The published version of this manuscript appeared in IEEE Transactions on Applied Superconductivity **20**, No. 1532 - 1536 (2010)

Internal Strain and Mechanical Properties at Low Temperatures of Surround Cu Stabilized YBCO Coated Conductor

Kozo Osamura, Shutaro Machiya, Yoshihiro Tsuchiya and Hiroshi Suzuki

***Abstract*—The mechanical properties of surround Cu stabilized YBCO coated conductor were assessed at 5.7, 77 and 298 K. The internal strain exerted on the superconducting YBCO layer was directly evaluated under tensile load at low temperatures down to 9.8 K by neutron diffraction techniques. The compressive internal strain, present in the YBCO layer without external load, is the thermally induced residual strain. When the external tensile load was applied, the compressive component of internal strain decreased and changed into tensile. The force-free strain, A_{ff}, was determined as the strain at which the internal strain becomes zero. The A_{ff} estimated from (200) diffraction data depended weakly on temperatures between 298 and 9.8 K. However, the A_{ff} estimated from (020) data decreased prominently with decreasing temperature.**

***Index Terms* — critical current, internal strain, neutron diffraction, YBCO coated conductor**

I. Introduction

To use YBCO coated conductors in practical applications, it is important to know the stress/strain dependence of critical currents, because they experience stress and strain during fabrication and during operation in magnetic fields. The coated conductors are a typical composite material, in which several components with different properties are layered. It is a key issue to directly determine the stress and strain in the YBCO superconducting layer for considering their influence on critical currents [1 – 4]. Quite recently we developed a cryogenic load frame with a GM refrigerator [5], which suitably fits into the neutron diffraction facility RESA operating at JRR-3 research reactor of JAEA (Japan Atomic Energy Agency). It thus became possible to measure simultaneously lattice spacing under load and stress *vs*. strain curves at low temperatures. In order to elucidate the pending problem on the stress/strain dependence of critical currents, the precise measurements of the plane spacing in YBCO layers were carried out under tensile load at low temperatures down to 9.8K. The force-free strains on the YBCO layer were experimentally determined in a wide range of temperatures.

Manuscript received 20 October 2009. This work was supported in part by a grant-in-aid of the Ministry of Education, Culture, Sports, Science and Technology, Japan (No. 19360289).
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II. Experimental Procedure

The samples (SCS4050) used here were the surround Cu stabilized YBCO coated conductors. The architecture of the present coated conductors is as follows. The original coated conductor consists of Hastelloy substrate (50μm thick) + IBAD MgO (10nm) + Homo-epi MgO (30nm) + LMO (30nm) + YBCO layer (1μm) +Ag cap layer (2 μm). The tape of about 4 mm width was electroplated with copper 20 μm thick.

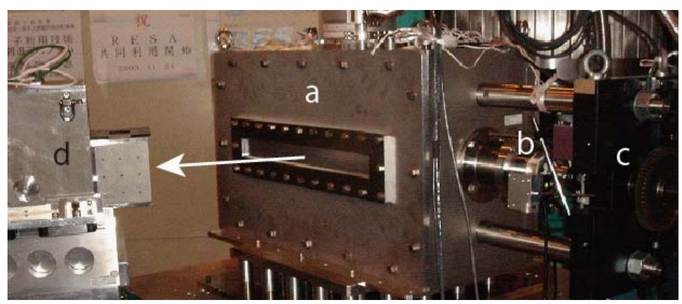

Fig. 1 Cryogenic load frame installed in the neutron diffraction facility RESA in JAEA. Here (a): main body of cryogenic load frame, (b) load cell, (c) loading mechanism and (d) neutron detector.

As shown in Fig. 1, the cryogenic load frame used here was installed in the neutron diffraction facility RESA at JRR-3. Simultaneous experiments of tensile test and neutron diffraction were carried out under the condition where the scattering vector is parallel to the load axis. As a result, the load axis should in the horizontal plane prescribed by the incident and diffracted neutron beams (d in Fig. 1). Inside the chamber, sample was gripped by copper chucks. Thermal sensors and heaters were attached to the grip chucks in order to monitor and control the temperature. The Nyilas type extensometers were attached to the sample to measure macroscopic strain. The free-standing sample was placed at a nearby position of the same temperature. The details were reported elsewhere [5]. Employing a GM refrigerator as cryogen-free cooler, the sample temperature was kept constant at set cryogenic temperatures. The loading mechanism (c) and the load cell (b) seen in Fig. 1 were installed at the outer of vacuum vessel. The loading capacity was in practice 10 kN.

