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Effects of differently hardened brass foil laminate on the electromechanical property of externally laminated CC tapes

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Abstract

The mechanical properties of REBCO coated conductor (CC) wires under uniaxial tension are largely determined by the thick component layers in the architecture, namely, the substrate and the stabilizer or even the reinforcement layer. Depending on device applications of the CC tapes, it is necessary to reinforce thin metallic foils externally to one-side or both sides of the CC tapes. Due to the external reinforcement of brass foils, it was found that this could increase the reversible strain limit from the Cu-stabilized CC tapes. In this study, the effects of differently hardened brass foil laminate on the electromechanical property of CC tapes were investigated under uniaxial tension loading. The tensile strain dependence of the critical current (I_c) was measured at 77 K and self-field. Depending on whether the I_c of CC tapes were measured during loading or after unloading, a reversible strain (or stress) limit could be determined, respectively. The both-sides of the Cu-stabilized CC tapes were laminated with brass foils with different hardness, namely 1/4H, 1H and EH. From the obtained results, it showed that the yield strength of the brass laminated CC tapes with EH brass foil laminate was comparable to the one of the Cu-stabilized CC tape due to its large yield strength even though its large volume fraction. It was found that the brass foil with different hardness was mainly sensitive on the stress dependence of I_c, but not on the strain sensitivity due to the residual strain induced in the laminated CC tapes during unloading.

Keywords: coated conductor, brass laminate, hardness, reversible stress/strain limit, volume fraction, uniaxial tension

1. INTRODUCTION

Rare Earth Barium Copper Oxide (REBCO) based second generation (2G) high temperature superconducting (HTS) coated conductors (CC) are now being made and supplied by a number of manufacturers for the development of various electrical devices and magnets [1, 2]. For those applications, the mechanical and electromechanical properties (EMP) are one of the most important characteristics of the HTS CC wires. The MEM behavior of CC tapes has been investigated under uniaxial tension [3-6]. Although there are many reports and publications, the properties are continuously focused since the CC manufacturing technology is still evolving and the practical application fields are growing. An ongoing high-field magnet project based on REBCO CC coils includes high resolution NMR spectrometers at 1.3 GHz, corresponding to a magnetic field of 30.5 T [7, 8], dipole magnets at 20 T. At those applications, the conductors have to withstand enormous longitudinal stress (~220 MPa in Bi-2223 NMR coils [9], ~ 330 MPa in HTS fusion magnets [10] and ~ 500 MPa in REBCO NMR coils [11]) making the electromechanical and mechanical properties as well as the limits of irreversibility of importance in the magnet design. In our previous study, it was presented that the addition of brass laminate to CC tapes could extend the reversible strain limit ($\varepsilon_{irr.}$) of the CC tapes and also the volume fraction of brass laminate added did influence significantly on the $\varepsilon_{irr.}$ [12-14]. In this study, the effects of differently hardened brass foil laminate on the electromechanical properties of HTS CC tapes were investigated at 77 K and self-field. The stress and strain dependences of I_c, which are called as the strain-sensitivity and the stress-sensitivity to I_c, were discussed. In addition, the mechanical properties of brass foil laminates were also evaluated at room temperature (RT) and 77 K.

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2. EXPERIMENTAL PROCEDURES

2.1. Samples

The samples are composed of Cu-stabilized and brass laminated CC tapes. In Table I, the specifications of both-side brass laminated and Cu-stabilized CC tapes were listed. They are fabricated by the ion beam assisted deposition (IBAD) technique and the reactive co-evaporation, deposition and reaction (RCE-DR) process. The CC tapes are consisted of 104 μm thick stainless steel substrate material, a thick of 1 μm GdBCO film with critical current, I_c, of approximately 220 A at 77 K and self-field conditions. It was slit into 4 mm width from the initial width of 12 mm CC tape and surround-electroplated by 15 μm thick copper. The Cu-stabilized CC sample was laminated on its both-sides with approximately 150 μm-thick brass foil laminate (C26800). Three kinds of brass foils with different hardness are adopted; 1/4H, 1H, and EH (extra hard).

