

RESIDUAL STRESS MEASUREMENT IN YBCO THIN FILMS*

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ABSTRACT

Residual stress in YBCO films on Ag and Hastelloy C substrates was determined by using 3-D optical interferometry and laser scanning to measure the change in curvature radius before and after film deposition. The residual stress was obtained by appropriate analysis of curvature measurements. Consistent with residual thermal stress calculations based on the thermal expansion coefficient mismatch between the substrates and YBCO film, the measured residual stress in the YBCO film on Hastelloy C substrate was tensile, while it was compressive on the Ag substrate. The stress values measured by the two techniques were generally in good agreement, suggesting that optical

interferometry and laser scanning have promise for measuring residual stresses in thin films.

INTRODUCTION

In recent years, substantial effort has been concentrated on processing Y-Ba-Cu-O (YBCO)-based coated conductors by various techniques because of their potential to provide improved electrical properties in magnetic fields [1,2]. Typical processing approaches include ion-beam-assisted deposition, rolling-assisted biaxially textured substrate method, pulsed laser deposition (PLD), e-beam co-evaporation, and metal organic deposition [3-7]. In a coated conductor system, a metallic or ceramic substrate is coated with a ceramic superconductor (i.e., YBCO) with buffer layers in between that act as diffusion barriers between the substrate and YBCO film. Various substrates such as LaAlO_3 , Hatelloy C, nickel, and silver (Ag) have been used to process coated conductors. Because the various layers in coated conductors have different expansion coefficients, residual strains (and hence stresses) develop in different layers during processing. These stresses may cause microcracking and damage of the superconductor layer, resulting in degradation of superconducting properties and reduction in service life. Therefore, it is critical to evaluate residual stresses in coated conductors and understand the role of various processing parameters that influence these stresses.

Several techniques can be used to measure residual stresses in various thin layers (films) of coated conductors. X-ray diffraction [8] has been used to measure residual stresses in films by determining the change in lattice spacing due to the stresses. In addition,

the curvature measurement technique [9] has been used to measure residual stresses in films by evaluating the change of the radius of curvature of the film as a result of the stresses. In this study, we determined the residual stresses in YBCO films on Ag and Hastelloy C substrates by a curvature measurement technique using 3-D optical interferometry and laser scanning.

MATERIALS AND METHODS

Coated conductors using YBCO films on Ag and Hastelloy C substrates were processed by the PLD technique. The substrates (1.5 cm x 1.2 cm) were polished to an approximately 1 μm finish on both sides and were subsequently subjected to an ultrasonic cleaning to obtain flat and clean surfaces. The substrate thickness (ranging from 30 μm to 200 μm) was measured by scanning electron microscopy.

The PLD process was carried out with a Lambda Physik COMPex 201 Excimer laser having a Kr-F₂ gas mixture as the laser medium [10]. The substrates were placed on a rotating inclined sample holder. The samples were glued to the holder with a silver paste and were heated to 700-800°C during the deposition process. A commercial YBCO target (1 inch in diameter and 0.25 inch thick) was used and the distance from target to substrate was maintained at 4-8 cm. The oxygen partial pressure in the deposition chamber was maintained in the range of 100-300 mTorr by flowing ultra-high-purity oxygen through the chamber. The energy density for deposition was estimated to be $\approx 1-3 \text{ J/cm}^2$. The thickness of the deposited YBCO films was measured

to be ≈ 300 nm. Four PLD specimens were prepared for each substrate. The details of the deposition process are described in Reference [10].

Residual stresses in the YBCO films on Ag and Hastelloy C substrates were evaluated by measuring the change in the radius of curvature of the substrates before and after the film deposition. It was assumed that the curvature change in substrate also represents the change in curvature of the film in the absence of film delamination. The radius of curvature was measured by 3-D optical interferometric surface mapping [11] and laser scanning [12]. For both the optical and laser scanning methods, three to five curvature measurements in the x- and y-directions were made for each specimen (Fig. 1).

