Stress Analysis of a High Temperature Superconductor Coil Wound With Bi-2223/Ag Tapes for High Field HTS/LTS NMR Magnet Application

Seyong Choi, Tsukasa Kiyoshi, Seung-yong Hahn, and Michinaka Sugano

***Abstract*—The electromagnetic stress distribution inside a HTS insert is one of the key issues for construction of a high field high/low temperature superconductor (HTS/LTS) magnet. The $r \cdot J \cdot B$ formulae is widely used for the stress calculation of the coil, due to its simplicity. However, the assumption of this calculation makes it impossible to consider the effects of the bobbin, an epoxy impregnated structure, on stress of the coil. In this work, stress analysis methods are reported. The governing equation defined from the force equilibrium state was adopted and used to analyze what the stress of the HTS coil wound with Bi2223/Ag conductor. The validness of the stress analysis method was confirmed by comparison with experimental results, especially in the coil with epoxy impregnation. The numerical and experimental procedures are described and both results are discussed.**

***Index Terms*—Bi-2223/Ag insert coil, hoop stress, NMR magnet, radial stress, stress analysis.**

I. INTRODUCTION

EFFORTS to increase the magnetic field of nuclear magnetic resonance (NMR) spectrometer have steadily progressed, because the magnitude of the magnetic field enhances the sensitivity and resolution of NMR. Recently, a 920 and 930 MHz NMR was developed and now operating by National Institute for Materials Science [1]. As the magnetic field increases, the contribution of the HTS insert coil is required in order to achieve 1 GHz NMR. HTS tape fabricated from materials such as Bi-2212, Bi-2223 and YBCO have enabled the magnetic to exceed 24 T, due to their high critical field. A few attempts to overcome 1 GHz NMR have continued: (1) NIMS in Japan has started an upgrade project of a 920 MHz magnet to develop a 1.05 GHz NMR (24.7 T) using a HTS insert [1]; (2) MIT in the USA has carried out a 3-phase program to achieve a 1 GHz HTS/LTS magnet [2].

The Bi-2223/Ag tapes used in the HTS insert coil are brittle materials so that their performance is considerably affected by strain [3]–[5]. The stress/strain level inside the coil should be strictly limited below the allowable specification of conductor to avoid failure caused by stress/strain during full operation of the magnet. For this purpose, it is important to precisely predict the stress distribution inside the coil winding using stress-related parameters, such as bending strain, thermal contraction, winding tension, or the effect of epoxy impregnation. Practically, much of the electromagnetic force acts on the coil in longitudinal direction during magnet operation, which is referred to as hoop stress. With many assumptions, hoop stress is simply expressed as $\sigma_h = r \cdot J(r) \cdot B(r)$, where r is the radius from the origin, J is the current density of the conductor and B is the magnetic field, [6]. This relation has been widely used to make rough stress estimation for the large winding, although it produces an exact solution only for the case of independent turns, ignoring the relation between the bobbin, each turn in the coil and the epoxy structure.

In the following sections, an analysis method to predict the stress in the HTS coil is introduced. The governing equation, taking into consideration the force equilibrium, is described and used for the stress analysis. It was experimentally demonstrated that magnetic force exerted on the HTS coil generates a significantly large amount of stress. Finally, discussion of the validity of the stress analysis method is presented by comparison of the experimental results.

II. NUMERICAL ANALYSIS OF STRESS IN HTS COIL

The theory for stress analysis has been classically defined in previous works [6]–[8]. The governing equation for stress analysis is described from force equilibrium in [8].

$$r\frac{\partial \sigma_r}{\partial r} + \sigma_r - \sigma_h + r \cdot J(r) \cdot B(r) = 0 \quad (1)$$

where r is the radius from the origin, σ_r is the radial stress, σ_h is the hoop stress, J is the current density, and B is the magnetic field. The governing equation requires numerical expansion, which is well defined elsewhere [8].

