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EFFECT OF BENDING DEFORMATION ON CRITICAL CURRENT IN Bi2223/Ag/Ag-ALLOY COMPOSITE SUPERCONDUCTING TAPES

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ABSTRACT

The strain dependence of the critical current, I_c, of $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$(Bi2223)/Ag/Ag-Mg composite superconducting tapes has been studied both experimentally and analytically under bending deformation. These tapes are composed of thin Bi2223 superconducting filaments and Ag and Ag-alloy matrices. Since the fracture of brittle Bi2223 filaments is directly translated into the decrease of I_c, we can use the change of I_c as the sensor to indicate the damage of filaments in composite tapes. The complex stress-strain behavior of each component was first analyzed in tension by comparing the stress-strain curves of composite tapes with those of Ag and Ag-Mg alloy tapes. Here, the work hardening of Ag and Ag-Mg alloy, and the thermal residual strain were taken into account. The calculated stress-strain curves agreed well with the experimental results. Then, the analysis was modified to fit the bending deformation. Here, the movement of the neutral axis was taken into account. The calculated decrease of I_c due to filament fracture agreed well with the experimental results when the microscopic damage distribution in the tapes was taken into account.

1. INTRODUCTION

The structures of superconducting tapes or wires are very similar to those of conventional composite materials. Typical superconducting tapes or wires are composed of very thin (several to several tens of micrometers) superconducting filaments and ductile Ag or Cu matrices as stabilizer [1,2]. Since the yield strengths of matrices are often very low, superconducting filaments carry certain amount of applied load. The fracture of superconducting filaments is directly correlated to the decrease in the critical current. Thus, the filaments in superconducting tapes or wires act as load bearing component and filament fracture sensor in composite superconducting tapes or wires.

We focused here on bismuth-based oxide high-temperature superconducting tapes which realize superconducting state at liquid-nitrogen temperature (77K). When these tapes are used in the engineering application fields such as superconducting cables etc., the mechanical properties and their relation to superconducting properties become important [3-6]. The ultimate fracture strain of $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{12}$ (Bi2223) filaments is extremely low (about 0.1%) [7,8]. Though Ag-Mg alloy matrix (sheath) is used in addition to Ag to achieve certain mechanical properties as well as the stability of superconducting properties, the mechanical properties of these tapes are intrinsically poor [9]. This structure gives rise to complicated stress and strain states owing to the difference in the thermal expansion coefficient during the manufacturing process [3,10]. The thermal residual stresses in Ag and Ag-Mg alloy components easily exceed their yield strength during the manufacturing process. Thus, the stress and strain states of each component are very complicated both under tensile and bending loadings [11-13].

In the present study, the strain dependence of the critical current, I_c, of Bi2223/Ag/Ag–Mg multifilamentary composite superconducting tapes has been studied both experimentally and analytically under bending deformation [14,15]. The complex stress–strain behavior of each component is first analyzed in tension. Then, the analysis is modified to fit the bending deformation. Microscopic observation of the spatial distribution of the filament fracture was also carried out using scanning electron microscopy to find the microscopic fracture mechanism of

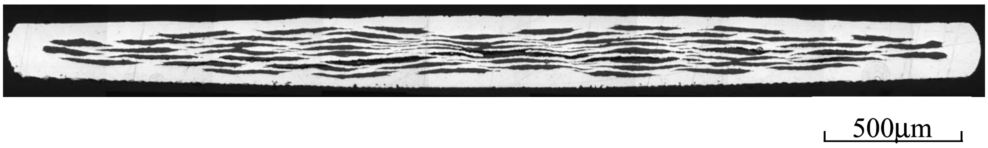

Fig. 1. Optical micrograph of transverse section of composite tape.

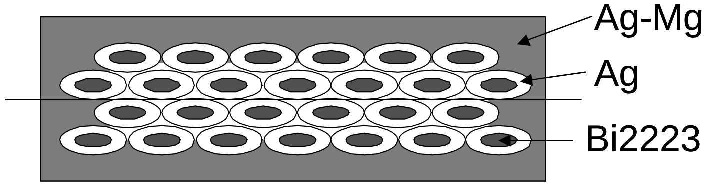

Fig. 2. Schematic model for transverse section of composite tape.

these composite tapes.

