PRACTICAL SUPERCONDUCTOR DEVELOPMENT
FOR ELECTRICAL POWER APPLICATIONS

ARGONNE NATIONAL LABORATORY

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This is a multiyear experimental research program focused on improving relevant material properties of high- T_c superconductors and on development of fabrication methods that can be transferred to industry for production of commercial conductors. The development of teaming relationships through agreements with industrial partners is a key element of this program.

Technical Highlights

Recent work on strain tolerance of Bi-2223 tapes, AC downlink construction, fundamental studies of flux pinning, and application of coils from powder-in-tube tapes to particle detectors is discussed.

Stress/Strain Performance of Sheathed Bi-2223 Superconductors

Studies have shown that Ag sheaths help to improve grain alignment, promote liquid-phase formation that enhances Bi-2223 formation kinetics, and increase core density. In an attempt to find a suitable, stronger sheathing material, one should also ensure that these advantages are still offered by the alternative sheath. In this project, Consil- (a commercial alloy that contains 0.25 wt.% Mg and 0.25 wt.% Ni) and Ag-sheathed powder-in-tube tapes were processed in parallel. The superconductor, with nominal composition of $\text{Bi}_{1.8}\text{Pb}_{0.4}\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_x$, was prepared by ANL's two-powder method. After swaging, drawing, and rolling, the tapes were sintered in 8% O_2 /balance N_2 at 815°C , with an intermediate pressing (2 GPa for 5 s) after the first 50 h of sintering. The Ag-sheathed tapes were sintered for 150 h. Because the Consil-sheathed tapes did not attain good phase purity after 150 h, they were sintered for an additional 100 h.

Strength and ductility of the tapes were measured in tension at room temperature (RT) and at 77 K (in liquid N_2). Critical current (I_c) was measured by the standard four-probe technique against a $1\text{-}\mu\text{V}/\text{cm}$ criterion. Strain tolerance in tension was measured in situ by mounting the tapes between fixtures on an Instron machine with a liquid N_2 reservoir mounted on top of the moving crosshead. Critical current measurements were obtained by temporarily stopping the crosshead at regular strain intervals. Microstructures were examined by standard methods.

The critical current of the Ag-sheathed tapes was higher than that of the Consil-sheathed tapes (Fig. 1) because conversion to the Bi-2223 phase was incomplete in the Consil-sheathed tapes.

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Fig. 1. Critical current as a function of time for Ag- and Consil-sheathed tapes.

SEM photomicrographs confirmed the poor phase purity and texture of the Consil-sheathed tapes (Fig. 2). The Ag-sheathed tapes contained long, aligned Bi-2223 grains. Individual Bi-2223 grains in the Consil-sheathed tapes were less textured, and more second phase was evident. Reactions between the Bi-2223 and the Consil sheath are being studied.

Tapes were soldered to steel plates and tested to failure in tension in an Instron machine at RT and at 77 K. Figure 3 shows stress-strain curves of Ag and Consil tapes under tension at RT and 77 K. The yield strength of the Consil tape was more than five times that of the Ag-sheathed tape. Elongation of the Consil tape remained constant at <10% at RT and 77 K, whereas the ductility of the Ag tape increased significantly from ≈ 13 to $\approx 37\%$ between RT and 77 K.

Figure 4 shows a plot of retained I_c versus applied tensile strain; the tapes that were used to produce the plots were sintered for only 50 h because our portable current source could not supply more than 10 A. The initial I_c of the Ag- and Consil-sheathed tapes was 9 and <3 A, respectively; the I_c of the Ag tape became more severely degraded. Moreover, the stress required to produce an equivalent strain in the Consil-sheathed tape was more than four times greater than that required for the Ag tapes. Consil-sheathed tapes are more stress tolerant.

Fig. 2. Backscattered electron photomicrographs of longitudinal sections of (a) Ag- and (b) Consil-sheathed Bi-2223 tapes.

Fig. 3. Stress-strain plots of Ag- and Consil-sheathed tapes at (a) RT and (b) 77 K. Ductility of Ag-sheathed tape increases markedly from $\approx 13\%$ at RT to $\approx 37\%$ at 77 K, whereas ductility of Consil-sheathed tape remains essentially unchanged.

Fig. 4. Retained I_c versus applied tensile strain for Ag- and Consil-sheathed tapes after 50 h of sintering.

We believe that the Ni present in Consil could play a role in decreasing the I_c of the superconductor. We are now examining an alternative alloy of Ag that contains 1.2 at.% Mg; it was provided by Prof. J. Schwartz of Florida State University.

