磁場中で REBCO CC テープの臨界電流−ひずみ効果評価におけるひずみの測定

Strain measurement technique in evaluating the I_c−strain response under magnetic field in REBCO CC tapes

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1. Introduction

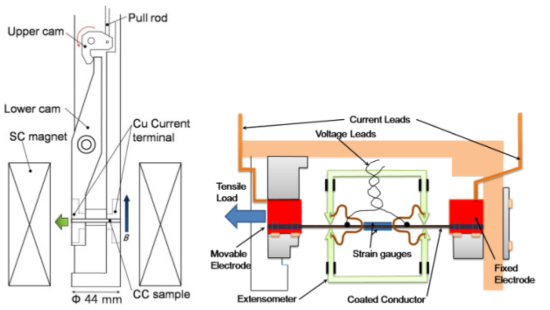
Nowadays, HTS tapes are being employed to some magnet and motors in replacement for the known LTS such as NbTi and Nb_3Sn [1-3] due to its high in-field critical current density, J_c and high mechanical tolerance. The 2nd generation (2G) REBCO CC tapes showed a good strain tolerance of critical current, I_c both at self field and under external magnetic field [4-9]. For such applications including magnets, SMES, and rotating machinery, the strain-temperature-magnetic field dependence of the critical current, I_c (ε-T-*B*), should be known to set its operating conditions. As of now, different testing apparatus or rig have been developed to evaluate the electromechanical properties of HTS tapes under magnetic field, which includes the Walter spring [5], CuBe bending rig [6,7], and tension/compression bending rig as described in ref [8-11]. Due to different design concepts of each experimental set-up like tension or bending test rigs, the strain measurement techniques may vary from every research group. They were done by attaching directly strain gauges on the sample, clamping double extensometers and by computer simulation etc. Sugano et al adopted the Nyilas double extensometers in determining the intrinsic strain effect on I_c under magnetic field [8]. On the other hand, Watanabe et al measured the residual strain state in Nb_3Sn by adopting strain gauges directly glued to the sample and succeeded in measuring the axial and lateral strains [12]. In addition, for the measurement of strain applied to HTS tapes under magnetic field using extensometer or strain gauge, each component of the measurement system must work well, including the signal conditioning device and proper calibration of the test equipment to obtain the actual stress-strain behavior of the sample [13]. In practical applications, the measurement of strains is not easy and they are complicatedly induced to the wires/tapes during operation.

In this study, strain gauge and extensometer were adopted for strain measurement of CC tapes at 77 K and under magnetic field and their performances were compared based on the stress-strain curves. The scope of this study is to give some insights on difficulties that we may encounter in strain measurement during test and how to get rid of them which may originate from testing apparatus, specifically on the strain measurement technique. Furthermore, the result of the electromechanical property evaluation in REBCO CC tapes under magnetic field is presented.

2. Experimental Procedure

A commercially available YBCO CC tape and two kinds of SmBCO CC tapes fabricated by the reel to reel RCE-DR process (reactive co-evaporation by deposition and reaction) and the batch type EDDC process (evaporation on dual drum chamber) were used as samples. All CC tapes adopt IBAD route substrate and were Cu-surround plated with thickness of 20 and 15 μm, respectively for thermal and electric stability. Critical current of the samples ranges from 87 to 110 A.

The electromechanical tests under magnetic fiels were carried out using the Katagiri-type tensile test rig. The tensile load is applied to the sample by moving the pull rod actuated by a stepping motor. This vertical motion was translated to horizontal one by a combination of the upper and lower cam which was shown in detail similarly in [8]. Consequently, the end of the lower cam pushes the movable current terminal as shown by the arrow in Fig. 1. Strain was measured by using the strain gauge and the Nyilas-type extensometer, respectively. In this test, strain gauges used have 0.2 mm gauge length and gauge factors of 2.02+1.5 %. Double extensometers have a gauge length of 15 mm. The strain gauges were attached axially with the load directions to both surfaces of HTS and substrate side. Bonding face of the strain



