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Title: TRANSVERSE STRESS AND FATIGUE EFFECTS IN  
YBCO-COATED IBAD TAPES

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# Transverse Stress and Fatigue Effects in YBCO-Coated IBAD Tapes

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**Abstract**—Measurements of the effects of static and cyclic (fatigue) transverse stress on the critical current of YBCO-coated IBAD tapes are reported at 76 K in self magnetic field. YBCO films ( $\sim 1 \mu\text{m}$  thick) on Inconel substrates ( $125 \mu\text{m}$  thick) with IBAD buffer layers had critical-current densities ( $J_c$ ) exceeding  $1 \text{ MA/cm}^2$  and  $n$  values of about 50 (where  $n$  is an index of the sharpness of the superconductor-normal transition). Under static loads of 100 MPa, the  $J_c$  degradation was less than 5% (7% at 120 MPa). When subjected to cyclic loading, there was less than 2% additional  $J_c$  degradation after 2000 fatigue cycles. Microscopic examination of the samples indicates that this limited  $J_c$  degradation may have arisen from longitudinal cracks forming near the edges of the sample after being subjected to these high transverse pressures. This fracture mode would indicate that longitudinal side support from high-yield substrates or epoxy impregnation of the magnet structure may provide additional tolerance against  $J_c$  degradation from transverse stress.

**Index Terms**—coated conductors, critical current, electro mechanical, IBAD, mechanical, stress, transverse stress.

## INTRODUCTION

HIGH critical current density ( $J_c$ ) in excess of  $1 \text{ MA/cm}^2$  in self field have been achieved recently at 77 K in flexible YBCO coated conductors [1]–[6]. Little data are available, however, on the electromechanical properties of these conductors, which can strongly affect their ultimate usefulness in applications. Even superconductors that show high  $J_c$  can have extremely different intrinsic stress tolerance, as shown earlier, for example, for Bi-2223 conductors [7]. Such electromechanical effects include  $J_c$  degradation arising from axial strain [10], bending strain, and transverse stress. For the coated conductors, there are only a few bending [8,4,9] and axial-strain data available. In this paper we present the first *transverse* stress data for YBCO coated conductors, measured for thick YBCO films on Ni alloy substrates with IBAD buffer layers. Both static and cyclic transverse stress effects on the critical current of these conductors were measured.

The effect of transverse stress on the critical current of

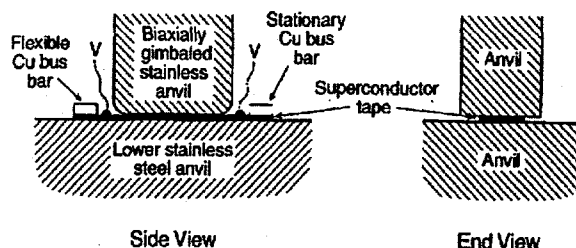


Fig. 1. Transverse-stress test geometry: *side view* with transport current along the tape; *end view* with current traveling into the plane of the figure.

superconductors is a critical design parameter for their application in magnets for high-energy physics accelerators, motors, generators, and superconducting magnetic energy storage. In such devices, the superconductor can be subjected to considerable transverse pressure, both from radial pressure developed in the winding of magnet coils and from the radial pressure of the Lorentz force when a magnet is energized. In the case of high-energy physics magnets, a benchmark transverse stress level is about 100 MPa.

## SAMPLE PREPARATION

The tape samples were fabricated using the technique described in [11]. A  $100 \mu\text{m}$  thick Inconel 625 substrate was coated with a  $\sim 0.9 \mu\text{m}$  YSZ IBAD layer and a  $\sim 40 \text{ nm}$   $\text{Y}_2\text{O}_3$  buffer layer. A YBCO layer  $0.9 \mu\text{m}$  thick was then deposited using pulsed laser deposition. Sample dimensions were  $3 \text{ mm}$  wide by  $3 \text{ cm}$  long.

