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Title: DEVELOPMENT OF METER-LONG YBCO COATED CONDUCTORS PRODUCED BY ION BEAM ASSISTED DEPOSITION AND PULSED LASER DEPOSITION

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Development of meter-long YBCO coated conductors produced by ion beam assisted deposition and pulsed laser deposition

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A "second-generation" of high T_c conductors, consisting of YBCO coatings on flexible metal substrates, has recently reached a milestone with meter-long tapes capable of carrying over 100 A in a 1 cm width at liquid nitrogen temperature. Having reached this level of performance, however, we have encountered difficulties in the self-field characterization of such high current material. In particular, measurement of critical current uniformity along the tape length has in some cases resulted in damage to weaker tape segments during measurement of higher-current ones. To address this problem we have developed a novel measurement technique that uses permanent magnets to locally suppress the critical current of the tape section being measured to a level that is "safe" for the rest of the tape.

1. INTRODUCTION

Since the discovery of materials that are superconducting at temperatures above the boiling point of liquid nitrogen, there has been an intense worldwide effort to make flexible conductors of these materials and to demonstrate their use in practical electric power applications.* The first fruit of this work was the development of the Bi-Sr-Ca-Cu-O based superconductor, made into a silver-clad wire using the oxide-powder-in-tube (OPIT) process. This wire is now produced in quantities of hundreds of km per year, and is the workhorse of the industry, being used to demonstrate the feasibility of superconducting motors, fault current limiters, power transmission lines and transformers. One problem with this material, however, is that there is a fundamental physical limitation – the irreversibility line of BSCCO – that precludes its use in high magnetic fields at liquid nitrogen temperature. This problem can be overcome by using YBCO, which has a much higher irreversibility field [1], but in order to exploit this advantage a different fabrication method must be used since high quality YBCO cannot be produced by the OPIT process.

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2. COATED CONDUCTOR FABRICATION

While several different techniques are used to make YBCO conductors, they all result in the same configuration: a YBCO coating (usually less than 2 μm thick) on a flexible metal substrate with one or more oxide layers in-between. In order to achieve high current density the YBCO must be biaxially textured – this is accomplished at Los Alamos with ion beam assisted deposition (IBAD), which results in a textured layer of yttria stabilized zirconia on the polycrystalline alloy substrate. The alloy used in this work is Inconel 625, rolled to 100 μm thick and slit to 1 cm wide. After the IBAD step, pulsed laser deposition at elevated temperature is used for the epitaxial growth of a buffer layer (typically 30 nm of Y_2O_3 or CeO_2) and the superconductor.

Initially, we worked with small stationary substrates, usually 4 cm long x 1 cm wide. After critical current (I_c) values of over 100 A (75 K, self field) were reached [2], the next step was to modify our systems to coat longer lengths of moving tape. Details of the system modifications and a more complete description of the processing steps have been published previously [3].

2.1 One meter tape results

Throughout the course of tape development, the most important characteristic has been I_c, measured over the full tape length. In reality, however, this is simply a measure of the worst section in the tape, and is not very helpful in analyzing weaknesses and improving performance. To assist with the latter objectives, we developed a probe that consists of a series of voltage taps at 1 cm intervals with current applied at the tape ends. With this probe an I-V curve is generated, and an I_c value is obtained, for each centimeter of tape. The best uniformity that we have measured in this way is ± 20 % in a sample with an end-to-end I_c of 96 A [3].

Figure 1 shows a more recent result: an I_c of 122 A over a measurement length of 97 cm. In characterizing the uniformity of this tape, it was found that a 78 cm length had a somewhat higher I_c of 144 A, but as this measurement was being made damage occurred elsewhere in the tape.

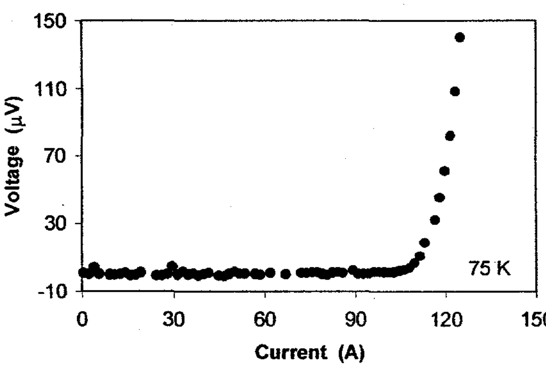

Figure 1. Current-Voltage curve for a 1 cm wide coated conductor with a critical current (1 μV/cm criterion) of 122 A over a 97 cm measurement length. The YBCO thickness is 1.4 μm.