(a) (b)

Fig. 1. (a) Loading mechanism of the probe, *B*//c and (b) schematics showing the load application and strain sensing devices (not to scale)

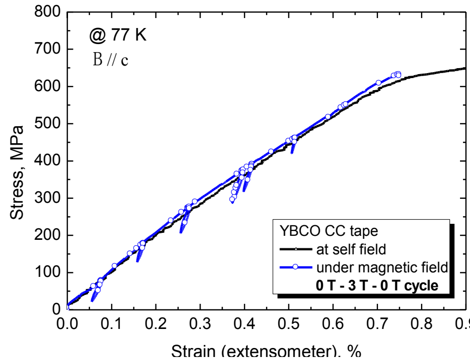
gauge was first polished to remove contaminations from the gauge bonding portion. Bond adhesive used was based on the gauge specifications. To bond the strain gauge, curing and aging time was set for about 3 hours at around 150°C. On the other hand, the double extensometer was clipped to the sample. The strain gauges were connected to wheatstone bridge while the double extensometer was directly connected to the signal conditioner. A Labview program was used for the data acquisition.

Measurement of the strain effect on I_c under magnetic field in CC tapes was carried out at 77 K. Critical current was measured by using 1 μV/cm criterion. Sample length, gauge length and voltage tap separation were 40, 20 and 10 mm, respectively. Reversibility test was done by loading and unloading scheme. Magnetic field was applied to the sample parallel to the c-axis using cryo-cooled superconducting magnet at HFLSM, IMR, Tohoku University. The stress-free cooling of the sample was considered to prevent the contraction effect of different materials during cool-down from RT to 77 K.

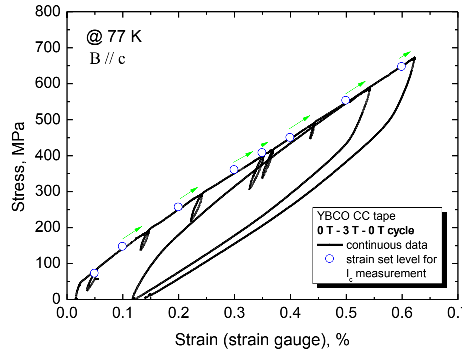
3. Results and Discussion

3.1 Performance of strain measuring devices under high magnetic field

Characteristics of the strain measuring device have been investigated from the obtained stress-strain (S-S) curves. Strain and stress were derived from the measured signals of strain measuring devices and from the load cell, respectively. Obtained strain values by strain gauge and double extensometers were compared. Extensometer-based curves under self-field and magnetic field fairly coincides which shows that the magnetic field has no significant effect on the strain measurement using double extensometers as depicted in Fig. 2a using the continuous data set. Figure 2b shows the S-S curves derived from the continuous data set using strain gauge in YBCO CC



(a)



(b)

Fig. 2. Stress-strain curves of YBCO CC tape (a) using extensometer obtained from the continuous test at self field and continuous data set under magnetic field and (b) using strain gauge showing anomalies during the strain effect measurement test on I_c under magnetic field.

tape. This represents the S-S curve behavior observed during the entire measurement of strain effect including loading and unloading. Open circles are the set values of strain for the I_c measurement test based on the strain gauge data. During the test, the strain value was set first before the magnetic field level. The strain dependence of I_c under magnetic field was measured from higher magnetic field level of 3 T down to 0 T. Upon increasing the magnetic field from 0 to 3 T, the load increases as indicated by the arrow and as the level of magnetic field is decreased the load also decreases but not the strain values, and it can be clearly observed that as the magnetic field applied increase and decrease it traces back to the original curve. The S-S curve using extensometer data also showed a similar behavior under magnetic field. Even though this anomaly occurred, the results are relatively good and reproducible, comparable to the reports of other groups for YBCO CC tapes [7-9].