Low contact resistivity was obtained by lightly cleaning the surface of the YBCO with an ion mill and then depositing a thick ( $10 \mu\text{m}$ ) Ag contact layer by thermal evaporation, which was later annealed in oxygen at  $550^\circ\text{C}$ . The Ag contact coating was  $10 \mu\text{m}$  thick in order to prevent the indium solder from alloying completely through the Ag layer and forming an indium oxide barrier at the superconductor interface [12]. Notice that the YBCO layer is near the top surface of the tape, separated from the surface by only the soft  $10 \mu\text{m}$  Ag contact layer.

## EXPERIMENTAL TECHNIQUES

In order to simulate the transverse stress environment these conductors will experience in service, testing was carried out in liquid nitrogen at 76 K by pressing the tape between two stainless steel anvils, shown in Fig. 1, and measuring the voltage vs. current characteristic of the test sample in self

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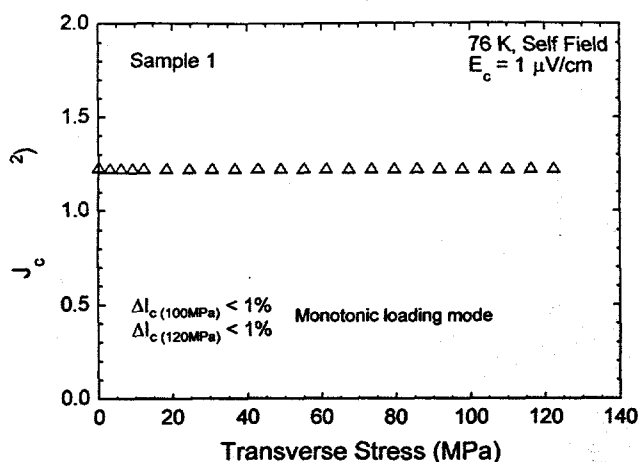


Fig. 2a. Effect of transverse stress on the critical current density  $J_c$  of a  $\sim 1$   $\mu\text{m}$  thick YBCO deposited on a 100  $\mu\text{m}$  thick Inconel 625 substrate with IBAD buffer layers, tested in the *monotonic-loading* mode (see text).

field while under load. Critical current was determined within about  $\pm 2\%$  using an electric field criterion of 1  $\mu\text{V}/\text{cm}$ .

Uniform transverse stress application was ensured by constructing the top anvil so it was biaxially gimbaled to conform precisely to the lower anvil surface. Stress concentrations were mitigated at the edges of the top anvil by making it wider than the tape width and flaring the edges, as shown in Fig. 1. Transverse stress was determined from the quotient of the applied load and the pressed area of the sample (equal to the product of the tape width and the length of sample under the upper anvil).

At each end of the sample, copper current-bus bars were soldered (without flux) onto the top thick Ag contact layer using eutectic In-3%Ag solder ( $T_{\text{melt}} = 143^\circ\text{C}$ ), using a technique described in [12]. Solder flux is not needed to wet the Ag layer if the Ag is fresh and not tarnished; it is omitted to insure that the surfaces of the test sample and pressure anvils remain clean. One of the current bus bars is a high-conductivity copper strip designed to flex and provide axial-stress-free cooling of the sample (that is, it eliminates axial stress from differential thermal contraction between the sample and stainless-steel anvils) [13]. No transverse stress is applied during cooling so that the test sample is cooled in a completely stress-free manner.

Voltage taps were soldered with In-3%Ag to the middle of the top surface of the tape sample, about 2 mm outside the pressing region. About 1 to 2 mm space was also allowed between the voltage tapes and the edge of the current contacts to eliminate current transfer voltages [14].

