

Assessment of strain of Bi2223 filaments in bent Ag-sheathed superconducting composites by synchrotron radiation

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Abstract

Bending strains of Bi2223 filaments in Ag-sheathed superconducting composite tapes at the Bi2223 /Ag sheath boundary have been evaluated by X-ray diffraction utilizing synchrotron radiation at room temperature. The strain in the Bi2223 filaments was found to be asymmetric between tension and compression sides, suggesting that the fracture strain is also asymmetric between tension and compression. The outermost part of the Bi2223 filaments is in the multiple fracture stage in the tension side.

Introduction

Performance of superconducting leads and wires under applied strain is one of the most important subjects to evaluate and design reliability of the composites. Therefore, the effects of applied strains as well as thermal residual strains introduced during fabrication have been discussed by many researchers [1]-[3]. In the recent experiments, we performed in-situ measurement of axial strain in Ag-sheathed Bi2223 superconducting composite with and without stainless steel lamination in Laue geometry at room temperature [4,5]. The results clearly showed the strain of Bi2223 filaments changing from residual compressive strain to eventually multiple fracture state on tensile deformation. From continuum mechanical analysis and critical current measurements, Ochiai et al.[6] examined the fracture strain in bent Ag/Bi2223 superconducting tapes, and concluded that the fracture strain in the compression side is much larger than that in tension side of 0.24 % when operated at liquid nitrogen temperature, although the fracture strain in compressive side should still be taken into account at strong bending. Recent analysis of the effect of bending strain on the critical current by Ochiai et al.[7] shows that the deterioration of Bi2223 filaments begins at a very small bending at the tension side of bending. Therefore, it is important to understand the asymmetry of fracture between tension and compression during bending deformation in order to design the superconducting tapes for magnets. However, there has been no direct experimental work to evaluate the strain of bent tapes at both

sides. In the present work, we examined the strain of bent Ag sheathed Bi2223 composite tapes by using synchrotron radiation diffraction.

Experimental

Ag-alloy sheathed multifilamentary Bi2223/Ag composite tape (high- I_c type) was supplied by American Superconductor Co. Ltd. The tape has been certified to have minimum critical current of 200 A at liquid N₂ temperature operation without external magnetic field [8]. Since the bending strain is proportional to the distance from the neutral plane, it is essential to control the depth that X-ray penetrates into the sample. In the present case, there are two choices to perform depth-sensitive strain measurements. One is an in-plane diffraction, whose scattering vector is parallel to the tangential direction of bending strain. This configuration has a merit that the measurement of the bending strain is direct, but at the same time, has a drawback that the scattering plane actually does not lie exactly in-plane in order to get the incident X-ray penetrated through the outer Ag-alloy sheath into the Bi2223 layer, and the direction of the scattering vector eventually deviates from the tangential direction of bending when we control the penetration depth. Then, it is difficult to separate the effects of the penetration depth and the direction of scattering vector, and strong c-plane texture of the sample may not give diffraction acceptable for evaluation. Therefore, we adopted the second approach, symmetric Bragg diffraction measurements with their scattering vector perpendicular to the tape face. The sample under bending and its experimental configuration are schematically shown in Fig. 1. As shown in the figure, the lattice constant perpendicular to the applied bending strain was evaluated. Although the present set-up has a problem that the absolute value of bending strain can be evaluated only through the right Poisson's ratio, it also has a merit that the penetration depth can be easily controlled for the present sample.

X-ray diffraction measurements have been made at beam-line 46XU of Spring8, Hyogo, Japan at 21 keV. The attenuation constants calculated from the table [8] for Ag and Bi2223 filaments are shown in Fig. 2. The absorption is reasonably small at photon energies from 20 to 25 keV. Choosing this energy range has another merit for the present experiment. As shown in the figure, the attenuation constant is almost the same for Ag and Bi2223. Therefore, the penetration depth is expected to be the same when the incident X-ray beam goes into the Ag part and when it goes into the Bi2223 part in the core Ag/Bi2223 composite region. This makes the assessment of penetration depth at the Ag/Bi2223 composite quite easy.

