Improvement of Reversible Strain Limit for Critical Current of DI-BSCCO Due to Lamination Technique

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***Abstract*—The DI (dynamically innovative)-BSCCO-Bi2223 tapes achieved high critical current as well as high modulus of elasticity. Further the reversible strain limit and the corresponding stress for critical current have been remarkably increased by means of lamination technique. During the course of development, their optimized architecture has been designed based on the principle of the rule of mixture for maximizing the force free strain exerted on the superconducting component. The reversible strain/stress limit ($A_{\rm rev}/R_{\rm rev}$) was defined as a strain, at which the critical current recovers to the level of 99% $I_{\rm co}$. Selecting several kinds of laminating materials and changing condition of the fabrication, the excellent Cu alloy-3ply tape with $I_{\rm co}$ of 311 A/cm was realized of which $A_{\rm rev}$ and $R_{\rm rev}$ reached 0.42% and 300 MPa, respectively. Further during the theoretical analysis, the increase of reversible strain limit were made clear to be attributed to the increase of thermally induced residual strain as well as the compensation effect of laminated layers against a local fracture mode.**

***Index Terms*—BSSCO-Bi2223, critical current, force free strain, modulus of elasticity, residual strain.**

I. Introduction

HIGH critical current DI-BSCCO-Bi2223 tapes have been successfully developed on the basis of controlled overpressure (CT-OP) technology. Voids included in the Bi2223 filaments were remarkably reduced and volume fraction of non-superconducting phases was reduced. Consequently the high modulus of elasticity and the high critical current have been realized. In order to improve further their performances, the residual stress/strain control as well as high strengthening is important issue to develop tapes with high tolerance against strain/stress. Due to the difference of coefficient of thermal expansion (CTE), a compressive strain is exerted on the superconducting (SC) component. As this compressive strain generates advantage to get the high performance, the high-alloying of the coverage layer and the lamination of metallic foil have been applied. In order to analyse the residual strain/stress effect, various models have been developed [1]–[3]. Some attempts to measure directly the residual strain exerted on the BSCCO component were carried out by diffraction techniques using synchrotron radiation and neutron beam [4]–[7]. However it is still necessary to get quantitative knowledge on the strain/stress effect with electromagnetic property in order to design the further higher performance tapes.

In the present study, the DI-BSCCO-Bi2223 tapes with different kinds of laminated layer have been investigated in order to make clear their mechanical property and its influence to critical current, and to discuss the improvement of reversible strain limit.

II. Experimental Procedure

Five types of DI-BSCCO composite superconductors have been examined. Their architecture is as follows; the insert tape consists of three components; superconductive filaments (component number 1) embedded in silver matrix (2) and the outer silver alloy (3). Four kinds of metallic foils (Brass, Sn bearing Cu and SUS) were used for the lamination. Their foil thickness was 20, 50 or 100 μm. One of these foils (5) was laminated by using the solder (4). The sample name, for instance, SUS20 indicates that the insert tape is soldered by stainless steel foils with thickness of 20 μm.

Tensile test was carried out at room temperature by using tensile machine Shimadzu AG-50kNIS installed with 1 kN load cell. The initial distance between chucks was kept as 100 mm. The Nyilas type double extensometer $({\rm GL}=25\ {\rm mm})$ was attached at the center of sample. The initial cross head speed was selected usually as $8\cdot 10^{-4}[{\rm s}^{-1}]$.

The critical current measurement was carried out under tensile load in order to investigate the change of $I_{\rm c}$ as a function of uniaxial tensile strain. The critical current was determined with a criterion of 0.1 mV/m and the n value was given from the slope of $I-V$ curve between 0.1 and 1 mV/m. The construction of experimental apparatus was similar to that for tensile test at room temperature mentioned above. In this experiment, two chucking parts were electrically isolated from the tensile machine. Two voltage taps were soldered on the tape outside the extensometers. The length of voltage taps was about 60 mm. The sample was immersed in the liquid nitrogen by using an open cryostat.