#### TRANSVERSE STRESS RESULTS: INITIAL LOADING

Two test modes were used for loading the conductors. In the *monotonic loading* mode, transverse stress was applied to Sample 1, a voltage vs. current ( $V$ - $I$ ) characteristic measured, and then, *without removing the load*, the pressure was increased to a higher value and the  $V$ - $I$  characteristic measured again. This procedure was repeated until pressures exceeding 100 MPa were reached. We believe this is an

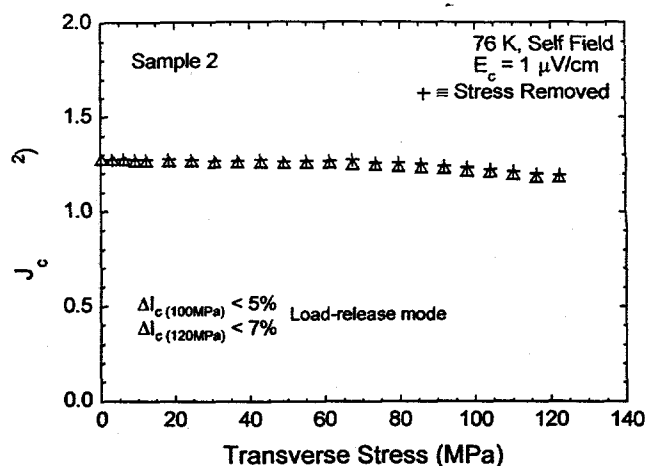


Fig. 2b. Same as Fig. 2a, except tested in the *load-release* mode.

optimistic measuring mode wherein the sample does not lose contact with the pressure anvils. The sample receives frictional support from being pressed against the stainless steel, providing additional strength against in-plane plastic strain.

The results of this test are shown in Fig. 2a, where the critical current is plotted as a function of transverse stress. Notice that the IBAD tape had a critical current density well over 1  $\text{MA}/\text{cm}^2$ . Also the sample had a very sharp superconductor-to-normal transition characterized by an "n" value of 47 (where  $V \propto I^n$ ), indicating the sample to be high quality and free of appreciable non uniformity's in the current distribution along the tape [15]. For this test mode, the critical current degradation was less than 1% up to 120 MPa, which is well beyond the design benchmark for accelerator magnets, for example.

In the second *load-release* test mode, transverse stress was applied to Sample 2,  $J_c$  was measured (shown by a triangle in Fig. 2b), and then the load was then *released*.  $J_c$  was remeasured at zero load and the result indicated by a cross in Fig. 2b, which was plotted for comparison purposes at the same load as its corresponding loaded- $J_c$  value. The sample was then loaded to a higher stress and the load-release procedure repeated. We believe this is a pessimistic, more conservative testing mode in which the YBCO is released from the upper stainless-steel anvil, allowing in-plane expansion of the tape between loading steps. Nevertheless, the degradation in this case was less than 5% at 100 MPa, increasing to 7% at 120 MPa.

Note that the  $J_c$  on unloading did not recover to the initial  $J_c$  value, indicating that the degradation in  $J_c$  was *irreversible*.

#### DISCUSSION

The monotonic-loading test mode should be representative of a tightly wound magnet structure wherein the coated conductor is co-fabricated or co-wound with a high-yield structural layer that would press against the YBCO superconductor layer. The second load-release mode represents a case where the coated conductor loses the frictional support of the pressure surface between each

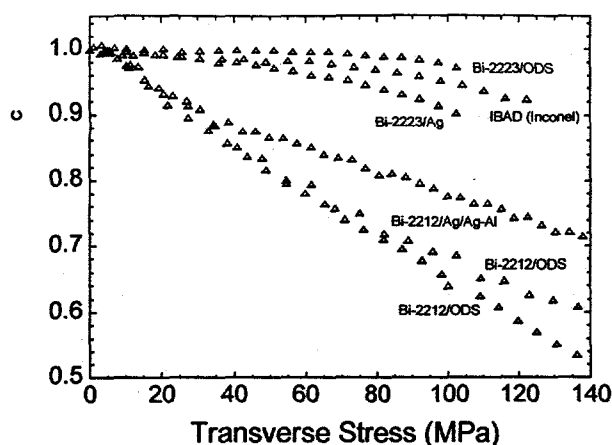


Fig. 3. Comparison of the effect of transverse stress on the  $J_c$  of various high- $T_c$  tape conductors: IBAD, Bi-2223 [with Ag and oxide dispersion strengthened (ODS) Ag matrices], and Bi-2212 (with ODS Ag matrix, and double sheathed with Ag and Ag-Al matrices). The results shown were obtained in the more severe load-release testing mode.

