IEEE Trans. Appl. Superconductivity, 7(2), 1319-1322, June 1997

Noncontacting Ultrasonic and Electromagnetic HTS Tape NDE

K.L. Telschow, F.W. Bruneel, J.B. Walter, L.S. Koo
Idaho National Engineering Laboratory, Idaho Falls, ID 83415-2209, USA

Abstract--Two noncontacting nondestructive evaluation techniques, one electromagnetic the other ultrasonic, for inspection of high temperature superconducting tapes are described. Results for Ag-clad BSCCO tapes are given.

INTRODUCTION

The goal of this nondestructive evaluation (NDE) research is to measure critical properties of materials in the laboratory in a manner that is suitable for industrial geometries and fabrication methods. The manufacture of high temperature superconducting (HTS) tapes is a good model because tapes are long lengths of a superconducting layer encapsulated within a silver sheath. *Noncontacting*, quantitative determination of the local low field critical current density, $J_C(H=0)$, is useful for monitoring processing parameters and spatial uniformity. Transport critical currents are most often measured by contact 4-point probes; however, noncontacting electromagnetic measurements are faster and easier. This approach consists of measuring the induced currents in the tape with small source/pickup probe coils that spatially scan over the surface [1-5]. Subsequently, the Bean critical state model is used to determine $J_C d$, where d is the local layer thickness, from the measured magnetic hysteresis. This approach measures the transport critical current density since intergrain critical current density is usually much smaller than intragrain critical current density. However, to obtain the local layer thickness or critical current independently, an additional measurement must be made. Ultrasonic wave propagation is a good probe for that measurement as it is dependent on layer thickness, elastic constants, and texture (anisotropy). In addition, using lasers for both generation and detection of elastic waves makes this method noncontacting and allows scanning along the tape with high spatial resolution [6]. This paper describes the first measurements of this type on Ag-clad BSCCO tapes.

ELECTROMAGNETIC PROBE

The electromagnetic scanning method is shown in Fig. 1. An oscillating current forces flux to enter the tape to a depth dependent on the local value of $J_C d$. When the full penetration value is exceeded, flux leaks through the tape and is measured by a pickup coil on the other side of the tape. Using alternating currents allows the use of lock-in techniques with small coil diameters, resulting in spatial resolutions of 1 mm or less. The value of the flux that leaks through can be used as a probe of local tape uniformity by scanning the two coils together along the tape. Scanning results along a sample of Ag/clad BSCCO (2223) tape with an average critical current of around 1000 A/cm^2 are shown in Fig. 1. The upper trace, obtained at room temperature, shows that the total tape thickness is essentially uniform. The lower trace shows local variations in the $J_C d$ product that identify nonuniformities produced by the fabrication process. Local variations in J_C, thickness, intergrain contacts, and grain orientation all affect the scanning results.

LASER ULTRASONIC MEASUREMENTS

Ultrasonic wave propagation in tapes offers an additional NDE measurement method with the potential for determining

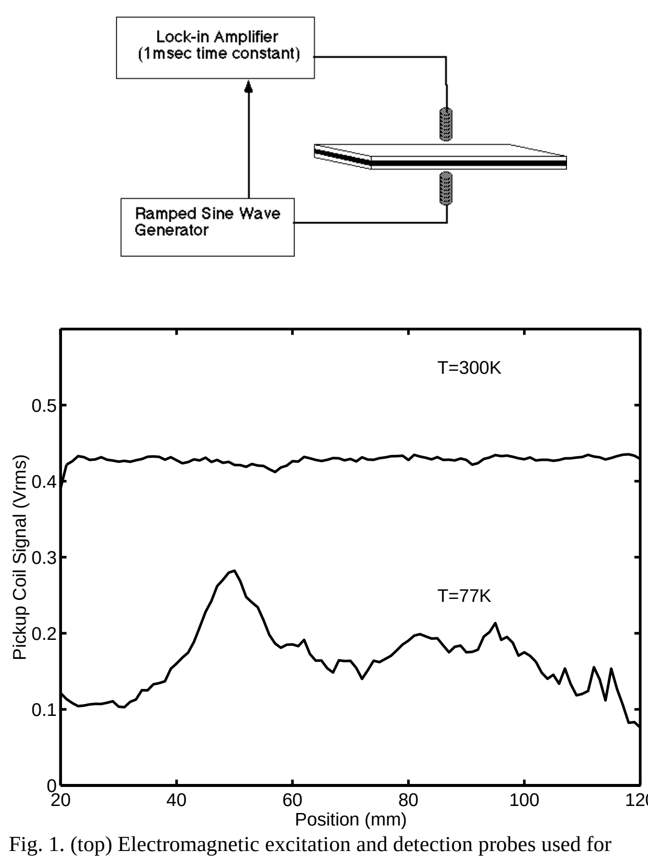

Fig. 1. (top) Electromagnetic excitation and detection probes used for scanning along tapes, (bottom) results along a Ag/clad BSCCO tape above and below the transition temperature showing variations in the local $J_C d$.