In the optical interferometric technique, the curvature of the film was determined by counting the number of interference fringes [13]. In the laser scanning technique, a laser beam was reflected off the curved surfaces of the coated substrate specimens. A rotating mirror guided the reflected laser beam to scan the curved surface in the desired direction. A position-sensitive photodetector determined the intensity change in the reflected beams from different locations resulting from the surface curvature [13]. The radius of curvature (R) was obtained from the gradient (κ) of the plot representing laser detection intensity as a function of mirror position (Fig. 2). With the measured value of κ , the radius of curvature was calculated from Equation 1 [12].

$$R=2/(0.36442\kappa) \quad (1)$$

Subsequently, the residual stress (σ) in the YBCO film was estimated from Equation 2 [14].

$$\sigma = E_f t_s^2 / (6\Delta R t_f) \quad (2)$$

In Equation 2, $E_f = E/(1 - \nu)$ is the bi-axial Young's modulus of elasticity, where E is the Young's modulus of elasticity, and ν is Poisson's ratio. Also, ΔR is the difference in the radius of curvature of the film (or the substrate) before and after the film deposition, t_s is the substrate thickness, and t_f is the film thickness. The thicknesses of the substrate and film were measured by scanning electron microscopy, and the elastic moduli were taken from the literature (Table 1) [15, 16].

RESULTS AND DISCUSSION

The optical interferometric images in Fig. 3 show the curvature of the two substrates before and after YBCO deposition. These images were constructed by computer based on an interference fringe analysis and were subsequently used to determine the radius of curvature of different substrates before and after the YBCO film deposition. Table 2 shows the radii of curvature measured by optical interferometric and laser scanning techniques for Hastelloy C and Ag substrates before and after deposition of YBCO film. From Table 2, the change in the radius of curvature (ΔR) after film deposition was derived for the different substrates and techniques. The residual stresses in the YBCO film were then estimated by substituting the measured values of ΔR , t_s , and t_f into

Equation 2. These measured stresses are plotted in Fig. 4. We also estimated the residual stresses (σ) due to the thermal expansion mismatch by analytical approach, using Equation 3 [17].

$$\sigma = \frac{E}{(1 - \nu)} \Delta \alpha \Delta T \quad (3)$$

where E and ν are the elastic modulus and Poisson's ratio of the film, respectively; $\Delta\alpha$ is the difference in thermal expansion coefficients of the substrate and the film; and ΔT is the difference between the room and processing temperature. For comparison, these calculated values of the residual stresses are shown in Figure 4.

As seen in Figure 4, there is a reasonably good agreement between the stress values measured by the optical and laser techniques. The residual stresses in the YBCO film on Hastelloy C substrate were measured to be 47 and 76 MPa by the optical and laser methods, respectively. The corresponding stresses in the YBCO film on Ag substrate were measured to be 1024 and 1078 MPa. However, these measured values differed from the residual stresses calculated from the thermal expansion coefficient mismatch with Equation 3: 160 MPa for Hastelloy C substrate and 882 MPa for Ag substrate.

We reached three important conclusions from our results. First, the residual stresses in YBCO film on Hastelloy C substrate are tensile, while the stresses are compressive for the Ag substrate. This is inferred from the expansion coefficient of YBCO being larger

than that of Hastelloy C and smaller than that of Ag (Table 1). Second, the measured tensile stress in the YBCO film on Hastelloy C substrate is slightly smaller than the calculated value, whereas the measured compressive stress in the film on Ag substrate is slightly larger than the calculated value (Fig. 4). This difference is believed to be due to the presence of an internal compressive stress that developed during the PLD processing due to Ar ion-peening effects. Verification of this hypothesis is underway. Third, the residual stresses measured by the two techniques with the same substrate are the same order of magnitude (Fig. 4), indicating that these techniques show considerable promise for stress measurements in thin YBCO films.

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Table 1. Mechanical and physical properties of Hastelloy and Ag substrates and YBCO

	Hastelloy C ¹⁵	Ag ¹⁵	YBCO ¹⁶
Melting Temperature (°C)	1300	961.9	1270
Thermal Expansion Coefficient (10 ⁻⁶ K ⁻¹)	12.5	19.4	13.4
Elastic Modulus (GPa)	170-220	100	135-157

Table 2. Radius of curvature measured by optical interferometric and laser scanning methods for Hastelloy and Ag substrates before and after deposition of YBCO film.