The young's modulus (E) of the bobbin was defined as 96 GPa. The E of HTS tape was measured using a universal tensile testing machine, with repetition of the load/unload sequence. E measured for Bi-2223/Ag tape was 107.3 GPa. The architecture of the conductor consisted of Bi-2223, Ag, Ag alloys and two

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TABLE I
SPECIFICATION OF HTS TAPE AND COIL

Specification of Bi2223/Ag conductor	
Width and thickness	4.43× 0.29 mm
Lamination	SUS304H
Thickness of lamination	20 µm
Maximum bending radius	50 mm
Critical current at 77.3K, self-field	198 A
Specification of the coil	
Inner diameter (I.D.) of bobbin	280 mm
Number of turn	1
Bobbin material	GFRP

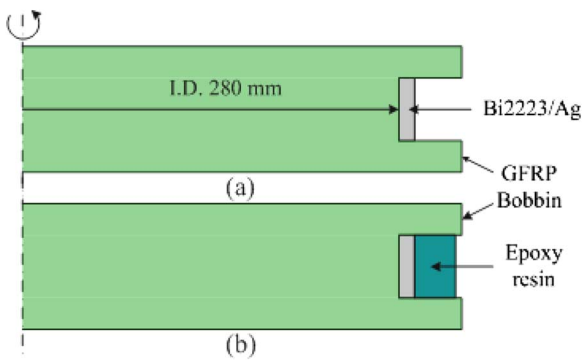

Fig. 1. Schematic diagram of the bobbin and single turn coil used in experiments. (a) Single turn coil without impregnation, and (b) coil with epoxy resin impregnation.

pieces of stainless steel plate. It was reported that E was calculated by rule of mixture to be 106.3 Gpa [4]. No discrepancy between measured and estimated E was found and 107.3 GPa used for the conductor in the stress calculation.

III. PROCEDURES OF EXPERIMENTAL MEASUREMENTS

A. HTS Tape and Single Turn Coil Preparation

A Bi-2223/Ag tape laminated with stainless steel was used for the experiment and calculation of stress in the coil winding. The conductors were provided by Sumitomo Electric Industries. The specifications of the HTS tape and coil are listed in Table I. The conductor performance in field was acquired in advance by measuring critical current (I_c) in short length sample from 0 to 28 T at 4.2 K [9]. The observed self-field I_c of the HTS tape was 198 A at 77.3 K and 1114 A at 4.2 K. The critical current of 14 T (magnetic field parallel to the tape surface) was 653 A at 4.2 K. Details of the conductor performance in a magnetic field have been reported [9].

Fig. 1 shows a schematic drawing of the bobbin and single turn coil used in this work. Two kinds of coil were prepared: (a) without impregnation, and (b) with epoxy resin impregnation, as shown in Fig. 1. The Bi-2223/Ag tape was wound on the GFRP bobbin. A winding tension of 5 N was applied to confirm stress reduction by winding tension. According to the vendor specifications, critical wire tension at room temperature is 255 N [10], so that the amount of winding tension would not cause mechanical damage to the coil.

After preparation of the coil, three strain gauges (Kyowa SKF-24521) were mounted on the surface of coil to measure the elongation of the conductor caused by hoop stress. In order to compensate the effect of temperature, an additional strain gauge was put on a short piece of the tape used in the winding, which was placed freely around the coil. The strain of the coil was obtained by the difference of the gauge on the coil and reference one. The other coil (b) was impregnated with epoxy resin (Nitto Denko, SK-229), in a similar method to that employed for a practical coil. The coil was cured for three days at room temperature for complete impregnation.

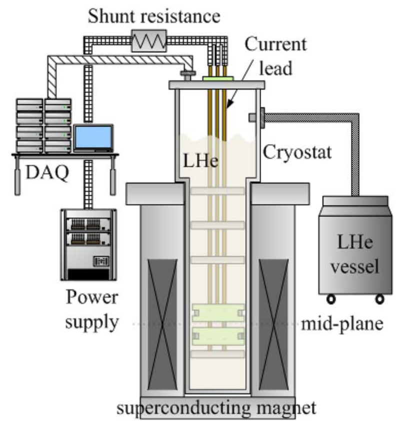

Fig. 2. Schematic illustration of the experimental setup for the stress/strain measurement.

B. Experimental Setup

The coils were assembled in the probe to measure the maximum hoop stress of Bi-2223/Ag conductor in the coil. The probe has three current leads and two coils were simultaneously connected to the current lead in parallel. The transport current flowing into the coils was measured through a digital voltmeter (Keithely DMM2000) with a precise shunt resistance of 50 mV/1000 A.

