading. The damage mechanism can also be explained by the change of the cross-sectional shape of fatigued specimen.

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