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Establishment of strain measurement system for evaluation of strain effect in HTS tapes under magnetic field

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Abstract**-- The evaluation of the electromechanical properties of HTS CC tapes is one of the foremost procedures to be done to ensure the applicability of superconducting wires to electric devices. A precise measurement of the stress and strain is important in deriving the mechanical properties under operating environment. Up to now, there is no standard test method yet for the electromechanical property evaluation of HTS tapes under self field and external magnetic field although there are already reports on the different devices used to evaluate these properties. Strain can be measured by adopting a strain gauge or a high resolution double extensometer. In this study, strain effect on I_c in HTS CC tapes under magnetic fields was evaluated. Comparison of advantages and setback of strain measuring devices were discussed. In addition, a dual strain measurement system using both the SG and extensometer may be practical to lessen the burden in case one of the measuring devices does not work well.**

1. INTRODUCTION

In practical applications of HTS tapes such as magnets, SMES, and rotating machinery, the strain-temperature -magnetic field effect on the critical current, I_c (ε-T-B), should be known to set its operating conditions. Nowadays, HTS coated conductor (CC) tapes are being employed to some magnet and motors in replacement for the known LTS such as NbTi and Nb_3Sn [1-3]. These CC tapes showed a good strain tolerance of I_c both at self field and under external magnetic field [4-9]. Under magnetic field, different testing apparatus or rig have been developed for the evaluation of electromechanical properties of HTS tapes which includes the Walter spring [5], CuBe bending rig [6,7], and tension/compression bending rig as described in ref. [8-11]. Due to the different design concepts of experimental set-up of tension or bending rigs, strain measurement techniques may vary from every research group. They were done by attaching directly a strain gauge on the sample, clamping double extensometers and by computer simulation. Sugano et al. adopted the Nyilas double extensometers in investigating the intrinsic strain effect on I_c under magnetic field. The double extensometers were calibrated at different temperature but neglected the influence of magnetic field between 0 and 10 T on the calibration factor since its effect was only less than 1% [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, these stresses/strains are complicatedly induced to the wires/tapes during operation.

Strain effects in superconducting wires/tapes have been intensively investigated by adopting different testing procedures [14-17]. Recently, fundamental stress-strain measurements on NbTi/Nb_3Sn wires were completed as international standards (IEC 61788-6) within the framework of IEC/TC90 and VAMAS/TWA 16 with the key task on assessment of the sensing system resolution, accuracy and precision when measuring the elastic modulus [13]. Also, the standardization of mechanical property testing of BSCCO wire/tape at room temperature and a plan to initiate in the case of coated conductors are underway.

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 not to present some statistical analysis of the data but rather 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.

2. EXPERIMENTAL PROCEDURE

SmBCO coated conductor (CC) fabricated by the EDDC process and commercially available YBCO CC were supplied for the test. CC tapes adopt IBAD route substrate and they were Cu-surround plated with thickness of 20 μm, for thermal and electric stability. Critical currents of the CC tapes range from 87 to 110 A.

Under self field at 77 K, electromechanical properties evaluation of the CC tapes under tension was done adopting the test rig reported in [14]. Loading frame was mounted on a universal test machine and load was applied

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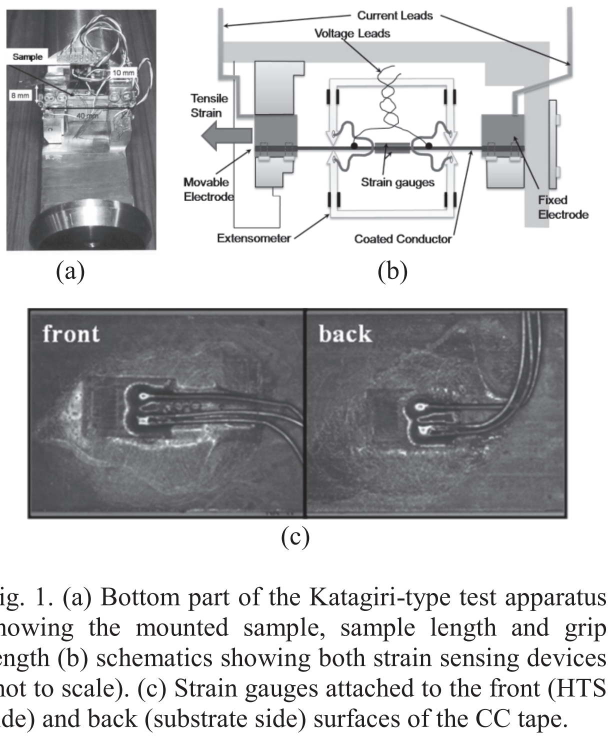
to the sample by moving the pull rod. The displacement of the sample was measured using the Nyilas double extensometers [13]. During continuous tensile test at a constant displacement speed of 1 mm/min, signals from the load cell transducer and extensometer signal conditioner were acquired using LabVIEW program. During I_c measurement, load and voltage output of the extensometer were noted and stresses were calculated dividing the load applied by the tape's original cross section. Strain values were calculated from the measured voltage output by using calibration factor (V/mm) and extensometers gauge length, respectively. Sample length, gauge length and voltage separation were 90, 40, and 20 mm, respectively.