A pair of voltage leads was soldered along the coil at a distance of 79 cm. This configuration could help to reduce the noise level in magnetic field. The voltage taps were connected to a nano-voltmeter (Keithley DMM2182) to measure the voltage drop in the coil. Each strain gauge was also separately connected to voltmeters (Keithley DMM2000). Every instrument was linked by to a computer through a GPIB interface for controlling and data acquisition. The experiment was carried out using a large bore superconducting magnet.

All measurements reported here were performed under 14 T at 4.2 K. The experimental setup used in the present work is schematically illustrated in Fig. 2.

IV. RESULTS AND DISCUSSION

When the temperature of the cryostat (4.2 K) and external magnetic field (14 T) became stable, the electric potential and

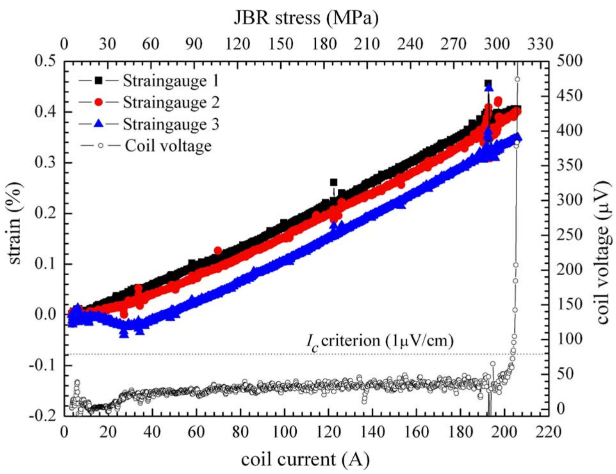

Fig. 3. Strains and coil voltage behavior as a function of transport current in the coil without impregnated epoxy.

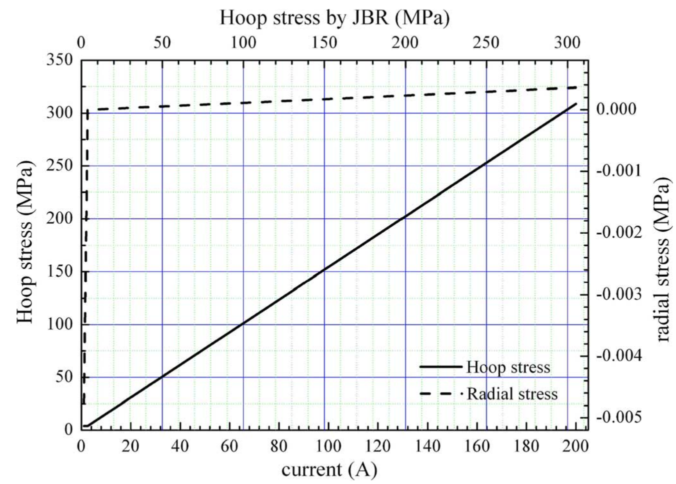

Fig. 4. Calculation of the hoop and radial stress in the coil without impregnated epoxy.

strain of the coil were simultaneously measured as a function of transport current until the coil voltage reached to the criterion of 1 $\mu\mathrm{V/cm}$. Fig. 3 shows the experimental results of coil voltage and strain behavior in the coil without impregnation (a). The coil voltage reaches the predetermined criterion at 204 A. The I_c of the coil is much lower than the short sample (653 A) under same condition (4.2 K, 14 T). This is mainly because the electromechanical force exerted on the coil significantly affected the performance of the conductor. The maximum strain under coil I_c was observed 0.4%, which is consistent with the fact that the performance of Bi-2223/Ag is decreased abruptly when the strain is applied exceeding its tolerance value [10]. The large difference between the short sample and coil I_c could be explained due to large hoop stress/strain in the coil.

In the top of the horizontal axis, hoop stress calculated from $r \cdot J \cdot B$ relation was also displayed with respect to coil current. According to the results of $r \cdot J \cdot B$ formulae, the coil experienced the stress of 309 MPa at the coil I_c.

