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Journal of Nuclear Materials 329–333 (2004) 1585–1589

journal of nuclear materials

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Damage evolution under bending and tensile stress and its influence on critical current of Bi2223/Ag superconducting composite tape

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Abstract

The influence of bending and tensile damage introduced at room temperature on the critical current at 77 K under zero magnetic field of a multifilamentary Bi2223/Ag/Ag alloy superconducting composite tape was studied. From the analysis of the tensile stress–strain curve, the residual strain and intrinsic tensile-fracture strain of Bi2223 filaments were estimated, with which the measured change of critical current with tensile strain was accounted for. A simple model, in which the damage evolution in both tensile and compressive sides was incorporated, was proposed to describe the change in critical current with bending strain. The application of the model to the experimental result indicated that the intrinsic compressive-strength of Bi2223 filaments, determining damages in the compressive side, is about five times higher than the tensile strength.

1. Introduction

The multifilamentary Bi2223/Ag superconducting composite tapes are subjected to mechanical stresses during the fabrication/winding process and to electromagnetic forces during operation of magnets [1]. It is needed to understand the stress-induced damage evolution and its influence on superconductivity towards the fusion uses. The tensile fracture strain of the Bi2223 filaments has been reported to be around 0.1% [2–4], being several to ten times lower than that of other superconducting filaments such as Nb_3Sn (0.5–1.2%) [5,6] and Nb_3Al (0.6–1.0%) for fusion uses [7]. Thus, under the applied strain, the critical current of Bi2223 composite is reduced severely [1–3,8–16].

The strain-dependence of critical current is dependent on the fabrication process and structure of the composite such as size and volume fraction of the constituents (Bi2223, silver and silver alloy sheath), as known from the comparison of the reported results [1–3,8–16]. Taking the case of the bending effect, the reduction in critical current with increasing strain has been attributed mostly to the damage in the tensile side. However, (i) the compressive strength is not infinite and (ii) it becomes different when the fabrication process and structure are different as well as tensile strength. Actually, the present experimental result could not be accounted for unless the fracture of filaments in the compressive side in addition to that in the tensile side is taken into consideration, as shown later. Thus the development of the comprehensive method, which can describe the differently fabricated composites in which the filaments in either or both sides are broken, is needed.

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doi:10.1016/j.jnucmat.2004.04.165

In the present work, a simple model of bending behavior and its relation to critical current was presented, as a first step for the construction of the comprehensive approach including the damage evolution in tensile and compressive sides. For application of the model, first the tensile behavior and its influence on critical current was studied, from which necessary information was extracted. Then, the applicability of the model to the measured relation between the bending strain and critical current was examined.

2. Experimental procedure

The multifilamentary Bi2223/Ag/Ag–Mg alloy composite tape consisting of a core of Bi2223 + Ag and a sheath of Ag–Mg alloy, prepared at the Korea Electrotechnology Research Institute, was used. The composite had an overall thickness $t^* = 0.29$ mm and a width $W = 3.7$ mm. The number of embedded filaments was 55. The volume fractions of Bi2223, Ag and Ag alloy were 0.42, 0.30 and 0.28, respectively.

Bending strain was given at room temperature by pressing the sample with the upper GFRP die to the lower one with the same curvature (Fig. 1). The bending strain ε_B (strain of the outer surface of the composite in the tensile side) was given by $\varepsilon_B = t^*/(2R)$ where R is the radius of the die. In this work, six pairs of dies with the radius $R = \infty$ (straight dies), 61.6, 34.0, 22.3, 17.3 and 13.8 mm were used.

The results were analyzed based on the model, which will be presented in 3.3. For applying of the model, tensile data were needed. To obtain them, tensile test was carried out at room temperature using a universal testing machine at a strain rate of 1.7×10^{-4} s^{-1} for a gage length 100 mm. The strain was measured with a non-contact type extensometer.

The critical current of the samples, strained up to the prescribed bending and tensile strains at room temperature, was measured at 77 K with a criterion of 1 μV/cm under no applied magnetic field. The distance between the voltage taps was 30 mm.