energizing of the magnet, and represents a worst case. Actual magnet performance is expected to be in-between these two situations. Since the *envelope* between the two sets of results for the IBAD coated conductors is narrow, we would expect the transverse stress tolerance for these IBAD tapes to be excellent, less than 5% at 100 MPa in the worst-case.

Fig. 3 compares these data with similar transverse-stress results obtained on several series of Bi-2223 and Bi 2212 tape conductors. Here we compare the data for only the worst-case load-release mode, to provide a lower limit on expected performance. The data fall into two distinct groupings. The IBAD and Bi-2223 results show high transverse stress tolerance, with less than 10% degradation at 100 MPa. The Bi-2212 performance was variable, between 20% and 35%  $J_c$  degradation at 100 MPa transverse pressure. This is not to say that the Bi-2212 conductors cannot be successfully utilized at high transverse compressive loads in magnet applications, which could be accomplished, for example, by providing good structural side support [16]. The results, however, show the *intrinsic* stress tolerance of these different conductors and in that vein, the IBAD coated conductors on Ni-alloy substrates look very robust. Note that Inconel has a relatively high yield stress compared with other substrate materials, which may account for their superior intrinsic stress tolerance.

#### FATIGUE RESULTS

Fig. 4 shows the effect of cyclic (fatigue) loading on the same conductors whose static test results are presented in Fig. 2. Cyclic testing was performed after the samples had been subjected to static stress from the initial loading. Load was cycled between 122 MPa and near zero at 0.33 Hz, but never fully released ( $J_c$  was not measured at near zero-load). As shown in Fig. 4, no further  $J_c$  degradation occurred after an additional 2000 constant load cycles had been given to Sample 1 (which showed less than 1% degradation in the initial monotonic loading). For Sample 2 (which showed a

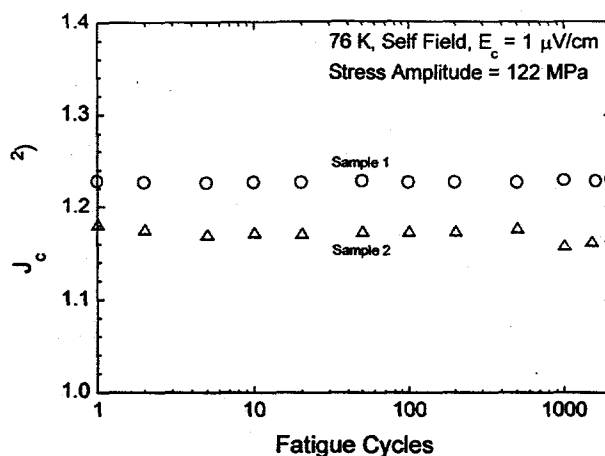


Fig. 4. Effect of cyclic loading on IBAD tapes (samples 1 and 2 correspond to Figs. 2a and 2b respectively).

total of 7%  $J_c$  degradation on initial loading in the incremental load-release mode) the effect of an additional 2000 constant load cycles resulted in only ~2% further  $J_c$  degradation. Again, this represents high fatigue tolerance for these Ni-alloy-substrate IBAD conductors.

#### MICROSTRUCTURAL CHARACTERIZATION

After all mechanical testing had been performed (both static initial loading and fatigue tests), the samples were examined using magneto-optical imaging (MOI) [17] and scanning electron microscopy (SEM). Fig. 5 shows the MOI results. A comparison of Samples 1 and 2 shows no remarkable differences, even though Sample 1 degraded a total of 9% (7% on initial loading plus 2% from fatigue), while Sample 2 had a total  $J_c$  degradation of less than 1%. Magnetic flux penetrated nearly uniformly and no obvious cracks were imaged at the MOI spatial resolution for these samples, about 10  $\mu\text{m}$ . Also, there was no observable difference between the central pressed region of the samples and the ends which received no transverse pressure.

