Strain Analysis of $I_C(\varepsilon)$ Characteristic of YBCO Coated Conductor Measured by a Walters Spring

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***Abstract*—I_c-strain characteristic of YBCO coated conductor was measured using a Walters spring (WASP). In this technique, additional bending and thermal strains induced to the YBCO layer should be considered. In order to produce different initial bending strain to the YBCO layer, the conductor was wound around the springs with different diameters and in the different bending directions. The clear evidence was obtained that I_c-strain curves using a WASP strongly depend on the initial bending strain state. However, when I_c-strain curves were normalized by a maximum I_c value, all of the curves even including the data measured by uniaxial strain method for a short sample fall on to the same curve. Strain analysis based on the rule of mixture probes that the shift along the strain axis for each I_c-strain curve can be explained by the bending and thermal strain during soldering. This result suggests that combined strain of bending and tensile strains can be regarded as simple summation in the present YBCO coated conductor.**

***Index Terms*—Critical current, intrinsic strain effect, Walters spring, YBCO coated conductor.**

I. Introduction

WALTERS SPRING (WASP) is a device to measure the strain dependence of critical current (I_c) of superconducting wires with relatively long length [1]. The advantages of using this technique are that lower electric filed criterion can be applied to determine I_c. Superconducting wire is wound along the outer surface of a spring and axial strain is applied to the wire by applying torque to the spring. Some groups have reported I_c-strain characteristics using a WASP [2]–[7]. Hampshire *et al.* have developed the prove with a Cu-Be spring which enables to apply the strain in the compressive direction without buckling by soldering along the whole length of a superconducting wire and extensively investigated $I_c(B,T,\varepsilon)$ characteristics for low temperature superconducting wires [2]–[4]. Uglietti *et al.* have employed strain-free-cooling-down process and first reported the result on $I_c(B,\varepsilon)$ for Bi2223 tapes using a WASP at 4.2 K and 15 T [5]. Recently, they have also presented the results on $I_c(B,T,\varepsilon)$ characteristics for YBCO coated conductor and showed that I_c is more sensitive to tensile strain at 77 K and 50 K than 4.2 K [8].

As described above, the merit of a WASP is that it can measure long length of wire comparing with other experimental technique such as free-hanging method [9]. On the other hand, for the measurement using a WASP, a superconducting wire is first wound around a spring and this causes bending strain to YBCO layer depending on bending diameter and geometry of a conductor. In the previous studies, the bending strain has not been considered because a WASP was a technique originally developed for a wind-and-reacted wire. During soldering the wire to the spring, additional thermal strain is applied to YBCO film due to difference of thermal expansion between YBCO and the spring material. These additional strains can not be avoided in the case of a WASP and this can lead to the error of absolute strain values applied to the composite conductor.

A coated conductor in a magnet also experiences combined strain state of bending and tensile strains. To design a magnet, it is important to know whether combined strain can be regarded as simple summation of each strain. Some reports have been presented on such combined strain tolerance of I_c [10], [11]. The wire is first wound around the mandrel with a certain bending radius and tensile load is applied to both ends. However, in this technique, friction between the wire and mandrel reduces actual applied strain to the wire. This makes it difficult to evaluate combined strain value accurately. On the other hand, a WASP is also measurement technique for such combined strain effect on I_c. In this case, bending and applied tensile strain can be defined more clearly than other methods.

In the present work, we analyze additional thermal and bending strain effect on I_c-strain characteristics using a WASP measured at 77 K comparing with the result by uniaxial strain method.

II. Experimental Procedure

YBCO coated conductors produced from SuperPower were used as samples. Fabrication process of the coated conductor is described in detail in [12]. In this conductor, YBCO layer is grown on the MgO/Hastelloy substrate. Thickness of the Hastelloy substrate and YBCO layer is 50 μm and 1 μm, respectively. After Ag layer is deposited as a protective layer, the conductor is surrounded by electro-plating Cu for electrical stabilization.

