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Title: HIGH-TC COATED CONDUCTORS - PERFORMANCE OF METER-LONG YBCO/IBAD FLEXIBLE TAPES

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High-Tc Coated Conductors – Performance of Meter-Long YBCO/IBAD Flexible Tapes

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Abstract **– One meter long tapes based on 50-100 μm thick by 1 cm wide nickel alloy substrates have been coated in a continuous process with a textured yttria-stabilized zirconia layer by ion beam-assisted deposition, followed by a 1-2 μm thick layer of YBCO by pulsed laser deposition. The best result to date is a tape with a critical current (I_c) at 75 K of 96 A over an 87 cm measurement length. The overall critical current density and engineering current density are 1 MA/cm^2 and 10 kA/cm^2, respectively. Using a special probe, individual I-V curves were generated for each centimeter of tape length in order to investigate longitudinal uniformity of the transport properties: the highest and lowest I_c values fall within a range of ± 25%.**

I. Introduction

During the past decade, tremendous progress has been made in the area of high T_c superconducting electric power applications such as magnets, motors, transformers, and transmission lines. This progress has been enabled by the availability of long lengths of wire fabricated by the oxide-powder-in-tube (OPIT) method using the Bi-based superconductor. As with any new technology, however, large-scale use has brought attention to certain deficiencies in this first-generation wire, prompting a search for solutions. The main difficulty with today's wire is intrinsic to the Bi-Sr-Ca-Cu-O superconductor: its low irreversibility line, related to anisotropy of the compound itself, precludes use at liquid nitrogen temperature in all but the weakest magnetic field. The present-day solution involves the use of cryocoolers to lower the superconductor operating temperature to 20-30 K, and while successful, this solution erodes the original promise of high-temperature superconductivity, which envisioned operation of electric power systems with cheap, plentiful liquid nitrogen.

Tomorrow's solution to this dilemma may lie in a second generation of wire based on the Y-Ba-Cu-O superconductor, which differs from BSCCO in two important ways. First, the more isotropic YBCO retains significant current carrying ability in liquid nitrogen at magnetic fields as high as several Tesla, and even above 10 Tesla for fields perpendicular to the YBCO c-axis [1]. Second -- and this is a disadvantage -- YBCO cannot be adequately textured by the type of thermomechanical techniques used in the OPIT process. In fact, the highest superconducting performance is achieved only for YBCO coatings that have been epitaxially grown on single crystal or highly textured surfaces.

Of the numerous ways to create textured surfaces and epitaxial YBCO, Los Alamos has chosen to use the techniques that thus far have produced the highest critical current levels: ion beam-assisted deposition (IBAD) and pulsed laser deposition (PLD). The goal has been to optimize each step of a complete process intended to produce the best I_c for a one meter tape length.

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II. Coated Conductor Processing

A. The IBAD Step

The ideal substrate for YBCO is a polished single-crystal oxide material with a good lattice match to the superconductor basal plane. For a coated conductor, however, the substrate must be flexible, strong, inexpensive, and available in lengths > 100 m. Joining these two disparate sets of requirements is the role of IBAD. The conductor requirements dictate that the substrate be metal, and metal in the appropriate form of long thin strip will generally be polycrystalline (for a notable exception, see [2]).

An ingenious solution to this problem was devised in the early 1990s [3], [4]. By bombarding a growing film of yttria-stabilized zirconia (YSZ) with argon ions at a few hundred eV, the film gradually acquires biaxial texture, and becomes a reasonable facsimile of a single-crystal oxide substrate. If the IBAD is carried out on thin strip of one of the Ni-Cr superalloys, such as Haynes 242 or Inconel 625, a nearly ideal substrate is created for subsequent deposition of YBCO. Details of the IBAD process on moving tape, relevant to the present work, have been published previously [5], [6].