AC Superconducting Downlink with Reduced Energy Loss

The goal of this project was to design and fabricate AC downlinks for service with liquid-helium-cooled fault-current limiters, such that the heat dissipated by each lead is ≤ 0.4 W at 2000 A (rms) and 50 Hz. In previous work, two highly efficient downlinks were made from Bi-2223 bars for use in a 77-4.2 K temperature gradient, to conduct 50 Hz AC to a fault-current limiter operating in liquid He. Each downlink could conduct a 1500-A peak current (1061 A rms), with ≈ 200 mW of heat delivered to the liquid He.

Our new downlink consists of a single Bi-2223 tube. (Tubes are desirable for downlinks because of magnetic field forces that stress the material. Circumferentially directed forces are balanced in the cylindrical geometry and radial forces are compressive.) The downlink was 26 cm long. It was fabricated by sequential cold isostatic pressing and sintering.

The tube geometry is advantageous for AC losses. Self field is low at the surface of the superconductor and current can easily redistribute itself. Studies have shown that reducing the cross-sectional area of a superconductor does not greatly influence the I_c of the sample. However, cross-sectional reduction significantly reduces

thermal losses. Our tube was designed to be mechanically robust enough to handle Lorentz forces while incorporating the advantages of the geometrical effect described above.

Known thermal-conductivity data for cold-isostatically-pressed bars was used to calculate the thermal losses of the tube. The thermal power delivered to the liquid-He-cooled end of a bar was calculated from the equation

$$Q = \frac{A}{l} \int_{4.2K}^{77K} k(T) dT,$$

where Q is heat delivery, A is the cross-sectional area of the sample (XSA), l is the length of the sample, and $k(T)$ is the thermal conductivity of the sample as a function of temperature. The resulting thermal loss for our geometry was ≈ 315 mW. The contact resistance at the bottom was ≈ 2.1 n Ω and the resulting power delivered to the liquid He was ≈ 8.4 mW. The allowable power delivered due to AC loss is $Q_{AC} = 400$ mW - $Q_{thermal}$ - $Q_{contact}$. Therefore, the energy delivered to the He from AC losses cannot exceed ≈ 75 mW (corresponding to $Q = 95$ μ J/cycle-cm).

A geometrical effect, caused by magnetic hysteresis, reduces thermal losses without greatly increasing AC losses. The tube was modeled as a series of bars by using the AC loss values of previously measured bars with varied geometries (Fig. 5). Data from Fig. 5 were used to calculate the necessary properties of the superconductor.

Fig. 5. AC loss versus I_{rms} for various cross-sectional areas (XSA).

Silver contacts, in the form of paint and foil, were applied to the Bi-2223 tubes. The Ag foil adhered well and resistance was low. Two full links were assembled (Fig. 6). Electrical characterization is in progress.

Fundamental Studies of Flux Pinning

Interaction of an Abrikosov vortex lattice with randomly placed strong pinning centers (produced experimentally with heavy-ion irradiation) was modeled with a particularly simple and powerful expression. Excellent quantitative fits to dissipation in ion-irradiated $Tl_2Ba_2CaCu_2O_x$ film were found for $T/T_c = 0.75-0.9$, over ranges of 10^5 in resistance and 60 in field. The three free parameters were within a factor of two of expectations.

Interaction of a single Abrikosov vortex with a single pinning site in superconductors is relatively easy to understand and calculate. The summation of these forces for a vortex lattice in a random spatial array of pinning sites has proved to be much more complex. We consider short-wavelength distortions of the vortex lattice brought about by very strong pinning sites. In a very simple model, the

Fig. 6. Prototype Bi-2223 downlinks; conductor length is ≈ 27 cm.

energy to move a single vortex in an Abrikosov lattice is calculated as a function of displacement. The maximum vortex displacement $r_{\max}$ is determined by equating the vortex-lattice distortion energy to the pinning-site energy. Vortices will move any distance up to that maximum displacement to take advantage of such pinning sites, and the probability that vortices are outside such pinning sites is

$$P_{\text{out}} = \exp[-2p(r_{\max}/a_0)^2 B_\phi / \sqrt{3B}],$$

where a_0 is the intervortex spacing and B_ϕ is the density of pinning sites written as an equivalent Abrikosov vortex density. For large-radius r_{def} ion tracks, this is

$$P_{\text{out}} = \exp\{-0.27 [1+4 \ln(r_{\text{def}}/\xi)] B_\phi/B\},$$

where ξ is the coherence length.

