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Measurement reliability of irreversible stress/strain limits in Sn-Cu double layer stabilized IBAD/RCE-DR processed GdBCO coated conductor tapes under uniaxial tension at 77 K

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Abstract

In this study, the electromechanical properties in Sn-Cu double layer stabilized GdBCO coated conductor (CC) tapes with and without external lamination under uniaxial tension were examined at 77 K and self-field. Their irreversible stress and strain limits were determined using a loading-unloading scheme based on different critical current (I_c) recovery criteria. The repeated tests were performed and statistical estimation was done to check the reproducibility depending on the criterion adopted in evaluating the electromechanical properties. From the results, it showed that the Sn-Cu double-layer stabilized CC tapes have the higher irreversible stress limit, but lower irreversible strain limit as compared to brass laminated ones. Through the repeated tests, it can be found that a small scattering of irreversible limits existed in both CC tape samples. Finally, similar strain sensitivity of I_c in both CC tapes was obtained.

Keywords: coated conductor, Sn-Cu double layer stabilizer, brass laminate, electromechanical property, irreversible strain/stress limits, I_c recovery criteria, uniaxial tension

1. INTRODUCTION

High temperature superconducting (HTS) rare-earth barium-copper-oxide (REBCO) coated conductors (CC) are now being made and supplied by a number of manufacturers for developing electrical devices including power cables, superconducting fault current limiter (SFCL), motors/ generators, and magnets [1-3]. Their mechanical and electromechanical properties are one of the most important characteristics of REBCO CC tapes to be considered in practical applications. Evaluation of electromechanical properties in CC tapes becomes important since various kinds of stresses and strains can be induced during manufacturing, cool-down and operation at extreme conditions. It was noted that the abrupt degradation of I_c occurred when the applied stress exceeded the irreversible limit and cannot be recovered reversibly due to the formation of micro-cracks on the superconducting film [4-8]. Therefore, the REBCO CC tapes nowadays have been mechanically supported by copper (Cu) materials layered either by electroplating or by solder laminating for stabilization during operation and quenching conditions [9]. For further mechanical reinforcement can be achieved by external lamination such as brass foils [10-13]. Also, it was reported that the electromechanical properties with additional Tin (Sn) stabilizer was not varied of the properties compared to the Cu-stabilized CC tapes [14]. From the study on the electromechanical properties evaluation of the REBCO CC tapes, it is necessary to investigate the variation caused by additional stabilizer and external reinforcement. At low temperature environment, it is necessary to consider the displacement variation including thermal shrinkage. In this case, it was usually used the extensometers to measure the displacement accurately. Therefore, the assessment of measurement reliability for the electromechanical properties characteristics of REBCO CC tapes using extensometers is also required.

In this study, the electromechanical properties of double layer Sn-Cu stabilized GdBCO CC tapes with and without brass lamination were investigated at 77 K and self-field. Two criteria based on the I_c recovery behaviors during unloading were used to determine the irreversible critical strain/stress limits as the electromechanical properties of the CC tapes. The strain and stress sensitivity of I_c in both CC tapes were also compared. Statistic estimation of results obtained through repeated tests was also performed to assess their reliability.

2. EXPERIMENTAL PROCEDURES

2.1. Samples

Two kinds of samples were prepared in this study. They are composed of the Sn-Cu double layer stabilized GdBCO CC tapes (designated as Sample 1) and brass foils

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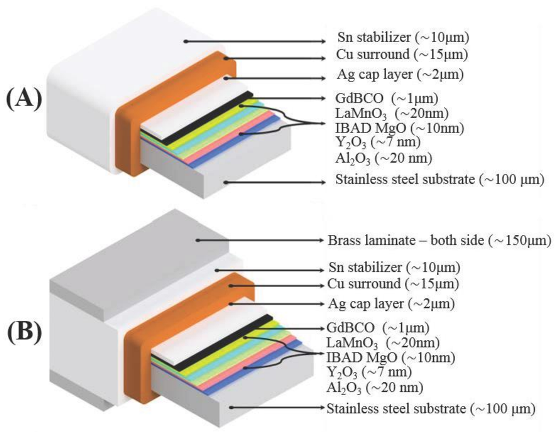

Fig. 1. Sample structures of Sn-Cu double-layer stabilized CC tape (a) without and (b) with external brass laminates.

TABLE I
SAMPLE SPECIFICATIONS.