Experimentally, both are possible to be used under severe test conditions of under magnetic field and at cryogenic temperature. For the strain gauge at low temperature, measured strain values should be calibrated considering the gauge factor change due to temperature. In addition, strain gauge worked well under magnetic field as have been reported in [5, 12].

Table 1. Advantages and setbacks of strain measuring devices

	Strain gauge	Extensometer
Attachment (Mounting/bonding to the CC tape	- Needs bond baking for use at cryogenic temperature	-Mounting-slippage possibility depending on skill
Applicability to 77K and under magnetic field (severe environment)	- Possible	- Possible Under high magnetic field, difficult to use due to substrate plate
Measurement range	- Less than 1.%	- Up to several % strain including plastic behavior
Effect of tape bending	- Removable by using two gage method	- Removable by using double ext-ensometer method
Usage (repeated)	-No (one time) Consumables	-Repeated usage is possible
Cost	- Expensive	- None

On the other hand, for the double extensometers, the possibility to be used under different temperature and magnetic fields were demonstrated in ref. [8, 9]. Compared to what have been reported by other groups, this time, using both the strain gauges and double extensometers was tried. In Table 1, advantages and setbacks of each device were described. In terms of handling and mounting, strain gauge mounting procedure is not simple, time consuming and requires skill, while double extensometers are quite easy to mount but also needs careful handling. The advantage of easy mounting however should be coupled with proper gripping to avoid slippage as what have been experienced in some of the test performed. Although the slip amount maybe removed by offsetting during data processing, but this will be an additional burden to the measurement procedures. The S-S curves obtained using the extensometer and strain gauge showed different behavior including yielding. Using strain gauge, the S-S curve did not show yielding behavior upon further application of load, but in the case of double extensometer, it entered the plastic region thus yielded resulting to an abrupt decrease of I_c. However, up to the elastic limit of the sample, both the strain gauge and double extensometers showed good results both at self field and under magnetic field at 77 K [15].

From the result of strain measurement tests, it can be concluded that the use of dual strain measuring system is reliable and better considering that the measurement process at cryogenic temperature and under high magnetic field is laborious and needs time for sample preparation and testing. Therefore, it is smart and practical to use both strain measuring devices together in order to save efforts, time and for data comparison if in case one did not function well as have been described as setbacks in Table 1.

From the issues mentioned above, measuring strain should start with a careful handling and mounting of devices. The deviations of result values are primarily due to the different test equipment, procedure and sample geometry. The analysis of the S-S curve is helpful but also statistical analysis is necessary for measuring the uncertainty of the results.

3.2 Strain effect on I_c under magnetic field, I_c (ε, B)

Fig. 3 shows the I_c/I_{c0}-ε relation under magnetic field in RCE and EDDC SmBCO CC tapes, respectively. In both SmBCO CC tapes, no I_c peak was observed during uniaxial tension test showing a monotonic decrease of I_c/I_{c0} with strain [16]. Under magnetic field, the degradation of I_c/I_{c0} becomes much significant at higher magnetic field. The result obtained for EDDC-SmBCO CC tapes (Fig. 3b) shows an abrupt decrease of I_c at 0.30% strain. This is attributed to the low strength of Hastelloy substrate which exhibited discontinuous yielding during test.

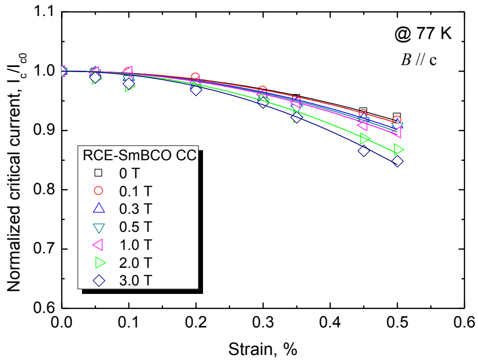
To analyze the variation in I_c/I_{c0} curves with magnetic field in SmBCO CC tapes, fitting analysis was employed in order to describe qualitatively the strain effect characteristics with varying magnetic field level. The curves were fitted using [8, 14]

$$\frac{I_c(\varepsilon_a,B,T)}{I_c(\varepsilon_a=0,B,T)} = \frac{1-a(\varepsilon_a-\varepsilon_p)^2}{1-a(-\varepsilon_p)^2} \quad (1)$$