B. The PLD Step

Laser deposition has played a key role in coated conductors from the beginning [3], [4], and today remains the preferred method for producing YBCO coatings, whether for electric power applications or electronic devices [7]. For coating one meter tapes, the only change to a conventional PLD system needed was a means to heat the moving tape to temperatures of 700 - 800 °C. This was accomplished by the use of a heated roller, which drives the tape via a stepper motor and heats it conductively, as shown in Fig. 1. An additional change was the use of a rotating and translating target to uniformly remove target material during extended

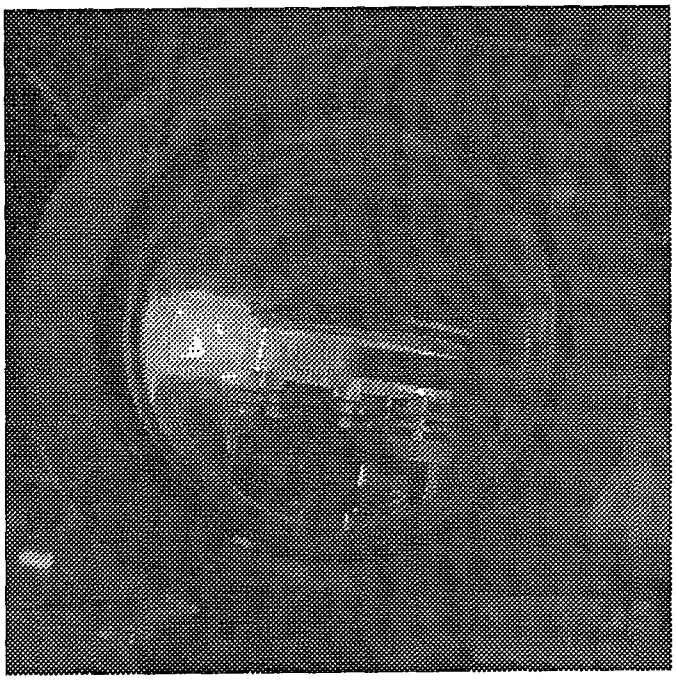

Fig. 1. Top view of heated roller system for continuous tape coating by PLD. Upon coming in contact with the roller, the tape is conductively heated to the deposition temperature, and remains heated as it passes through the laser plume (bright area at left center).

coating runs. Details of the construction and operation of the PLD system have been published elsewhere [8].

C. Producing A One Meter Tape

Tapes are prepared in three separate deposition chambers. First, a 115-cm-length of 1-cm-wide strip -- typically Inconel 625, obtained commercially -- is spot-welded into a continuous loop. Next the tape is polished with diamond paste to a roughness (R_a, as measured by a 100 μm long profilometer scan) of about 3 nm, cleaned, and loaded into the IBAD chamber.

During the IBAD step the tape is moved continuously on a pair of rollers through the deposition zone, which is wide enough to accommodate two tapes in each run. The ultimate in-plane alignment of the YSZ improves with coating thickness, saturating at about 15° FWHM for moving tape. Texture is characterized by a an x-ray ϕ-scan and the loop is then transferred to the PLD chamber.

Although YBCO can be deposited directly on the IBAD YSZ, a 20 – 30 nm-thick buffer layer of Y_2O_3 is typically used to improve lattice matching and prevent formation of $BaZrO_3$ at the interface. The YBCO is then deposited at a temperature of 750° C, and in 0.2 Torr flowing oxygen. At 14 W of excimer laser power, a 1-μm-thick layer of YBCO can be deposited at a tape speed of 2.5 cm/minute.

In a third chamber, the loop is coated with 1-3 μm of Ag by magnetron sputtering. This layer allows electrical contact to be made to the tape, and protects the YBCO surface during handling and measurement. Following this deposition, the loop is cut and the tape is wrapped around a drum and loaded into a tube furnace, where it is annealed at 550° C for 30 minutes in flowing oxygen. This step reduces the contact resistance of the silver and also serves to convert the YBCO to the superconducting orthorhombic phase.

Finally, current leads are soldered to the tape ends, and it is loaded into a measurement probe consisting of 100 pressure contacts spaced at 1 cm intervals. I-V curves are generated for each interval, and the results are plotted as a bar graph showing the I_c for each tape segment.