After carefully etching away the Ag using a solution of (25%  $\text{H}_2\text{O}_2$ , 25%  $\text{NH}_4\text{OH}$ , 50%  $\text{H}_2\text{O}$ , made fresh each time), the surface of the YBCO layer was examined using SEM. In Fig. 6 we see that a series of relatively thin longitudinal cracks (~0.05  $\mu\text{m}$  to ~0.2  $\mu\text{m}$  in width) formed in the region near the tape edges for both samples. However, Sample 1 (with less than 1%  $J_c$  degradation) had a cracked region that extended only about 0.05 mm in from only one edge, while Sample 2 (which showed 9%  $J_c$  degradation after being subjected to the more severe load-release loading) had a cracked region that occupied a much wider band, about 0.2 mm wide along one tape edge and about 0.1 mm wide along the other edge. Both crack bands extended uniformly the entire length of the sample. The affected cross-sectional area of the Sample 2 was measured to be about ~9% of the tape width, corresponding closely to the observed 9%  $J_c$  degradation. The cracks were predominately in the longitudinal direction (along the direction of the transport



Fig. 5. Magneto optical imaging of magnetic flux penetration at 800 gauss into IBAD tapes after being subjected to static and cyclic transverse stress (samples initially cooled to 15 K in zero field).

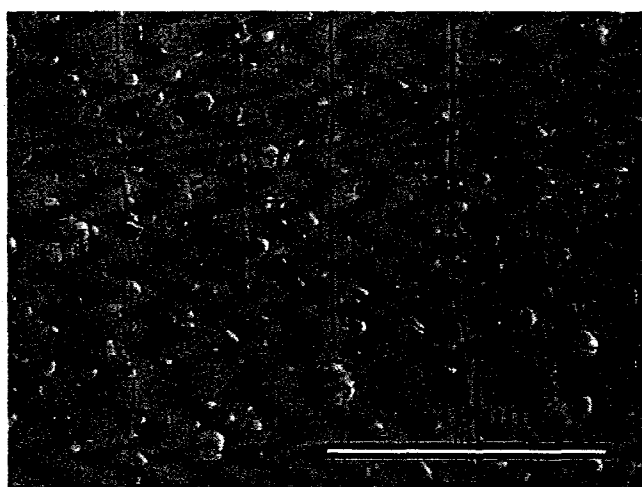


Fig. 6. Scanning electron micrograph showing surface of YBCO layer after static and cyclic transverse stress testing, showing the pattern of longitudinal cracks along the length of the tapes. For Sample 1, the affected region was only about 0.05 mm wide and occurred along only one edge of the tape. For Sample 2, the longitudinally-cracked region was much wider: ~0.4 mm in width along one tape edge and 0.1 mm along the other edge.

current), with occasional crosslinking. The center of the tape was free of any observable cracks.

### CONCLUSION

These initial transverse stress tests of YBCO coated IBAD tapes, show the conductors to exhibit strong transverse-stress tolerance: less than 1%  $J_c$  degradation when monotonically pressed against a stainless-steel anvil at pressures up to 120 MPa, and about 7%  $J_c$  degradation when alternately incrementally loaded and released at pressures up to 120 MPa. Two thousand fatigue-loading cycles at 120 MPa produced less than 2% additional  $J_c$  degradation. Micrographic examination of these samples after mechanical testing indicates that transverse in-plane strain near the tape edges may play a significant role in determining the  $J_c$  degradation from transverse pressure applied to the surface of these IBAD tape conductors. This would suggest that in

magnet applications, improvement in transverse stress tolerance may be achieved by providing transverse support to the conductors through the use of additional structural material co-fabricated or co-wound with the coated conductors, as well as from good lateral-side support in the design of the magnet winding pack.

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