2. EXPERIMENTAL AND ANALYTICAL PROCEDURES

2.1 Materials and tests

The composite superconductors used in this study were multifilamentary Bi2223/Ag/Ag-Mg tapes (Vacuumschumeltze) which were supplied as the standard samples for the VAMAS round-robin program (classified as VAM1). Figure 1 shows the transverse section of the tape. The number of filaments was 57. The averaged width and thickness were 3.62 and 0.228 mm, respectively. The critical current (I_c) at 77 K under the self-field was about 50 A, and the critical current density was about 20 kA/cm^2. The matrix (sheath) was composed of pure Ag and Ag-Mg alloy, where pure Ag was located around Bi2223, and Ag-Mg alloy was placed at outer part (Fig. 2). The volume fractions of Bi2223, Ag and Ag-Mg are 0.31, 0.36 and 0.33, respectively [15]. Pure Ag and Ag-1at%Mg alloy tapes of the similar size were also prepared to obtain the stress-strain curves for calculation [16,17].

The tensile tests were carried out at a crosshead speed of 0.3 mm/s. Manual flat-face grips were used for all tests. For the tests of composite tapes, rubber was inserted between the specimen and jaws as a cushion material. The total length of the specimen was 80 mm and the distance between two grips was 50 mm. A pair of lightweight extensometers designed by Nyilas was used for the measurement of strain. The details of this strain measuring system are explained elsewhere [16,17]. The specimens with a length of 80 mm were placed between a pair of glass fiber/epoxy curved dies of the radius, *R,* of ∞, 61.5, 34.0, 22.3, 17.3 and 13.8 mm. The specimens were first deformed at room temperature, and subsequently cooled to 77 K by immersing in liquid nitrogen. The critical current was determined from the relation between voltage and current using a four-probe technique in liquid nitrogen. The distance of the voltage taps was 30 mm, and I_c was defined with the 1 μV/cm-criterion.

2.2 Analysis

Work hardening of the Ag and Ag-Mg alloy after yielding is approximated as linear (Ag) or bilinear (Ag-Mg) functions as follows:

$$\sigma_i = \sigma_{yi} + K_i(\varepsilon_i - \varepsilon_{yi}) \tag{1}$$

where σ_{yi} and ε_{yi} are the yield strength and strain or bilinear work hardening parameters, and K_i is the coefficient of work hardening (i = Ag and Ag-Mg alloy). The stress-strain relation of Bi2223 is estimated to be linear until final fracture. The Young's modulus of Bi2223 filaments is selected as 100 GPa from the measurements of extracted single filaments from composite tapes [8]. This value is also similar to that obtained from the unloading curve of composites [14].

The change of the temperature, ΔT, is determined from the difference between the heat treatment temperature (1073K) and room temperature [3]. Then, the thermal residual strain of each component, $\varepsilon_{\mathrm{R}i}$, is given by the following equations:

$$\varepsilon_{\mathrm{R}i} = (\alpha_{\mathrm{c}}^{*} - \alpha_i)\Delta T \qquad (2)$$

Here, α_{c}^{*} is the composite apparent coefficient of thermal expansion determined later, and α_i is that of each component (i = Bi2223, Ag and Ag-Mg alloy). α_{Bi} = 15x10^{-6} and $\alpha_{\mathrm{Ag}} = \alpha_{\mathrm{Ag\text{-}Mg}}$ = 20x10^{-6} /K are used for calculation [3,17]. Then, the simple rule of mixture is applied to determine the stress-strain relation of each component. Here, the composite stress and Young's modulus are expressed by

$$\sigma_{\mathrm{c}} = \sum_i V_i \sigma_i , \qquad E_{\mathrm{c}} = \sum_i V_i E_i \qquad (3)$$

where σ_i, E_i and V_i are the stress, Young's modulus and volume fraction of each component. α_{c}^{*} is calculated by the following equation.