Tensile tests were carried out at 298 and 77 K by using the tensile machine Shimadzu AG-50NIS equipped by 1 kN load cell. The initial distance between the chucks was kept as 100 mm. The Nyilas type double extensometer (GL = 25 mm) was attached at the center of the specimen. The initial cross head speed was usually selected as 1.7 x 10^{-5} s^{-1}.

III. Experimental Results and Discussion

A. Mechanical Properties

Figure 2 shows the results of tensile test at different temperatures. The analytical results are summarized in TABLE 1. Here two experiments at 298 and 77 K were carried out by using the Shimadzu tensile machine and another experiment at 5.7 K was carried out by using the present cryogenic load frame. Mechanical properties are usually divided into two regions of elastic and plastic deformation. In the elastic region, the linear stress vs strain relation was observed to hold up to about 0.3% strain. The macroscopic yielding took place at $R_{0.2p}$ = 850 MPa at 298 K and increased to 1020 MPa at 77K. The mechanical properties saturated almost at the further low temperatures from 77 to 5.7 K. The modulus of elasticity E_c was determined from the initial slope and is listed in TABLE 1.

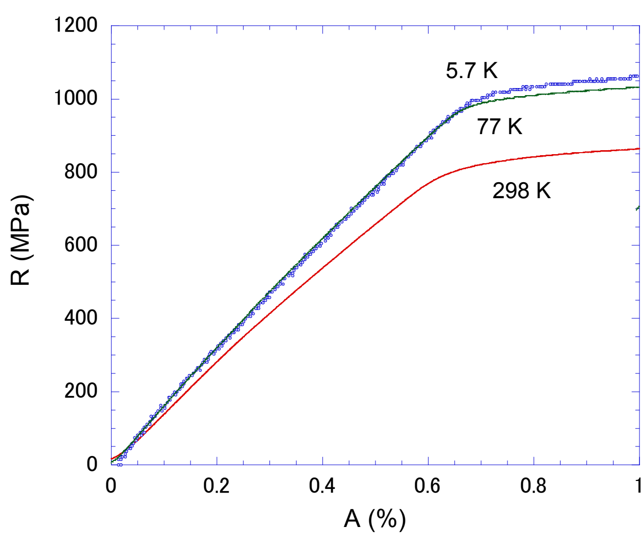

Fig. 2 Stress – strain curves at different temperatures for the surround Cu stabilized YBCO coated conductors.

TABLE I. MECHANICAL PROPERTIES OF SCS4050-TYPE YBCO COATED CONDUCTOR

Temp. (K)	E_c (GPa)	$R_{0.2}$ (MPa)	$A_{0.2}$ (%)
5.7	161	1045	0.865
77	160	1020	0.840
298	141	850	0.805

The present tape sample consists of several components; superconducting YBCO layer (i =1), Hastelloy substrate (2), oxide buffer layer (3), cap layer (4) and surrounded Cu layer (5). From the rule of mixture, the modulus of elasticity E_c is approximately given by

$$E_c = \sum V_i E_i \approx V_{sub} E_{sub} + V_{Cu} E_{Cu} \qquad (1)$$

where V_i is the volume fraction of the component i, where the contribution from minor components of buffer layer was neglected. The constants E_{sub} = $E_{Hastelloy}$ and E_{cu} were 210 and 118 GPa at RT, respectively. Then E_c is evaluated to be 161 GPa, where V_{sub} = 0.53 and V_{Cu} = 0.42. This means that the major contribution to the mechanical properties is attributed to the two metallic components: Hastelloy and copper.

B. Plane Spacing Measured by Neutron Diffraction

The measurement of plane spacing in the YBCO layer structure was carried out under the uniaxial tensile load at different temperatures in the following sequence of experiments: deformed at 298 K up to 0.35% strain and released the load, then cooled down to 9.8 K. At temperatures of 9.8, 20, 65 K, the sample was deformed up to 0.35%, the load was released and sample warmed up to the next step. Finally, the sample was deformed up to 1.5% at 77K. Sample consisting of two glued together tapes was used.

