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*Title:* Continuous Processing YBCO/IBAD Coated Conductors on Flexible Substrates

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# CONTINUOUS PROCESSING OF YBCO/IBAD COATED CONDUCTORS ON FLEXIBLE SUBSTRATES

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## ABSTRACT

A continuous coating system has been developed for depositing $YBa_2Cu_3O_{7-\delta}$ (YBCO) on 1 cm wide flexible tapes up to 113 cm long. Our best result to date is a 12 cm long tape with a critical current ($I_c$) of 70 A at 75 K. Variations along the length of the tape limited the overall current, but indicated the potential for long length critical currents in excess of 100 A.

## INTRODUCTION

A number of organizations in Japan, Europe and the United States have produced thick YBCO films capable of carrying over 100 A of supercurrent per cm width at liquid nitrogen temperature; Los Alamos, for example, has achieved a critical current of nearly 200 A (75 K, self field) on a 1 cm wide x 4 cm long Ni-alloy strip. Coatings on this strip consisted of a textured YSZ layer produced by ion beam assisted deposition (IBAD) and a 2 μm thick YBCO film produced by pulsed laser deposition (PLD). The strip was fabricated in a batch process, with both the IBAD and PLD layers coated on stationary substrates, that is not capable of generating the long lengths of coated conductor required for most applications. In order to demonstrate that high-current coated conductors can be produced in a continuous process, we have developed a system capable of coating meter lengths of 1 cm-wide tape with high-quality YBCO.

## CONTINUOUS COATING

For these initial experiments the IBAD layer was not produced continously, but rather a 21 cm long stationary tape was coated using a 5 cm diameter ion-beam sputtering source and a 23 cm x 2.5 cm linear ion-assist gun. Significant modifications were required, however, for the YBCO layer, dictated primarily by the need to deposit the superconductor at elevated temperature. Whereas shorter samples can simply be pasted to a heater, a continuous deposition process requires heating a moving tape to between 700 and 800°C in the area where deposition is occurring. This has been accomplished in Japan [1] by sliding the tape over a heated block. In the present work we describe a different technique, involving deposition on a tape that is both conductively heated and driven by a hot roller. An experimental schematic is shown in Figure 1. In order to simplify this prototype, it was configured to coat a continuous loop (as opposed to using reel-to-reel tape transport), and was constructed of standard vacuum hardware with 6 inch flanges. The heater consists of a 2 ½ inch diameter nickel disk with a coaxial heating element brazed inside; thermocouple and power leads exit the vacuum chamber through a rotating hollow

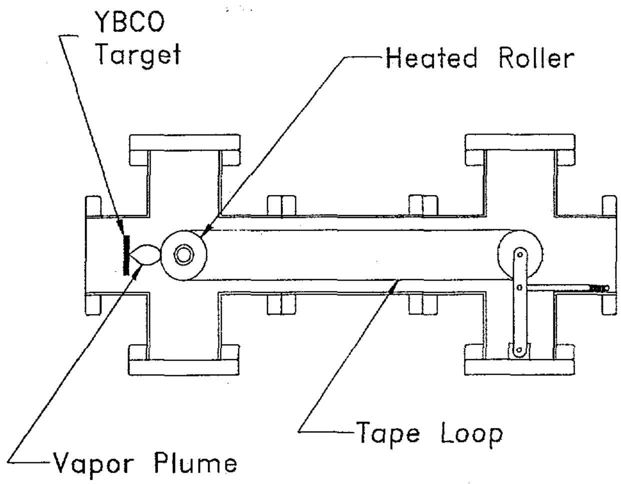


Figure 1. Schematic diagram of continuous-loop tape coater.

shaft that is driven by an external stepper motor through a worm gear. The stepper motor speed range allows for linear tape speeds from about 1 mm/minute to 24 cm/minute. A 1 μm film can be deposited at 1 cm/minute at relatively low laser power. The target is attached to a magnetically-coupled rotating feedthrough that can be translated into a load lock (not shown in figure) to permit target changes without breaking main vacuum.

During deposition, typical roller temperature is 840°C, giving a tape temperature -- determined separately by a thermocouple spot-welded to a bare tape; or, during deposition, by optical pyrometry -- of about 790°C. Deposition pressure is 0.2 Torr oxygen, and since the tape cools to room temperature as it comes off the roller, a separate anneal at 450°C and 1 atm. $O_2$ is required to convert the YBCO to the superconducting orthorhombic phase. In order to coat the 21 cm long tape strip produced with the linear-gun IBAD system, it was spot-welded to a length of bare tape to make up a loop of the proper length. The tape used in this study was Inconel 625 of 100 μm thickness that had been mechanically polished to a RMS surface roughness of 100 Å.