$$\sum_i V_i \sigma_{\mathrm{R}i} = 0 \qquad (4)$$

Here, $\sigma_{\mathrm{R}i}$ is the thermal residual stress of each component. Then, $\varepsilon_{\mathrm{R}i}$ is obtained using Eq.(2). Finally, the stress of each component is expressed as follows:

$$\sigma_i = E_i(\varepsilon_c + \varepsilon_{\mathrm{R}i}) \qquad \text{for elastic state}$$
$$\sigma_i = \sigma_{yki} + K_{ki}(\varepsilon_c + \varepsilon_{\mathrm{R}i} - \varepsilon_{yki}) \quad (k = 1 \text{ and } 2) \qquad \text{for plastic state} \qquad (5)$$

where ε_{c} is the composite strain. The fracture strain of Bi2223 filaments, $\varepsilon_{\mathrm{Biu}}$, is determined to meet the experimentally obtained stress-strain curve using Eqs. (3) and (5). The load carried by Bi2223 filaments after their fracture ($\varepsilon_{\mathrm{Bi}} > \varepsilon_{\mathrm{Biu}}$) is also determined to meet the experimentally obtained stress-strain curve where $\varepsilon_{\mathrm{Bi}}$ is the strain of Bi2223 filaments. Since Ag component yields in tension under as received condition, kinematic hardening is taken into account to determine the yield strength in compression.

The distribution of composite strain under bending deformation is determined using Bernouli-Navier hypothesis, $\varepsilon_{\mathrm{c}} = y/R$. Here, R is the radius of the tape and y is the distance from the neutral axis. The details of the analysis are presented in our separate paper [15]. Since the thermal residual stress and the yielding of Ag and Ag-Mg alloy components result in unsymmetrical stress-strain behavior against the origin, the neutral axis moves with the increase of the curvature of the composite tape.

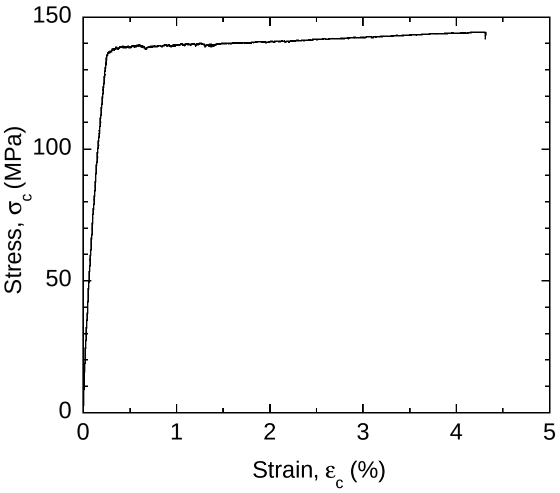

Fig. 3. Stress-strain curve of Bi2223/Ag/Ag-Mg composite tape.

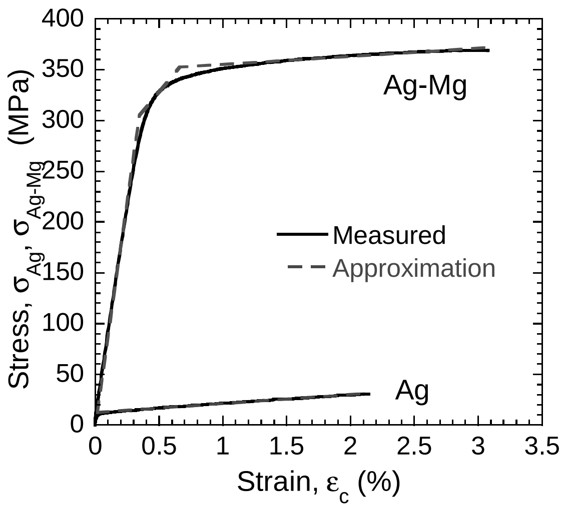

Fig. 4. Stress-strain curve of Ag and AG-Mg alloy, and their linear work hardening approximation for analysis.