III. Results

Since one meter coating operations began in March of 1997, a total of 28 full-length tapes have been coated, as well as a large number of 20-cm test tapes. Halfway through this series, the first "good" result – a 29 A end-to-end I_c – was achieved [6]. (All measurements in this work were carried out at 75 K.) Subsequent runs have yielded three tapes in the 5–10 A range, four in the 10-20 A range, plus 33 A and 47 A tapes, and the result shown in Fig. 2. This tape, with I_c = 96 A over an 87 cm measurement length is approaching in performance the best results that have been obtained with short, batch processed, samples. At a YBCO thickness of 0.95 μm, the overall J_c is 1 MA/cm^2, and with a total tape thickness of ≈100 μm (mostly substrate) the J_e is nearly 10 kA/cm^2. Further, the I_c uniformity is quite good at better than ± 25%, although it should be noted that the measurement was terminated at 120 A, and the segments at this level in Fig. 2 are actually somewhat higher.

Continued incremental improvement in tape performance has resulted from efforts in several areas. Most notable,

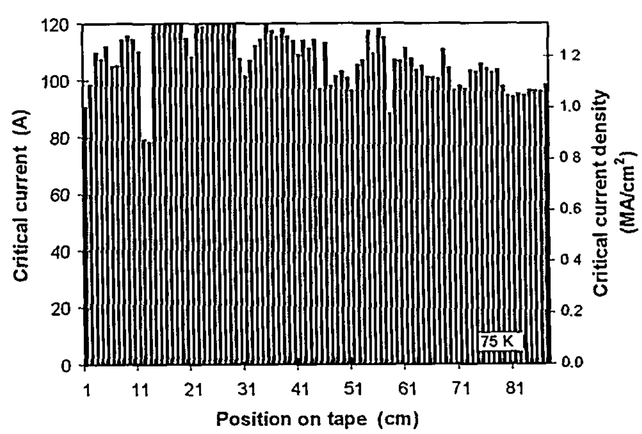

Fig. 1. I_c and J_c values for each segment of an 87 cm long tape. The I_c for the full length of the tape is 96 A The apparent discrepancy between this value and the < 80 A I_cs for segments 12 and 13 arises from the 1 μV/cm criterion for critical current. Since the I-V curve for the full tape is the same as that for the weakest segment, different critical currents are obtained, depending on whether the voltage criterion calls for 1 μV or 87 μV.

however, have been improvements in the IBAD texture for moving tapes, from an early value of 25 ° FWHM to the present level of about 15 ° FWHM. In addition, numerous "housekeeping" details, such as tape cleaning and handling, and optimization of deposition conditions have led to higher I_cs and better uniformity.

IV. Performance of Coated Conductors in a Strong Magnetic Field

As noted previously, one of the main attractions of second-generation wire based on YBCO is the promise that it will be useful at liquid nitrogen temperature in applications -- such as magnets, motors, and generators -- where high magnetic fields will be present. To study this issue in detail, a new apparatus has been developed that allows coated conductor tapes to be characterized in fields up to 7 T, at a full range of field orientations. This apparatus is described in detail in [9].

A typical result is shown in Fig. 3. In this case, a tape with I_c = 127 A (75 K, self field) has been measured at six magnetic field levels from 0.5 T to 7 T. At each level, I_c has been measured as a function of field orientation angle. The distinctive features are the intrinsic pinning peak at 90 ° (field parallel to the film plane), and the peaks at 0° and 180°, which correspond to flux pinning by c-axis correlated defects [1]. At 2 T – a typical magnetic field level encountered in industrial electric motors -- I_c in the least favorable orientation is still above 10 A.