2.2. Mechanical and electromechanical test procedures

The hardness of differently hardened brass foil was measured using the micro-Vickers hardness tester (Shimadzu HMV-2000) at a load of 200 N and then the measured hardness data were converted in terms of strength and listed in Table II. In order to measure the mechanical property of CC tapes, a set-up for uniaxial tension test was used as shown in Fig. 1. The CC sample was gripped by using the same gripping tool at both ends with a 2 mm gap on the lower grip in order to compensate the thermal contraction during cooldown, which was electrically isolated from the tensile machine. For testing at 77 K, the sample and the gripping holder were immersed into the liquid nitrogen filled in an open cryostat. Then the tensile test was carried out according to the same procedure as at RT. In order to examine the EMP of the brass laminated CC tapes, the I_c measurement was carried

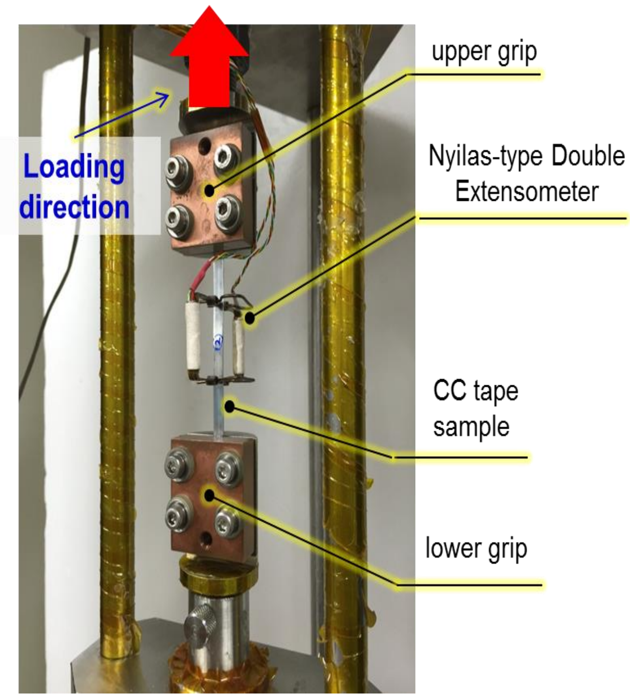


Fig. 1. Set-up for mechanical property evaluation under uniaxial tension.

TABLE I
SPECIFICATIONS OF BOTH-SIDE BRASS LAMINATED AND CU-STABILIZED CC TAPES.

Fabrication/ REBCO	Brass laminated CC tapes	Cu-stabilized CC tapes
Superconducting film	GdBCO (~ 1 μm)	
Substrate	Stainless steel (~104 μm)	
I_c	~ 220 A	
Dimension, t x w	0.137 mm x 4.08 mm	
Stabilizer	Electroplated Copper (~15 μm)	
Lamination	Brass laminate (both-side) (~150 μm)	-
Manufacturer	SuNAM	

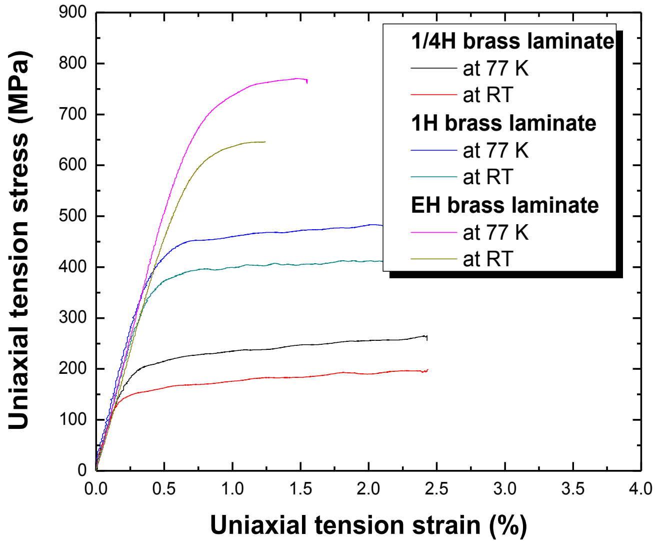


Fig. 2. Stress-strain curves of differently hardened brass foil laminate foils obtained at RT and 77 K.

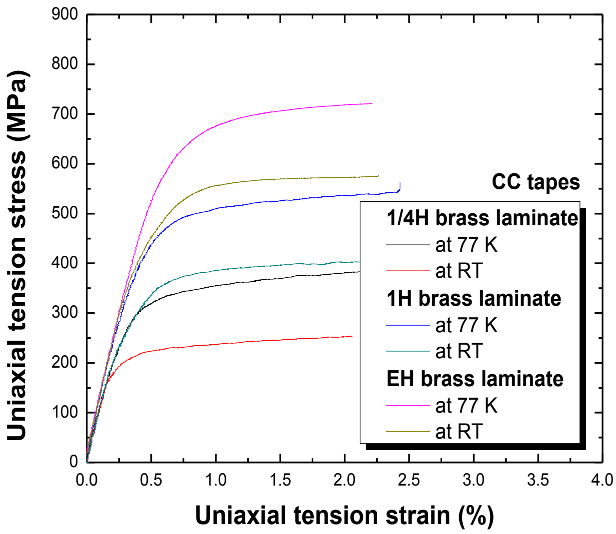


Fig. 3. Stress-strain curves of brass foil laminated CC tapes obtained at RT and 77 K.

out at 77 K and self-field conditions. The voltage taps were soldered on the center portion of the CC sample, 20 mm apart. At the outside of the voltage separation, the Nyilas type double extensometer with the gage length of 25 mm was attached. The I_c was defined with a criterion of 1 μV/cm. The reversible stress/strain limit was defined by 99% I_c given at the tensile strain (ε) criterion. For each case, twice tests were conducted.