When the specimen was cooled to 77 K in liquid nitrogen for the critical current measurement, the compressive thermal residual stress was added to the Bi2223 filament. Then, no further tensile fracture of Bi2223 filaments occurred during cooling. Thus, the fracture of Bi2223 filaments under the deformed state at room temperature was directly correlated to the decrease of the critical current, I_c, at 77 K. Thus, the critical current density, J_c, is determined as follows in the present analysis.

$$J_c/J_{c0} = 1 \qquad \varepsilon_{Bi} < \varepsilon_{Biu}$$
$$J_c/J_{c0} = 0 \qquad \varepsilon_{Bi} > \varepsilon_{Biu} \qquad (6)$$

where J_{c0} is the critical current density when the composite strain, $\varepsilon_c = 0$. Finally, the decrease of the critical current due to bending deformation is calculated from the estimated fraction of the broken filaments in the analysis.

3. RESULTS AND DISCUSSION

3.1 Tensile behavior

Figure 3 shows the experimental results of the stress-strain curve for the composite tape. The multiple fracture of Bi2223 filaments gives an almost horizontal curve where ε_c is larger than 0.27% [3-5], and the final fracture strain of the composite tape, ε_{cu}, is about 4.3%. The initial part is not straight owing to the yielding of Ag and Ag-Mg alloy sheaths discussed later in the next part.

Figure 4 shows the stress-strain curves for Ag and Ag-Mg alloy. The dashed lines in this figure are the approximation used in the analysis [15]. The yield strength (determined by the intersection of the initial elastic line and linear work hardening line) of Ag tape is extremely low at only 12 MPa, and that of Ag-Mg alloy tape ($\sigma_{y1Ag\text{-}Mg}$ = 305MPa) is about 30 times higher. The Young's modulus of Ag-Mg alloy tape, $E_{Ag\text{-}Mg}$, determined by the slope of the initial part of the stress-strain curve, is about 10% higher than that of Ag tape, E_{Ag}. These results agree well with the reported values by Goretta et al. [18]. They attributed this increase to the high Young's modulus of MgO of 311 GPa.

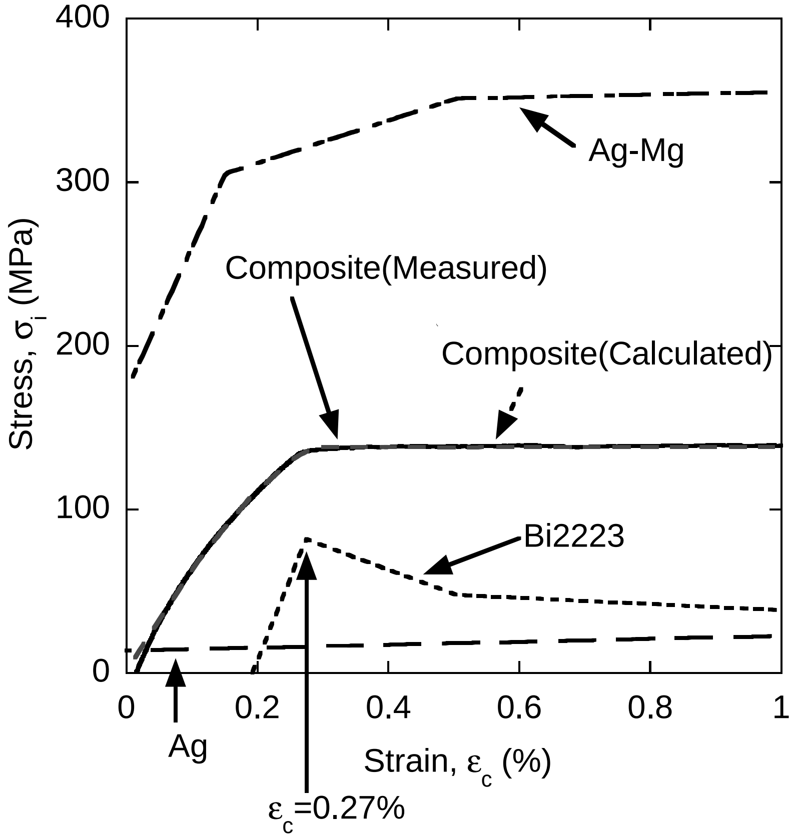

Fig. 5. Comparison between experimental and calculated stress-strain curves for composite tapes and each component.

