MECHANICAL PROPERTIES OF HIGH–TEMPERATURE SUPERCONDUCTING WIRES

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ABSTRACT

Bending strength, fracture toughness, and elastic modulus data were acquired for $YBa_2Cu_3O_x$, $Bi_2Sr_2CaCu_2O_x$, $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$, and $Tl_2Ba_2Ca_2Cu_3O_x$ bars. These data and thermal expansion coefficients strongly suggest that the maximum possible tensile strain without fracture of bulk tapes or wires is ≈0.2%. In Ag–clad conductors, residual stresses will be of limited benefit, but fractures produced by larger strains can be accommodated by shunting current through the Ag.

INTRODUCTION

Large–scale application of high–temperature superconductors requires high critical current (I_c) and critical current density (J_c). In addition, the superconductors must also exhibit mechanical reliability and chemical and cryogenic stability.[1] In this paper, mechanical property data are summarized for Ag, $YBa_2Cu_3O_x$ (Y-123), $Bi_2Sr_2CaCu_2O_x$ (Bi-2212), $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (Bi-2223), and $TlBa_2Ca_2Cu_3O_x$ (Tl-2223) and implications on wire performance are assessed.

EXPERIMENTAL METHODS

The Ag was 99.9% pure and was purchased as 6.35-mm-diameter rods.[2] The Y-123 powder was synthesized by solid-state reaction at reduced O_2 pressure,[3] and bulk bars were fabricated by cold-pressing and sintering in O_2; in some cases, Ag particles were added.[4,5] The Bi-2212 powder was $Bi_2Sr_{1.7}CaCu_2O_x$ that was consolidated into dense, highly textured forms by sinter forging.[6,7] The Bi-2223 was $Bi_{1.8}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ that also was consolidated by sinter forging.[7-9]

The Tl-2223 powder was prepared as $Tl_2Ba_2Ca_2Cu_3O_x$ from reagent-grade oxides and carbonates. Pellets were cold-pressed and then heated in O_2 at a rate of 1°C/min to 895°C and held for 10 h. The furnace was cooled at 1°C/min to 650°C, held for 5 h, and then turned off, and the pellets were cooled to room temperature. X-ray diffraction revealed that the pellets were highly phase pure.[10]

Geometric densities and microstructures were obtained for all specimens. Elastic-modulus (E) data were obtained from the literature[11-14] or measured by ultrasonic methods.[6]

Strength tests were conducted on bars approximately 3 x 3 x 25 mm. The bars were tested in four-point flexure at a loading rate of 1.27 mm/min. Fracture toughness (K) values were determined by the single-edge notched beam method.[15] The test bars were similar to the bars used for strength testing and were loaded in three-point bending at a rate of 1.27 mm/min. K was calculated from the equation

$$K = 3\,P\,L\,Y\,(C)^{0.5}/B\,W^2\,, \qquad (1)$$

where P is the load at fracture, L is the support span (14–19 mm for these tests), Y is a constant related to specimen geometry,[15] C is the notch depth, B is the specimen width, and W is the specimen height.

RESULTS AND DISCUSSION

Data for E, strength (σ), and K are shown in Table 1. The values quoted were taken from materials of high phase purity and density (ρ). The Tl-1223 data are new and were obtained from specimens that were ≈ 88% dense. By available mathematical approximations, these values can be related to those of more dense materials.[16,17]

The data set for Y-123 was taken from dense, nearly randomly oriented polycrystals. The Bi-based specimens, except the Bi-2223 specimen used to determine E, were highly textured. The Tl-2223 exhibited little texture, but also was less dense than the other specimens. Photomicrographs of representative microstructures, obtained by either optical microscopy or scanning electron microscopy (SEM), are shown in Fig. 1. Of all of the specimens, only the Bi-2223 used for σ and E testing exhibited appreciable phase impurity: ≈10% total of Bi-2212 and alkaline-earth cuprates were present.[9]

The Vickers hardness of the Tl-2223 was 2.9 GPa, which is closer to that of Y-123 than of the Bi-based materials.[6,20] Based on the similarity of microstructure, hardness, and modulus, it appears that the mechanical properties of the Tl-based superconductors will be close to those of Y-123.

Table 1. Summary of mechanical-property data and approximate specimen densities for Ag, Y-123, Bi-2212, Bi-2223, and Tl-2223.

Material	ρ (g/cm^3)	E (GPa)	σ (MPa)	K (MPa$\sqrt{m}$)	References
Ag	10.6	77	200*	—	18
Y-123	6.3	148	230	1.5–2.0	4,12,19
Bi-2212	6.5	118, 44**	150	3.0	9,14
Bi-2223	6.4	82	150	3.0	9,11
Tl-2223	6.0	101	—	1.2	This work

* Value for average yield stress.
** Values are for highly textured specimens and represent the a-b plane and c-axis direction.