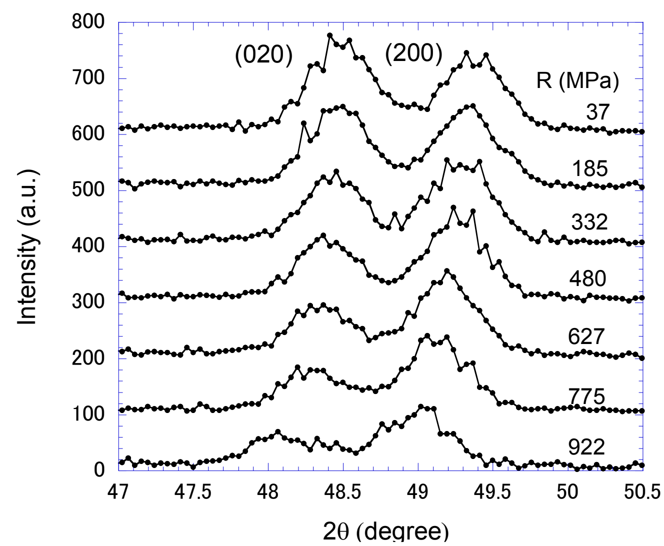

Fig. 3 Change of diffraction profiles with increasing applied stresses at 77 K.

As the width of incident neutron beam was 5 mm, the approximate irradiation volume for the YBCO layer was 2x1μm (YBCO thickness) x 4mm (tape width) x 5mm (beam width) = 0.04 mm^3. Figure 3 shows the diffraction profiles around the (020) and (200) Bragg peaks from the YBCO layer. The diffraction profile was measured at each sequential step, while the macroscopic strain was simultaneously measured by means of Nyilas type extensometers. The diffraction peak positions shifted with increasing applied load towards lower 2θ angle values. The representative peak position was determined by fitting experimental data with the Gaussian function. The plane spacing was then obtained from the peak position. It should be pointed out that the sufficient diffraction intensity was obtained, even though the actual irradiation volume was so small. The likely reason is that the YBCO layer was almost single crystalline. The relationship between stress and strain was measured simultaneously during the neutron diffraction experiments as shown in Fig. 4. Comparing with the results shown in Fig.1, both data were identical with each other. The following results and discussion deal with the strain dependence.

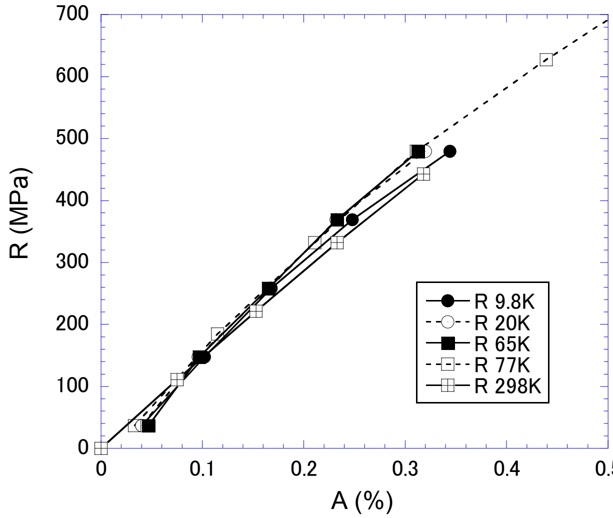

Fig. 4 Relation between stress and strain measured simultaneously during the neutron diffraction experiments.

Generally, the plane spacing may change due to several causes. Here, the plane spacing of the YBCO component embedded in the tape is expressed as $d(R,T)_{hkl}$, where the first and second terms in the parentheses are the magnitude of external load and the temperature, and the subscript indicates the lattice plane. The plane spacing of the YBCO ideal crystal without any strain is given as $d_0(T)_{hkl}$, which corresponds to the value observed in YBCO fine powders in the strain-free state.