The precise measurement of lattice constant was carried out at Residual Stress Analysis (RESA) station in research reactor JRR-3 of JAEA. The residual strain of Bi filaments was determined by comparing the lattice constant of the powder samples extracted from the same insert tapes investigated in the present

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TABLE I
MECHANICAL PROPERTIES AT ROOM TEMPERATURE

Sample	Experiments E_o (GPa)	Experiments $R_{0.2}$ (MPa)	Experiments $A_{0.2}$ (%)	Calculation E_o (GPa)
Insert	86	(118)	(0.14)	89
Brass50	89	268	0.50	89
Brass100	96	272	0.49	90
Sn bearing Cu50	94	230	0.45	88
SUS20	97	258	0.46	96

TABLE II
RESIDUAL STRAIN EXERTED ON THE SC COMPONENT AT ROOM TEMPERATURE AND 77 K

Sample	Calculation A_{r1} at RT (%)	Calculation A_{r1} at 77K (%)	Experiments A_{r1} at RT (%)
Insert	-0.055	-0.099	-0.008
Brass50	-0.081	-0.146	-
Brass100	-0.088	-0.158	-0.1098
Sn bearing Cu50	-0.053	-0.095	-0.0820
SUS20	-0.052	-0.094	-0.0895
Insert [1]	-0.059	-0.107	-0.0069

study. The details of the strain measurement will be reported elsewhere [6].

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Mechanical Properties

Stress—strain behavior at room temperature is given in Table I all the tapes. Here the modulus of elasticity, E_o was estimated from the initial slope. The 0.2% yield stress, $R_{0.2}$ and strain $A_{0.2}$ are given here, while the insert tape fractured at the stress/strain indicated in the parentheses.

The initial slope was experimentally determined as E_o as listed in Table I. On the other hand, this initial slope is given by the equation for both insert and laminated tapes [1],

$$E_o \cong E_1 V_{f1} + E_3 V_{f3} + E_5 V_{f5} \tag{1}$$

where E_i and V_{fi} are the modulus of elasticity and volume fraction of component i. The calculated results are listed in Table I, where the physical parameters necessary to the calculation were selected from the [1]. Both experimental and theoretical values are identical each other. This indicates that the modulus of elasticity is mainly contributed from three components of BSCCO, the silver alloy and the laminated alloy.

B. Analysis of Residual Strain

In order to understand fully the mechanical properties of the present composite superconductors, it is necessary to analyse the thermally induced residual strain during the fabrication process. The process applied to the insert tapes is as follows. Firstly all the tapes were cooled down to 77 K from the heat treatment temperature T_A in order to measure the critical current at the manufacturer's laboratory. After that, they were delivered outside. At room temperature, mechanical test was carried out at our laboratory. Then critical current as well as mechanical test were carried out at 77 K.

During the heat treatment, the internal residual strain/stress generates in each component due to the difference of the coefficient of thermal expansion (CTE). The procedure to calculate residual strain/stress has been previously reported by our groups [1], [2] At high temperature, however, residual stress should be thermally relaxed. The residual strain/stress start to accumulate in the tape practically at T_0. In the previous paper [1], 563 K has been fixed as T_0 for the similar BSCCO tapes. In the present analysis, T_0 was assumed to be the same value. As discussed below, some correction will be applied.

As mentioned previously, the procedure to get exactly the residual strain is very time-consuming. So the approximated expression was proposed in order to evaluate the residual strain exerted on the SC component. The following equation is given for both the insert and laminated tapes,

$$A_{r1} = \frac{(\alpha_3 - \alpha_1)E_3 V_{f3} + (\alpha_5 - \alpha_1)E_5 V_{f5}}{E_o} \Delta T \tag{2}$$

where α_i is the CTE of component i. ΔT is equal to 298 (or 77)—T_o. The results are listed in Table II. As a summary, the residual strain exerted on the SC component is compressive and their magnitude increases by the lamination. When the tensile strain is applied to the tape, the compressive strain exerted on the SC component decreases and reaches zero, then the strain changes tensile component. This specific strain is called the force free strain A_{ff} and it is given by

$$A_{ff} = -A_{r1} \tag{3}$$

C. Strain Measurement by Neutron Diffraction

The precise lattice constant for BSCCO (220) was measured under the geometry as the scattering vector is parallel to the longitudinal axis of the tape and to the tape surface. So the change of lattice constant was detected parallel to the longitudinal axis of the tape as the details are reported at [6]. In order to measure the lattice constant in the zero strain state, the powder sample was provided. The residual strain determined by neutron diffraction is defined as $100 * (d - d_0)/d_0$, where d and d_0 are the lattice constant from BSCCO (220) for the tape and the powder sample, respectively. The results are listed in Table II together with the calculated results obtained in the present residual strain analysis. In the case of the insert tape, both results were very different each other. This discrepancy has been discussed to be related to the thermally induced relaxation at room temperature [1]. It is interesting to know that the residual strains determined from neutron diffraction are larger within 40% than the calculated ones except the case of insert tape.