GdBCO CC	Sample 1	Sample 2
Type	Sn-Cu stabilized	Brass laminated
Fabrication process	IBAD/RCE-DR	
Structure	Ag/GdBCO/LaMnO/Homo-epi MgO/ IBAD MgO/Y_2O_3/Al_2O_3/Stainless steel	
Stabilizer, t	Tin(~10μm)-Copper(~15μm)/ electroplating	
Substrate, t	Stainless steel, ~100 μm	
Critical current, I_c	~264 A	~238 A
Dimension, t x w (mm)	0.147 x **4.05**	0.435 x **4.45**
External lamination	-	Brass foil (both side) (~150μm)
Manufacturer	SuNAM Co., Ltd.	

externally laminated to both sides of Sample 1 (as Sample 2), respectively, as shown in Fig.1. Their specifications are listed in Table I. They are fabricated by the ion beam assisted deposition (IBAD) technique and the reactive co-evaporation, deposition and reaction (RCE-DR) process. They have ~100 μm thick stainless-steel substrate, a thickness of 1 μm GdBCO film with I_c of ~250 A at 77 K and self-field. It was slit from the original wide of 12 mm CC tape and was surround-electroplated by ~15 μm thick Cu followed the second stabilizer of ~10 μm thick Sn. The addition of Sn layer electroplating to the Cu-stabilized CC tapes has many advantages in shortening the electroplating time. This includes the improvement in the CC manufacturing process, as well as reducing the oxide film formation on the surface of the CC tape which may improve the lamination process and the interface resistance of the soldered CC joints. In the case of Sample 2, approximately 150 μm-thick brass foils were laminated on both-sides of Sample 1 for the reinforcement.

2.2. Electromechanical properties tests under uniaxial tension

In order to evaluate the mechanical and electromechanical properties of CC tape samples, the setup for uniaxial tension test at 77 K was used. The sample

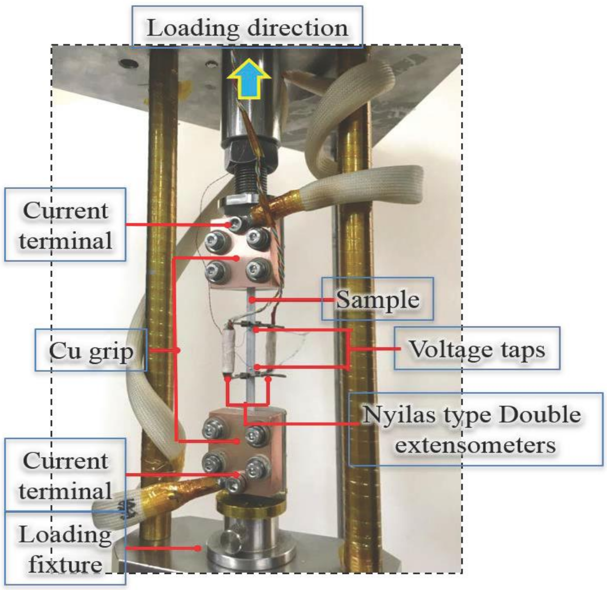

Fig. 2. Appearance of CC tape sample installed with double extensometers and voltage taps for electromechanical property test by uniaxial tensile test at 77 K.

installed with double extensometers is shown in Fig. 2. The sample was gripped by using the Cu gripping blocks at both ends with a 2 mm gap on the lower grip part in order to compensate the thermal contraction during cooldown, which was electrically isolated from the tensile testing machine frame. For testing at 77K, the loading frame including the sample and the gripping part was immersed in the liquid nitrogen filled in open cryostat. The critical current, I_c measurement was carried out at 77 K and self-field conditions. The voltage taps with a 20 mm separation were soldered on the center part of the CC sample. The strain induced in the CC sample was measured by Nyilas type double extensometer with a gage length of 25 mm and was attached outside the voltage taps separation. The I_c was defined with a criterion of 1 μV/cm using a four-probe method. The reversible recovery of I_c was measured by a repeated loading-unloading scheme using 99%I_{c0} recovery criterion which was described in [15]. The irreversible stress/strain limit of I_c was defined by 99% I_c (ε) criterion [12].

3. RESULTS AND DISCUSSION

3.1. Mechanical properties of Sn-Cu stabilized CC tapes under uniaxial tension at 77 K

First of all, the mechanical properties of both Samples 1 and 2 were obtained at 77 K. The elastic moduli of both samples were measured from the initial linear slope of stress-strain curves during loading and the yield strength was also defined by 0.2% offset yield criterion. The elastic modulus of Sample 2 decreased to 120 GPa from the 173 GPa of Sample 1. This was caused by low stiffness and strength of brass laminate and also its thicker profile compared with the substrate layer in CC tapes. The yield strength of Sample 1 determined by 0.2% strain offset at 77

