

Organization:	National Institute of Standards and Technology, Boulder, CO
Project Title:	Electromechanical Studies for Superconductor Development
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Project Purpose and FY 2006 Objectives: This project provides the electromechanical research needed to develop YBCO and BSCCO superconductors for high-field magnet and electric power applications. Stress and strain management is one of the key feedback parameters needed to move the second generation conductors to the market place. The project utilizes the expertise and unique electromechanical measurement facilities at NIST to provide performance feedback to companies and organizations developing the conductors (AMSC, SuperPower, ORNL, LANL), as well as to provide engineering design data to the SPI partners. We have achieved significant progress in our primary objectives for FY 2006:

- 1) **YBCO transverse tensile strength:** Study the effect of conductor slitting on the transverse tensile strength of YBCO coated conductors in more detail, measure the effect of transverse tensile stress on the critical current, and collaborate with industry to enhance the delamination strength of the conductor.
- 2) **Stress-strain database:** Continue to add new substrate materials to the stress-strain (σ - ϵ) database.
- 3) **YBCO single grain boundary strain effect:** Design and build an apparatus to determine the effect of strain on the critical current of single YBCO grain boundaries on bi-crystalline samples with various grain boundary angles.
- 4) **Effect of bending in the ‘hard’ direction:** Design and build an apparatus to measure the effect of ‘hard’ bending strain and determine a critical bend radius for engineering design.
- 5) **Tensile strain effect on new conductor geometries:** Measure the effect of tensile strain on the critical current of YBCO coated conductors produced with new geometries and fabrication techniques.
- 6) **In-field strain effect:** Design an apparatus to measure the effect of tensile strain on the critical current as a function of magnetic field and field angle.

FY 2006 Performance: Key results from the FY 2006 program are summarized below:

- 1) Transverse tensile strength measurements on YBCO RABiTS conductors, including conductors with new geometries, have been performed at 76 K to study the effect of conductor slitting. The *internal* strength of the conductor, where edge effects were not included, was compared to the delamination strength of *slit* conductors. The dependence of the critical current on transverse tensile stress has been measured on both RABiTS conductors, and detailed feedback was provided to industry.
 - The results showed that the delamination strength is reduced significantly due to slitting, from 27 MPa to 17 MPa for RABiTS conductors. However, the effect of conductor slitting does not play a role in the laminated RABiTS architecture, where the superconductor is laminated on both sides with a thin strip of copper. The solder fillets at the edges reinforce the slit conductor, resulting in a delamination strength that exceeds the internal strength of the superconductor. These results were also obtained on more recent RABiTS samples.
 - The dependence of the critical current on *c*-axis tension was measured. RABiTS conductors with delamination strength above about 15 MPa did not show a significant drop in critical current before the conductor delaminated. However, in weaker samples (delamination strength below about 15 MPa), a stepwise decrease in critical current has been measured in the range of about 3 MPa below the delamination strength.
- 2) The stress-strain database on substrate materials for coated conductors has been expanded with data on new 50 μ m thick Hastelloy C276 substrates from SuperPower. The yield strength of the bare substrate material is 1300 MPa at room temperature, and 1700 MPa at 76 K. A *fully-coated* YBCO conductor, copper-plated at all sides, has a yield strength of 1000 MPa at room temperature and

1200 MPa at 76 K, which is almost double the yield strength of the previous 100 μm thick substrates (700 MPa at 76 K). The increase in yield strength at both room temperature and 76 K is significant, providing opportunity for further enhancing the *engineering* critical current density while maintaining tensile load limits.