3. RESULTS AND DISCUSSION

3.1. Mechanical properties of brass laminated CC tapes

The stress-strain curves of brass foil laminates obtained at RT and 77 K were shown in Fig. 2. Depending on hardened condition, the flow stress including yield stress of each brass foil laminate varied significantly, indicating

TABLE II
MECHANICAL AND ELECTROMECHANICAL PROPERTIES OF DIFFERENT TYPES OF BRASS FOILS AND LAMINATED CC TAPES.

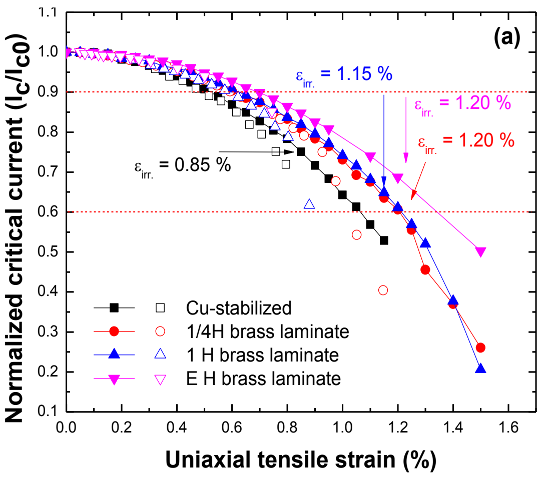
	At RT				At 77 K				
					Mechanical			Electromechanical	
	Vicker's Hardness, H_v (MPa)	Elastic modulus, E (GPa)	Yield stress, σ_y (MPa)	Yield strain, ε_y (%)	**Elastic modulus, E (GPa)**	**Yield stress, σ_y (MPa)**	**Yield strain, ε_y (%)**	Reversible strain limit, ε_{irr} (%)	Reversible stress limit, $\sigma_{irr.}$ (MPa)
Brass foil									
1/4H	402	76	156	0.38	**85**	**211**	**0.42**	-	-
1H	552	102	381	0.60	**103**	**444**	**0.61**	-	-
EH	759	94	618	0.87	**104**	**721**	**1.01**	-	-
CC tapes									
Cu-stabilized	-	170	413	0.47	**185**	**752**	**0.70**	0.85	701
Brass laminated, 1/4H	-	106	218	0.42	**107**	**317**	**0.48**	1.20	301
Brass laminated, 1H	-	108	338	0.55	**120**	**452**	**0.60**	1.15	490
Brass laminated, EH	-	112	501	0.66	**112**	**633**	**0.81**	1.20	629

some extent of strain-hardening behavior. The brass foil laminates showed an increase of its yield strength but almost similar Young's modulus. There also existed a significant low temperature hardening. From the micro-Vickers hardness test, the EH brass foil laminate has the highest hardness of 759 MPa and the 1/4H one was 402 MPa, as shown in Table II.

For the brass laminated CC tapes, on the other hand, depending on the hardness of brass foils adopted, the yield stress increased significantly with less scattering as shown in Fig. 3. There also existed a similar low-temperature and a little bit less strain hardening behaviors as compared to the cases shown in Fig. 2, but almost similar Young's modulus were determined by initial slope. Therefore, in the cases of EH brass foil laminated CC tapes, it is expected that large resilience energy can be stored during elastic deformation. It was due to the large volume fraction of brass laminate on the CC tape configuration which corresponds to around two-third of its total thickness.

3.2. Strain and stress dependences of I_c under uniaxial tension at 77 K

In the cases of RCE-DR processed Cu-stabilized GdBCO CC tapes externally reinforced with differently hardened brass foils, the I_c/I_{c0} - tensile strain relations are shown in Fig. 4(a) where the filled symbols and the empty symbols means the loading and unloading conditions of the CC tape, respectively. Where the normalized critical current, I_c/I_{c0} was plotted as a function of applied tensile strain, ε. The reversible strain limit, $\varepsilon_{irr.}$, which was defined as a strain corresponding to 99% I_c at the recovered ε during unloading process, was designated by the arrows on the curves. In Fig. 4(b), the I_c/I_{c0} was plotted as a function of applied tensile stress, σ. The reversible stress limit, $\sigma_{irr.}$, similarly defined to the case of $\varepsilon_{irr.}$, was also designated by the arrow on the curves. The mechanical and electromechanical properties obtained for differently hardened brass foils and brass laminate CC tapes are listed in Table II. The 1/4 H brass laminated CC tapes exhibited the $\varepsilon_{irr.}$ and $\sigma_{irr.}$ of 1.20% and 301 MPa, respectively. It can be found that with