The calculation by force equilibrium was also performed in the non-impregnated coil, and the stress of the radial and longitudinal component was obtained. The radial and hoop stress are plotted with dotted and solid lines in Fig. 4, respectively. During the calculation, the bobbin was removed when the radial stress became positive from a negative state, so that the coil turn acts freely from the bobbin from the moment of radial stress variation. The sign of the radial stress changed to positive at a current of 3 A, as shown in the figure (dotted line). As a result, the hoop stress drastically increased when the conductor was independent from the bobbin. The hoop stress of the coil calculated by numerical methods was 315 MPa at the coil I_c. The strain measured by experiment, and calculated hoop stresses using both methods are good agreement with each other. This suggests that the stress distribution in the coil without impregnation can be predicted, even using the simplest approach by the $r \cdot J \cdot B$. Generally, the critical current of Bi-2223/Ag does not exhibit a reversible way once it has been subjected beyond the critical stress/strain value. It was confirmed by the following measurement that the critical current exhibited a sharp decrease of 115 A from the second run and did not return.

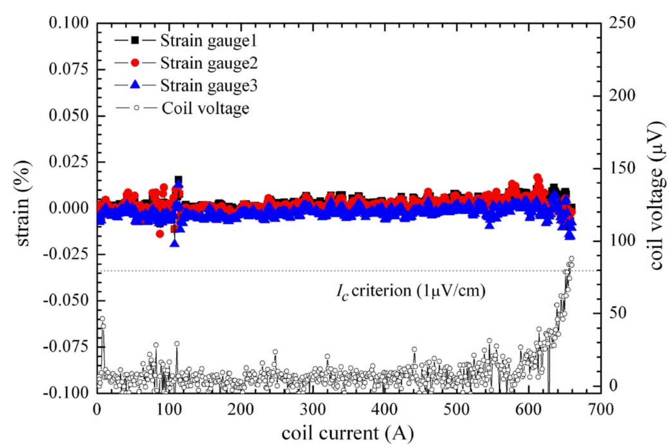

Fig. 5. Strains and coil voltage behavior as a function of transport current in the coil with epoxy resin impregnation.

The test results of epoxy impregnated coil are presented in Fig. 5. The strain behavior of the epoxy impregnated coil is quite different from that of non-impregnated coil. One can see in the figure that the strains are balanced on zero for the wide transport current region. It means the coil is no stress/strain state until the coil current reached I_c. This can be also confirmed by comparison with the short sample and coil I_c. In case of epoxy impregnated coil, I_c of the coil was 657 A, which is almost identical to the short sample I_c (653 A). This also implies that the hoop stress hardly influence on the coil performance as well as amount of hoop stress is quite low.

The stress by the calculation of force equilibrium is depicted in Fig. 6. It is shown that the calculated hoop stress (solid line) of the coil is 9 MPa at the coil I_c. The hoop stress at I_c using $r \cdot J \cdot B$ formulae is also calculated as 1002 MPa. The discrepancy between the stress results was too large. However, the stress inside the impregnated coil is thought to do not exist even at the critical current. The experimental results such as magnitude of the strain value in Fig. 5 and the critical current comparison are good evidence of the stress/strain value of the coil. Consequently, it suggests the force equilibrium is only method to calculate stress

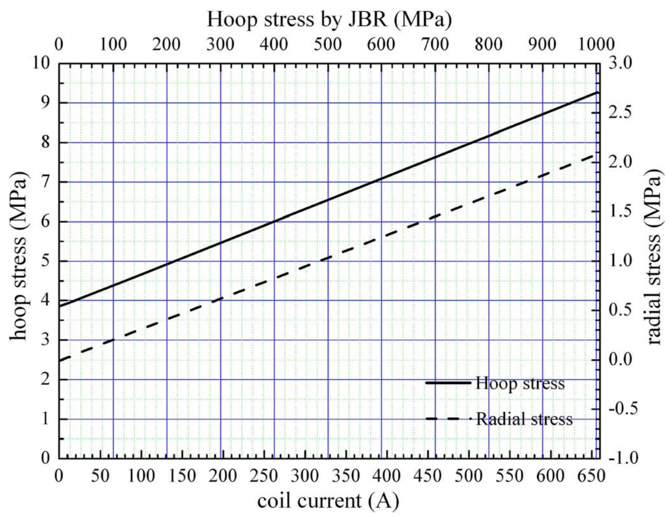

Fig. 6. Calculation of the hoop and radial stress in coil with epoxy resin impregnation.

TABLE II
SUMMARY OF STRESS ANALYSIS

	The coil without impregnation	The coil with epoxy resin impregnation
I_c of short sample at 77.3K, 0 T	198 A	
I_c of short sample at 4.2 K, 0 T	1114 A	
I_c of short sample at 4.2K, 14 T(B//)	653 A	
I_c of coil at 4.2 K, 14 T	204 A	657 A
Maximum strain at I_c	0.4 %	< 0.01 %
The $r \cdot J \cdot B$ stress	309 MPa	1002 MPa (false)
Stress calculation by force equilibrium	315 MPa	9 MPa

correctly, as well as the $r \cdot J \cdot B$ approaches overestimates the stress in the case of epoxy impregnated coil.