Results and discussions

The thickness of outer Ag-alloy sheath evaluated from optical micrograph is about $27.5 \pm 2.5 \mu\text{m}$. The core Ag / Bi2223 filaments layer is about $150 \mu\text{m}$ thick. In the present analysis, evaluation of penetration depth in the X-ray measurements is important. Assuming that the Ag alloy sheath is ideally flat and Bi2223/Ag composite core is uniform, then the intensity of the diffracted beam with a Bragg angle of θ_B is given by;

$$I(2\theta) = \int I(2\theta, z)T(z)dz \quad (1)$$

with

$$z = r - r_0 \quad (r_0 - t_0 < r < r_0 + t_0)$$

The transmission coefficient for the Bragg case, $T(z)$, is given by ;

$$T(z) = T_0 \exp(-2\mu_C \pm (t_0 - z)/\sin(\theta_B)) \quad (2)$$

where μ_s , μ_C are the linear attenuation constants for the sheath and the Ag / Bi2223 core, and $\pm(t_0 - z)$ correspond to X-ray incoming from tension (convex) side and compression (concave) side respectively. $T_0 = \exp(-2\mu_s(t_1 - t_0)/\sin\theta_B)$ is the transmission by the Ag-alloy sheath. With an average thickness of Ag alloy sheath of $27.5 \mu\text{m}$ and a calculated linear attenuation coefficient for Ag alloy for the present photon energy, T_0 was about 1.2×10^{-2} . The ratio of the 0 0 14 peak of Bi2223 for the as-supplied sample to that for the sample whose Ag alloy sheath was removed by chemical etching was about 1.7×10^{-2} . The intensity from the etched sample was slightly stronger than the simple calculation, possibly due to the thickness distribution of the sheath, and also because some of the Ag in the Ag/Bi2223 core was also removed during etching, thereby increasing the effective volume fraction of Bi2223 at the etched surface.

For bending deformation, the strain is proportional to the distance from the neutral plane. In the present analysis, we assumed that the neutral plane is at the center of the Bi2223/Ag composite core, i.e., the shift of neutral plane due to the yield of Ag and the fracture of Bi2223 filaments can be neglected. Then the tangential strain distribution in the theta direction across the sample is simply given by :

$$\varepsilon^\theta(z) = z/r_0, \quad (3)$$

Therefore, if the X-ray penetrates completely throughout the sample, as for in Laue geometry, the effective strain obtained from X-ray diffraction vanishes. This is the reason we need to use Bragg geometry, although the measurements give us indirect information of the strain in the r direction, ε^r , instead of the one in tangential direction, ε^θ , which controls the fracture and transport behaviors of the composites. The effective strain picked up by the present diffraction measurements is given by ;

$$\begin{aligned}\bar{\varepsilon}^r &= \nu \int_{-t_0}^{t_0} T(z) \varepsilon^\theta(z) dz / \int_{-t_0}^{t_0} \varepsilon^\theta(z) dz \\ &= \pm \frac{\nu}{r_0} \left[\frac{t_0}{\tanh(2\mu t_0 / \sin \theta_B)} - \frac{1}{2\mu t_0 / \sin \theta_B} \right] \quad (4)\end{aligned}$$

for the strain measured from convex and concave side of the sample, which is related to the strain in θ direction by the Poisson's ratio, ν ;

$$\varepsilon^\theta(z) = \frac{1}{\nu} \bar{\varepsilon}^r(z) . \quad (5)$$

The nominal maximum bending strain in the θ direction, $\varepsilon_{\max}^\theta$, is given by $\pm t_0 / r_0$. The nominal maximum tangential strain and the effective tangential strain averaged over the penetration depth calculated by (4) and (5) for the present 0 0 14 diffraction condition of Bi2223 are shown in Table 1. For example, if the sample is bent with $r_0=34.1$ mm, nominal tangential strain at the core/sheath interface is $\pm 0.22\%$, and the average tangential strain by eq. (4) and (5) is $\pm 0.20\%$ if the Bi2223 filaments in the core still deform elastically. Therefore, it is concluded that the strain evaluated by the present X-ray diffraction reflects the strain very close to the maximum bending strain at the core/sheath interface.