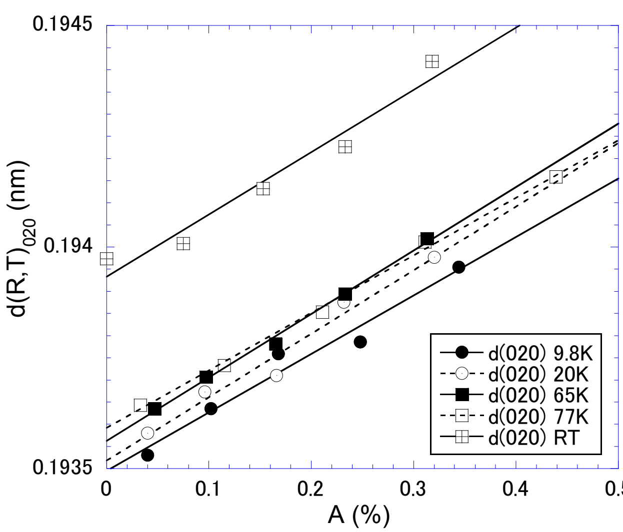

Fig. 5 Applied strain dependence of the plane spacing (020) measured at different temperatures, where the straight lines were obtained by regression analysis.

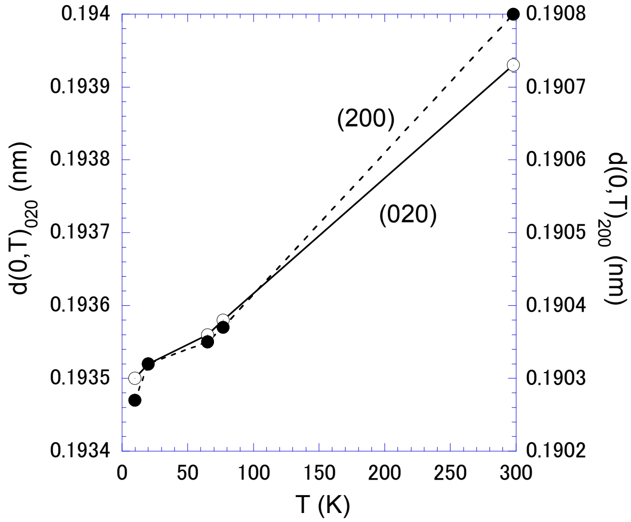

Fig. 6 Temperature dependence of plane spacing without applied load.

Figures 5 shows the change of plane spacing $d(R,T)_{020}$ as a function of applied strain A at different temperatures. The similar result was obtained for the plane spacing $d(R,T)_{200}$. The plane spacing increased linearly with increasing applied strain in the range up to near 0.5 %., The regression analysis was carried out by using the following straight line relation:

$$d(R,T)_{hkl} = d(0,T)_{hkl} + kA \tag{2}$$

The slope k indicates the elastic response with applied strain; its magnitude depends primarily on the diffraction elastic constant. According to our recent result using the synchrotron radiation [6], at room temperature the slope was almost unity for both (020) and (200) planes. However, the value of k at 298 K in the present study was 0.72 and 0.90 for the (020) and (200) planes, respectively. We need a further careful comparison to solve this discrepancy. The constant $d(0,T)_{hkl}$ was obtained from Eq.(2). The result is shown in Fig.6.

C. *Internal strain exerted on YBCO layer*

Due to different coefficients of thermal expansion (CTE) of the constituent tape components, the internal residual strain is generated in each component when the tape is cooled down from high temperature after the heat treatment. During cooling, the local strain initiates at a specific temperature T_o. In several cases (BSCCO, YBCO), the initiation temperature has been estimated [6]. When L_o is the initial length of the tape at T_o, the change of tape length after cooling at T from T_o is given as $\Delta\langle L\rangle$,

$$\Delta \langle L \rangle = L_o \alpha_c (T - T_o) \tag{3}$$

where α_c is the average CTE for the tape. However, the hypothetical length change of pure component i is given by the equation

$$\Delta L_i = L_o \alpha_i (T - T_o)\,. \tag{4}$$

The thermally induced strain of component i is thus given by the equation

$$A_{tri} = \int_{T}^{T_o} \left(\frac{L_o}{<L>} \frac{\Delta L_i - \Delta <L>}{L_o} \right) dT . \quad (5)$$

So it is possible to calculate the thermally induced strain at different temperature, when CTE of each component is given and the α_c is obtained analytically or experimentally.