The Cu-Be springs with two different diameters of ϕ23.8 mm and ϕ29.5 mm were prepared. The conductor was wound around the spring. For the spring with diameter of ϕ23.8 mm, the conductors were wound in two directions, in which YBCO or substrate faces the spring surface, respectively. As a result, com-

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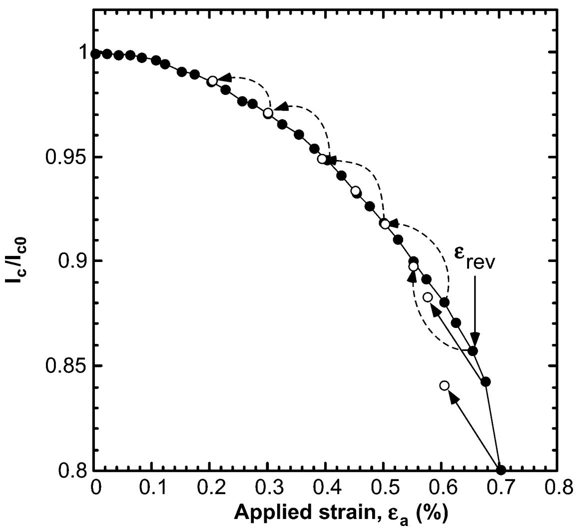

Fig. 1. Normalized I_c as a function of uniaxial strain measured at 77 K in self field. Solid and open circle correspond to I_c under loading and after unloading by 0.1%, respectively.

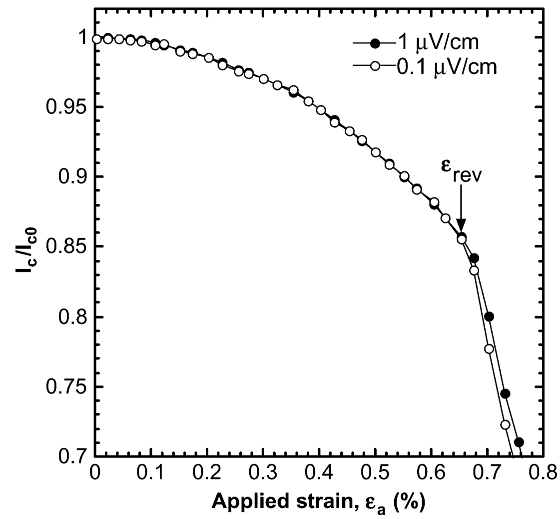

Fig. 2. Normalized I_c-strain characteristic defined by different electric field criteria.

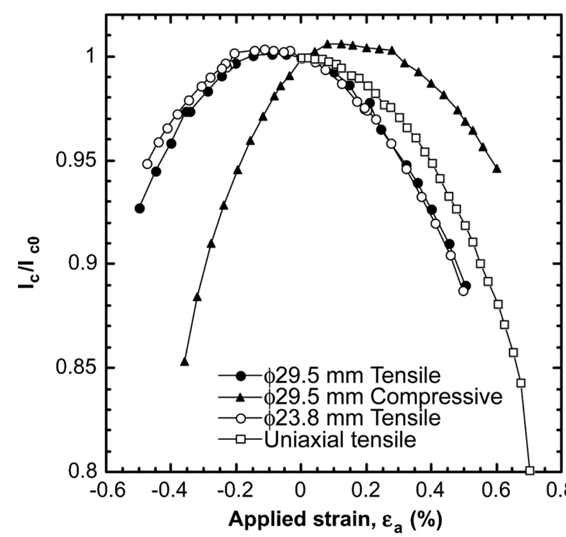

Fig. 3. Normalized I_c as a function of strain measured using a WASP at 77 K in self field. The results for three different initial bending strain state were plotted together with that of uniaxial strain.

pressive or tensile bending strain was induced to the YBCO layer. In order to solder the conductor along the whole length, the conductor was dipped into the solder bath after winding. In-Sn alloy whose melting temperature is 390 K was selected as a low temperature solder. Soldering temperature was set to be 413 K.

Strain gauge was attached at the surface of the conductor around the middle turn. The dummy sample with strain gauge is also prepared to monitor additional thermal strain during cooling down from RT to 77 K. Spacing of the voltage taps were 300–380 mm.

I_c measurement under applied strain was carried out in liquid nitrogen and self field.

To obtain the data excluding the influence of bending and thermal strain, uniaxial strain dependence of I_c was measured for the short sample using an Instron-type tensile testing machine. The sample length was 90 mm and spacing of voltage taps was 20 mm, respectively. Strain was measured by the double extensometers directly attached to the conductor. This measurement technique is called as uniaxial strain method in the following discussion.