RESULTS

The best result to date from this system is an $I_c$ of 70 A over a 12 cm measurement length. (Some of the original 21 cm length was lost due to spot welding the ends, removal of end pieces after deposition for checking transition temperature ($T_c$), and attachment of current leads). To prepare the strip for this measurement, it was first coated with 1 μm of silver, which was annealed at 550°C for 30 minutes to improve adhesion and contact resistance. Then current leads and voltage taps were attached with indium solder, and a standard 4-point I-V curve was generated.

To investigate uniformity of electrical properties along the sample length, the silver was then removed from the strip, it was cut into 1 cm lengths, and each segment was patterned into a 500 μm x 5 mm bridge for critical current density ($J_c$) and resistance vs. temperature measurements. X-ray ϕ-scans on both the YSZ (111) and YBCO (103) peaks were also conducted, with the results shown in Figure 2 . Because of roll-off of both vapor flux and assist ion current in the IBAD system, the YSZ in-plane alignment is slightly degraded at the tape ends, but is excellent in general. As usual, the YBCO texture is 5-6° sharper than that of the YSZ template; slight deviations may be due to measurement of the YBCO on patterned bridges, while the full area of YSZ, which was not affected by patterning, was available for the x-ray analysis. Figure 3 is a plot of segment-by segment transport critical current density measurements on the microbridges. The YBCO thickness is 1.7 μm. Given the 70 A $I_c$ of the overall tape, the average $J_c$ is somewhat in excess of 400 kA/cm$^2$ and is indicated by the solid line in the figure. Considerable variation in $J_c$ is evident -- the highest segments are in the range of 800 kA/cm$^2$, while the lowest is 290 kA/cm$^2$. One question is why the lowest individual $J_c$ is below the average for the tape as a whole. A possible explanation is that of a sampling error: The tape is not perfectly uniform in the lateral direction, and a 0.5 mm wide bridge is not adequately representative of a 10 mm wide tape. Nonetheless, the non-random appearance of the variations (i.e. fairly uniform $J_c$ except for the dip in the middle of the tape) suggest that the higher values of $J_c$ are indicative of the potential of this coating process once the cause of the weak areas is identified and removed. If this is the case, then $I_c$ values well in excess of 100 A can be expected.

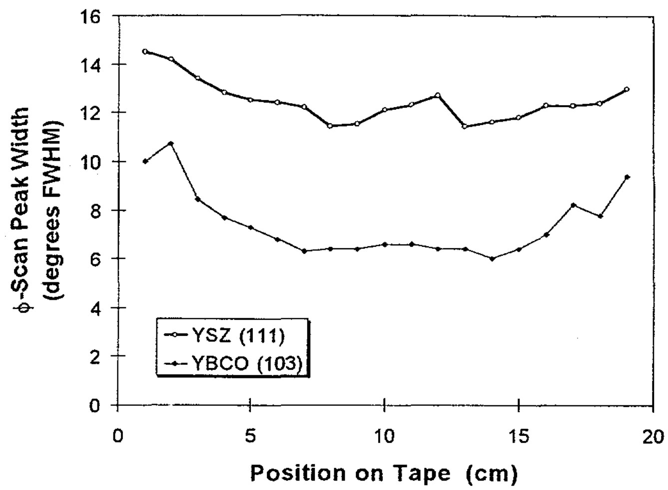


Figure 2. Variation of in-plane texture along tape length.

The task, then, is to search for and eliminate the cause(s) for $J_c$ reduction in the center of the tape. One obvious possibility is that, because of incomplete contact between roller and tape, the substrate temperature during deposition fell outside of the range necessary for high $J_c$. This seems unlikely for several reasons, including the uniform appearance of the coating (low temperatures produce black shiny films, while the surface is gray and rough if the temperature is too high); experiments with a thermocouple spot-welded to a moving tape, which measured temperature variations within ±10°C; and the results shown in Figure 4, which demonstrate that the lowest Jc segments are not correlated with drops in Tc, as would be the case for deposition outside the optimum temperature range.