Under magnetic field, the electromechanical tests were carried out using the Katagiri-type tensile test rig as shown in Fig. 1(a) [8]. The tensile load is applied to the sample by moving the pull rod actuated by a stepping motor. The vertical motion was translated to horizontal one by a combination of the upper and lower cams which was shown in detail in [8, 18]. Consequently, the end of the lower cam pushes the movable current terminal as shown by the arrow in Fig. 1(b). Strain was measured using both strain gauge and Nyilas-type extensometer together. In this test, strain gauge used have 0.2 mm gauge length and gauge factor of 1.88±1.5%. Double extensometers have gauge length of 12.5 mm. Strain gauges were attached along with the load direction at both surfaces of the sample as shown in Fig. 1(c). Bonding face of the strain gauge was first polished to remove the grease 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 while on pressure and annealed with the same temperature without pressure for two hours and slowly cooled to RT similarly in ref [12]. On the other hand, double extensometers were



(a) (b)

(c)

Fig. 1. (a) Bottom part of the Katagiri-type test apparatus showing the mounted sample, sample length and grip length (b) schematics showing both strain sensing devices (not to scale). (c) Strain gauges attached to the front (HTS side) and back (substrate side) surfaces of the CC tape.

clipped to the sample. The strain gauges with a Wheatstone bridge while the double extensometers were directly connected to the signal conditioner. The double extensometers are wired together into a single type extensometer, thus averaging the two displacement records electrically.

Measurement of the strain effect on I_c under magnetic field and at self field using CC tape samples was carried out at 77 K. Critical current was measured 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 of superconducting film using 10 T cryo-cooled superconducting magnet at HFLSM, IMR, Tohoku University. Stress-free cooling was considered to prevent the contraction effect due to different materials of the rig and sample during cool-down from RT to 77 K for both of the test procedures at self field and under magnetic field.

3. RESULTS AND DISCUSSION

3.1. Comparison of stress-strain curves under magnetic field according to strain measuring device adopted

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 measurement devices and from the load cell, respectively. S-S curves derived during the strain effect measurement test on I_c under magnetic fields are shown in Fig. 2 together with the S-S curve at self field. During I_c measurement test at specified strain level, strain effect on I_c was measured from 3 T down to 0 T creating magnetic field cycle of 0 T – 3 T – 0 T. Obtained strain values using strain gauge and extensometer were compared. Extensometer-based curves under self-field and magnetic field fairly coincides which shows that magnetic field has no significant effect on the strain measurement using double extensometers. Extensometer performance at self field and under magnetic field conforms well as depicted in Fig. 3 using the continuous data set. On the other hand in Fig. 2, the strain gauge-based curve deviates from the extensometer-based curves when the strain exceeded 0.35 % representing a little bit smaller strain values. Figure 4 shows the S-S curves derived from the continuous data set

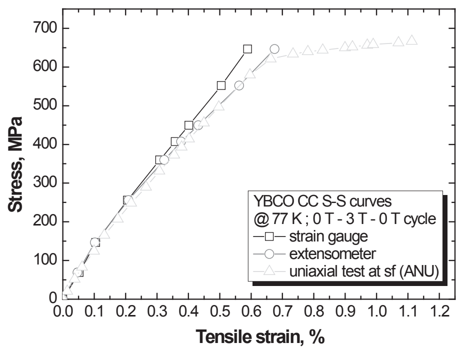


Fig. 2. Stress-strain curves of YBCO CC tape obtained during the strain effect measurement test on I_c.

