Transverse compressive stress effects on the critical current of Bi-2223/Ag tapes reinforced with pure Ag and oxide-dispersion-strengthened Ag

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We have measured the effect of transverse compressive stress on the critical current of two similar sets of $Bi_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) tapes in a direct comparison between tapes reinforced with pure Ag and oxide-dispersion-strengthened (ODS) Ag. The critical-current degradation at a transverse stress of 100 MPa was about 10% for the Bi-2223/pure Ag tapes and only about 3% for the ODS Ag tapes. In one case for each sample type the degradation was significantly greater, and there was an apparent correlation with porosity in the superconductor filaments. The degradation was the same for critical-current criteria from 5 μV/cm down to 0.1 μV/cm. © *2000 American Institute of Physics.* [S0021-8979(00)01514-0]

Considerable progress has been made in transforming BiSrCaCuO compounds into viable commercial conductors.[1–4] Fundamental elements of this maturation are steady increases in conductor length and critical-current density. The near realization of commercial applications, though, brings with it new challenges. The conductors must tolerate mechanical stresses associated with fabrication, differential thermal expansion, and Lorentz forces. In superconductor magnet applications, the dominant stress arises from the Lorentz force, which can be resolved into its two main components of axial tensile stress and transverse compressive stress acting on individual conductor strands. It is not uncommon in large magnets for transverse stress to exceed 100 MPa. In many high-magnetic-field applications, operating limits will likely be dictated by the conductors' electromechanical properties rather than their critical current, temperature, or magnetic field. In this study we concentrate on the effect of transverse stress, for which there are fewer data available, as well as extending these measurements to more sensitive criteria, which is important for magnet design.

The effects of transverse compressive stress on critical current (I_c) were measured and compared for two sets of different types of $Bi_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) conductors. The conductors were prepared using the oxide-powder-in-tube process.[5] The conductor characteristics are given in Table I. The first conductor in the table has a pure Ag matrix, and the remaining two have an oxide-dispersion-strengthened-Ag[6] (ODS Ag) sheath. All three conductors have engineering critical-current densities ($J_e \equiv I_c$ divided by total conductor area) over 11 kA/cm^2 and superconductor critical-current densities ($J_c \equiv I_c$ divided by the superconductor area) over 34 kA/cm^2. The study focused on a comparison of the first two conductors in the table. The third conductor, the small cross-section ODS, was included to allow testing at higher stress levels without exceeding the load limit of our measurement apparatus.

Details of the measurement apparatus have been reported previously.[7] The stress-application portion of the apparatus uses a double-gimbaled pressure foot to ensure uniform stress application over the tape's surface. Also, the apparatus uses a flexible high-current lead[8] at one end of the test specimen to avoid axial stress that might otherwise arise from differential thermal expansion between the test fixture and specimen.

Figure 1 shows the response of the pure Ag and the ODS Ag conductors to transverse stress in self field at 76 K. The data are averages for several specimens of each conductor type, three specimens for the pure Ag and four specimens for the ODS Ag. Degradation of J_e at 100 MPa is approximately 10% for the pure Ag conductor, and 3% for the ODS Ag. These results are consistent with the dependence of critical current on tensile stress in these conductors,[9] which has been attributed to the increased yield stress of strengthened Ag versus pure Ag.[10] None of the specimens exhibited significant J_e recovery when the applied transverse stress was removed. That is, the degradation was irreversible. The initial,

TABLE I. Characteristics of Bi-2223 conductors.

	Pure Ag	ODS	Small cross-section ODS
Filaments	85	85	85
I_c(76 K, self field)	100.2 A	86.6 A	54.5 A
J_c(76 K, self field)[a]	34.1 kA/cm[b]	36.1 kA/cm[b]	35.5 kA/cm[b]
J_e(76 K, self field)[b]	11.6 kA/cm[b]	11.2 kA/cm[b]	11.0 kA/cm[b]
Tape width	3.91 mm	3.86 mm	2.7 mm
Tape thickness	0.22 mm	0.20 mm	0.178 mm
Superconductor content	34%	31%	31%

[a]$J_c \equiv I_c$ divided by superconductor area.
[b]$J_e \equiv I_c$ divided by total conductor area.