TABLE 1. Maximum tangential strain at the Ag-sheath/core interface, and the effective strain at the penetration depth calculated for the radii examined in the present experiment.

r_0 (mm)	34.1	17.4	11.4
$\varepsilon_{\max}^\theta$ (%)	0.22	0.43	0.66
$\bar{\varepsilon}_{0014}$ (%)	0.20	0.40	0.60

Figure 3 shows the strain in the r direction obtained by the 00 14 diffraction peaks as a function of calculated tangential strain at the penetration depth, $\varepsilon_{0014}^\theta$. The strain-free lattice parameter of Bi2223 filaments in r direction was evaluated from the peak position of the filaments fully exposed at the surface of the flat composite by chemical etching of Ag layers. The strain changes almost linearly with tangential strain in compression side, that is, the strain in the Bi2223 filaments at the sheath / core interface increases with increasing bending strain applied to the composite up to 0.6%.

In contrast, the strain remained almost constant with some scattering from relatively small strain in the tension side as shown in Fig.3. The penetration depth in the Bi2223/Ag core layer calculated by eq. (1) for the present condition is about 6.2 μm , in agreement with the ratio between the average strain calculated from (4) to the maximum strain as shown in Table 1. The penetration depth corresponds to about 30% of the average thickness of single Bi2223 filament. Therefore, we may discuss the change of the observed strain as the change of the strain in the outer side of the outermost filaments. This implies that the crack formation of the outermost Bi2223 filaments occurs at very small strain in the tension side. This result seems consistent with the preceding works [5] that the intrinsic fracture strain of the Bi2223 filaments was about 0.1 % at room temperatures in tension. As the average tangential strain increases, the outermost Bi2223 filaments with largest tensile strain experience multiple crack formation, resulting in a very low and almost constant filament strain as observed in the multiple fracture stage of Bi2223 filaments in stainless-steel laminated Ag/Bi2223 composites[5]. Recent assessments by Ochiai et al [9] suggest that relatively early fracture of superconducting filaments may occur at the outermost part of the composites under bending, but these early and statistical fracture does not result in rapid degradation of superconducting performance of the composite.

The slope given in the compression side of the data, -0.11 ± 0.01 , implies that the effective Poisson's ratio for the Bi2223 filaments appears quite low. This tendency has been reported in the preceding works [10]-[13]. For example, the tensile test with Bragg geometry reported by ten Haken et al. in Fig.4 of [10] suggests that the Poisson's ratio for Bi2212 in moncore Ag/Bi2212 composites obtained by the X-ray diffraction measurements is about 0.14. The origin of the low Poisson's ratio has been explained either by its intrinsic low value due to the crystal structure [11] and also by the existence of micro voids and micro cracks in the samples [12,13]. Fracture also at the compression side may be another possibility. Concerning the latter case, however, the slope should decrease monotonically with increasing applied strain, eventually vanish as observed in the tension side. Therefore, the origin of low Poisson's ratio should be the former one, with both aspects may apply since the microstructure of the sample is a textured polycrystal with slightly wavy Bi2223 filaments. Since the fracture of Bi2223 filaments in the tension side was observed for all the bent sample, the neutral plane may slightly move towards compression side during deformation, whose process is strongly microstructure dependent such as the yielding and work hardening of Ag alloy sheath and crack propagation in Bi2223 polycrystal fibers, critical intercrack length of the superconducting filaments. Therefore, we can not conclude that the present slope

directly gives the Poisson's ratio for the present Bi2223 filament. To evaluate the Poisson's ratio precisely, simple uniaxial condition should be required. Bi2223 filaments in the bent composites experience much stronger compressive strain under low-temperature operation. Therefore, further study at low temperatures will be required.

Summary

Bending strains of Bi2223 filaments in Ag-sheathed Ag/Bi2223 superconducting composite tapes on both tension and compression sides have been evaluated by the shift of a Bragg peak utilizing synchrotron radiation.