A subsequent tape processed in the same manner yielded a similar result with one distinct difference: The end-to-end I_c was zero due to a resistive section somewhere in the tape. The search for this section produced the results shown in Figure 2. No voltage was measured for the first 25 cm at up to 100 A, and the measurement was halted. The same result was obtained for the central 50 cm, so a higher current limit was chosen and a transition was observed corresponding to an I_c of 110 A. This isolated the resistive section to the final 25 cm, so to more precisely pinpoint its location the first half of this section was measured next. No transition was

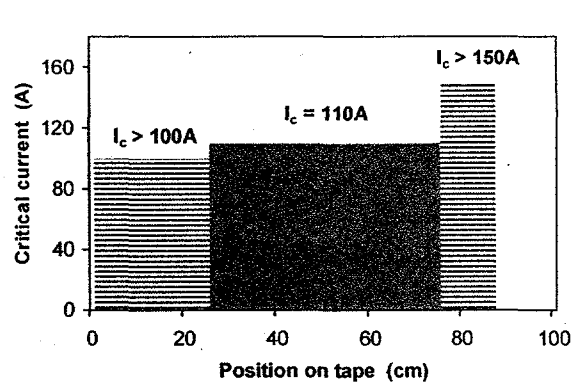

Figure 2. Critical current values (75 K) for three sections of tape. The section from 88-100 cm contained a resistive segment that was damaged at 150 A.

observed at up to 150 A, at which point damage occurred near the end of the tape, precluding the possibility of further analysis at this end.

Two things can be concluded from this measurement sequence: at least 88 cm of the tape had an I_c of between 100 and 110 A; and a better (i.e. nondestructive) measurement technique is needed in order to fully characterize high-current tapes.

2.2 Damage in high-current tapes

To determine the highest I_c in the tape of Figure 2, a section from the 75-88 cm region was removed and measured: A 3 cm length of this section had an I_c of over 200 A. In addition to helping in the evaluation of critical current uniformity, this result also helps illustrate the difficulty in making a segment-by-segment measurement. In Figure 3, an I-V curve for this high I_c section is compared to one from elsewhere on the same tape. In a typical measurement, current is ramped through the full length of the tape as voltage is monitored sequentially in each 1 cm length. The current ramp is terminated when the voltage reaches a few μV, which is sufficient to allow determination of a critical current value. In order to measure the best section, the applied current must exceed I_c for the rest of the tape, resulting in significant power dissipation as the voltage rises.

For example, in Figure 3, most of the tape has an

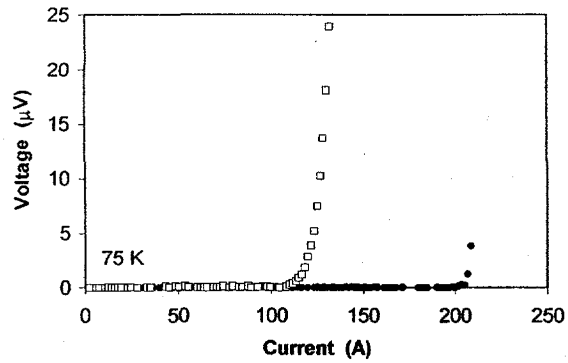

Figure 3. Two I-V curves from different sections of the tape of Figure 2. The curve at right is for a 3 cm section with $I_c = 207$ A, while the one at left is for a 3 cm section with $I_c = 120$ A. Without cutting the tape, the measurement at right would result in tremendous power dissipation in and damage to the section at left.

I-V characteristic represented by the curve at left. As I_c is approached and exceeded, the voltage rises as $V \propto I^n$, with an n-value of approximately 25. In order to measure the best segment (curve at right) it would be necessary to pass more than 200 A through the whole tape, causing the voltage in some areas to rise to perhaps 1 V, generating 200 W of resistive heating. So it is not surprising that, in very high current tapes, damage can result from this type of measurement.

3. A NEW MEASUREMENT TECHNIQUE

As our tape performance continues to improve, the need to non-destructively evaluate I_c is becoming increasingly acute. One possibility is to just make end-to-end measurements, which are "safe" because current does not exceed the lowest I_c in the tape. Unfortunately, this tells us nothing about I_c variations within the tape, and at the present stage of development, such information is vital. Another possibility would be to use four sliding or rolling electrical contacts, limiting the current-carrying portion of the tape to the part being measured. This technique was rejected (for now) because of the desire to keep the contact area small – about 1 cm^2 at each end – and the resulting requirement that the contact resistance be very low. We elected instead to continue to use soldered or clamped current leads at each end of the tape and determine segment-by-segment I_c values by means of a pair of sliding voltage taps attached to a moveable carriage. A pair of NdFeB permanent magnets, riding on the carriage between the voltage taps, generates a ≈ 0.6 T magnetic field parallel to the YBCO c-axis. This field considerably reduces I_c of the section being measured and, in turn, lowers the current outside of the measurement area to a non-damaging level. A schematic of this measurement system is shown in Figure 4.