The stress results are summarized in Table II, with respect to the analysis methods. Both methods enable to estimate the hoop stress of the coil without impregnation. The usage of $r \cdot J \cdot B$ formulae for stress calculation should be strictly limited on such condition. On the other hands, stress calculation based on force equilibrium will be applicable to every coil configuration. For precise estimation of hoop stress in epoxy impregnated coil, numerical calculation based on force equilibrium should be applied.

V. CONCLUSIONS

The electromechanical stress in a HTS coil wound with Bi-2223/Ag conductor laminated with stainless steel plates was investigated both numerically and experimentally. The stress/strain dependence of the critical current on the coil was examined with respect to epoxy impregnation. In case of the non-impregnated coil, the stress using $r \cdot J \cdot B$ formulae and force equilibrium equation were in good correspondence with each other. On the other hand, the $r \cdot J \cdot B$ overestimated the hoop stress excessively, due to the lack of relation between the bobbin, coil and epoxy impregnation. The experimental results also represented that the strain behavior is well explained by the force equilibrium for the epoxy impregnated coil, which confirmed the validness of the method. It was confirmed that true stress on the coil with epoxy impregnation could only be obtained by taking into account the coil and the material properties of its surroundings, such as bobbin and impregnation.

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REFERENCES

[1] T. Kiyoshi, A. Otsuka, S. Choi, S. Matsumoto, K. Zaitsu, T. Hase, M. Hamada, M. Hosono, M. Takahashi, T. Yamazaki, and H. Maeda, "NMR upgrading project towards 1.05 GHz," *IEEE Trans. Appl. Supercon.*, vol. 18, no. 2, pp. 860–863, June 2008.

[2] S.-Y. Hahn, J. Bascunan, W.-S. Kim, E. S. Bobrov, H. Lee, and Y. Iwasa, "Field mapping, NMR lineshape, and screening current induced field analyses for homogeneity improvements in LTS/HTS NMR magnets," *IEEE Trans. Appl. Supercon.*, vol. 18, no. 2, pp. 856–859, June 2008.

[3] S. Ochiai, H. Rokkaku, J. K. Shin, S. Iwamoto, H. Okuda, K. Osamura, M. Sato, A. Otto, and A. Malozemoff, "Thermally and mechanically induced residual strain and atrain tolerance of critical current in stainless steel-laminated Bi2223/Ag/Ag alloy composite superconductors," *Supercond. Sci. Technol.*, vol. 21, pp. 1–13, 2008, 075009.

[4] K. Osamura, S. Machiya, H. Suzuki, S. Ochiai, H. Adachi, N. Ayai, K. Hayashi, and K. Sato, "Mechanical behavior and strain dependence of the critical current of DI-BSCCO tapes," *Supercond. Sci. Technol.*, vol. 21, p. 054010, 2008.

[5] M. Sugano, K. Osamura, and A. Nyilas, "Analysis of stress-strain behavior in Bi2223 composite tapes," *Physica C*, vol. 412–424, pp. 1114–1119, 2004.

[6] M. N. Wilson, *Superconducting Magnets*. : Oxford University Press, 1983.

[7] D. B. Montgomery, *Solenoid Magnet Design*. : Robert E. Krieger Publishing Company, INC., 1969.

[8] W. H. Gray and J. K. Ballou, "Eletromechanical stress analysis of transversely isotropic solenoids," *J. Appl. Phys.*, vol. 48, no. 7, pp. 3100–3109, July 1977.

[9] S. Choi, T. Kiyoshi, S. Matsumoto, D. Uglietti, K. Zaitsu, T. Hase, and M. Hamada, "The electrical and mechanical characterization of metal-reinforced Bi-2223/Ag conductor for high field insert coil," presented at the 2008 Applied Superconductivity Conference, Chicago, Illinois, USA, August 17–22, 2008, 3MPF01, unpublished.

[10] A website of Sumitomo Electrics Industries Ltd. [Online]. Available: http://www.sei.co.jp/super/hts_e/index.html