III. Results and Discussion

Fig. 1 shows I_c-uniaxial strain characteristic for the present coated conductor measured at 77 K in self field. To check the reversibility in variation of I_c with increasing applied strain, applied strain was reduced by 0.1% after loading up to some characteristic strains. From this procedure, reversible strain limit was determined as $\varepsilon_{rev} = 0.65\%$ as shown in Fig. 1. For larger strain, I_c after unloading starts to deviate from the curve under loading. The curvature of this curve at the origin is approximately zero and this suggests that the strain at a peak of I_c locates around zero applied strain.

Fig. 2 shows I_c-strain characteristic determined by different electric field criteria. Normalized I_c as a function of strain agrees completely with each other below ε_{rev} which was determined using 1 $\mu\mathrm{V/cm}$ criterion. On the other hand, degradation of I_c was observed more remarkably for I_c by 0.1 $\mu\mathrm{V/cm}$ criterion at higher strain than ε_{rev}.

Fig. 3 shows I_c-strain relationship measured using a WASP. The springs with two different diameters were used and windings in the directions to the spring were employed to produce different initial bending strain state of YBCO layer. For all of the conditions using a WASP, reversible variation of I_c was confirmed within the present experiment. Therefore, variation of I_c shown in Fig. 3 is only attributed to intrinsic strain effect and irreversible degradation due to brittle fracture of YBCO film is not included. All three curves measured using a WASP exhibit a peak of I_c at a certain strain. However, the peak strain shifts along the horizontal axis compared with the result under uniaxial strain plotted simultaneously. When the conductor was wound around the spring as the YBCO layer experiences tensile bending strain, the peak strain moves to the direction of compressive applied strain. Small bending radius results in more

TABLE I
STRAIN ANALYSIS FOR THE PEAK SHIFT OF I_c MEASURED BY A WASP

	WASP			Uniaxial tensile method
	ϕ29.5 Tensile	ϕ29.5 Compressive	ϕ23.8 Tensile	
Peak strain (%)	-0.08	0.15	-0.12	0%
Bending strain (%)	0.17	-0.17	0.21	-
Predicted peak strain (%)	-0.07 ~ -0.17	0.17 ~ 0.27	-0.11 ~ 0.21	-

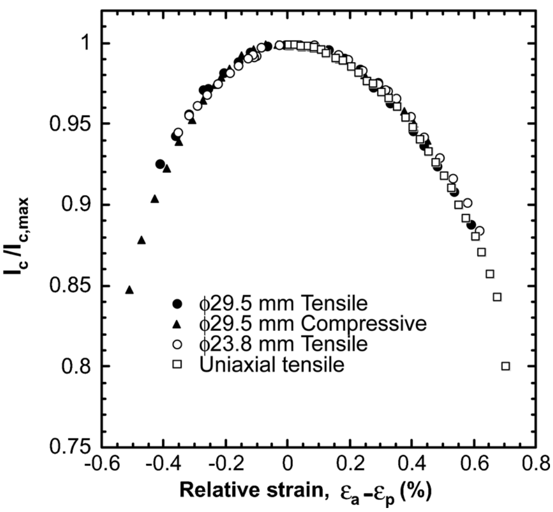

Fig. 4. Normalized I_c by $I_{c,max}$ as a function of relative strain from the peak one.

strain shift. On the other hand, a peak moves to the direction of tensile applied strain when the bending direction is compressive. As a result, measured I_c-strain characteristic is strongly influenced by the initial bending strain state.

For each curve, normalization along the following way is carried out. I_c was normalized by a peak value $(I_{c,max})$ and relative strain was defined as applied strain subtracted by peak strain (ε_p). The peak strain for each curve is listed in Table I. From such normalization, all of the curves fall on to the same curve including in the curve under uniaxial loading for a short sample as shown in Fig. 4. Since the internal strain of YBCO layer at the peak strain can be regarded as same value, good agreement between the results from a WASP and uniaxial strain method suggests that strain state of YBCO can be calculated by simple summation of strains such as bending, thermal and applied strains.

Similar scaling as Fig. 4 has been reported by van der Laan *et al.* [13]. They measured compressive as well as tensile strain dependence of I_c using a bending beam for various kinds of YBCO coated conductors. They found the reversible variation of I_c in both tensile and compressive strain regions. When the horizontal and vertical axes were set in the same manner as Fig. 4, the I_c-strain curves for the YBCO coated conductors with or without Cu lamination and Dy additives fall on to the same curve. In their experimental method, only axial tensile or compressive strain was applied to the coated conductor. On the other hand, it is noted that combined strain composed of bending and uniaxial strains is induced in the conductor in the case of a WASP. The reason for the similarity in the results measured by the different techniques is discussed later.