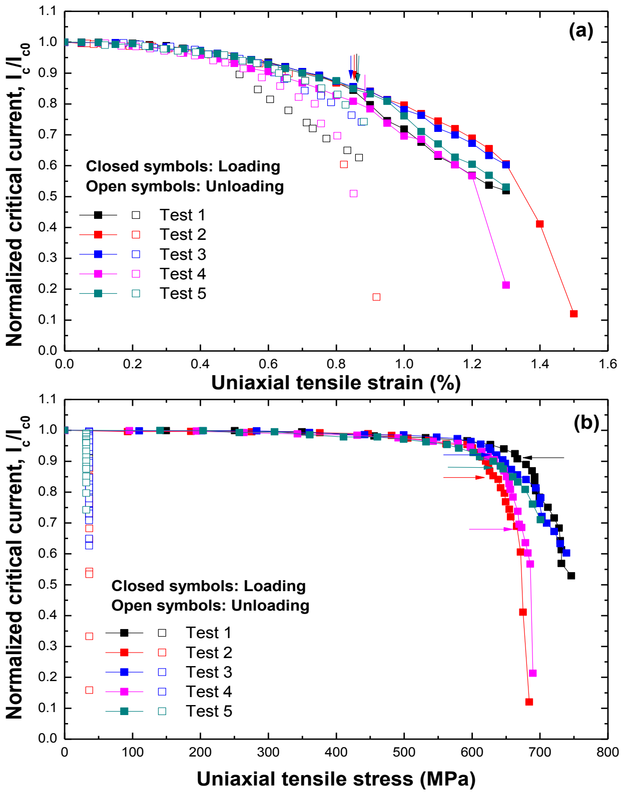

Fig. 3. Normalized critical current, I_c/I_{c0} as a function of (a) uniaxial tensile strain and (b) uniaxial tensile stress for Sn-Cu double-layer stabilized CC tapes (Sample 1) using the 99% $I_c(\varepsilon)$ recovery criterion.

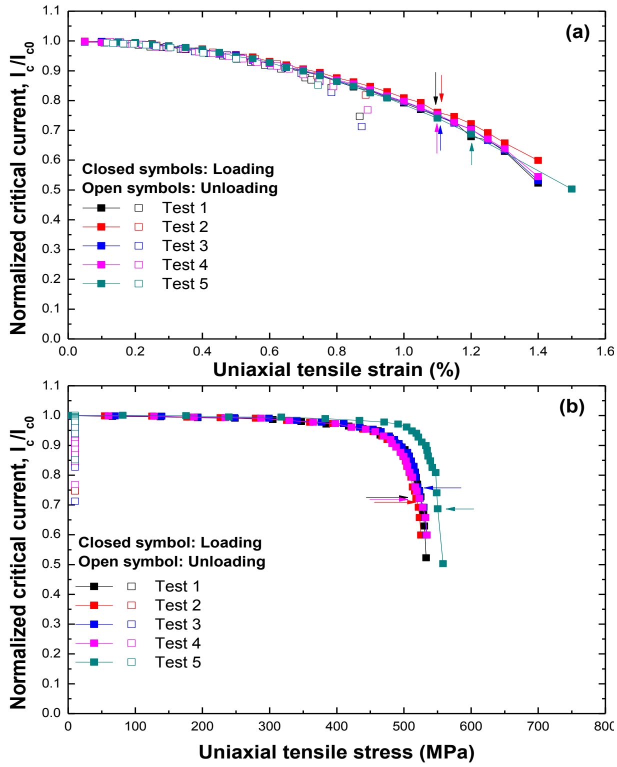

Fig. 4. Normalized critical current, I_c/I_{c0} as a function of (a) uniaxial tensile strain and (b) uniaxial tensile stress for brass laminated Sn-Cu double-layer stabilized CC tapes (Sample 2) using the 99% $I_c(\varepsilon)$ recovery criterion.