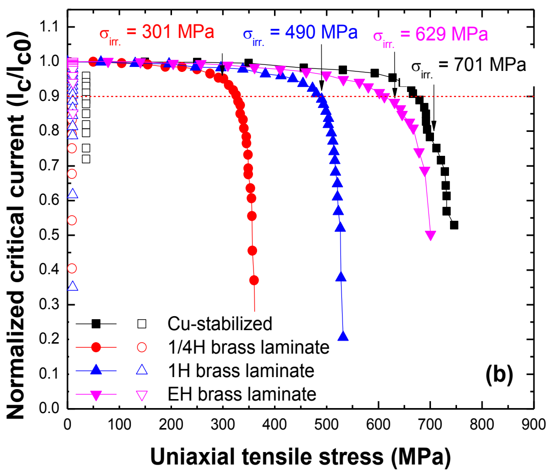


Fig. 4. Normalized critical current, I_c/I_{c0} as a function of; (a) uniaxial tensile strain (b) uniaxial tensile stress for brass laminated CC tapes and Cu-stabilized ones for comparison.

the applied tensile strain, I_c was degraded significantly. It was already degraded to 60% of I_{c0} at the $\varepsilon_{irr.}$ of 1.20%, but recovered up to 80% of I_{c0} by unloading. At the $\sigma_{irr.}$ of 301

MPa, I_c was degraded to 95% of I_{c0}, and recovered up to 99% of I_{c0} during unloading to 20 N. However, the I_c degradation appeared as relatively insensitive to the applied tensile stress. The 1H brass laminated CC tapes exhibited the $\varepsilon_{irr.}$ and $\sigma_{irr.}$ of 1.15% and 490 MPa, respectively. At the strain limit, however, I_c was degraded to 68% of I_{c0}, and recovered up to 90% of I_{c0} during unloading. At the $\sigma_{irr.}$ of 490 MPa, I_c was degraded to 90% of I_{c0}, and recovered up to 99% of I_{c0} during unloading to 20 N. The EH brass laminated CC tape exhibited the $\varepsilon_{irr.}$ and $\sigma_{irr.}$ of 1.20% and and 629 MPa, respectively. At the strain limit, however, I_c was degraded up to 70% of I_{c0}, and recovered up to 95 % of I_{c0} during unloading. At the stress limit of 629 MPa, I_c was degraded to 89% of I_{c0}, and recovered up to 99% of I_{c0} during unloading.

In Fig. 4, as a whole, it can be found that similar strain sensitivity behaviors and similar reversible strain limit values of 1.15%~1.20% were obtained for brass laminated CC tapes, regardless of the hardness of brass foil adopted. The EH brass laminated CC tapes showed slightly less strain sensitive behavior. On the other hand, on the $\sigma_{irr.}$, the EH brass laminated CC tapes showed the highest one of 629 MPa, and 1/4H one was the lowest one of 301 MPa. However, until the $\sigma_{irr.}$, they showed a less stress sensitive I_c degradation behaviors for all of the brass foil laminated CC tapes. As a result, it can be found that within the reversible region, the brass foil externally laminated CC tapes showed a less-sensitive behavior on I_c degradation for the tensile stress as compared to the tensile strain one. In addition, when compared to the Cu-stabilized CC tape plotted for comparison, the EH brass foil laminated CC tapes represented slightly less reversible strain and stress limit, respectively, although it showed a larger volume fraction of brass foil laminates.

4. SUMMARY

In this study, the mechanical and electromechanical behaviors of differently hardened brass foil laminated CC tapes were investigated. Laminated CC tapes with EH brass foils exhibited the highest yield strength at both RT and 77 K as compared to 1/4H and 1H brass foil ones, but similar Young's modulus regardless of hardness of brass foils adopted. It can be found that in the brass laminated CC tapes the obtained reversible strain limits for I_c degradation were exceeded the yield strain, but the reversible stress limits showed a similar value to the yield strength of laminated CC ones. It means that the hardness of brass foils affected significantly to the reversible stress limit of laminated CC tapes, however, less affected to the reversible strain limit. In addition, within the reversible region, the brass foil externally laminated CC tapes showed a less-sensitive behavior on I_c degradation for the tensile stress as compared to the tensile strain one.

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