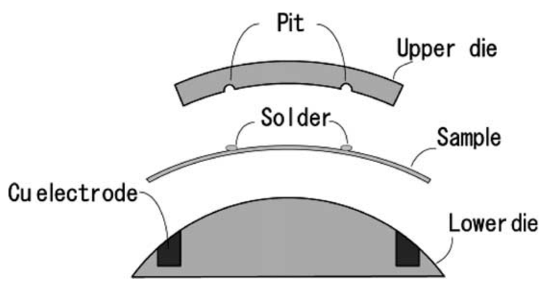

Fig. 1. Configuration of the sample and dies to give a bending strain.

3. Results and discussion

3.1. Tensile stress–strain behavior and its influence on critical current

Fig. 2 shows the measured tensile stress ($\sigma_{c,T}$)–strain (ε_T) curve. The yield stress $\sigma_{y,Ag}$ of Ag annealed at 1073 K has been reported to be 13 MPa [17], suggesting that Ag yields in tension during cooling to room temperature [2–4]. Thus, Bi2223 and Ag alloy deform elastically and Ag plastically in the early deformation stage. With increasing strain ε_T, Ag alloy reaches yield. Such a deviation point can be identified from the change in slope of the curve, as indicated by A in Fig. 2.

With further increasing ε_T, Bi2223 filaments fracture. The deviation can be identified also from the change in the slope of the curve, as indicated by B. As the strength of Bi2223 filaments is not unique but scattered [2,18], B has some strain range. Fig. 3 shows the change of critical current I_c, normalized with respect to the original value I_{c0}, with ε_T. The I_c is reduced in the range of B, indicating that the fracture of Bi2223 filaments is the reason for the reduction in I_c. The strain at B, ε_T(B), was determined to be 0.25–0.29% from Figs. 2 and 3.

3.2. Estimation of residual- and tensile-intrinsic fracture-strains of Bi2223 filaments

As stated in 3.1, Ag yields in tension during cooling from the heat-treatment to room temperature [2–4]. Under such a condition, the residual strain of Bi2223 along the filament axis ($\varepsilon_{r,Bi}$) is approximately given by [17]

$$\varepsilon_{r,Bi} = \frac{(\alpha_{Alloy} - \alpha_{Bi})E_{Alloy}V_{Alloy}\Delta T - \sigma_{y,Ag}V_{Ag}}{E_{Bi}V_{Bi} + E_{Alloy}V_{Alloy}}, \quad (1)$$

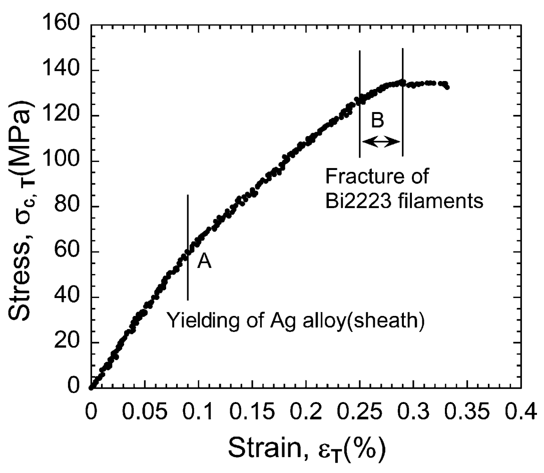

Fig. 2. Tensile stress–strain curve of the composite tape.

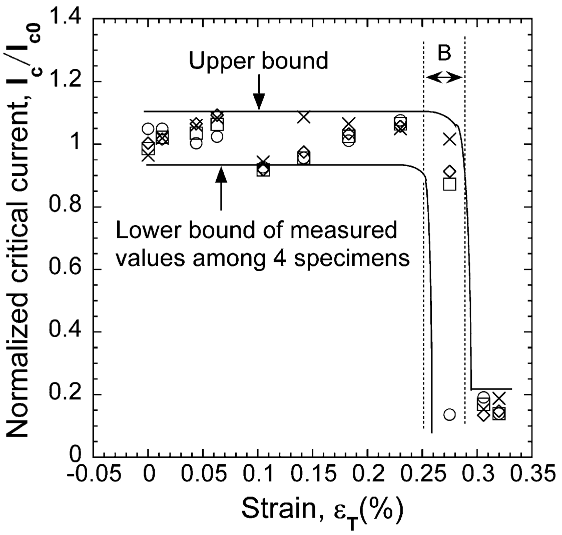

Fig. 3. Change of critical current with tensile strain.

