Effect of axial strain on the critical current of Ag-sheathed Bi-based superconductors in magnetic fields up to 25 T

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The irreversible strain limit ϵ_{irrev} for the onset of permanent axial strain damage to Ag-sheathed $Bi_2Sr_2Ca_1Cu_2O_{8+x}$ and $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ superconductors has been measured to be in the range of 0.2%–0.35%. This strain damage onset is about an order of magnitude higher than for *bulk sintered* Y-, Bi-, or Tl-based superconductors and is approaching practical values for magnet design. The measurements show that the value of ϵ_{irrev} is not dependent on magnetic field, nor does the critical current depend on strain below ϵ_{irrev} at least up to 25 T at 4.2 K. Both of these factors indicate that the observed strain effect in Ag-sheathed Bi-based superconductors is not intrinsic to the superconductor material. Rather, the effect is extrinsic and arises from superconductor fracture. Thus, the damage onset is amenable to further enhancement. Indeed, the data suggest that subdividing the superconductor into fine filaments or adding Ag to the superconductor powder prior to processing significantly enhances the damage threshold ϵ_{irrev} to above 0.6%.

Superconductor magnet applications subject the conductor winding to hoop strain typically on the order of 0.2%. For a safety factor of 2, the superconductor must therefore have a minimum axial strain tolerance of about 0.4% strain. Bulk sintered $YBa_2Cu_3O_7$ superconductors, unfortunately, fracture at a strain of only ~0.05%.[1] Strain tolerance about an order of magnitude greater than this is needed for high T_c superconductors to be used in practical magnet applications.

Here we present critical-current measurements of the effect of *uniaxial*-strain applied along the conductor axis of Ag-sheathed, $Bi_2Sr_2Ca_1Cu_2O_{8+x}$ [Bi(2212)] and $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ [Bi(2223)] high T_c superconductors, both textured and untextured. These results[2] show the irreversible strain limit ϵ_{irrev} for the onset of permanent critical-current degradation is about an order of magnitude greater than that of bulk-sintered superconductors.[1] Furthermore, we observe no intrinsic elastic strain effect in Bi(2212) or Bi(2223) at 4.2 K, as evidenced by the lack of any measurable change in critical current density J_c with strain below ϵ_{irrev} at magnetic fields up to 25 T. The data also indicate that further improvement in ϵ_{irrev} can be obtained by subdividing the superconductor material into fine filaments and by adding Ag to the superconductor powder prior to processing.

Results for three samples fabricated by different techniques are presented, representing both Bi(2212) and Bi(2223) crystal structures. Sample fabrication information is given in Table I. The first sample was a monocore Bi(2212) wire made by melt processing.[3,4] This sample was a high-J_c sample, but not necessarily optimized for strain tolerance and had in the core about a 30% void, which could well be a significant source of crack initiation sites. The second sample was a 19 filament Bi(2223) sample,[5] which we tested to see the effect of subdividing the superconductor into filaments, as well as whether there were any significant electromechanical differences between the Bi(2212) and Bi(2223) compounds. The third sample was a Bi(2223) conductor having a dispersion of Ag in the superconducting matrix.[6] The Ag particles were roughly equiaxed and about 5 μm in diameter; the Bi(2223) had the usual platelike structure, but the texturing was not nearly as high as that reported by Sato *et al.*[7] or Tagano *et al.*[8]

The apparatus for determining the effect of uniaxial strain up to 25 T was described earlier.[9] The critical current was measured with an accuracy of about ±2% and critical current density J_c was calculated based on the area of superconductor (not including the Ag sheath). The magnetic field was oriented perpendicular to the conductor axis (along which current and strain were applied) and in the plane of the tape samples.

The *offset criterion*[10] was used to determine the critical-current density J_c using a criterion value of either 1 or 1.5 μV/mm (the difference in the J_c for the two criteria values is negligible using the offset method). The offset criterion is essential for the Ag-sheathed Bi conductors because of high normal-current conduction through the Ag sheath and the linear V-I curve generated at strain-induced weak

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TABLE I. Ag-sheathed Bi-based high T_c samples.

Sample	1	2	3
Superconductor	$Bi_2Sr_2Ca_1Cu_2O_{8+x}$ (untextured)	$Bi_{1.8}Pb_{0.3}Sr_{1.9}Ca_{2.0}Cu_{3.1}O_{10+x}$ (textured)	$Bi_2Sr_2Ca_2Cu_3O_{10+x}$ (partially textured)
Type	Monocore wire	19 filament	20 vol % Ag monocore
Final cross section	Wire: 1.0 mm diam	Tape: 0.19×2.7 mm	Tape: 0.2×2.8 mm
Process	Powder-in-tube	Multifilament oxide powder in tube	Powder-in-tube 1 μm Ag powder mixed with Bi(2223) powder
Reduction ratio	Drawn 8 mm diam to 1 mm diam	Multifilament bundle drawn 40:1 area reduction, Rolled to tape	Swaged and drawn 6.25 mm diam to 1.1 mm diam Rolled to tape
Superconductor area fraction	~50%	18%	28%
Heat treatment	Partially melted at >800 °C plus 100 h anneal at lower temperature	150 h at 805–830 °C in 7.5% O_2/92.5% Ar with intermediate press	80 h at 830 °C in 10:1 mixture of N_2-O_2, pressed twice at 1 GPa, then 80 h at 830 °C in same gas mixture
Reference(s)	3,4	5	6

