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Estimation of Residual Stress in ReBCO Coated Conductor Tapes Using Various Methods

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***Abstract*-- The residual stress induced in the superconducting layer was estimated using analytical approach coupled with electro-mechanical test results and XRD measurements. The residual stress measured based on the I_c/I_{c0}–strain degradation behavior showed similar value with the measured residual stress using XRD. The calculated residual stress based on the thermal analysis showed the lowest value. This could be explained by the additional intrinsic residual stresses induced in the superconducting film during deposition.**

1. INTRODUCTION

Recent advances in the fabrication technology of ReBCO coated conductors (CC) have widened their application fields to electric power cables, motors, magnets, etc. Long length YBCO CC tapes with high current density, J_c, have been achieved through the rolling-assisted biaxially textured substrates (RABiTS) and ion beam assisted deposition (IBAD) substrates [1-3].

The understanding of I_c-strain/stress relations in ReBCO CC tapes is important in the design of superconducting devices. For YBCO CC tapes, some electro-mechanical properties such as tensile and bending strain dependencies of the critical current, I_c, have already been investigated by several research groups [4-7]. Under tensile stress, it was observed that the I_c can increase or decrease reversibly with strain up to an irreversible strain limit, ε_{irr} [5-7]. Also, the lamination of stabilizers which enhances the mechanical properties of these tapes resulted in the increase in ε_{irr} [5]. A peak value of I_c was also observed before decreasing at higher strain values [5,7].

In practical applications to electrical devices, HTS wires/tapes will be subjected to various kinds of stress/strain. With the many different processes used for the deposition of the various layers comprising the coated conductor structure, different residual stresses/strains will be induced in the ReBCO superconducting layer. Knowing the nature and magnitude of the residual stress in the superconducting layer is important in understanding the I_c-stress/strain behavior of CC tapes under loading, which makes it possible to tailor HTS tapes for specific application. In the case of BSCCO tapes, the strain window size increased when a high modulus material was used as reinforcement. Also, the strain window may be shifted into the tensile side reinforcement with high CTE and pre-stress [8]. Considering that various materials are used for the substrate, buffer and stabilizing layers as constituent components of CC tapes, the strain window size and location in CC tapes could also be designed based on individual layer's CTE and modulus. Another important observation is about the deposition stresses induced in ReBCO CC tapes during deposition. In particular, the IBAD and PLD process may generate compressive strains in films, while sol-gel processing may generate negligible intrinsic strains in films [9]. Table 1 lists the different methods for substrate texturing and deposition of various layers together with the different materials used in the CC architecture.

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TABLE I
DIFFERENT METHODS FOR SUBSTRATE TEXTURING AND DEPOSITION OF LAYERS, WITH THE DIFFERENT MATERIALS USED IN THE CC STRUCTURE.

Methods for substrate texturing	Rolling-assisted biaxially-textured substrate (RABiTS), Ion beam-assisted deposition (IBAD), etc.
Methods for deposition of layers	Evaporation, Sputtering, Sol-gel, Metal-organic chemical vapor deposition (MOCVD), Metal-organic deposition (MOD), Electroplating, etc.
ReBCO materials	YBCO, SmBCO, DyBCO, HoBCO, etc
Materials in the CC structure	Substrate: Hastelloy, Ni, Ni-W, etc. Buffer layers: Y_2O_3, YSZ, CeO_2, LMO, MgO, Homo-epi MgO, etc. Stabilizer: Ag, Cu, SUS, etc.

Depending on the requirements, it may be possible to control the size and position of the strain window based on individual CTE and modulus. Being able to understand and control the nature and magnitude of the residual stress would help explain the occurrence of peak I_c values in ReBCO CC tapes, and help design and tailor these tapes to meet the requirements for certain device application.

In this study, the residual stress/strain induced in the superconducting ReBCO film in ReBCO CC tapes using experimental methods has been investigated. The prediction of residual stress/strain in the ReBCO film using analytical approach coupled with electromechanical test results and XRD measurement has been tried.