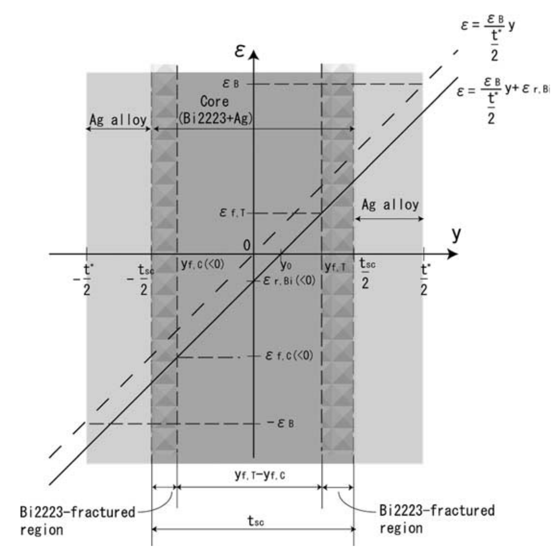

Fig. 4. Schematic representation of the bending strain in relation to the specimen configuration.

where α is the coefficient of thermal expansion, E the Young's modulus, ΔT the difference between the heat-treatment and room temperatures and V the volume fraction, and the subscripts Bi, Ag and Alloy refer to Bi2223, Ag and Ag alloy, respectively. Substituting $\sigma_{y,Ag} = 13$ MPa [17], $\alpha_{Bi} = 15 \times 10^{-6}$ K^{-1} [19], $\alpha_{Alloy} = 21 \times 10^{-6}$ K^{-1} (assumed to be same as Ag), $E_{Bi} = 98$ GPa (estimated from the slope of the stress–strain curve below the strain A in Fig. 2), $E_{Alloy} = 88$ GPa [19], $\Delta T = -830$ K, $V_{Bi} = 0.42$, $V_{Ag} = 0.30$ and $V_{Alloy} = 0.28$ into Eq. (1), we have $\varepsilon_{r,Bi} = -0.16\%$.

Noting the intrinsic tensile-fracture strain as $\varepsilon_{f,T}$, it relates to the $\varepsilon_{r,Bi}$ and $\varepsilon_T(B)$ in the form $\varepsilon_T(B) = \varepsilon_{f,T} - \varepsilon_{r,Bi}$. Substituting the measured value of $\varepsilon_T(B) = 0.25$–0.29% and the estimated one of $\varepsilon_{r,Bi} = -0.16\%$ into this relation, we have $\varepsilon_{f,T} = 0.09$–0.13%.

3.3. Change of critical current at 77 K with increasing applied bending strain

The present composite wire consists of the inner core with Bi2223 filaments in Ag, and the outer sheath of Ag alloy. The core is responsible for the current transport. In order to describe the relation of the bending damage to critical current, the following simple model (Fig. 4) was proposed. The neutral axis was fixed in this model.

The bending strain ε_B is defined as the tensile strain at the outer surface. Noting the distance from the center of the thickness as y, the bending strain ε at y (the broken line in Fig. 4) is expressed as

$$\varepsilon = \frac{\varepsilon_B}{t^*/2} y. \tag{2}$$

As the filaments has the residual strain, $\varepsilon_{r,Bi}$ (compressive and therefore minus value), the total strain of the filaments at y in the bent sample is expressed as

$$\varepsilon = \frac{\varepsilon_B}{t^*/2} y + \varepsilon_{r,Bi}, \tag{3}$$

as shown with the solid line. Noting the thickness of the core as t_{sc}, the filaments exist for $-t_{sc}/2 < y < t_{sc}/2$. The volume fraction of the core V_{sc} is the sum of that of Bi2223 (V_{Bi}) and Ag (V_{Ag}), being 0.72 in the present samples. t_{sc} is approximately given by $t^* V_{sc}$. The strain of the filament ε is zero at $y = y_0$ $(= -\varepsilon_{r,Bi} t^*/(2\varepsilon_B))$, tensile for $y_0 < y < t_{sc}/2$ and compressive for $-t_{sc}/2 < y < y_0$.