	Optical Interferometry		Laser Scanning	
	Hastelloy C	Ag	Hastelloy C	Ag
Radius of Curvature before Deposition (μm)	2.07e+05	4.92e+05	2.18e+05	5.12e+05
Radius of Curvature after Deposition (μm)	2.06e+05	6.02e+05	2.16e+05	6.46e+05

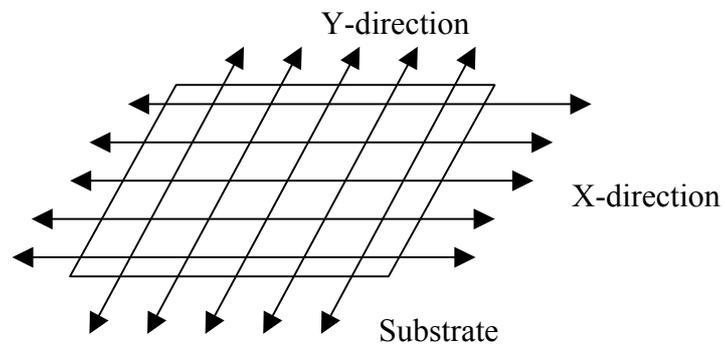


Fig. 1. Schematic showing x- and y-directions on the measured curved substrates.

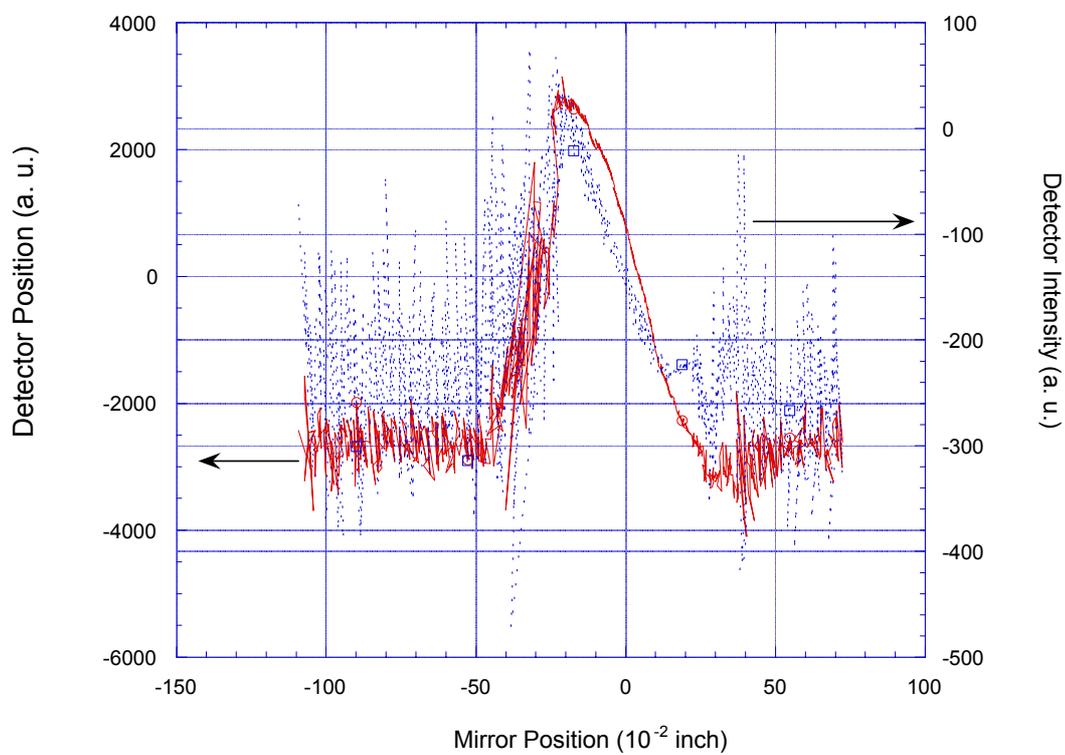


Fig. 2. Typical variation of laser detection intensity as a function of mirror position.