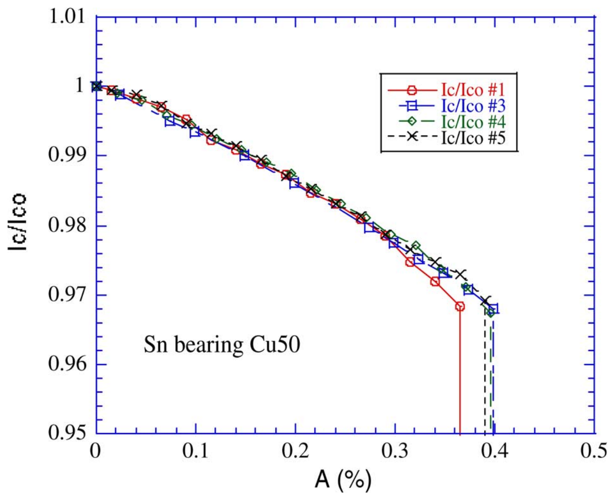

Fig. 1. Strain dependence of the normalized critical current for four Sn bearing Cu50 tapes.

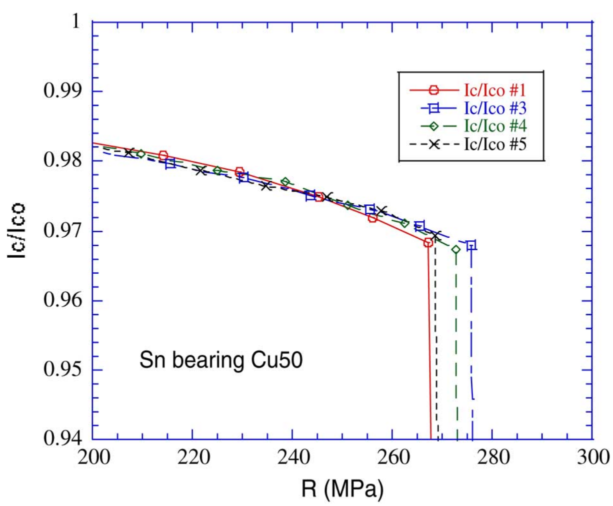

Fig. 2. Enlarged picture of stress dependence of the normalized critical current for four Sn bearing Cu50 tapes.

D. Critical Currents

Fig. 1 shows the strain dependence of normalized critical currents for four Sn bearing Cu50 tapes. In general, the critical current decreased gradually in the reversible region and abruptly it decreased beyond critical strain due to the fracture of BSCCO filaments as reported elsewhere [1]. Fig. 2 is the enlarged picture of the normalized critical current vs applied stress for the Sn bearing Cu tapes. Similarly the critical current decreased gradually as a function of stress and dropped down due to the macroscopic fracture of BSCCO filaments. Fig. 3 shows the change of the n value as a function strain. The n value was almost constant in the reversible region.

The same measurements have been carried out for other tapes. Table III shows the summary for the initial values of critical current and the n value. Comparing the data for the insert tapes with those for the laminated tapes, both quantities are almost the same for each other. This indicates that the tapes did not degrade during the lamination process. Here the engineering critical current J_e is defined as the critical current divided by the cross sectional area of the tape. The J_e became smaller because of the increase of tape thickness due to the lamination.

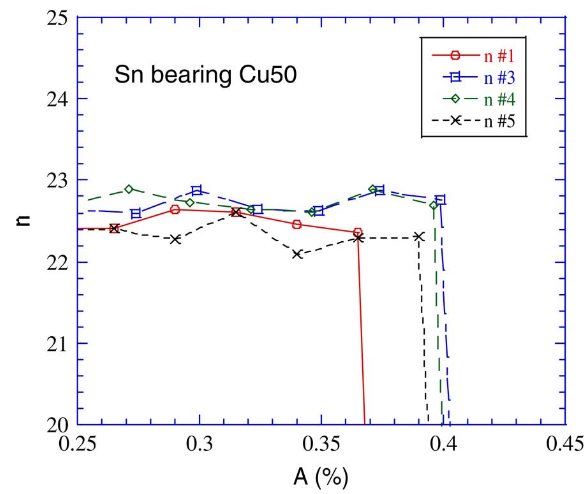

Fig. 3. Enlarged picture of strain dependence of the n value for four Sn bearing Cu50 tapes.