links. In such case, the *V-I* characteristic acquires a low-sloped linear rise. The offset criterion is a simple procedure that corrects for this normal (ohmic) conduction by taking the *tangent* to the *V-I* characteristic at E_c and extrapolating to $V=0$. The offset criterion is not very sensitive to the choice of criterion E_c since in the ohmic limit, it is completely independent of where the point of tangency is taken.

The magnetic field was cycled several times to stabilize the pattern of trapped flux in the samples prior to starting the J_c experiment (to eliminate changes in J_c arising from changing trapped-flux patterns). At each strain, J_c was then measured for monotonically increasing magnetic field.

The results for J_c as a function of magnetic field B and axial strain ϵ are given for the powder-in-tube Bi(2212) superconductor at 4.2 K in Fig. 1. As seen in Fig. 1, a precipitous drop in the transport J_c occurs at about 0.2%. This strain limit is associated with the irreversible strain limit ϵ_{irrev}.[11] As shown below, it is the primary parameter

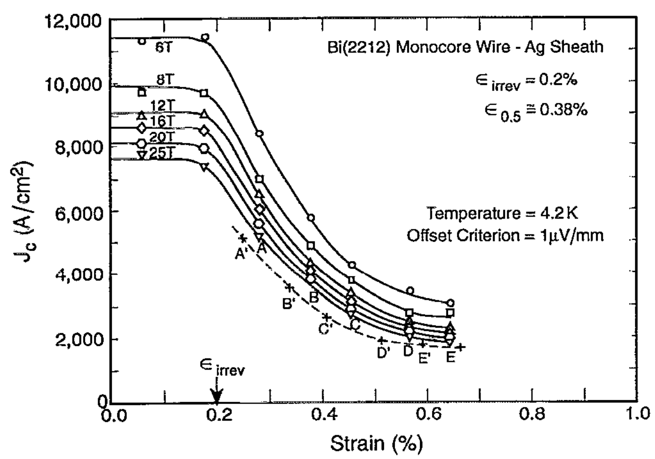

FIG. 1. Axial strain dependence of J_c up to 25 T for sample 1—a melt-processed, Ag sheathed $Bi_2Sr_2Ca_1Cu_2O_{8+x}$ superconductor, showing an irreversible strain limit ϵ_{irrev} of 0.2%. Unprimed and primed letters show corresponding loaded and unloaded data points, respectively, used to determine the irreversible strain limit (see Ref. 12).

for characterizing the electromechanical properties of the Ag-sheathed Bi superconductors, at least at 4 K.

The mechanical data for this melt-processed monocore sample represent a worst-case because of the large void volume in the core that can act as a source of crack initiation sites. Even so, the increased strain tolerance over *bulk-sintered* materials is impressive; ϵ_{irrev} is more than 4 times greater.[1] Beyond ϵ_{irrev}, J_c falls to half its original value at about 0.38% strain ($\epsilon_{0.5}$), which is more than 7 times the comparable strain limit in typical bulk-sintered samples.

For these materials, there is no change in J_c for strain less than ϵ_{irrev}, even at 25 T. This suggests that the J_c degradation arises from superconductor fracture, rather than an intrinsic uniaxial-strain degradation of the superconductor energy gap, as with the A-15 and Chevrel superconductors.[13] (This does not rule out any intrinsic strain effect, however, since these results were obtained well away from the critical temperature and upper critical field of these Bi-based superconductors.) Furthermore, as seen in Fig. 1, there is no magnetic-field dependence to ϵ_{irrev}.

A microscopic examination of the Ag/Bi(2212) interface in the powder-in-tube conductor is shown in Fig. 2 after the conductor had been strained over 1% at 4.2 K. The micrograph indicates that the Ag/Bi(2212) interface is intact, with no obvious shearing or delamination. There is, however, a series of transverse cracks distributed along the length of the Bi(2212) core, as seen in Fig. 2.

Figure 3 shows the J_c-ϵ characteristic for the 19-filament $Bi_{1.8}Pb_{0.3}Sr_{1.9}Ca_{2.0}Cu_{3.1}O_{10+x}$ conductor. The irreversible strain limit ϵ_{irrev} is about 0.32%, more than 6 times that of bulk-sintered $YBa_2Cu_3O_7$. Again there is no field dependence to ϵ_{irrev} and no elastic strain effect is observed below ϵ_{irrev}, even at magnetic fields up to 20 T. The only effect is the irreversibility of the J_c-ϵ curve above ϵ_{irrev}, which results from superconducting fracture. Thus, the primary parameter characterizing the electromechanical properties of these high T_c conductors at low temperature is simply the irreversible strain ϵ_{irrev}.