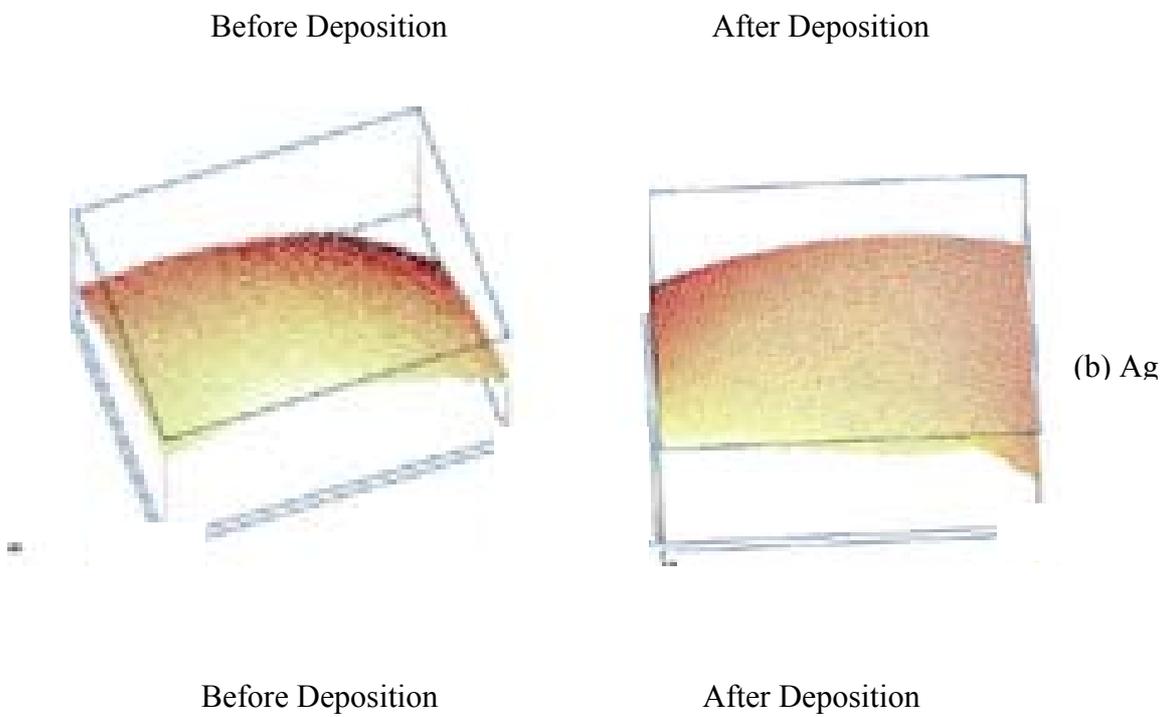
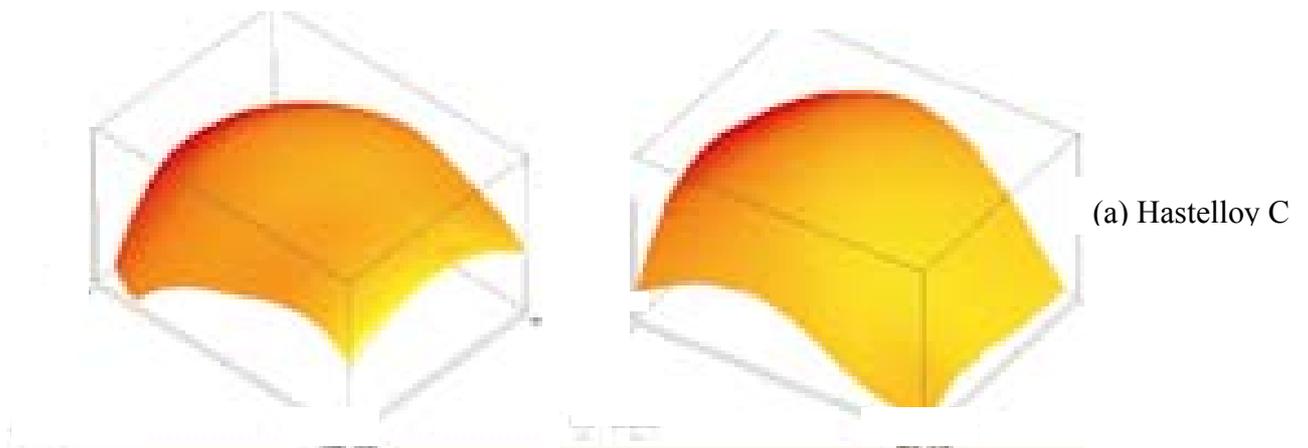