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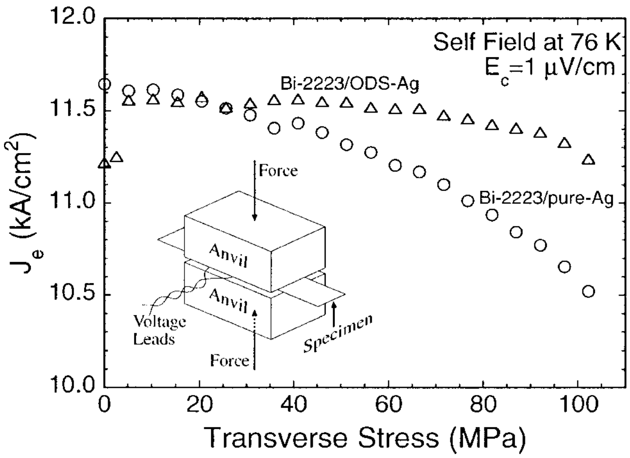

FIG. 1. Effect of transverse stress on the J_e of Bi-2223/pure Ag and Bi-2223/ODS Ag tapes. Pure Ag data are averaged over three specimens, and ODS Ag data are averaged over four specimens. Inset shows method for applying stress to test specimen.

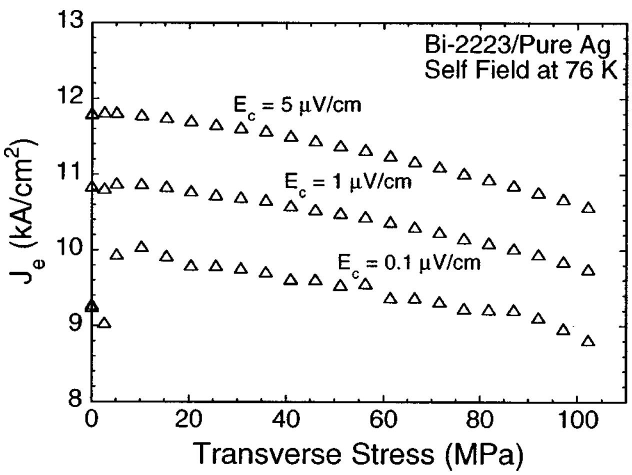

FIG. 2. Effect of transverse stress on the J_e of a selected Bi-2223/pure Ag specimen showing that the relative degradation is independent of the criterion.

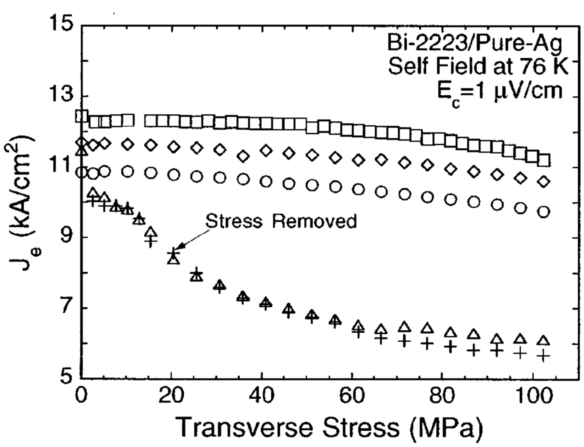

FIG. 3. Effect of transverse stress on the J_e of four Bi-2223/pure Ag specimens. One of the four specimens degraded abruptly with stress. The + symbols represent the critical current on unloading and show that the effect was irreversible.

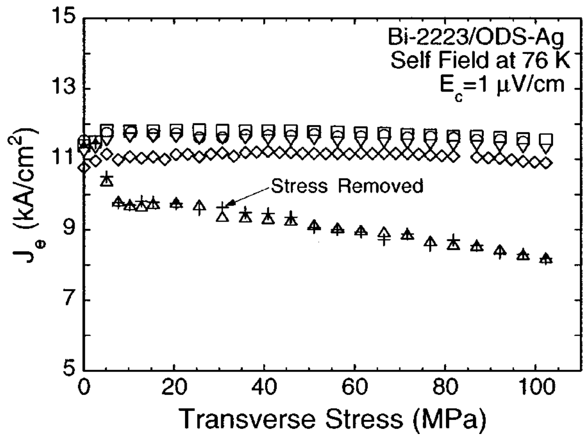

FIG. 4. Effect of transverse stress on the J_e of five Bi-2223/ODS Ag specimens. One of the five specimens degraded abruptly with stress. The + symbols show that the effect was also irreversible when the stress is removed.

small, anomalous rise in J_e with stress for the ODS Ag conductors was observed in all four for these test specimens. The overall uncertainty is approximately 0.5% for the critical-current measurements and 1% of the stress measurements.