In order to consider the strain shift of the curves by a WASP compared with the uniaxial one quantitatively, strain analysis of YBCO was conducted. First, bending strain is applied to the YBCO films in the coated conductor during winding to the spring. The bending strain can be approximated by (1),

$$\varepsilon_b = \frac{y}{R} \tag{1}$$

where R and y are bending radius and distance from a neutral axis to YBCO film, respectively. Here, thickness of the buffer layer is neglected and y is taken to be a half value of thickness of the substrate. During the subsequent soldering and cooling down, thermal strain is induced to the YBCO film due to the difference of coefficient of thermal expansion between superconductor and other components. The thermal strain is expressed as (2),

$$\begin{aligned} {\varepsilon_{r,YBCO}}^{413\text{ K}\rightarrow 77\text{ K}} &= (\varepsilon_{Spring} - \varepsilon_{YBCO})^{413\text{ K}\rightarrow 77\text{ K}} \\ &= (\varepsilon_{Spring} - \varepsilon_{YBCO})^{413\text{ K}\rightarrow 293\text{ K}} \\ &\quad + (\varepsilon_{Spring} - \varepsilon_{CC})^{293\text{ K}\rightarrow 77\text{ K}} \\ &\quad + (\varepsilon_{CC} - \varepsilon_{YBCO})^{293\text{ K}\rightarrow 77\text{ K}}. \end{aligned} \tag{2}$$

The first term is thermal strain through soldering process starting from 413 K. The second term is thermal strain from the spring during cooling down from 293 K to 77 K. This strain can be measured as difference between strain from the sample gauge and from the dummy one. Since the measured strain values ranged from $-0.02 - 0.01\%$ and these values are one order lower than other strain components, this term was neglected in the following analysis. The last term arises from difference of coefficient of thermal expansion between the YBCO and other components in the composite conductor. This strain also arises in the sample measured in the uniaxial strain method, so this is not the additional strain for a WASP. Resultantly, additional thermal strain component to be considered is only thermal strain during soldering.

As mentioned above, the sample wound to the spring was dipped into the solder bath melted at 413 K. Thermal strain during cooling to RT starts to be induced to the YBCO film from a certain temperature (T_s) below melting temperature of the In-Sn alloy. Since this temperature includes uncertainty, thermal strain was calculated as T_s situates between 413 K and 293 K. From this consideration, thermal strain was calculated as $-0.10 \sim 0\%$.

From (1) and (2), the predicted peak strain was calculated as shown in Table I. The experimental peak values locate around predicted one. This agreement suggests that the combined strain state consisting of thermal, bending and tensile strains can be estimated by simple summation. Conductors in a magnet experience similar strain state as a WASP. Bending strain is applied to the conductor during winding at RT. Thermal strain arises during annealing solidification of epoxy resin and cooling down to operated temperature. Tensile strain is applied by hoop stress during operating magnet. If coated conductor is utilized as a high field magnet, the conductor should withstand large tensile strain. For such application, winding in the compressive bending direction for YBCO layer is more desirable because this can widen tensile strain margin. If such I_c-strain behavior at operated temperature and magnetic field can be obtained, I_c under operated condition can be predicted considering intrinsic strain effect.

Such simple relationship will be unique for coated conductor. In both round and tape conductors, superconductor in shape of filament spreads in a cross-section of composite conductor. This leads to different bending strain for each filament at a given bending radius. On the other hand, superconductor is a film shape deposited on much thinner than substrate in coated conductors. Therefore, bending strain determined by (1) is homogeneous in the film. This enables simple summation of strains for predicting I_c-strain characteristics with different bending radius.

IV. Conclusion

I_c-strain characteristic of coated conductor was evaluated using a Walters spring. In order to investigate the effect of bending strain applied before axial tensile strain, diameter of springs and bending directions were varied. The peak shift of I_c-strain curve was observed depending on the initial bending strain value. When the I_c was normalized by a peak value and the strain was adjusted as the peak strain was set to be zero, all of the curves measured by a WASP fall on to the same curve. This master curve is also confirmed to agree with the result measured by uniaxial strain method. As a result of strain analysis, strain shift for each bending condition can be explained by the initial bending and thermal strain during soldering. This suggests that I_c under combined strain state of bending and tensile strain, which typically corresponds to the superconductor in a magnet, can be estimated by simple summation of strain in the present coated conductor.

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