According to our previous room temperature study of the same tape sample, the YBCO layer was constrained in the compressive state with A_{tr1}=-0.20% [6]. In the present experiment, the plane spacing of the YBCO layer was measured as $d(0,298)_{200}$ =0.19080 nm and $d(0,298)_{020}$ =0.19393 nm as shown in Fig. 6. Therefore, the plane spacing without thermally induced strain shall be determined as $d_0(298)$ = $d(0,298)_{200}/(1+A_{tr1})$ = 0.19118 nm and $d_0(298)$ = $d(0,298)_{020}/(1+A_{tr1})$= 0.19431 nm at 298 K.

At present, the temperature dependence of CTE of YBCO ideal crystal is not known and so it was assumed to be constant at temperatures below room temperature and equal 11.0 ppm/K [3,6]. The temperature dependence of YBCO plane spacing without thermally induced strain is thus given by the equation,

$$d_0(T) = d_0(298)[1 + 11.0 \cdot 10^{-6}(T - 298)] \quad (6)$$

In this work, the plane spacing $d(0,77)_{200}$ and $d(0,77)_{020}$ of the YBCO component in the tape was measured as shown in Fig. 6. Then the thermally induced strain of YBCO component in the tape can be experimentally determined by the equation

$$A_{tr1}(T) = \frac{d(0,T) - d_0(T)}{d_0(T)} . \quad (7)$$

The thermally induced residual strain is shown in Fig. 7 as a function of temperature. Its absolute value tended to decrease gradually with decreasing temperature.

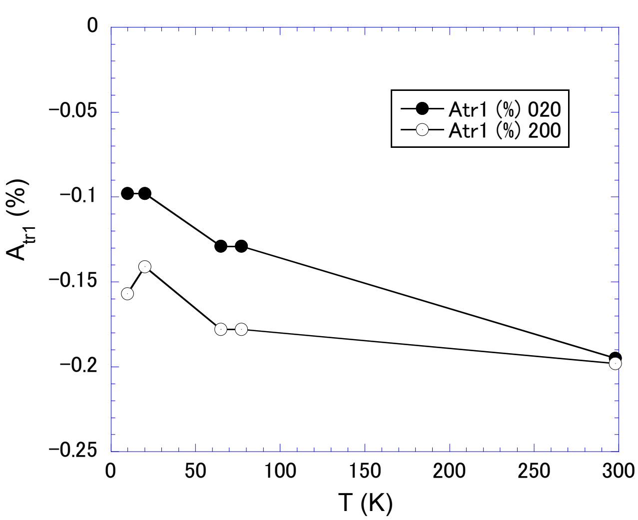

Fig. 7 Thermally induced residual strain in the YBCO layer as a function of temperature.

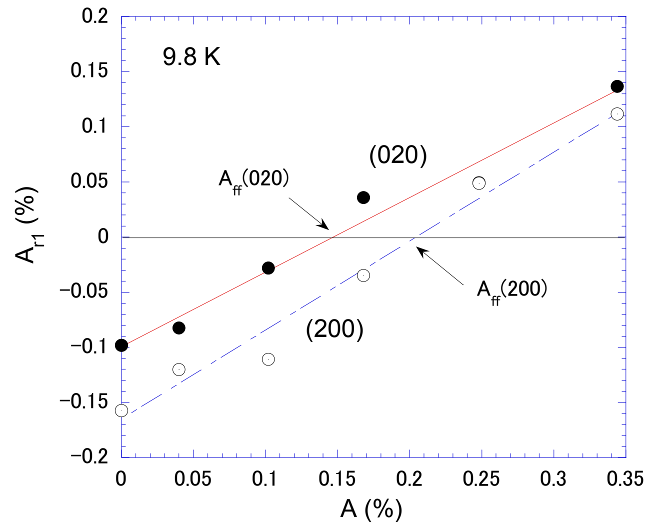

Fig. 8 Change of internal strain on YBCO layer as a function of applied strain.

Finally, the total internal strain exerted on the YBCO layer at different temperatures is given by the equation,

$$A_{r1}(T) = A_{tr1}(T) + \frac{d(R,T) - d(0,T)}{d(0,T)} \quad (8)$$

The change of total internal strain as a function of applied strain A at 9.8 K is shown in Fig. 8. At the zero applied strain, the compressive thermally induced residual strain between -0.10 and -0.16 % remains in the YBCO layer. When the external tensile load is applied, the compressive residual strain in the YBCO layer reduces and reaches zero at 0.13 – 0.20 % applied strain. Here this specific strain is defined as the force free strain, A_{ff}. At still higher A, the residual strain exerted on YBCO layer changes to tensile.