An electric-field criterion (E_c) of 1 μV/cm was used to determine the J_e values shown in Fig. 1. A lower E_c criterion, 0.1 μV/cm for example, would be preferred but was not practical for most of these measurements. The test apparatus allows a spacing between the voltage sensing leads of only 6 mm, which results in a low signal-to-noise ratio at a low E_c criterion. However, in several cases where the noise was acceptably low, the data were analyzed at $E_c = 0.1$ μV/cm, and the level of J_e degradation was found to be unaffected. Figure 2 shows this lack of criterion dependence for a pure Ag specimen where the noise was unusually low. This is particularly significant for magnet design, which is usually carried out at these more sensitive criteria.

Figure 1 suggests that these conductors are quite tolerant of transverse stress, particularly the ODS Ag conductor. However, one specimen of each conductor type (not included in the averages of Fig. 1) had poor stress tolerance. Figure 3 shows the data for the stress-sensitive pure Ag conductor, along with a deconstruction of the pure Ag average data. Figure 4 shows similar data for the ODS Ag conductors. In both cases, the stress-sensitive specimen has an initial J_e comparable to the other specimens but then degrades

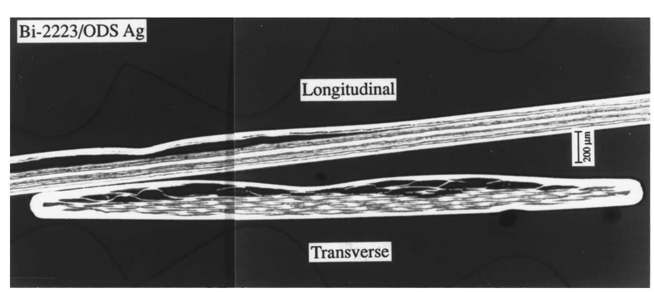

FIG. 5. Micrograph of the high-degradation specimen of Bi-2223/ODS Ag showing surface bubble from transverse and longitudinal views.

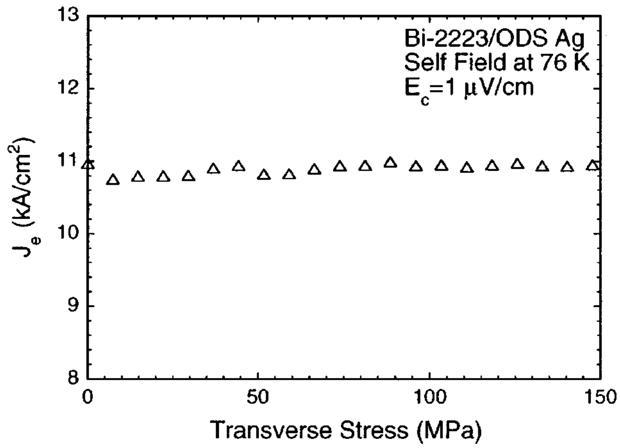

FIG. 6. Effect of transverse stress on the J_e of small cross-section ODS specimen.

abruptly with transverse stress. The unloaded data show that the effect is irreversible when stress is removed.

Visual inspection of the specimens, after testing, suggested that a source of stress sensitivity in these isolated cases may be internal superconductor porosity. The stress-sensitive ODS Ag specimen had a bubble on one of its surfaces, which was observed only after it was warmed to room temperature. A cross-sectional micrograph of the bubble is shown in Fig. 5. None of the stress-tolerant specimens showed any sign of bubbles. The bubble is a sign of porosity within the superconductor filaments. In the generally accepted model, liquid nitrogen seeps through the ends of the specimen into the porous regions during testing. When the specimen is warmed, the trapped nitrogen expands and forms the bubble. The bubble is not the source of the stress sensitivity and was not present in the sample initially; it is just an indicator of porosity, which may be the actual source of stress sensitivity. It has been reported for some time that the presence of porosity correlates with I_c degradation. However for these measurements, the initial I_c's of the stress-sensitive samples, prior to stress application, were comparable to the I_c's of the stress tolerant samples. The present data give strong evidence that porosity can result in high stress sensitivity, even in samples that have high initial J_c.

The third conductor listed in Table I, the small cross-section ODS, was also tested to look at the effects at higher transverse stress levels. Only one specimen of this conductor was tested, but as shown in Fig. 6, the degradation was negligible at a transverse stress of almost 150 MPa.

Overall, these results are very encouraging. Although two of the specimens showed low stress tolerance, the majority had very good performance under transverse stress, particularly the ODS Ag conductor. This demonstrates that Bi-2223 tapes are not intrinsically sensitive to transverse stress at engineering design stresses of ~100 MPa, a promising result for magnet applications.

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