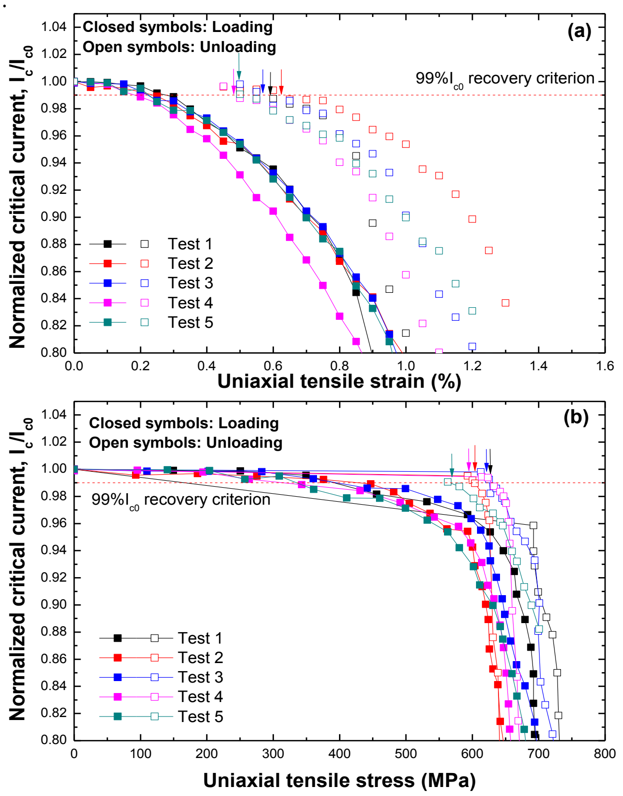

Fig. 5. Normalized critical current, I_c/I_{c0} as a function of (a) uniaxial tensile strain and (b) uniaxial tensile stress for Sn-Cu double-layer stabilized CC tapes (Sample 1) using 99%I_{c0} recovery criterion. The closed symbols indicate the loading and open symbols indicate the unloading.

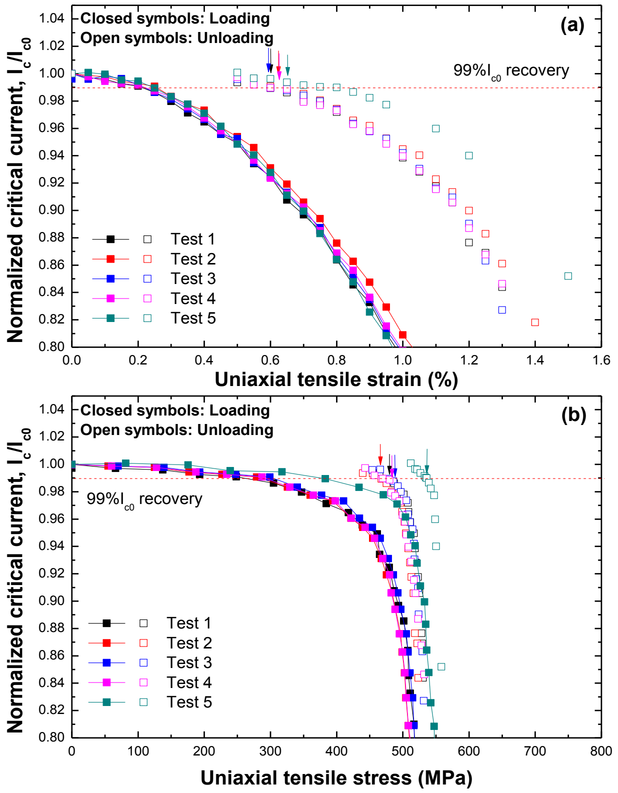

Fig. 6. Normalized critical current, I_c/I_{c0} as a function of (a) uniaxial tensile strain and (b) uniaxial tensile stress for brass laminated Sn-Cu double-layer stabilized CC tapes (Sample 2) using 99%I_{c0} recovery criterion. The closed symbols indicate the loading and open symbols indicate the unloading.

TABLE II
ELECTROMECHANICAL PROPERTIES OF DOUBLE LAYER Sn-Cu STABILIZED CC TAPES UNDER UNIAXIAL TENSION.

	99% $I_c(\varepsilon)$ recovery				**99% I_{c0} recovery**			
	Sample 1		Sample 2		Sample 1		Sample 2	
	ε_{irr} (%)	σ_{irr} (MPa)	ε_{irr} (%)	σ_{irr} (MPa)	ε_{irr} (%)	σ_{irr} (MPa)	ε_{irr} (%)	σ_{irr} (MPa)
Test 1	0.85	667	1.10	524	0.58	626	0.60	477
Test 2	0.85	630	1.10	514	0.62	606	0.62	467
Test 3	0.85	628	1.10	523	0.56	625	0.60	479
Test 4	0.89	680	1.10	518	0.49	599	0.62	478
Test 5	0.85	602	1.20	550	0.50	569	0.65	537
Mean	**0.86**	**641**	**1.12**	**526**	**0.55**	**605**	**0.61**	**488**
STD	**± 0.018**	**±31.6**	**±0.045**	**±14.1**	**±0.045**	**±14.1**	**± 0.044**	**± 28.0**

K was 644 MPa and it much higher compared to 488 MPa of Sample 2.