TABLE III
INITIAL VALUES OF I_C AND n

Sample	Number of Tapes Tested	I_{co} (A)	n_o	J_e (A/mm^2)
Insert	4	139.7	22.4	149.0
Brass50	3	141.2	22.3	93.6
Brass100	3	140.6	22.8	69.8
Sn bearing Cu50	4	140.8	22.5	89.1
SUS20	3	136.8	22.2	110.5

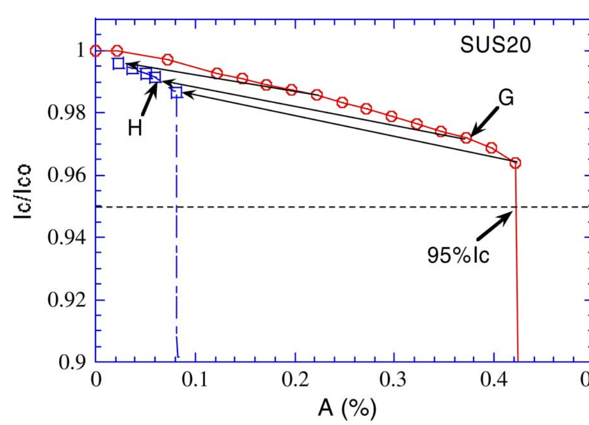

Fig. 4. Definition of the reversible point. The point G is the reversible point defined as 99% I_c recovery when the I_c at the point H is 99% or more

E. Reversible Strain Limit

The strain tolerance for critical current was determined as follows. As shown in Fig. 4, the sample was loaded up to a certain strain level and there the $I-V$ characteristic curve was measured to determined I_c as indicated by the sign G. Then the load was released to zero level, until the strain was reduced to a permanent strain, where the I_c was measured as indicated by the

TABLE IV
REVERSIBLE STRAIN LIMITS

Sample	99%Ic Recovery		95%Ic Retention	
	R_{rev} (MPa)	A_{rev} (%)	R_{95} (MPa)	A_{95} (%)
Insert	126	0.206	138	0.230
Brass 50	307	0.445	333	0.495
Brass 100	300	0.424	318	0.487
Sn bearing Cu 50	262	0.362	270	0.381
SUS 20	282	0.389	306	0.431

TABLE V
TENSILE STRAIN EXERTED ON THE SC COMPONENT AT THE REVERSIBLE STRAIN LIMIT

Sample	A_{ff} (%)	A_{rev}-A_{ff} (%)	A_{95}-A_{ff} (%)
Insert	0.099	0.107	0.131
Brass50	0.146	0.299	0.349
Brass100	0.158	0.266	0.329
Sn bearing Cu50	0.095	0.267	0.286
SUS20	0.094	0.295	0.337
Insert [1]	0.107	-	0.125
SUS 3-ply [1]	0.117	-	0.233
Brass 3-ply [1]	0.161	-	0.249

sign H. This procedure was repeated. When the critical current at the point H is 99% of the initial value (I_{co}), the strain at the point G is defined as A_{rev}. This 99% I_c recovery criterion has been accepted by several authors [7] for discussing the transport properties of YBCO coated conductors. Another conventional criterion has been used as the 95% I_c retention. This point is indicated in Fig. 4. It is clear that the tape has already fractured at this point. Their critical values are summarized in Table IV.

It has been made clear that the lamination improves the strain/stress dependence of critical current as summarized in Table IV. As discussed previously [1], [5], the relation between the force free strain and the reversible strain is given by the equation;

$$\Delta A = A_{rev} - A_{ff} \tag{4}$$

which indicates the tensile strain exerted on the SC component. As summarized in Table V, this quantity became about 0.1% for the insert tapes, while it increased almost by 2 times by the lamination. When tensile load is applied to the tape and the strain exceeds the force free strain, the BSCCO filaments start to be pulled by tensile stress. That is, the fracture strength of filaments is given by ΔAE_1. In the case of insert tapes, it is 160 MPa, while it becomes 400–450 MPa for the laminated tapes. Those experimental facts suggest the change to the uniform plastic deformation from the heterogeneous one of the tapes. During the uniform plastic deformation process, the work-hardening takes place uniformly and then a locally concentrated fracture mode is prevented.

F. Estimation of T_o

In the present residual strain analysis, the temperature T_o was *a priori* assumed to be 563 K. In order to estimate the real number of T_o, it is reasonable to use the approximate expressions (2). By inputting the observed residual strain listed in Table II, T_o was re-estimated to be ranged between 628 and 754 K. Thus when the residual strain can be experimentally obtained by the precise lattice constant measurement by neutron beam or synchrotron radiation, it is easy to know the initial value T_o.

IV. CONCLUSION

The major conclusions obtained here are as follows;

1) Residual strains exerted on the SC component were calculated according to a simple model based on the rule of mixture. The observed residual strains by the neutron diffraction technique were found to be larger within 40% than the calculated values.
2) Strain and stress dependence of critical currents had good correlation with the change of force free strain in the BSCCO component. The difference between the strain corresponding to the 99% I_c recovery and the force free strain was explained as the fracture strain of BSCCO filaments.
3) Improvement of reversible strain limits could be explained in terms of the increase of force free strain and the homogenization effect of fracture behavior due to the lamination.

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