2. EXPERIMENTAL PROCEDURES

Two kinds of coated conductor tape samples have been supplied for the experiments, which were manufactured with RABiTS and IBAD substrate, respectively. Both samples have no reinforcements. Fig. 1 shows a schematic of the architecture of the coated conductor samples used.

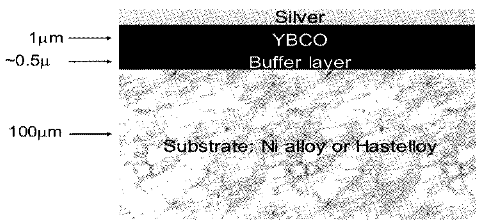

Fig. 1. Schematics of the coated conductor samples used.

Electro-mechanical test procedure to determine $\varepsilon_{irr.}$

For the tensile test of CC tapes at 77 K and self-field, a universal testing machine (loadcell capacity: 5 kN) was used. The total length of the specimen and the gauge length between the gripping holders were 80 mm and 40 mm, 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 through a universal joint and the lower one was set on the loading frame fixed to the testing machine. A connecting structure on the lower part which gives a clearance of 2 mm was devised to release the thermal contraction during cooling and to prevent any bending or twisting loads expected on specimen fixing. For testing at 77 K, the specimen was slowly cooled down taking about 10 min. The strain applied to the CC samples was measured using the double extensometers developed by Nyilas, with a gauge length of 12.5 mm, which were directly attached to the specimen [5]. From the obtained stress-strain curves, the Young's modulus and the yield stress could be determined.

For the I_c measurement during tensile tests, GFRP sheets were inserted between the specimen and the gripping holders for electrical insulation, where Cu blocks cover the specimen serving as current terminals. Voltage taps were attached at the central region of the specimen with a separation of 20 mm [5]. An I-V curve was measured using the four-probe method at 77 K under self-field, and the I_c was defined by a 1 μV/cm criterion. During tensile testing, the I_c was measured at specified strain levels, and also at the unloaded state down to 10 MPa for RABiTS/PLD and IBAD/PLD tape samples, each time to check whether the I_c recovers reversibly. The I_c was normalized by the I_{c0} value obtained at the as-cooled state.

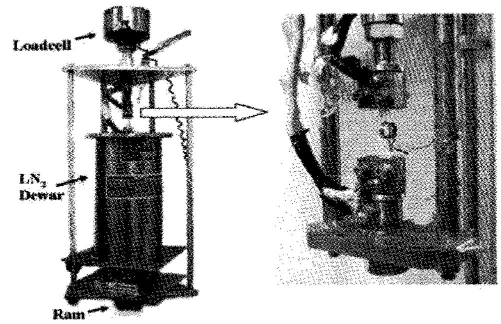

Fig. 2. Tensile test set-up used for the electromechanical characterization of coated conductor tapes.

Residual stress measurement using X-ray diffraction method

The residual stress was measured along the longitudinal direction of the sample using X-ray diffractometer (Rigaku, D/Max 2000, X-ray target: Cu Ka 2 kW). For the YBCO film, the residual stress was measured at $\phi = 0°, 5°, 10°, 15°, 20°, 25°$. An average value of residual stress was determined by calculating the mean of 2-3 measurements.

Residual stress calculation by an analytical approach

The residual stress (σ_R) in coated films is mainly due to the CTE mismatch between the films and the substrate, and partly from the intrinsic stresses (σ_X) developed during film deposition, and can be expressed as

$$\sigma_R = \sigma_\alpha + \sigma_X \qquad (1)$$

where σ_α is the stress due to the thermal mismatch, and σ_X is the intrinsic stress generated during the growth of the YBCO coating film by deposition.