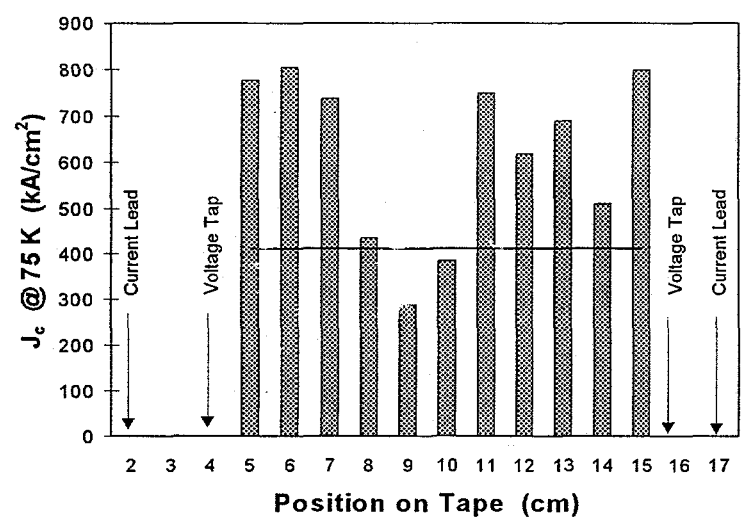


Figure 3. Critical current density for 12 cm tape with an $I_c$ of 70 A. Bars represent segment-by-segment $J_c$s, solid line is average $J_c$ for entire tape. YBCO film thickness is 1.7 μm.

Other possible causes for low Jc in segments 8-10 include poor texture (already ruled out in Fig. 2), oxygen deficiency (ruled out by x-ray analysis of c-axis lattice constants), a-axis film growth (ruled out by x-ray

$\chi$-scans), cracks (ruled out by SEM examination), and contamination due perhaps to film-substrate interdiffusion. The latter is currently under examination by TEM, and will also be investigated by surface analysis techniques such as SIMS.

In evaluating the change from a batch, paste-up process for YBCO to a continuous one with a moving substrate, it is useful to compare the present results to those achieved previously with pasted substrates. Published results[2] for $I_c$ values on 1 cm wide x 4 cm long strips of IBAD-coated Hastelloy indicate that $J_c$ varies with in-plane texture as:

$$J_c(\phi) = 3.25\ e^{-0.23\phi}\ (\mathrm{MA/cm^2}) \qquad (1)$$

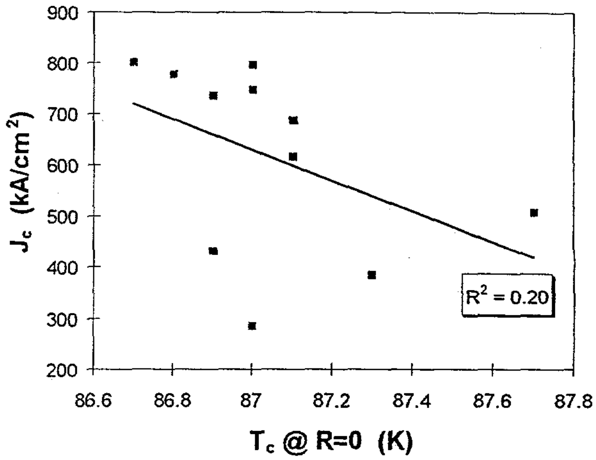


Figure 4. Relationship between $T_c$ and $J_c$ for segments of the 12 cm tape. Although there appears to be a weak tendency toward lower $J_c$ as the $T_c$ increases, the low $J_c$ segments are well below this trend line. The solid line is a linear regression fit to all the data.

The average YBCO texture over the 12 cm measurement length is 6.9° FWHM, so the expected $J_c$ is 665 kA/cm$^2$. However, the film thickness in this study was 1 μm, and the thickness for the long tape is 1.7 μm, and other published data [3] indicate that $J_c$ for YBCO on single-crystal YSZ decreases with film thickness as:

$$J_c(t) = 4.7\ e^{-1.2t} + 1.05\ \ (\mathrm{MA/cm^2}) \qquad (2)$$

Thus, $J_c$ for a 1.7 μm film should only be 67% of that for a 1 μm one. Therefore, for the same texture and thickness as on the 12 cm tape, we would have expected 450 kA/cm$^2$ from a batch-processed sample, which compares favorably with the average value of 410 kA/cm$^2$ that was actually achieved with the continuous process.

## CONCLUSIONS

We have demonstrated that the production of high-current YBCO coatings on flexible substrates can be scaled from a batch to a continuous process for the fabrication of long lengths. Future work will center on improving $I_c$ uniformity and developing a continuous IBAD process leading to tape lengths in excess of 1 meter.

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