V. Fabrication of a Coated Conductor Solenoid

To begin to evaluate the potential of coated conductors in real applications, we have fabricated a small solenoid from a one meter tape (Fig. 4). The inner diameter of the coil is 9.5 mm, demonstrating the remarkable flexibility achievable with coated conductors: The compressive bending strain of the YBCO in this configuration is 0.8%. (In early bend-test

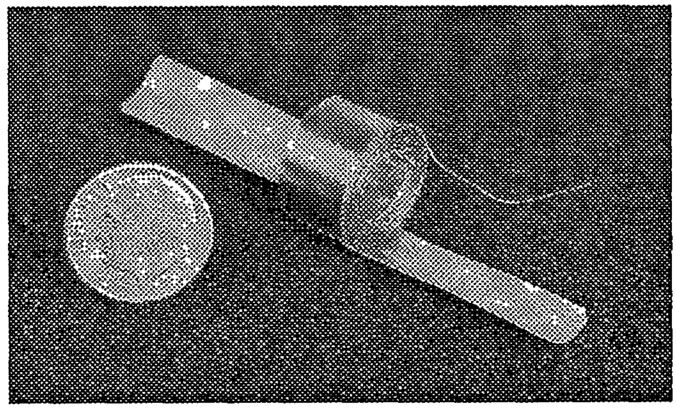

Fig. 4. Small solenoid wound from a one meter coated conductor. Long tabs are current leads; one voltage tap is visible in the photograph.

experiments [10] it was found that I_c was reduced by only 10% at a compressive strain of 1%, and that this reduction was reversed when the sample was straightened.)

The coil consists of 25 turns of I_c = 16 A tape, which, when modeled as a short thin solenoid, should be capable of generating a magnetic field of about 300 Oe at I_c. Fig. 5 shows the measured magnetic field and voltage developed along the length of the conductor as a function of current, indicating good agreement between calculated and measured values.

While such a small field is hardly spectacular in itself, the potential for coated conductors is clear. With continued increases in performance (we have already demonstrated a tape with a 6x higher I_c) and conductor length, the time is rapidly approaching when these materials will be ready for use in real-world electric power applications.

VI. Conclusions

We have shown that the initial small-sample results -- that coated conductors are capable of carying 100 A in the form

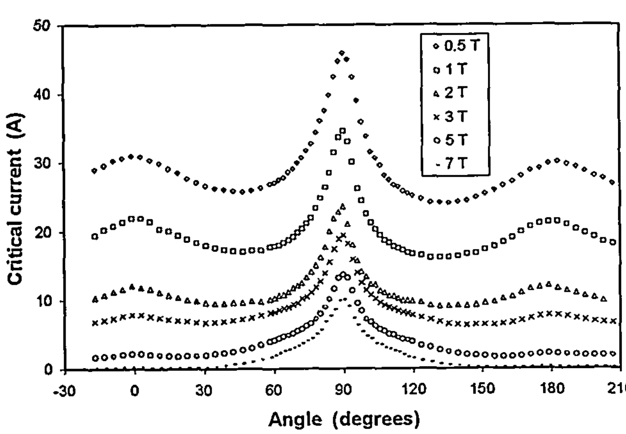

Fig. 3. Magnetic field dependence of a coated conductor I_c (75 K) over a full range of field orientations. At 0° and 180°, the field is parallel to the YBCO c-axis. Critical current in self field is 127 A.

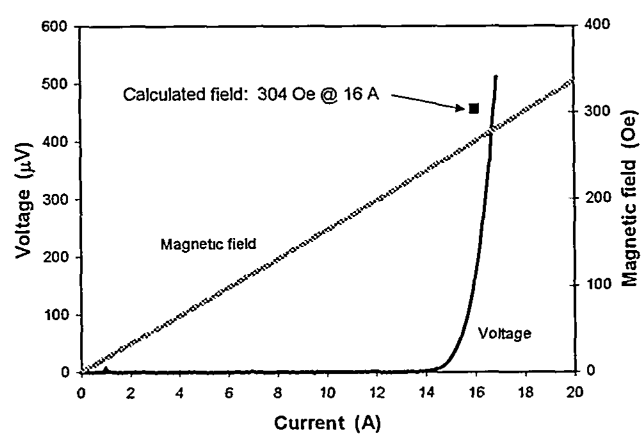

Fig. 5. Performance of a small solenoid wound from a one meter coated conductor. The measured field generated by the coil at Ic = 16 A is 280 Oe.

of centimeter-wide flexible tape -- can be extended to lengths of one meter. Further, we have shown that this level of performance can be maintained in a continuous process with moving tape, demonstrating the feasibility of reel-to-reel coating of commercially useful lengths of second generation wire.

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