The thermal mismatch stress (σ_α) in the film can be calculated analytically by:

$$\sigma_\alpha = \frac{E}{(1-\upsilon)} \Delta\alpha\Delta T \qquad (2)$$

where E and ν are the elastic modulus and Poisson ratio of the film ($\nu \approx 0.3$), respectively, $\Delta\alpha$ is the difference in CTE between the substrate and the film, and ΔT is the difference between room and processing temperature. Material properties used in the calculation are given in Table 2 [9].

TABLE II
MATERIAL PROPERTIES USED IN THE CALCULATION OF RESIDUAL STRESS.

Material Property	Hastelloy C	YBCO
Elastic Modulus (GPa)	170 - 220	157
Thermal expansion coefficient (10^{-6} K^{-1})	12.5	13.4

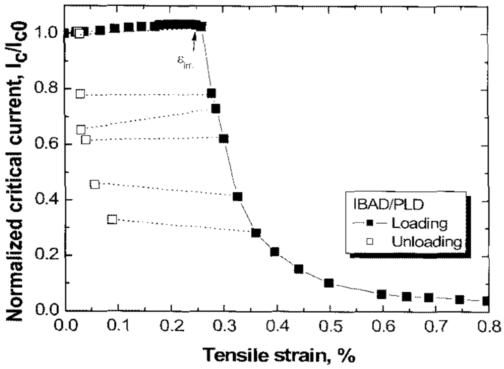

Fig. 3. I_c-strain behavior in IBAD/PLD YBCO CC tape.

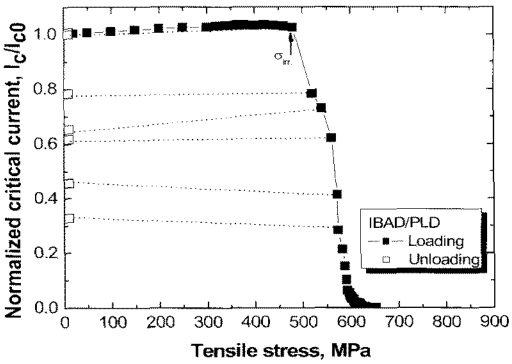

Fig. 5. I_c-stress behavior in IBAD/PLD YBCO CC tape.

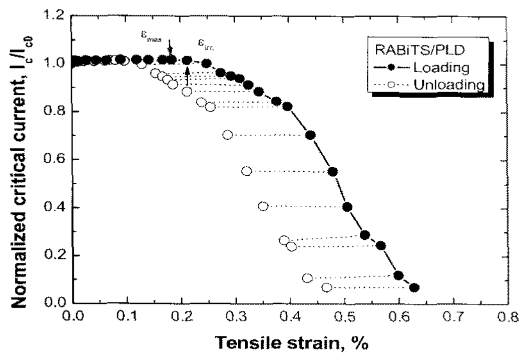

Fig. 4. I_c-strain behavior in RABiTS/PLD YBCO CC tape.

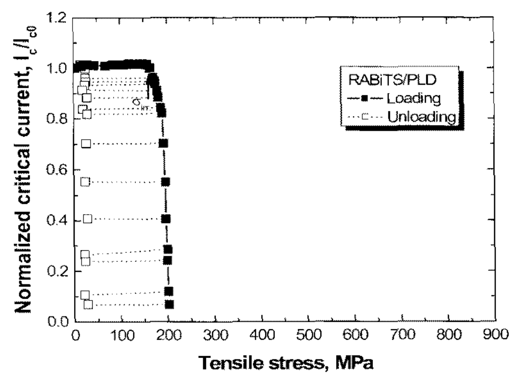

Fig. 6. I_c-stress behavior in RABiTS/PLD YBCO CC tape.

TABLE III
EXPERIMENTALLY DETERMINED IRREVERSIBLE STRAIN VALUES FOR BOTH RABITS AND IBAD CC TAPE SAMPLES.