Fig. 3. Optical interferometric images showing the curvature of substrates before and after YBCO deposition on (a) Hastelloy C and (b) Ag substrates.

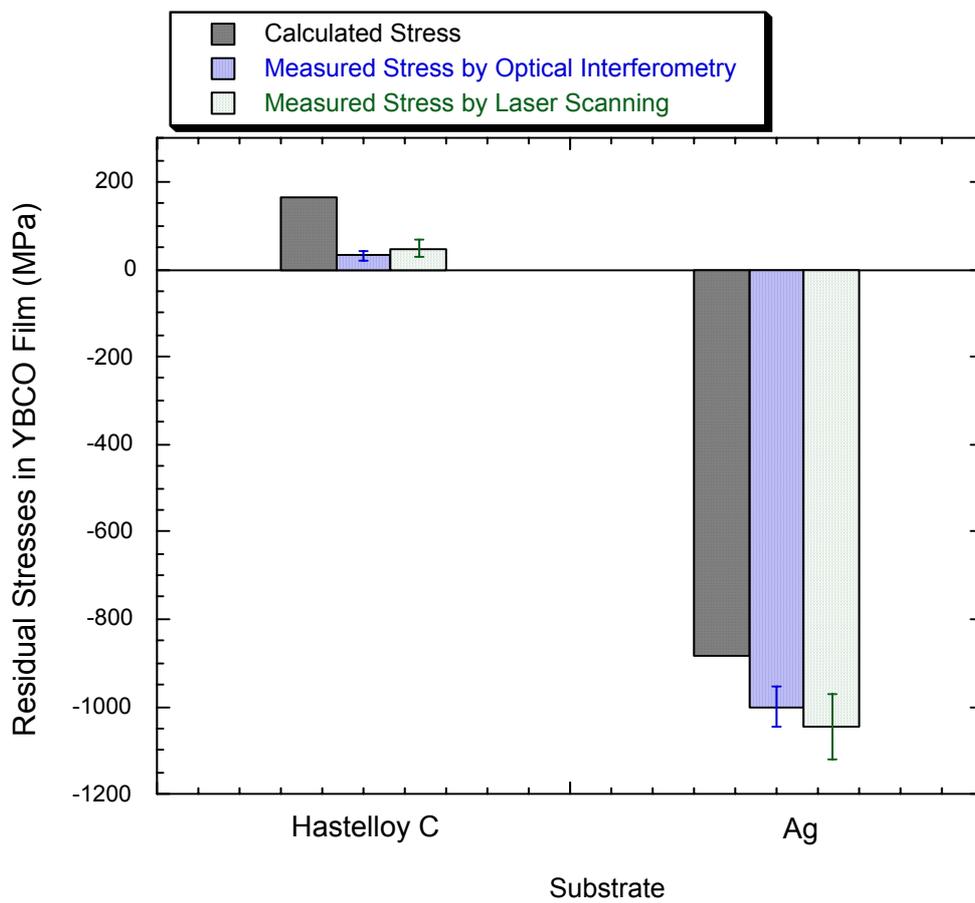


Fig. 4. The measured and calculated (based on thermal mismatch) residual stresses in YBCO films on Hastelloy C and Ag substrates.