Manuscript received August 26, 1996. This work was sponsored by the U.S. Department of Energy, Office of Energy Research, Office of Basic Energy Sciences, under DOE Idaho Operations Office Contract DE-AC07-94ID13223.

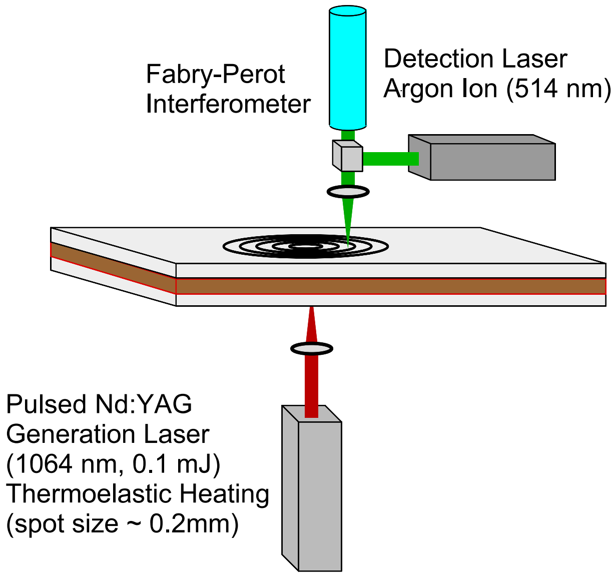

Fig. 2. Laser ultrasonic setup for tapes showing the pulsed generation laser and the continuous laser/interferometer for detection.

local layer thickness along the tape. Normally, this type of measurement requires piezoelectric probes to be in contact with the tape surface; however, a new method, laser ultrasonics, has evolved that is totally noncontacting, requiring only optical access to the tape surface. Fig. 2 shows the setup used at INEL for laser ultrasonic investigations on tapes. A pulsed Nd:YAG laser (1064 nm, 10 ns pulse width, 10 Hz repetition rate, and pulse energies of around 0.1mJ) was used to thermoelastically generate ultrasonic waves in the Ag layer by local heating. Low energy densities precluded any damage to the tape. The rapid localized strain deformation launches ultrasonic motion in the form of longitudinal and transverse (shear) waves into the tape layers [7]. For detection, an argon ion laser beam (514 nm) is scattered from the tape surface. Ultrasonic motion of the surface causes a very small Doppler shift in the scattered light that is demodulated with a special adaptation of the Fabry-Perot interferometer. Sub-nanometer normal surface motions are detectable with bandwidths of 100 MHz.

Significant anisotropy in the elastic constants of BSCCO-2212 due to the crystal structure have been measured [8]. In particular, the longitudinal wave speed along the c-direction is given as 2670 m/s and within the ab-plane as 4370 m/s. The shear wave speed depends on orientation and polarization; it is 1750 m/s along the c-direction, 2460 m/s within the ab-plane (ab polarization) and 1740 m/s parallel to the ab-plane (c polarization). The isotropic silver layer wave speed values are 3650 m/s longitudinally and 1610 m/s transverse. These values are used as an approximation to those of BSCCO-2223, the tape material used in this study.

There are many complicated elastic wave modes in a layered geometry, and a layered tape is yet to be successfully described theoretically. However, the lowest frequency modes can be understood and approximated by ignoring the sides of the tape. The tape acts as a waveguide, producing propagating modes that are dispersive and involve motion of all layer surfaces simultaneously. The lowest of these modes, termed Lamb waves, are well understood for single component plates without sidewall boundaries such as found in tapes. The two wave modes, flexural (antisymmetric) and extensional (symmetric), travel along the plate with different dispersive properties and wave speeds. The extensional mode is always faster than the flexural.