Strain value, %	RABiTS/PLD	IBAD/ PLD
$\varepsilon_{95\%}$	0.28	0.26
ε_{peak}	0.18	0.22
$\varepsilon_{irr.}$	0.22	0.26

TABLE IV
IRREVERSIBLE STRESS VALUES FOR BOTH RABITS AND IBAD PROCESSED CC TAPE SAMPLES.

Stress value, MPa	RABiTS/PLD	IBAD/ PLD
$\sigma_{95\%}$	162	480
σ_{peak}	149	420
$\sigma_{max.}$*	280	345
$\sigma_{irr.}$	162	480

3. RESULTS AND DISCUSSION

Figs. 3 and 4 show the I_c degradation behavior as a function of tensile strain for the IBAD/PLD- and RABiTS/PLD-processed CC tape samples, respectively. The IBAD/PLD-processed sample had an I_{c0} of 112A, while the RABiTS/PLD-processed sample had an I_{c0} of 133.9A. The irreversible strain values for both samples are also indicated in the graphs. These values as well as the 95% I_c retention strain limit and the strain at peak I_c, ε_{peak}, are tabulated in Table 3. Based on the strain values given in Table 3 together with the Young's modulus given in Table 2 , the residual stress calculation was performed.

Figs. 5 and 6 show the I_c degradation behavior as a function of tensile stress for the IBAD/PLD- and RABiTS /PLD-processed samples, respectively. The irreversible stress values for both samples are also indicated in the graphs. These values as well as the 95% I_c retention stress limits and the stress at peak I_c values are tabulated in Table 4. Also, the strain measured in the last section, ε_{peak} was used to calculate the residual stress σ_{max}*.

Fig. 7 shows the measured and calculated residual stress values for the IBAD/PLD tape sample. The first data was measured using X-ray diffraction, although there existed a significant scattering in the residual stress value measured depending on the coating film state. The second one was calculated based on the measured strain value at the peak I_c value and Young's modulus of YBCO. This data was obtained in order to see if the intrinsic strain characteristics of the YBCO layer will have an influence on the residual stress in the superconducting film. The σ_{peak} in the third data was obtained using I_c-σ measurement. And the fourth data was calculated using Eq. 2.

The measured average residual stress using XRD showed similar value with σ_{peak} measured using I_c degradation characteristics. The calculated residual stress using thermal analysis showed the lowest value. This could probably be explained by the additional intrinsic residual stresses induced in the superconducting film during deposition which was not accounted for in the calculation process using Eq. 2 [9]. While the second data, $\sigma_{max.}$* calculated using measured strain value and E (157 GPa) of YBCO shows a relatively close value with that of data 1 and 3.

Through the comparison of obtained results, it can be said that the X-ray diffraction method provides a reasonable residual stress induced in the superconducting layer. It should be noted that more tests should be made in order to get good statistical integrity considering scattering in measured value and proper care of coating film should be taken when doing XRD measurements. More measurements on several samples should be taken in order to give a better representative data.

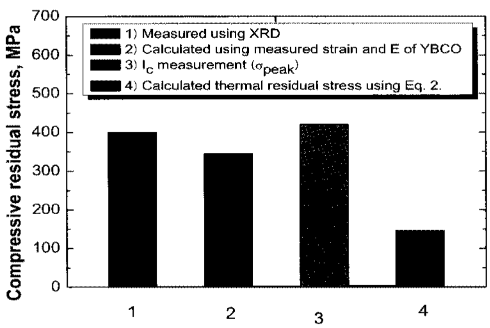

Fig. 7. Measured and Calculated Residual Stress values for the IBAD/PLD tape sample.

4. CONCLUSION

The residual stress measured based on the I_c/I_{c0}–strain degradation behavior showed similar value with the measured residual stress using XRD. The calculated residual stress using thermal analysis showed the lowest value. This could probably be explained by the additional intrinsic residual stresses induced in the superconducting film during deposition.

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