Study on deposition of YBCO for coated conductor using pulsed laser deposition

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Abstract. YBa$_2$Cu$_3$O$_x$ (YBCO) superconductors were coated on the CeO$_2$/YSZ/Y$_2$O$_3$ buffered Ni5W tape by reel-to-reel pulsed laser deposition (PLD). To achieve high current carrying capacities, combinations of various deposition conditions were explored. X-ray diffraction measurements showed good in-plane and out-plane texture in YBCO films. The transition temperature of the coated YBCO was typically 89 K. The critical current is over 50 A at 77 K in meter-long YBCO tapes with a width of 1 cm. Their surface morphology was found being thickness-dependent. Further research work is under way.

1. Introduction
The intensive research has been made to develop the second generation YBa$_2$Cu$_3$O$_x$ (YBCO)-based coated conductors for various applications. It is of great interests to establish a highly reliable and relative simple process to fabricate such coated conductors. At the present stage of development, the Rolling Assisted Biaxially Textured Substrate (RABiTS) method has been widely employed [1-3]. The YBCO films, on the other hand, are typically grown by pulsed laser deposition (PLD) [4-6]. To block the severe interaction between YBCO and substrate, buffer layers play a crucial role. Different materials and their combinations have been developed as buffer for coating YBCO on metallic tapes. However, the growth of a thicker YBCO film on a metal substrate, which is difficult to maintain a good c-axis alignment, still presents a real challenge [7-8].

We report a successful fabrication of YBCO on buffered metallic NiW tapes. The YBCO conductor is coated by using a self-designed reel-to-reel PLD system. The deposition conditions such as substrate temperature, laser repetition rate, deposition rate, oxygen pressure, etc. were optimized to gain a high current carrying capacity. Attention was also focused on the effect of the tape moving speeds on the critical current of YBCO. The transition temperature of the coated YBCO was typically 89 K. The critical current is over 50 A at 77 K in meter-long YBCO tapes with a width of 1 cm.

2. Experimental
A reel to reel PLD system designed by ourselves had been set up for deposition of YBCO. In brief, it was a PLD system with a reel to reel mechanism. The background pressure could reach 5×10$^{-3}$ Pa. Non-contact heater assemblies met the needs of deposition temperature as high as 850°C. The deposition temperature was monitored by a thermocouple located near the moving tape. The tape was driven by stepper motors and could freely move forth and back. The moving speed of the tape could be varied in a range of 0.01mm/sec to 10mm/sec. The tension on the tape was monitored by a tension sensor and controlled by a computer.
Biaxially textured Ni-5at%W tapes with a width of 1 cm and thickness of 80 µm, prepared by the RABiTS approach, were used as substrates. Prior to the deposition of YBCO, a tri-layer epitaxial buffer of CeO$_2$/YSZ/Y$_2$O$_3$ had been prepared on cube texture NiW tapes using magnetron sputtering. The details of CeO$_2$/YSZ/Y$_2$O$_3$/NiW buffer layers fabrication were published elsewhere [9].

YBCO layers were coated continuously on the buffer surface with a KrF Excimer Laser (LPX Pro220). Laser pulse energy was 200-300 mJ. The incident angle of laser beam was 45° and the laser pulse repetition rates were 5-80 Hz. High density YBCO disc were used as the ablation target. The YBCO target was rotated during deposition in order to keep the flat ablation surface of the target. The other experimental parameters were listed in table 1. The thickness of YBCO was obtained by controlling the tape moving speeds and the laser pulse repetition rates. Film thickness was measured with a Dektak II D step-profilometer.

Table 1. YBCO deposition parameters

| Parameter                              | Range  |
|----------------------------------------|--------|
| Background pressure (Pa)               | < 3×10$^4$ |
| Deposition temperature (°C)            | 760~820 |
| Oxygen pressure (Pa)                   | 10~80  |
| Energy density (J/cm$^2$)              | 1.5~2.5 |
| Laser pulse repetition rate (Hz)       | 5~80   |
| Distance from target to tape (mm)      | 40~65  |
| Reel to reel tape moving speed (mm/s)  | 0.075~0.4 |
| Annealing temperature (°C)             | 480~530 |
| Annealing time (min)                   | 20~60  |
| Film thickness (µm)                    | 0.3-2.5 |

The epitaxy and crystallinity of the grown samples were characterized by X-ray diffraction (XRD) measurements. The surface morphology was evaluated by scanning electron microscopy and atomic force microscopy. The critical current $I_c$ was determined by a conventional four probe method using a criterion of 1 µV/cm with 1.0 cm wide sample. $I_c$ and $J_c$ measurements were operated at 77 K and in self magnetic field.

3. Results and discussions

To improve the critical current, one simple way is to increase the thickness of YBCO layer. In this work, two approaches were used to enlarge the thickness of YBCO film. One method was to increase the deposition rate by controlling the laser pulse repetition rates. Another way was to alter the deposition time by changing the tape moving speeds during the deposition.