- 3) After our previous discovery of a *reversible* strain effect in YBCO coated conductors in 2003, it is still not known if the effect occurs within the YBCO grains or at the grain boundaries. Last year we proposed an investigation of the strain dependence of the critical current of single YBCO grains and of single grain boundaries. A new apparatus has been built and tested to measure the strain effect on thin films deposited on single-crystalline substrates and bi-crystalline substrates with different grain boundary angles. The sample is bonded to a titanium bending beam, which is flexed at 76 K in a four-point bender to apply compression or tension to the sample. The critical current density of the YBCO film is measured as a function of applied strain. Several bonding techniques have been tested, of which the strongest one allows an applied strain between -0.15% and +0.05%. Initial tests have been performed on single-crystalline films, which confirmed that this technically challenging experiment is feasible. The experiment is now ready for testing high-quality single crystalline and bi-crystalline samples, which are being prepared by Paul Barnes and Timothy Haugan at the Air Force Research Laboratory.
- 4) A new experimental apparatus has been designed and built to measure the critical-current degradation due to bending in the ‘hard’ direction of RABiTS and IBAD conductors. Coated conductors experience such a deformation when they are cabled in a braided configuration and when the cable is bent during for instance installation. The superconductor is soldered to the side of a CuBe bending beam, which is deformed at 76 K in a four-point bender. The critical current of the conductor is then measured as a function of bending radius of the neutral axis of the beam.
 - Preliminary results show a *reversible* degradation of 3% in critical current density at a bending radius of 0.3 m for slit bare RABiTS and laminated RABiTS. No irreversible degradation was measured in these conductors down to a minimum bending radius of 0.21 m.
 - A *reversible* degradation of 3.5% was measured at a bending radius of 0.3 m for slit copper plated IBAD conductors.More tests are underway to compare different samples and to relate the degradation in critical current to the strain gradient in the sample.
- 5) A new technique has been developed (based on a four-point bending beam apparatus) to study the effect of compressive as well as tensile strain on the critical current of YBCO coated conductors.
 - A large *reversible* degradation in critical current of over 40% is measured under compressive strains up to -1% for both RABiTS and IBAD conductors. No irreversible degradation is measured under compression.
 - The critical current passes through a maximum at positive applied strains and degrades reversibly as tensile strain is increased further up to an irreversible strain limit.
 - The critical current degrades irreversibly at +0.5% *intrinsic* strain for both slit, bare RABiTS and laminated RABiTS (0% intrinsic strain is defined at the peak in critical current).
 - The critical current degrades irreversibly at +0.57% intrinsic strain for slit, copper plated IBAD conductors.
 - The dependence of the critical current on strain is symmetric around the peak in critical current, within the range where the critical current changes reversibly. The location of the peak depends on the type of sample and is determined by the precompression of the YBCO layer.A number of intrinsic properties of the coated conductor can now be probed for the first time with this new experimental technique.
- 6) The design of a new apparatus to measure the critical current of coated conductors as a function of strain, magnetic field, and magnetic-field *angle* has almost been completed. Based on the recent results at high compression, we intend to change the design in such a way that the critical current of

the coated conductor will not only be measured as function of tensile strain, but also at high compressive strains.

FY 2007 plans: The FY 2007 plans are determined in consultation with the manufacturers and a number of research collaborators within the DOE/OEDER community. Direct feedback is given to the wire manufacturer within each project and then disseminated to the general wire-development and SPI community:

- Collaborate with the manufacturers to improve the *delamination strength* of *slit* coated conductors, including modifying the measurement procedure and the development and testing of new conductor designs. This is a key area in the present scale-up process for providing data feedback to AMSC, SuperPower, ORNL, and LANL.
- Test new configurations of YBCO coated conductors under *uniaxial compression* and *tension* in the newly developed apparatus; test the universality of the reversible critical current degradation at high compressive/tensile strains; begin to look at *engineering/physics modeling* of the intrinsic strain effect.
- Continue the critical-current vs. *hard-bending-strain* measurements, testing new conductor designs and providing engineering design data to the manufacturers to set cable bending limits.
- Study the effect of YBCO *film thickness* on the strain response of YBCO coatings. This will be carried out in collaboration with SuperPower, ORNL, and AMSC as samples become available.
- Acquire a fundamental understanding of the origin of the reversible strain effect in coated conductors to guide engineering of new conductor designs through a series of experiments on single crystals vs. patterned grain-boundary *bi-crystals*. The research is designed to isolate the source of the intrinsic strain effect in YBCO.
- Provide additional stress-strain data on *new substrate materials* to the wire manufacturers as requested.
- Modify the design of the new high-field apparatus to incorporate high-compressive/tensile strain testing of J_c as a function of magnetic-field/sample *angle*. The modifications will be completed next year, and the apparatus constructed and commissioned to enable measurements to commence in the following year.

Research Integration: NIST collaborates closely with researchers and managers at AMSC, SuperPower, ORNL, LANL, and universities to implement a research program that utilizes NIST's specialized electromechanical test facilities and expertise. The resulting data provide feedback to the wire manufacturers, national labs, and SPI application developers, where they are integrated into conductor development and system design processes. A number of collaborative papers with these organizations have been published or are being written.