The first damage in the tensile side occurs when the strain of filaments reaches the tensile fracture strain $\varepsilon_{f,T}$ at $y = t_{sc}/2$, and the first damage in the compressive side occurs when the strain reaches the compressive fracture strain $\varepsilon_{f,C}$ at $y = -t_{sc}/2$. Substituting $\varepsilon = \varepsilon_{f,T}$ and $y = t_{sc}/2$, and $\varepsilon = \varepsilon_{f,C}$ and $y = -t_{sc}/2$, into Eq. (3), we have the corresponding ε_B:

$$\varepsilon_B = \frac{\varepsilon_{f,T} - \varepsilon_{r,Bi}}{V_{sc}} \quad \text{for tensile side,} \tag{4}$$

$$\varepsilon_B = -\frac{\varepsilon_{f,C} - \varepsilon_{r,Bi}}{V_{sc}} \quad \text{for compressive side.} \tag{5}$$

The irreversible bending strain $\varepsilon_{B,irr}$, at which the critical current starts to be reduced, is given by the lower ε_B between Eqs. (4) and (5):

$$\varepsilon_{B,irr} = \frac{\varepsilon_{f,T} - \varepsilon_{r,Bi}}{V_{sc}} \quad \text{if } \varepsilon_{f,T} + \varepsilon_{f,C} - 2\varepsilon_{r,Bi} < 0, \tag{6}$$

$$\varepsilon_{\mathrm{B,irr}} = -\frac{\varepsilon_{\mathrm{f,C}} - \varepsilon_{\mathrm{r,Bi}}}{V_{\mathrm{sc}}} \quad \text{if } \varepsilon_{\mathrm{f,T}} + \varepsilon_{\mathrm{f,C}} - 2\varepsilon_{\mathrm{r,Bi}} > 0. \tag{7}$$

With increasing ε_{B}, the damages spread in the core. Namely the y-value at the tensile damage front decreases from $t_{\mathrm{sc}}/2$ toward zero, and that at the compressive damage front increases from $-t_{\mathrm{sc}}/2$ toward zero. The y-values at the damage fronts, $y_{\mathrm{f,T}}$ (tensile side) and $y_{\mathrm{f,C}}$ (compressive side) is calculated by substituting $\varepsilon = \varepsilon_{\mathrm{f,T}}$ and $y = y_{\mathrm{f,T}}$, and $\varepsilon = \varepsilon_{\mathrm{f,C}}$ and $y = y_{\mathrm{f,C}}$ into Eq. (3), respectively:

$$y_{\mathrm{f,T}} = \frac{(\varepsilon_{\mathrm{f,T}} - \varepsilon_{\mathrm{r,Bi}})(t^*/2)}{\varepsilon_{\mathrm{B}}}, \tag{8}$$

$$y_{\mathrm{f,C}} = \frac{(\varepsilon_{\mathrm{f,C}} - \varepsilon_{\mathrm{r,Bi}})(t^*/2)}{\varepsilon_{\mathrm{B}}}. \tag{9}$$

The filaments are damaged for $-t_{\mathrm{sc}}/2 < y < y_{\mathrm{f,C}}$ and $y_{\mathrm{f,T}} < y < t_{\mathrm{sc}}/2$. If we assume simply that only the surviving filaments in $y_{\mathrm{f,C}} < y < y_{\mathrm{f,T}}$ transport the current, the ratio of the critical current of the damaged specimens I_{c} to that of the original ones I_{c0} is given as a function of ε_{B} as follows:

(A) When $\varepsilon_{\mathrm{B}} < \varepsilon_{\mathrm{B,irr}}$, no damage arises and therefore $I_{\mathrm{c}}/I_{\mathrm{c0}}$ is given by

$$\frac{t_{\mathrm{sc}}/2 - (-t_{\mathrm{sc}}/2)}{t_{\mathrm{sc}}} = 1.$$

(B) With increasing ε_{B}, either tensile or compressive side is damaged first. If $\varepsilon_{\mathrm{f,T}} + \varepsilon_{\mathrm{f,C}} - 2\varepsilon_{\mathrm{r,Bi}} < 0$ (Eq. (6)), tensile side is damaged earlier. In such a case, until the compressive side is damaged, $I_{\mathrm{c}}/I_{\mathrm{c0}}$ is given by

$$\frac{y_{\mathrm{f,T}} - (-t_{\mathrm{sc}}/2)}{t_{\mathrm{sc}}} = \frac{1}{2}\left[1 + \frac{\varepsilon_{\mathrm{f,T}} + \varepsilon_{\mathrm{r,Bi}}}{\varepsilon_{\mathrm{B}} V_{\mathrm{sc}}}\right].$$