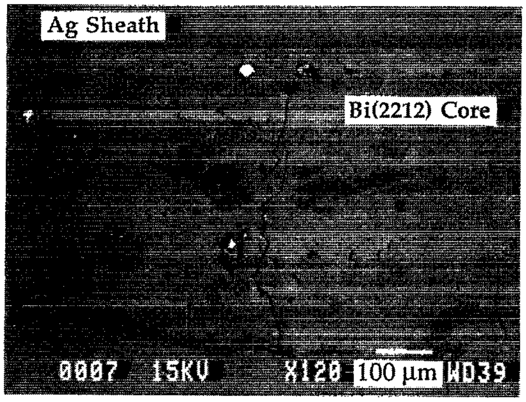

FIG. 2. Micrograph of sample 1, showing a series of cracks transverse to the $Bi_2Sr_2Ca_1Cu_2O_{8+x}$ core after the conductor had been strained 1% at 4.2 K.

The extrinsic nature of the effect is fortunate since it affords the possibility of improving ϵ_{irrev} through different processing. Indeed, one method for enhancing the mechanical properties is to subdivide the superconducting material into fine filaments and embed them in a ductile matrix to fill crack initiation sites at the surface of the filament. This is a technique that has worked well in the past for enhancing ϵ_{irrev} in the brittle, low T_c superconductors.[12] Some evidence for this is seen in the enhanced ϵ_{irrev} value for the multifilamentary sample 2. Another potential method is to coprocess the Bi powder compound with Ag powder to provide a ductile matrix within the superconductor core. The Ag matrix serves as a crack arrester and provides a region of plastic flow to relieve some of the stress.[6]

Figure 4 shows the improved mechanical results for an experimental conductor employing the second technique. Although J_c is not particularly high, the results for the *monocore* conductor, given in Fig. 4, show that ϵ_{irrev} can be

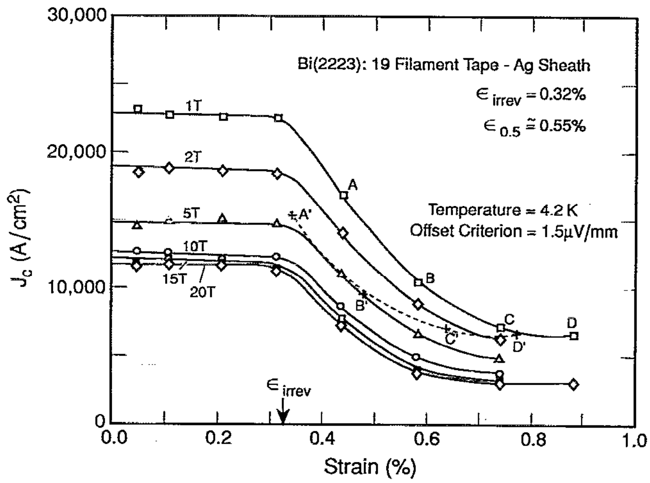

FIG. 3. Axial strain dependence of J_c for sample 2—a 19-filament, Ag-sheathed $Bi_{1.8}Pb_{0.3}Sr_{1.9}Ca_{2.0}Cu_{3.1}O_{10+x}$ superconductor, showing a field-independent ϵ_{irrev} of 0.32%. Data points plotted with a + symbol (labeled by primed letters) denote J_c determined after unloading from the data point labeled by the corresponding unprimed letter. Magnetic field was parallel to the tape surface.

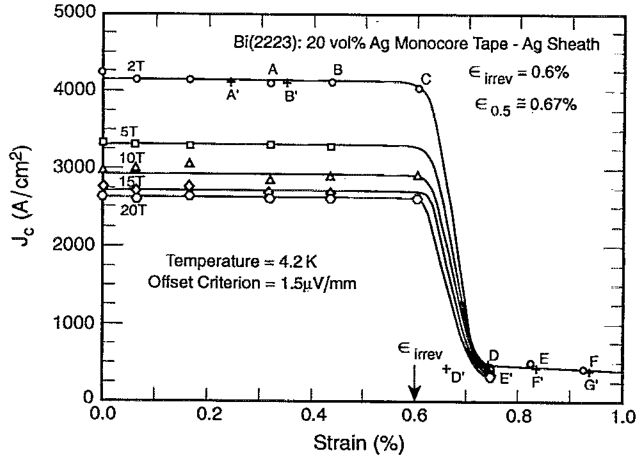

FIG. 4. Axial strain dependence of J_c for sample 3—an experimental monocore $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ conductor with a 20 vol % Ag dispersion in the Bi core; ϵ_{irrev} was 0.6%, independent of magnetic field. Data points plotted with a + symbol (labeled by primed letters) denote J_c determined after unloading from the data point labeled by the corresponding unprimed letter. Magnetic field was parallel to the tape surface.

increased to about 0.6% by adding 20 vol % Ag to the powder core, even without subdividing the superconductor material into fine filaments. The results in Figs. 3 and 4 at least indicate the potential of using these two techniques for significantly enhancing ϵ_{irrev} in high T_c superconductors.

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