From the lattice constant perpendicular to the tape face, it is concluded that the strain of Bi2223 filaments under bending has strong asymmetry between compression and tension. The strain in the tension side remained slightly smaller than the one reported for simple tension with relatively wide distribution. On the compression side, however, Bi2223 filaments still support applied compressive stress at a large bending strain of 0.6%.

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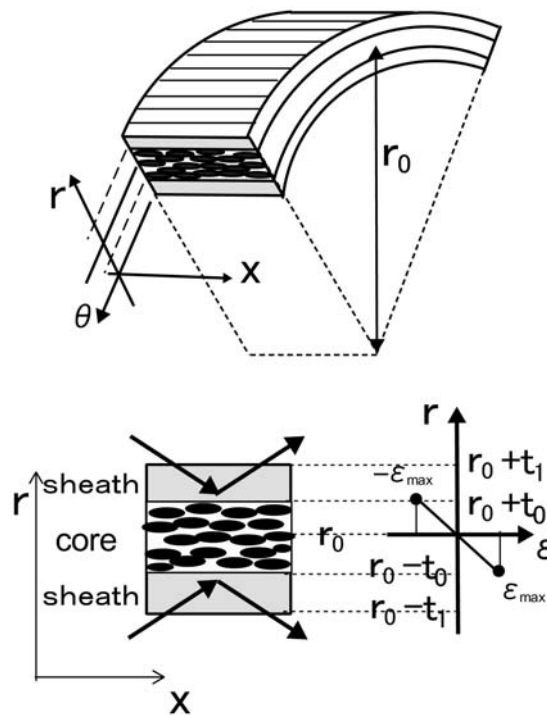


Fig.1 Schematic drawing of the sample structure and experimental set-up used in the present experiments.

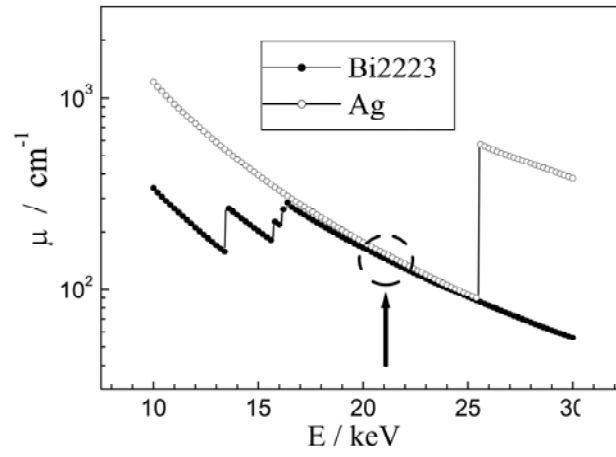


Fig.2 Attenuation constants calculated from Sasaki's table[8] for Bi2223 phase and Ag as a function of incident X-ray energy. The arrow corresponds to the present photon energy.

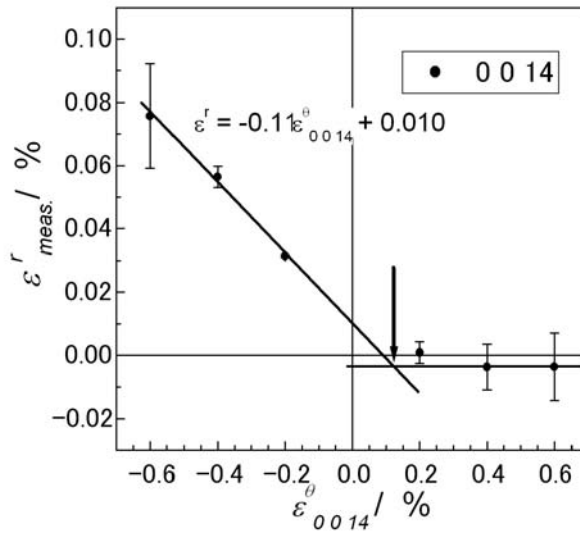


Fig.3 Strain of Bi2223 filaments in the compression and tension sides as a function of calculated tangential strain. The arrow indicates the fracture strain of Bi2223 filaments in the tension side at room temperature estimated from the peak shift.