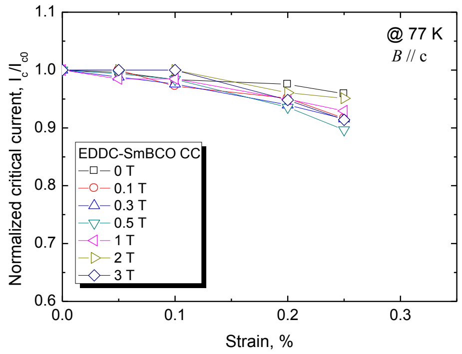
where a and ε_p correspond to curvature or sensitivity of I_c under magnetic field and the peak strain of the curve, respectively. Although we can predict that the I_c peak might be located at compression side for some SmBCO CC tapes, our current experimental data are only limited to tension side. Therefore, in order to analyze the strain sensitivity of I_c in SmBCO CC tape from our current data, it is assumed that the I_c peak is located at 0 % thus simplifying the Eq. (1) into

$$\frac{I_c}{I_{c0}} = 1 - a(\varepsilon_a)^2 \quad (2)$$

Fitted curves are also plotted in Fig 3a in the case of RCE-SmBCO CC. Strain has been limited up to 0.5% which is below the irreversible strain limit of the RCE-SmBCO CC tape, while it was up to 0.25% only in the case of EDDC-SmBCO CC due to the continuous increase of strain observed during the test. From these fitted curves, a-value was obtained and plotted as a function of magnetic field in Fig. 4. With increasing magnetic field, the a-value which describes the strain sensitivity of I_c increases. a-value increased linearly with B but some scattering is observed in the



(a)



(b)

Fig. 3. Normalized critical current, I_c/I_{c0} as a function of uniaxial strain under various magnetic fields (B//c) at 77 K in (a) RCE-SmBCO and (b) EDDC-SmBCO CC tape. In the case of RCE-SmBCO CC tape, fitted curves are shown as solid lines.

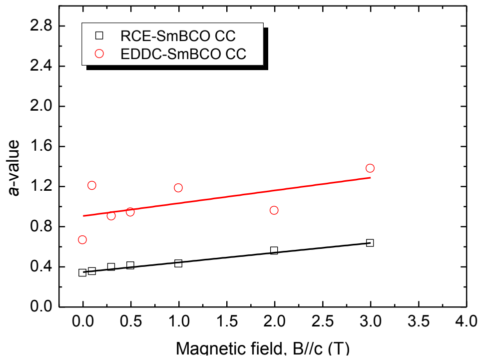


Fig. 4. *a* values obtained using only experimental data results at tension side as a function of magnetic field at 77 K in RCE and EDDC-SmBCO CC.

case of EDDC due to the limited number of data. Slopes are similar but the absolute values of I_c strain sensitivity differed in differently processed SmBCO CC tapes. The irreversible strain limit was not so much affected by the magnetic field level applied in these tests and reversibility was observed even up to 0.5%. As the strain sensitivity of I_c increases with increasing magnetic field, the reversible reduction in I_c with strain becomes larger. These behaviors of the strain effect on I_c will then give an insight on how the I_c maybe affected by high magnetic field.

4. Summary

Respective strain measuring device showed good characteristics in measuring the induced strain under high magnetic field and at cryogenic temperature. Using dual strain measuring devices together may ease the burden in case one does not work well under severe test conditions. SmBCO CC tapes showed increasing I_c strain sensitivity with increasing magnetic field up to 3 T. In addition, the irreversible strain is independent on the magnetic field in the range tested.

Acknowledgement

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