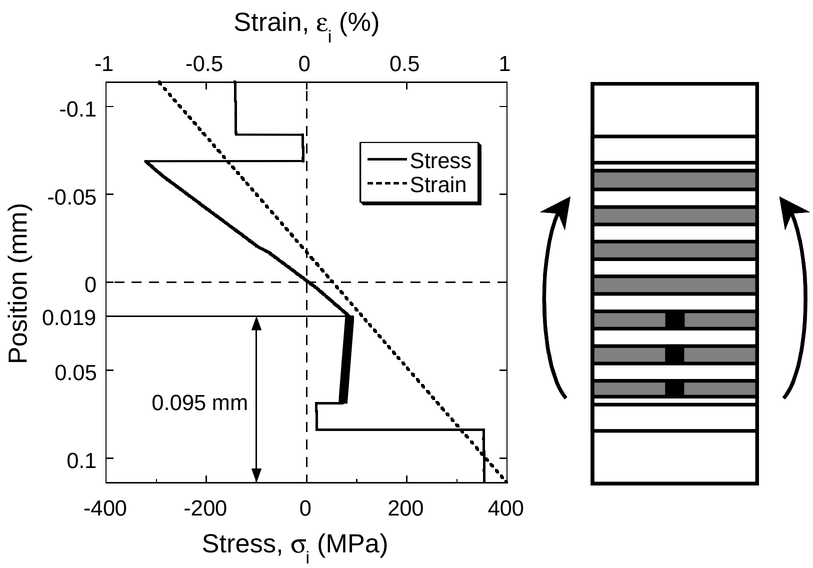

Fig. 6. Stress distribution under bending deformation and expected filament damage.
R=13.8 mm（1/R＝0.072 mm^{-1}）.

Figure 5 shows the stress-strain curves of composite tapes up to ε_c = 1% with those for each component. As mentioned before, the composite strain, ε_c, at the onset of Bi2223 filament fracture is 0.27%. Here, the thermal residual strain of filament, ε_{RBi}, is -0.19%, and the strain of Bi2223 filament at onset of fracture, $\varepsilon_{Biu} = \varepsilon_c + \varepsilon_{RBi}$, is finally determined as 0.08%. This value gives the strength of Bi2223 filaments, σ_{Biu}, as 80 MPa using E_{Bi} = 100 GPa. These values agree fairly well with the reported fracture strain of extracted Bi2223 filaments of around 0.1%, and the fracture strength of 70 to 100 MPa [6-8]. The estimated stress carried by Bi2223 filaments after the onset of filament fracture is also indicated in Fig. 5. The density of the multiple fracture first increases and then saturates.

3.2 Bending behavior and critical current analysis

Left-hand side of Fig. 6 indicates the calculated results of the stress and strain distribution where R = 13.8 mm (1/R = 0.072 mm^{-1}). Here, the indicated stresses are the averaged composite stresses in the width direction. The location of the filament fracture is indicated by thick solid line in the

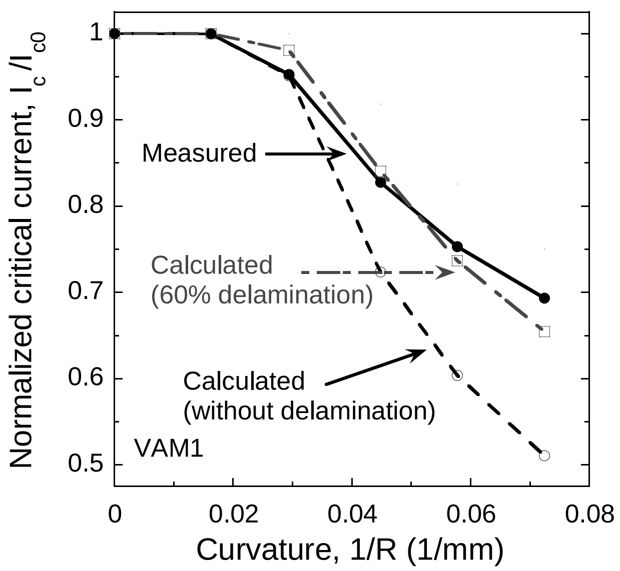

Fig. 7. Comparison between measured and calculated critical current under bending deformation.