Figure 9 shows the temperature dependence of the force free strain. The recent room-temperature result by synchrotron radiation [6], indicated by the cross-square in the graph is nearly the same as the present values. The A_{ff} estimated from the (200) data decreased only weakly with temperature, by changing from 0.22% at 298 K to 0.20% at 9.8 K. However, the A_{ff} estimated from the (020) data decreased prominently with decreasing temperature by changing from 0.27% at 298 K to 0.13% at 9.8 K. The reason is not clear at present, but is interesting from the scientific viewpoint.

D. *Strain dependence of critical current*

The present information on the force free strain (A_{ff}) is important when one considers the dependence of critical current I_c on applied strain. For the present YBCO tapes, the strain dependence of I_c was precisely determined in [6], where a small I_c maximum was observed at 0.035% applied strain. This behavior is well known as the intrinsic strain effect [7], and was reported to appear commonly in Nb_3Sn multifilamentary wires. According to Ekin, The I_c strain dependence is expressed by the empirical formula:

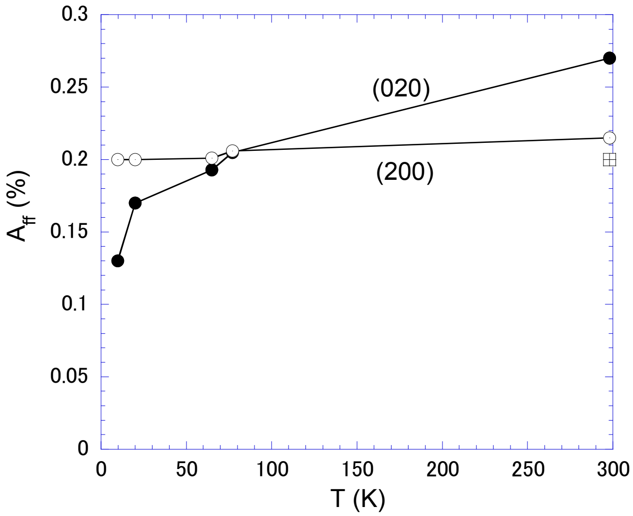

Fig. 9 Force free strain on YBCO layer as a function of temperature. The cross-square is data from [6].

$$I_c / I_{c\max} = 1 - a \,|\, (A_a - A_{c\max}) \,|^b \qquad (9)$$

where a and b are the constants, and $A_{c\max}$ is the strain, at which the I_c/I_{cm} becomes maximum. The residual stress in the Nb_3Sn component has been supposed to become zero at $A_{c\max}$. In our case, the value of $A_{c\max}$ from [6] is 0.035%, thus clearly different from A_{ff} determined by neutron diffraction. So it becomes necessary to re-examine the hypothesis for the YBCO coated conductors supposing that the critical current maximum appears at the force free strain. The detailed analysis will be reported elsewhere [8].

IV. Summary

The major results obtained in the present study can be summarized as follows.

Mechanical properties of YBCO tape were assessed at temperatures of 5.7, 77 and 298 K. The major contribution to the mechanical properties is given by the two metallic components: Hastelloy substrate and Cu stabilizing layers.

The internal strain exerted on the superconducting YBCO layer was directly evaluated under tensile load at low temperatures down to 9.8 K by means of neutron diffraction techniques. The compressive internal strain presented at the initial state without external load was attributed to the thermally induced residual strain. When increasing external tensile load was applied, the compressive component of internal strain decreased and changed into tensile. The force free strain, A_{ff}, was determined as the strain at which the internal strain on the YBCO layer becomes zero. The A_{ff} estimated from (200) data depended weakly on temperature. On the other hand, the A_{ff} estimated from (020) data decreased prominently with decreasing temperature.

Acknowledgment

The authors express their hearty thanks to Dr Yi-Yuan Xie, SuperPower Inc. for his valuable suggestions and sample supply. This work was supported in part by a grant-in-aid of the Ministry of Education, Culture, Sports, Science and Technology, Japan (21360312)

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