Figure 1 and figure 2 showed the XRD θ-2θ scans of YBCO deposited with different repetition rates (Hz) and different tape moving speeds (mm/s) on CeO$_2$/YSZ/Y$_2$O$_3$/NiW tapes, respectively. In figure 1 the spectra indicated that all YBCO films at different repetition rates had a pure c-axis alignment except the one at 60 Hz. YBCO film deposited at 60 Hz repetition rate not only had (00l) reflections, but also (h00) reflections. The (h00) reflections were not observed at the other repetition rates. When the other experiment conditions were constant, the higher the laser repetition rate was, the larger the YBCO film thickness was, and the a-axis alignment appeared. In our experiment, the same result was observed when YBCO was deposited at different tape moving speeds, showed in figure 2. The YBCO layer became thicker when the tape moved slowly, if the laser repetition rate was a constant.
In our PLD system, the tape was heated from the back side by Halogen lamps during the deposition. This heating method made the tape surface temperature drop as the YBCO layer became thicker. At this situation the (h00) reflections of YBCO appeared. Figure 3 showed the XRD $\theta$-2$\theta$ scans of YBCO deposited on buffered metal tapes with different substrate temperature. It was clearly seen that strong a-axis appeared when the relative deposition temperature was lower, and it became weaker as deposition temperature was higher. The XRD $\phi$-scan and pole figure were employed to characterize the orientation and in-plane texture of films. Figure 4 displayed the XRD pole figure for YBCO (102) peak grown at lower temperature, which presented both c and a-axis alignment. The amounts of a-axis oriented grains of YBCO ($A_{a}=100 \times \frac{I(200)}{I(200)+I(006)}$) were investigated. The deposition temperature and the film thickness for YBCO dependence of $A_{a}$ were shown in figure 5 and figure 6, respectively. They indicated that $A_{a}$ was increased at the lower growth temperature or more than 2$\mu$m thickness.

The surface morphology for YBCO with different laser repetition rates were observed by scanning electron microscopy (SEM) showing in figure 7. The YBCO thickness increased as adding laser repetition rate or reducing the tape moving speed during YBCO growth. In this situation the surface morphology for thicker film became much rougher than that of thinner one, which made the surface temperature of YBCO decrease and the amount of a-axis orientation in YBCO increase. The formation of a-axis oriented grains was harmful for the increasing $I_{c}$ value of YBCO.
XRD ω-scan (rocking curve) and φ-scan were employed to characterize the out-of-plane and in-plane alignment for YBCO. The YBCO films showing in figures 8 and 9 were deposited on the buffered tapes with 40 Hz repetition rate, 780°C growth temperature and 0.1mm/sec tape moving speed. The thickness of YBCO was about 1.8µm. Figure 8 showed the YBCO (006) ω-scan which full width at half maximum (FWHM) was about 3°. Figure 9 showed the φ-scan of YBCO (103) peak. It revealed that the diffraction peaks of (103) φ-scan appeared at 90° intervals and had a four-fold symmetry, which FWHM value was 8°. It was the best result we had got. But for 1 meter long tape, the average φ-scan FWHM value was more than 10° which was not good enough to obtain high $I_c$. Experimental parameters with 10 Hz repetition rate, 780°C growth temperature and 0.1mm/sec tape moving speed were also used to deposited YBCO films. The results showed similar tendency to the 40 Hz. The YBCO films grown at 10 Hz with 780°C and 0.1mm/sec tape speed showed the best out-of-plane and in-plane alignment with ω-scan FWHM of 3° and φ-scan FWHM of 8°. However, for longer tapes, the average φ-scan FWHM was more than 10° which was not good enough to obtain high $I_c$. The YBCO films with optimized parameters were deposited on the buffered tapes and characterized by XRD, SEM, and other techniques. The results showed that the YBCO films with optimized parameters had excellent superconducting properties, which were suitable for various applications in superconductivity technology.
moving speed were used for 1 meter-long YBCO tape, which thickness was about 0.5 µm. The superconducting transition with zero-resistance critical temperature $T_c$ was 89 K. The critical current transport measurement at 77 K, self field with the 1 µV/cm criterion and 1 cm wide was 50 A.

4. Conclusion
The base reel to reel process has been obtained with PLD system. A series of YBCO films have been deposited with different deposition temperature, laser repetition rates and tape moving speeds. It has been found that either increasing laser repetition rate or reducing the tape moving speed could enhance the YBCO film thickness. The meter long-length YBCO have been successfully grown on biaxially textured multi-layer CeO$_2$/YSZ/Y$_2$O$_3$ buffer layers using PLD technique. YBCO samples with $T_c$ 89 K and $I_c$ 50 A/cm-width (77 K, 0T) have been made successfully on buffered NiW tapes. Further research is underway.

5. References
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