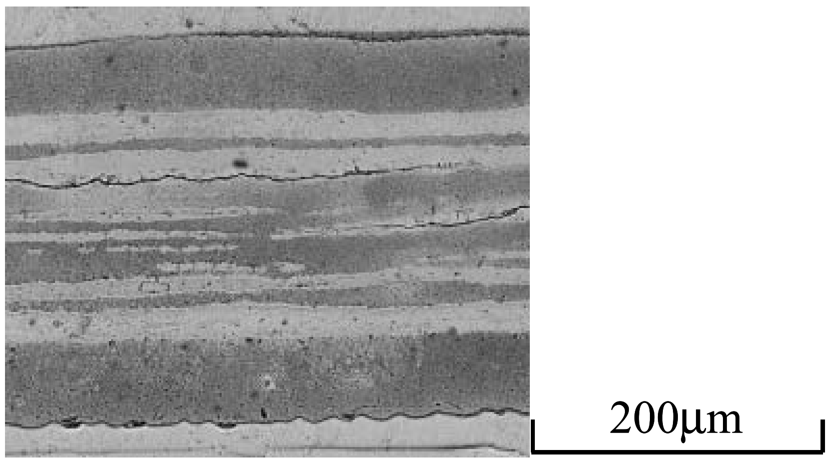

Fig. 8. Optical micrograph of damage at longitudinal section under bending deformation, R=17.3 mm.

stress distribution, and the corresponding damage is schematically shown in the right-hand side of the figure. The damage growth of the Bi2223 filaments from tensile side with the increase of the curvature is clearly shown. The movement of the neutral axis is also indicated in this figure.

Figure 7 shows the relation between the curvature of the composite tape, 1/R, and the normalized critical current, I_c/I_{c0}, for the composite tape. Solid circles indicate the experimental data of the critical current. The open circles in this figure correspond to the calculated results with the neutral axis movement. There is a certain discrepancy between the experimental and calculated results, and the calculated I_c/I_{c0} values are much lower than the experimental values.

3.3 Microscopic damage

Figure 8 shows a scanning electron micrograph of the longitudinal sections of the specimen after bending deformation. In our analysis, we assume transverse cracks as damage in Bi2223 component. However, clear delamination inside Bi2223 or Bi2223/Ag interface is indicated in this figure. Thus, the actual stress states are different from what we calculated in section 3.2. Moreover, delamination was also observed for as received specimens at mid section of the tapes.

Since the distribution of delamination is rather complicated, we recalculated the stress states of each component assuming that delamination exits at mid section of the tape throughout the width direction. The calculated I_c/I_{c0} values are higher than the measured values. Then, the measured values are between the calculated values with and without delamination. The dash-dotted line with open square marks in Fig. 6 indicates the calculated results when the delamination ratio is 60% in width direction. The agreement between these calculated results and the experimental results is fairly well. Thus, the necessity of the consideration of delamination is indicated for the detailed analysis of the stress state in superconducting composite tapes.

4. CONCLUSIONS

The mesoscopic stress distribution is first analyzed in tension for Bi2223/Ag/Ag-Mg composite superconducting tapes. Then, the results are applied for bending deformation. The results are summarized as follows:

(1) The analyzed tensile stress-strain curve of composites based on that of each component agrees well with the experiments. The resulting fracture strain of Bi2223 filaments is estimated as 0.08%.

(2) The analysis of bending deformation has been carried out and the decrease of the critical current is calculated from the Bi2223 filament damage. The calculated decrease of the critical current agrees fairly well with the experimental results when the movement of the neutral axis and the existence of delamination are taken into account in the analysis.