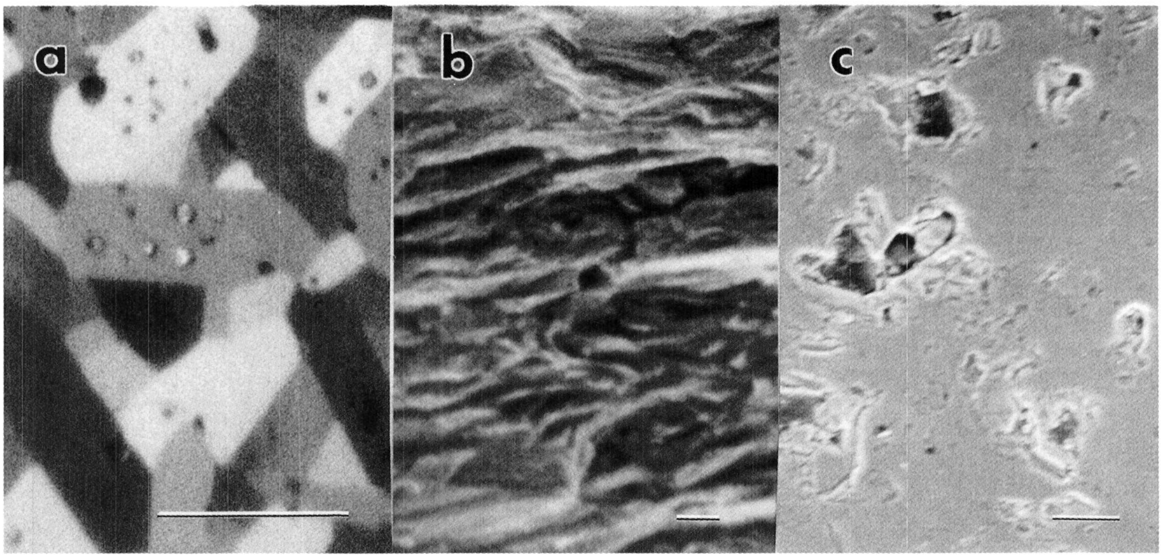

Figure 1. Representative microstructures: (a) optical image of Y-123, (b) SEM image of Bi-2212 fracture surface, and (c) SEM image of Tl-2223; bars = 10 μm.

Although further improvements in strength and fracture toughness can be expected, possibly through creation of composite structures,[21] the values in Table 1 are likely to be close to those of commercial bulk superconductors. These properties define the limits of flexibility of wires and tapes. For any wire or tape of thickness 2t, the bending radius R is defined as[22]

$$\sigma = (t/R)E \quad (2)$$

For a typical strength of ≈200 MPa and a typical modulus of ≈120 GPa, the strain to failure is < 0.2%, but, for sufficiently thin conductors, the allowable bending radius can be quite small.

The presence of an Ag sheath or of Ag in the core substantially complicates predictions of overall strength and flexibility. The thermal expansion coefficient of Ag is higher than the average value for any of the high-temperature superconductors.[18,23-26] Therefore, a favorable residual stress state would be expected in a superconductor/Ag composite. In fact, increases in strength of ≈10% have been observed for Y-123/Ag particulate composites.[5,27] Ag is also less stiff than the superconductors, and thus particulate composites can have lower elastic moduli than the corresponding monolithic material.[28] However, the effect on modulus for a 15% Ag core was only ≈15%. Thus, even with higher strength and lower stiffness, the flexibility of a superconductor/Ag composite is likely to improve by no more than ≈25%. The limit on strain would still be ≈0.2%.

For powder-in-tube tapes, several investigators report strains reaching at least ≈0.5% before J_c is significantly degraded.[29-33] A possible explanation for the high strain tolerance is that favorable residual stresses are imparted by the Ag sheath. Recent neutron-diffraction measurements of residual strains in Ag-clad Bi-2223 tapes cast serious doubt on that possibility. It was found that for highly textured tapes the directions in the Bi-2223 near the c-axis were indeed in a compressive stress state, but the a-b plane was in residual tension.[34] Fracture will occur perpendicular to the a-b plane; thus residual stresses induced by the Ag sheath are deleterious.

A more likely explanation for the apparent strain tolerance of Ag-clad conductors is that current can shunt through the Ag where cracks are present and reenter the superconductor once it is past the crack. A mathematical model of this effect was published recently.[35] The model indicated that, if the resistivity of the superconductor/Ag interface is sufficiently low relative to that of Ag, nearly all of the current will return to the superconductor from the Ag. The resistivity of pure Ag at 77 K is ≈0.3 μΩ-cm;[36] thus, it is quite reasonable that the current will return to the superconductor. Generation of 1 μV of voltage may thus require several transverse cracks.

SUMMARY

The basic mechanical properties of all high–temperature superconductors are similar. Bi-2212 and B-2223 are slightly softer than the others, and the Bi-based conductors are much more easily textured. The maximum strain that these ceramics can sustain is ≈0.2%. Ag particles can improve strain tolerance by ≈25% at most, but Ag sheaths may impart unfavorable residual stresses. The apparent strain tolerance of Ag-clad wires is probably due to current shunting through the Ag sheath at cracks.

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