3.2. Electromechanical properties evaluation under uniaxial tension through repeated tests at 77 K

The I_c of Sn-Cu double layer stabilized GdBCO CC tapes (Samples 1 and 2) was measured and it was plotted against the applied tensile strain during loading and the residual strain at the unloaded state, respectively. Figures 3(a) and 4(a) show the I_c/I_{c0}-tensile strain relation obtained using the repeated loading-unloading scheme through 5 repeated tests for Samples 1 and 2, respectively, where the irreversible strain limit, ε_{irr} was determined using the 99% I_c (ε) recovery criterion as designated by the arrows on the curves. On the other hand, figures 3(b) and 4(b) show the I_c/I_{c0}-tensile stress relation obtained through 5 repeated tests. Where the irreversible stress limit, σ_{irr} was determined using the 99% $I_c(\varepsilon)$ recovery criterion. Both Samples 1 and 2 exhibited significant tensile strain-sensitive I_c degradation behavior. The mean values of ε_{irr} were 0.86% for Sample 1 and 1.12% for Sample 2, respectively. In the case of Sample 1, with the applied tensile strain at the ε_{irr} of 0.86%, I_c was degraded to 85% I_{c0}, but recovered up to 95% I_{c0} by unloading. For Sample 2, at the ε_{irr}, I_c was already degraded to 67% I_{c0}, but recovered until 90% I_{c0} by unloading. On the other hand, both Samples 1 and 2 exhibited tensile stress insensitive I_c degradation behavior. The mean values of σ_{irr} were 641 MPa for Sample 1 and 526 MPa for Sample 2, respectively. At the applied tensile stress after σ_{irr}, scattering in I_c degradation behaviors became significant especially in Sample 1.

The irreversible strain/stress limits were also defined by 99% I_{c0} recovery criterion and shown in Fig. 5 and 6. The measured electromechanical properties depending on respective recovery criterion are listed in Table II, together with the mean values and standard deviations obtained through 5 repeated tests for both samples. The mean values and standard deviations of ε_{irr} and σ_{irr} in both samples were compared using both recovery criteria. It can be seen that the mean ε_{irr} obtained by the 99% I_{c0} recovery criterion in both CC samples was significantly lower compared to the cases obtained by the 99% $I_c(\varepsilon)$ recovery criterion which used the residual strain induced in the CC tapes. However, the mean $\sigma_{irr.}$ obtained by the 99% I_{c0} recovery criterion exhibited a little lower value corresponding to ~36 MPa when compared to the case of the 99% $I_c(\varepsilon)$ recovery criterion.

As a whole, the external lamination of brass laminate resulted in an increase of the ε_{irr} but a decrease of σ_{irr} values Almost similar strain sensitivity behaviors against I_c degradation during loading were obtained for Sample 1 and Sample 2 regardless of the existence of additional brass foil. The strain sensitivity against I_c degradation obtained was 0.22 for Sample 1 and 0.20 for Sample 2, respectively. As a whole, it can be found that brass laminated Sn-Cu double layer stabilized CC tapes showed a less-sensitive behavior on I_c degradation for the tensile stress as compared to the tensile strain one. From the performed repeated tests, the ε_{irr} of Sample 1 showed a minimal deviation of ±0.018% compared to Sample 2 of ±0.045%. However, in the case of σ_{irr}, Sample 2 showed less deviation of ±14.1 MPa compared to Sample 1 of ±31.6 MPa. If we consider the 99%I_{c0} recovery criterion, the Sample 1 and 2 showed a similar strain deviation of ±0.045% however the stress limit showed a little large deviation.

When the 99% $I_c(\varepsilon)$ recovery criterion was adopted, the standard deviation was within 5% of the average value of the measured values. However, when the 99% I_{c0} recovery criterion was used, the standard deviation increased a little bit, in particular, in the case of the strain limit value due to its lower values compared to the the 99% $I_c(\varepsilon)$ recovery criterion case. Considering that I_c was measured at 0.05% intervals, the strain deviation of that extent is still reasonable.

4. SUMMARY

The electromechanical properties of Sn-Cu double layer stabilized GdBCO CC tapes with and without external reinforcement were evaluated at 77 K and self-field. The results showed that brass lamination to Sn-Cu double layer stabilized CC tapes improved the irreversible strain limits, however the irreversible stress limits decreased. The addition of Sn stabilizer to Cu-stabilizer produced similar irreversible strain limits, however, the irreversible stress limits became lower due to the low stiffness of Sn stabilizer. Through repeated tests, it could be found that the electromechanical properties determined by 99% $I_c(\varepsilon)$

criterion provided reliable limit values. The 99% I_{c0} recovery criterion showed lower limit values and large variation in Sample 1, however, Sample 2 showed a comparable deviation in both criteria adopted.

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