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References

1. **Osamura, K.,** ed., *Composite Superconductors*, Marcel Dekker (1994).
2. **Ochiai, S.,** ed., *Mechanical Properties of Metal Matrix Composites*, Marcel Dekker (1993).
3. **Ochiai, S., Hayashi, K.** and **Osamura, K.,** "Influence of thermal cycling on critical current of superconducting silver-sheathed high T_c oxide wires", *Cryogenics,* **31** (1991), 954-961.
4. **ten Haken, B., Godeke, A., Schuver, H.-J.** and **ten Kate, H.H.J.,** "Strain reduced critical current in Bi-2223/Ag superconductors under axial tension and compression", *Adv. Cryog. Eng.* **42** (1996), 651-658.
5. **Osamura, K.** and **Sugano, M.,** "Mechanical properties of powder-in-tube processed mono- and multi-filamentary Bi2223 tapes" *Physica* **C 357-360** (2001), 1128-1133.
6. **Passerini, R., Dhalle, M., Giannini, E., Witz, G., Seeber, B.** and **Flükiger, R.,** "The influence of thermal precompression on the mechanical behavior of Ag-sheathed (Bi,Pb)2223 tapes with different matrices", *Physica* **C 371** (2000), 173-184.
7. **Passerini, R., Dhalle, M., Seeber, B.** and **Flükiger, R.,** "Mechanical properties of Bi,Pb(2223) single filaments and $I_c(\varepsilon)$ behavior in longitudinally strained tapes", *Supercond. Sci. Technol.* **15** (2002), 1507-1511.
8. **Sugano, M., Osamura, K.** and **Hojo, M.,** "Mechanical properties of Bi2223 filaments extracted from multifilamentary tape evaluated by the single-fibre tensile test", *Supercond. Sci. Technol.* **16** (2003), 571-575.
9. **Kitaguchi, H.** and **Kumakura, H.,** "Advances in Bi-based high-T_c superconducting tapes and wires" *MRS Bull.* **26** (2001), 121-125.
10. **Arendt, R.H., Garbauskas, M.F., Meyer C.A., Rotella, F.J., Jorgensen, J.D.** and **Hitterman, R.L.,** "Thermal expansion measurements using neutron diffraction of $(Bi,Pb)_2Ca_2Sr_2Cu_3O_x$", *Physica* **C 194** (1992), 397-402.
11. **Savvides, N., Thorley, A.** and **Reilly, D.,** "Critical current and strain tolerance of Bi-2223/Ag multifilament tapes" *Adv. Cryogen. Eng.* **44** (1998), 569-576.
12. **Katagiri, K., Ishimori, I., Tsukinokizawa, T, Kasaba, K., Kuroda, T., Itoh, K.** and **Wada, W.,** "Tensile and bending strain characteristic of critical current in Ag/Bi-2223 superconducting tapes", *Proc. The International Workshop on Mechano-Electromagnetic Property of Composite Superconductors* , (2001), 5-6.
13. **van Eck, H.J.N., Vargas, .L, ten Haken, B.** and **ten Kate, H.H.J.,** "Bending and axial strain dependence of the critical current in superconducting BSCCO tapes", *Supercnd. Sci. Technol.* **15** (2002), 1213-1215.
14. **Hojo, M., Matsuoka, T., Nakaoka, S., Tanaka, M., Ochiai, S., Sugano, M.** and **Osamura, K.,** "Bending deformation and its influence on critical current in Bi2223 composite superconducting tapes", *Physica* **C**, **392-396** (2003), 1156-1161.
15 **Hojo, M., Nakamura, M., Matsuoka, T., Tanaka, M., Ochiai, S., Sugano, M.** and **Osamura, K.,** "Microscopic fracture of filaments and its relation to the critical current under bending deformation in $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$ composite superconducting tapes", *Supercond. Sci. Technol.*, **16** (2003), 1043-1051.
16. **Sugano, M., Osamura, K.** and **Nyilas, A.,** "Estimation of the coefficient of thermal expansion of Bi2223 at low temperature", *Supercond. Sci. Technol.*, **16** (2003), 1064-1070.
17. **Sugano M.,** "Mechano-electromagnetic property of Bi2223 superconducting composite tapes" *Doctor Thesis*, Dept. Materials Science, Kyoto University, Japan (2003).
18. **Goretta, K. C., Routbort, J. L., Thayer, R. L., Carroll, J. P., Wolfenstine, J., Kessler, J.** and **Schwartz, J.,** "Deformation of Ag/1.2at.% Mg", *Physica* **C 265** (1996), 201-206.