Ion-irradiated epitaxial films are ideal for experimental testing of this model. The ions create a spatially random array of uniform, very strong, pinning sites ($r_{\text{def}} \approx 5$ nm) in each Cu-O bilayer. Epitaxial Tl-2212 films used here were reproducible, free of detrimental weak links, and they exhibited homogeneous, but significantly weaker, pinning without irradiation. An additional advantage of the highly anisotropic Tl-2212 is the almost two-dimensional nature of the vortex dynamics owing to weak interbilayer Josephson coupling.

Quite impressive quantitative agreement with experiment is shown in Fig. 7 at four temperatures and over four decades of resistance and almost two decades of field. The three free parameters of the model seem reasonably close to expectations, and thus support the basic validity of the model.

The ability to write down these expressions is interesting and potentially powerful. For example, thermal activation from such pinning sites can be incorporated by multiplying $(1 - P_{\text{out}})$ by $\exp(-E_{\text{pin}}/k_B T)$, where E_{pin} is the site pinning energy. One can also add over a distribution of pinning sites of varying strengths (E_{pin}) and densities (B_ϕ). The Lorentz force can be simulated, e.g., by introducing a current-dependent E_{pin} .

Critical currents and dissipation are controlled by the size of the flux-bundle. Voltage noise is one way to estimate the size of the flux-bundle in superconductors that are undergoing flux creep. By modeling such data from epitaxial films of Y-123, we show that, at high temperatures, the bundle size grows with the c-axis correlation length of pancake vortices (residing in the Cu-O planes), whereas, at low

Fig. 7. Fit to dissipation by simple, general model described in text.

temperatures, flux creep is consistent with vortex-line bundles, that are larger than a minimum size. The separation of these regimes is roughly at the vortex lattice melting line.

We have obtained fairly complete data on epitaxial films of Y-123 for fields parallel to the c-axis. Because this experiment was performed within the limits of small currents, i.e., linear response, any flux-bundle correlations should closely resemble those in thermal equilibrium. The data display a noise peak versus temperature. The peak is field-dependent, corresponds closely to the vortex-lattice melting line, and separates two regimes. At higher temperatures, we present strong evidence that the interbilayer Josephson coupling energy, when compared with $k_B T$, determines the noise voltage by setting the c-axis correlation length of pancake vortices residing in individual bilayers. This, in turn, reinforces the length of the ab-plane correlation and thus determines the average bundle size. At low temperatures, the c-axis correlation length exceeds the sample size and is thus irrelevant; nevertheless, the bundle-size dependence and bundle statistics must be explicitly included. A sum over *all* bundle sizes adequately follows the temperature dependence of $S_v(0)/V_{DC}$, but experimentally, $S_v(0)/V_{dc}^2$ exhibits a strong thermal activation that the model does not predict. We show that a consistent solution to this dilemma can be found by assuming that there is a minimum bundle size that can be activated at low temperature. Data give the minimum bundle size as ≈ 28 vortex lines.

This last result is important to high-temperature, high-field conductors. Without it, values of I_c would be significantly lower. As we better understand what controls this minimum bundle size, we have a real opportunity to further improve performance.

Low-Loss Coil System for High-Energy-Physics Detectors

As part of a Phase I SBIR from DOE, we are working with Ability Engineering Technology, Inc. (South Holland, IL) to develop an HTS-based particle detector. Technology to reduce ambient heat leakage to a low-temperature cryostat has been available for many years, but extreme minimization of leakage through the power leads has not been solved. Operation of a coil in the persistent mode, with flux pumping to make up for losses, is a powerful way to eliminate the largest source of heat leakage. Our activities toward this goal will include the conceptual design of a flux pump, construction of a small-scale model, performance evaluation, and development of design methodologies and applicable scaling factors for follow-up work. Bi-2223 tapes will be used for the coil.

Interactions

On July 8, 1997, Balu Balachandran met in Cleveland, OH, with members of Reliance Electric. Among the topics discussed was development of coated conductors.

Balu Balachandran and Ken Goretta presented papers and chaired sessions at the 1997 ICMC in Portland, OR, July 28–August 1.

On August 1, 1997, Pavel Diko of the Institute for Experimental Physics, Kosice, Slovakia, joined ANL on funding provided through a Fulbright Fellowship. Dr. Diko is working with us and Ming Xu of the University of Chicago for five months, studying microstructural development in superconductors.

Balu Balachandran presented an invited paper at the meeting of the International Union of Materials Research Societies in Chiba, Japan, September 16–18, 1997. While in Tokyo, he presented lectures on high- T_c superconductor development to Showa Electric, ISTEK, Tokyo Electric Power, and Fujikura.

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