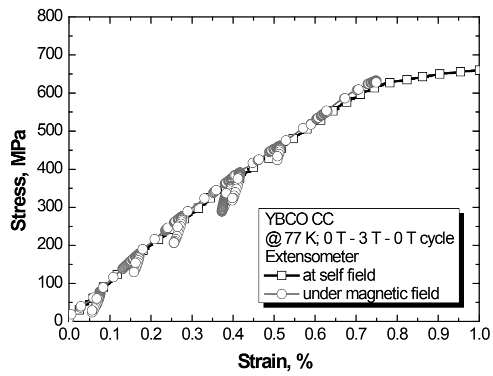


Fig. 3. Stress-strain curves of YBCO CC tape using extensometer obtained from the continuous test at self field and continuous data set under magnetic field.

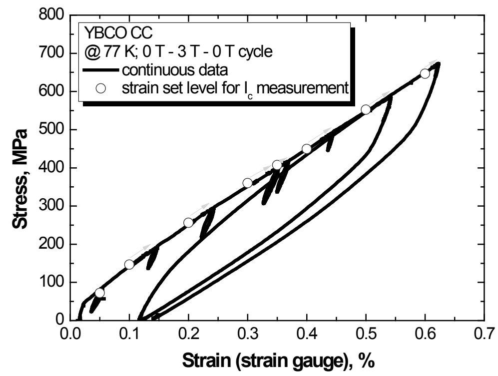


Fig. 4. Stress-strain curve of YBCO CC tape showing anomalies during the strain effect measurement test on I_c under magnetic field.

using strain gauge in YBCO CC tape. This represents the S-S curve behavior observed during the entire strain effect measurement test including loading and unloading unlike in Fig. 2. Open circles are the strain values set for I_c measurements based from 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. 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 in the case of YBCO CC tapes [7-9].

3.2 Features of strain measuring devices under high magnetic field

It is very interesting to note the advantage and disadvantages of each strain measuring device. Experimentally, both are possible to be used under severe test conditions that are under magnetic field and at cryogenic temperature. For strain gauge at low temperature, measured strain values should be calibrated considering

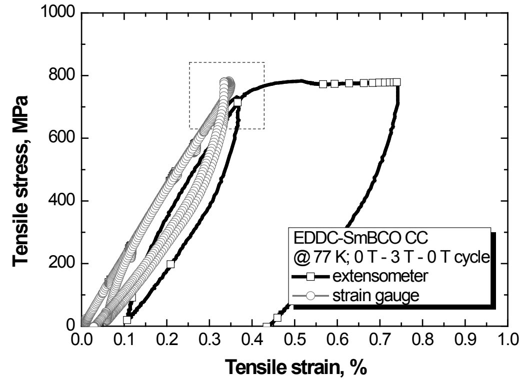


Fig. 5. Stress-strain curves of EDDC-SmBCO CC tape during the test under magnetic field.

the gauge factor change due to temperature. In addition, strain gauge worked well under magnetic field as have been reported in [5, 12]. For the double extensometers, the possibility to be used under different temperature and magnetic fields were demonstrated from the work of Sugano et al [8, 9]. Compared with what have been reported by other groups, this time the adoption of both the strain gauge and extensometer 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. In Fig. 5, it showed a representative example of robust behavior of both the strain gauge and extensometer in EDDC-SmBCO CC tapes. S-S curve obtained using the extensometer and strain gauge showed different behavior including yielding. Using strain gauge, S-S did not show yielding behavior upon further application of load, but in extensometer, strain continuously increased and enter the plastic region thus yielded and resulted to an abrupt decrease of I_c. Up to the elastic limit of sample, both the SG and extensometer showed good results under self field and magnetic field at 77 K.

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

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

TABLE I
ADVANTAGES AND SETBACKS OF STARAIN 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 two gage method
Usage (repeated)	-No (one time) Consumables	-Repeated usage is possible
Cost	- Expensive	- None

4. CONCLUSION

Respective strain measuring device showed good characteristics in measuring the induced strain under high magnetic field and at cryogenic temperature, but proper procedures in handling especially during mounting should be taken in order to achieve its full potentials along with the proper data acquisition for much reliable results. Therefore, adopting dual strain measuring device may ease the burden in case one does not work well under severe test conditions.

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