On the contrary, if $\varepsilon_{\mathrm{f,T}} + \varepsilon_{\mathrm{f,C}} - 2\varepsilon_{\mathrm{r,Bi}} > 0$ (Eq. (7)), compressive side is damaged earlier. In such a case, until the tensile side is damaged, $I_{\mathrm{c}}/I_{\mathrm{c0}}$ is given by

$$\frac{t_{\mathrm{sc}}/2 - y_{\mathrm{f,C}}}{t_{\mathrm{sc}}} = \frac{1}{2}\left[1 + \frac{-\varepsilon_{\mathrm{f,C}} + \varepsilon_{\mathrm{r,Bi}}}{\varepsilon_{\mathrm{B}} V_{\mathrm{sc}}}\right].$$

(C) With further increasing ε_{B}, both tensile and compressive sides are damaged. The $I_{\mathrm{c}}/I_{\mathrm{c0}}$ is given by

$$\frac{y_{\mathrm{f,T}} - y_{\mathrm{f,C}}}{t_{\mathrm{sc}}} = \frac{\varepsilon_{\mathrm{f,T}} - \varepsilon_{\mathrm{f,C}}}{\varepsilon_{\mathrm{B}} V_{\mathrm{sc}}}.$$

In this way, depending on $\varepsilon_{\mathrm{f,T}}$ and $\varepsilon_{\mathrm{f,C}}$ values, the $I_{\mathrm{c}}/I_{\mathrm{c0}}$ varies as a function of ε_{B}. In the calculation, $\varepsilon_{\mathrm{f,T}}$ and $\varepsilon_{\mathrm{r,Bi}}$ were taken to be 0.1% and −0.16%, respectively, from 3.1. As the $\varepsilon_{\mathrm{f,C}}$-value of the present filaments was unknown, various $\varepsilon_{\mathrm{f,C}}$-values were input into the calculation and the fit to the experimental result was sought.

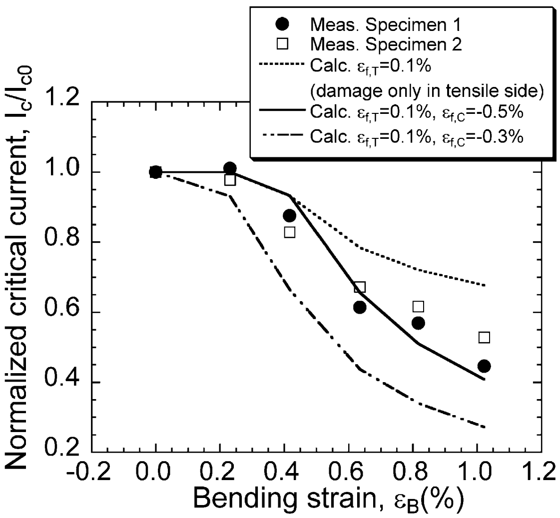

Fig. 5. Variation of critical current with increasing bending strain.

The case, where only the tensile side is damaged, calculated by inputting $|\varepsilon_{\mathrm{f,C}}| \gg |\varepsilon_{\mathrm{f,T}}|$, did not describe the measured change of $I_{\mathrm{c}}/I_{\mathrm{c0}}$ with ε_{B}, as shown in Fig. 5. Also the low compressive-fracture strain such as $\varepsilon_{\mathrm{f,C}} = -0.3\%$ did not fit to the experimental result. It was found that $\varepsilon_{\mathrm{f,C}} = -0.5\%$ can describe the experimental result. The present result indicates that the intrinsic compressive-fracture strain of the filaments (0.5%) is about five times higher than the tensile fracture strain (0.1%).

4. Conclusions

(1) The residual strain and intrinsic tensile-fracture strain of the Bi2223 filaments at room temperature were −0.16% and 0.09–0.13%, respectively. Accordingly, the critical current of the specimens pre-stressed at room temperature decreased for tensile strain values greater than 0.25–0.29%.

(2) A simple model, in which fracture of filaments in both tensile and compressive sides is incorporated, was presented, which could describe the experimentally observed critical current-bending strain relation. It was indicated that the intrinsic compressive-fracture strain of the filaments is about five times higher than the intrinsic tensile fracture strain.

Acknowledgements

The authors wish to express their gratitude to The Ministry of Education, Culture, Sports, Science and Technology, Japan, for the grant-in-aid (No. 14350360).

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