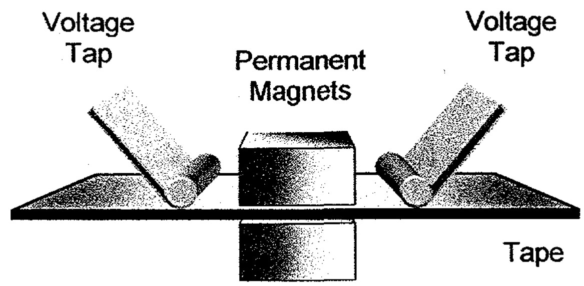

Figure 4. Schematic of the probe used to make in-field segment-by-segment I_c measurements on a meter-long tape. The voltage taps and magnets are attached to a moveable carriage that is driven by a lead screw and stepper motor; the magnetic field is 0.5 - 0.6 T over 1 cm^2 at the tape surface, and is parallel to the YBCO c-axis. Under computer control, the carriage is positioned, current is applied at the ends of the tape, an I-V curve is generated and recorded, the carriage is moved to the next position (a 1 cm step size is typical), and the process is repeated until the full tape has been measured.

3.1 Initial Results

Figure 5 compares two sets of results for an early tape with an end-to-end critical current of 29 A. The bars represent the original characterization of each centimeter in self-field, showing that I_c values ranged from 27 to 63 A [4]. (It was possible to fully characterize this tape in self field because, in general, the kind of tape damage described in Section 2.1. does not occur at I_c levels below 120 A.) The open circles were obtained by remeasuring the tape with the permanent-magnet probe.

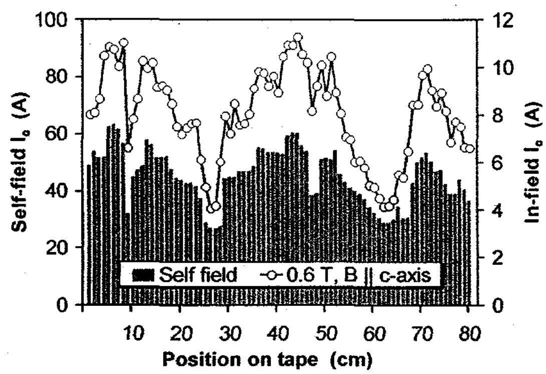

Figure 5. Critical current at 75 K for each cm of a tape with an end-to-end I_c of 29 A. The values in self field (bars) are roughly six times higher than those obtained from the permanent-magnet probe (see text).

3.2. Comparison with self-field results

In Figure 5 there appears to be a direct relationship between the I_c values in self-field and at 0.6 T, with the latter being lower by a factor of about six. This is confirmed in Figure 6, which shows that the scale factor is nearly independent of self-field I_c, although it does decrease by about 15% over the full measurement range. A constant scale factor is advantageous in that it would allow us to quantitatively determine tape uniformity without risking damage in a self-field measurement.

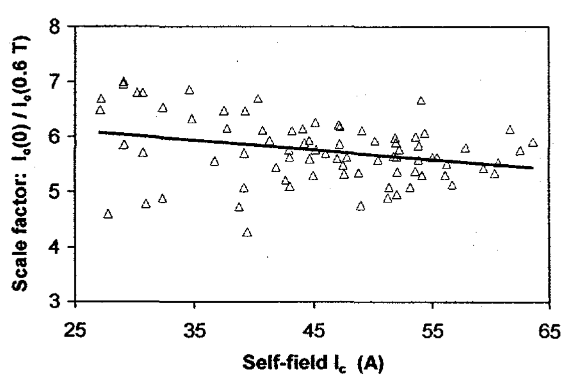

Figure 6. For the tape of Figure 5, the ratio of self-field to in-field critical current is nearly constant. The shallow downward trend for higher I_cs (indicated by a linear regression fit) may be significant for very high current samples.

However, in more recent tapes we have measured in-field I_c levels of 60-100 A: Scaling by the factor of six suggests that the corresponding self-field values could be as high as 600 A, but, as desirable as this would be, our best material at present is limited to I_c values of 200 – 250 A [5]. For these high-current materials, then, the scale factor must be lower, perhaps in the range of 2-3. This decrease would be consistent with the downward slope in the data of Figure 6, which extrapolates to a scale factor of 2.7 at a self-field I_c of 225 A; the implication is that there is a systematic relationship between the two quantities. Other possible explanations are that the greater supression by field in lower-I_c material is due to a higher concentration of weak links or other microstructural defects, or variations in the enhanced flux pinning that is sometimes observed when B is aligned with the c-axis [6-8]. While this will be an interesting area for future research, the permanent magnet probe has already become an indispensable part of our program by allowing us to safely and fully characterize high-current coated conductors.

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