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In situ synchrotron-radiation measurements of axial strain in laminated Bi2223 superconducting composite tapes at room temperature

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Axial strain of Bi2223 superconducting filaments in Ag-sheathed superconducting composites reinforced by stainless steel lamination has been evaluated by in situ synchrotron-radiation diffraction. The Bi2223 filaments in the laminated composites were under 0.11% of compressive residual strain, whereas the residual strain of filaments in the composite after removing stainless steel layers was only 0.02% in compression. Under large tensile load, the composite showed a clear multiple fracture with an almost constant filament strain of about 0.11% in tension.

Keywords: Ceramic superconductors; Residual stresses; X-ray diffraction; Fiber reinforced composites; Laminated Ag-sheathed Bi2223 superconducting tapes

Controlling strain of $Bi(Pb)_2Sr_2Ca_2Cu_3$ oxide superconductor (Bi2223) filaments in Ag-sheathed composites is one of the most important factors in realizing high performance superconducting composites for future industrial use [1]. Small tensile strain of about 0.2–0.3% leads to fracture of superconducting Bi2223 filaments, resulting in a breakdown of superconducting current at the liquid nitrogen temperature [2–4]. On the other hand, the fracture strain was expected to be higher on the compressive side [4]. Therefore, there has been a strong motivation to design the composite material so that the Bi2223 filaments are under adequate compressive strain for better performance under axial tensile load such as hoop stress. One of the prospective solutions is giving compressive strain to the brittle Bi2223 filaments by thermal residual strain or attaching prestrained stainless steel sheets to the composite [5–8]. Although an accurate evaluation of the strain in Bi2223 layer is necessary for optimal design of the composite, analysis from mechanical testing had some ambiguities stemming from the complex processes the composite experienced during fabrication and testing.

As calculated by Otto et al. [9] the residual strain in the Bi2223 layer in the Ag/Bi2223 composites reinforced by preprocessed stainless steel sheets is expected to be much higher than for those without. However, too much prestrain may lead to compressive fracture of the Bi2223 layer [4,8,10], which in turn results in degradation of the superconducting performance. Therefore, it is quite important to evaluate the actual strain state of the sample that went through complicated fabrication processes and thermal history. In the previous experiments, we evaluated the change of axial strain of Bi2223 filaments in Ag-sheathed Bi2223 superconducting composites in Laue geometry [11]. The measurements were carried out to confirm if the elastic–plastic mechanical approach used to estimate residual strain in Bi2223 filaments is accurate. In the present study, the change of axial strain of Bi2223 filaments in Ag/Bi2223 multifilamentary superconducting composites reinforced with stainless

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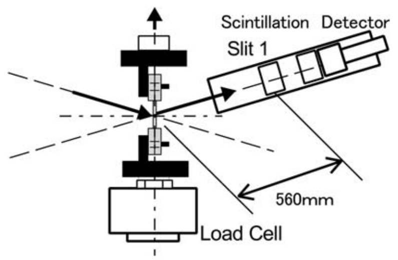

Figure 1. Experimental set-up.

steel sheets under tensile load was evaluated in situ utilizing synchrotron-radiation at room temperature.

The samples used in the present measurements were a high-strength type of silver sheathed Bi2223 superconducting composite tape provided by American Superconductor Co. Ltd. [8] The samples were characterized by a pair of prestrained stainless steel laminating sheets that mechanically reinforce and give compressive strain to the superconducting composite layer having 55 Bi2223 filaments implemented in a Ag matrix. The samples were fixed to pairs of grooved Al tabs by epoxy glue for tensile tests.

In situ measurements were made at the beamline 46XU, an undulator beamline of a synchrotron-radiation facility, SPring8, Japan. An in situ tensile test machine was mounted on a multiaxis goniometer as shown in Figure 1. Tensile load up to 400 N was applied to the composite tapes, and the shifts of the Bragg peaks for Bi2223 filaments were measured as a function of the applied load. Two indices, i.e., 200 and 220 of Bi2223, were used for the present analysis. As shown in the figure, the present measurements were made in the Laue geometry with the scattering vector parallel to the longitudinal direction. Therefore, the change in the lattice parameter directly corresponds to the axial strain relevant to the strain analysis of the superconducting composites. Since the lattice parameter depends not only on the strain but also on the stoichiometry of the Bi2223 filaments, and may be slightly different between manufacturers, Bi2223 filaments extracted from the test sample by H_2O_2/NH_4OH solution were used as the standard samples for the Bragg peak positions in the strain-free state. To obtain a desirable balance between transmission and the angular resolution, the photon energy of the incident X-ray was chosen to be 22.00 keV in the present experiment. The beam size used in the present experiment was $0.5 \times 1\ \mathrm{mm}^2$ in the present measurements, which was larger than the previous measurements of $0.1 \times 0.5\ \mathrm{mm}^2$ [11], to obtain an averaged strain of the Bi2223 filaments at each stress level.

In order to suppress the error in 2θ measurements due to displacement of the sample from the center of rotation of the goniometer, the center of the sample was controlled at the rotation center by a translation stage with a real-time charge-coupled device telescope monitor. The position of the sample center was controlled to within 10 μm for laminated samples, corresponding to the error within 3×10^{-4} degree for the 220 peak of Bi2223. The off-center error was also corrected by using a standard Y_2O_3 powder sample painted on the test

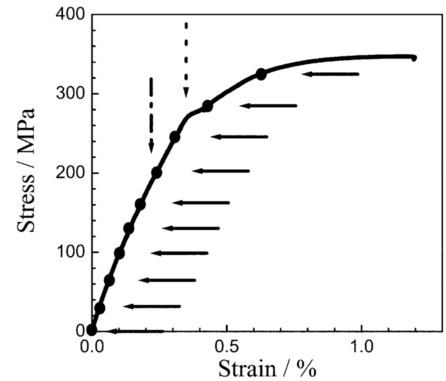

Figure 2. Stress–strain curve of the laminated composite.

samples. From the Bragg peak angle of the Bi2223 filaments in the composite, θ_{comp}, and that for extracted filaments, θ_0, the axial strain of the Bi2223 filaments in the composite was evaluated by:

$$\Delta a/a = \{(1/\sin(\theta_0) - 1/\sin(\theta_{comp.}))/(1/\sin(\theta_0))\}. \quad (1)$$

The stainless steel laminates fixed with solder layers did not detach from inner Ag-alloy/Bi2223 layer during the in situ measurements.

Figure 2 shows a stress–strain curve of the sample at room temperature. The most remarkable difference from the Ag/Bi2223 composites without stainless steel lamination reported in the previous work [11] is that a clear yield and work hardening are observed even after multiple fracture of the Bi2223 filaments in the present sample, and the average stress of the composite continues to increase up to as large an average strain as about 1%, although the Bi2223 filaments are apparently broken into pieces due to multiple fracture at much lower strain. The horizontal arrows in the figure are the average stress of the composite where the Bragg peak shifts were measured in situ.

The change of axial strain of Bi2223 filaments under tensile load is shown in Figure 3 as a function of average composite strain. The strains of the filaments in Ag/Bi2223 composites after removing the stainless steel laminates are also shown in the figure. The residual strain in the laminated composites was $-0.108 \pm -0.015\%$, and that for the sample after removing the lamination was $-0.018 \pm -0.006\%$, both under compressive strain. The results clearly indicates that an additional compres-

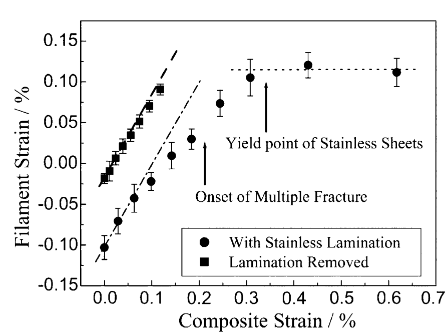

Figure 3. Axial strain of Bi2223 filaments obtained from the Bragg peak shifts.