Laser ultrasonic measurements on a 0.25 mm thick stainless steel plate are shown in Fig. 3 as an example of propagation on a single component plate. Waveforms are shown for various separations between the source and detection laser beams. When the source and detection beams are coaxial, initial surface expansion is seen along with the fundamental longitudinal wave resonance in the thickness direction of the plate. This resonance provides a direct measure of the longitudinal wave speed and thickness at the detection point. The inset to Fig. 3 shows the power spectrum for this resonance, which has a strong peak at the frequency corresponding to one-half wavelength within the plate thickness. As the separation between source and detection increases, the waveform evolves into that of a pulse traveling along a dispersive waveguide. The two Lamb wave modes have different wave

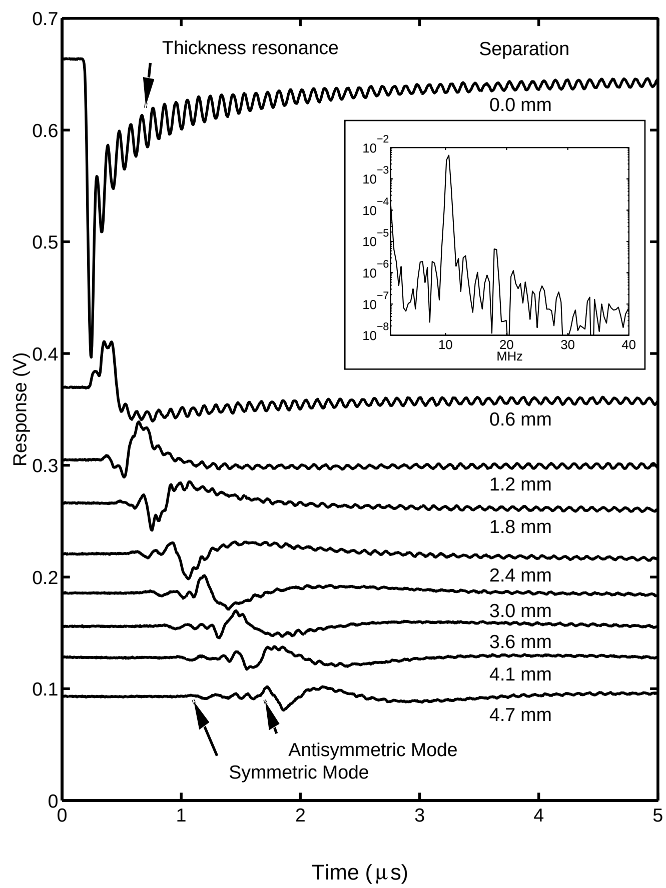

Fig. 3. Laser ultrasonic measurements on a single component plate of comparable thickness to the HTS tapes. The inset shows the thickness longitudinal resonance power spectrum.

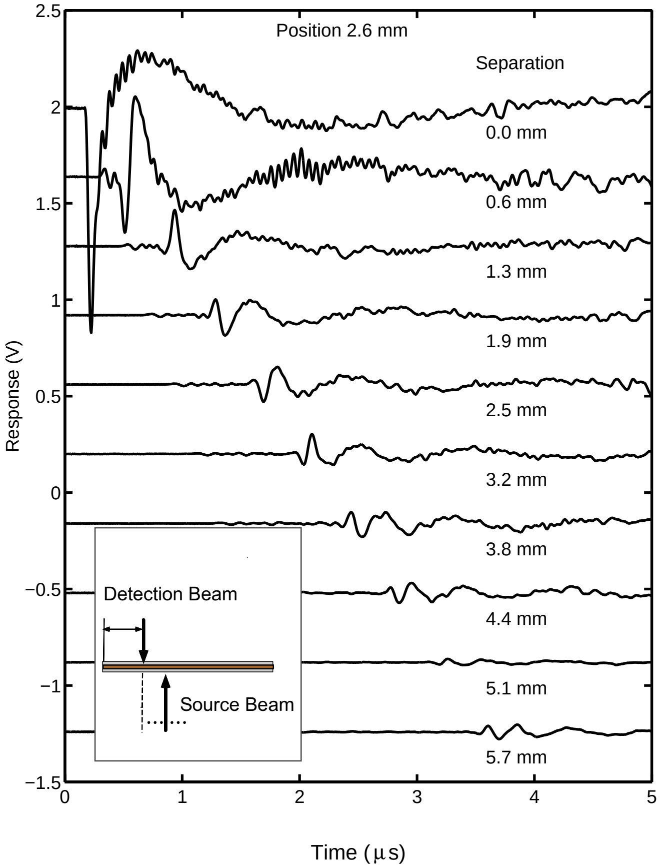

Fig. 4. Laser ultrasonic measurements on a BSCCO tape sample with a total thickness of 0.11 mm at a detection point very near the tape end point, where the BSCCO layer is absent.

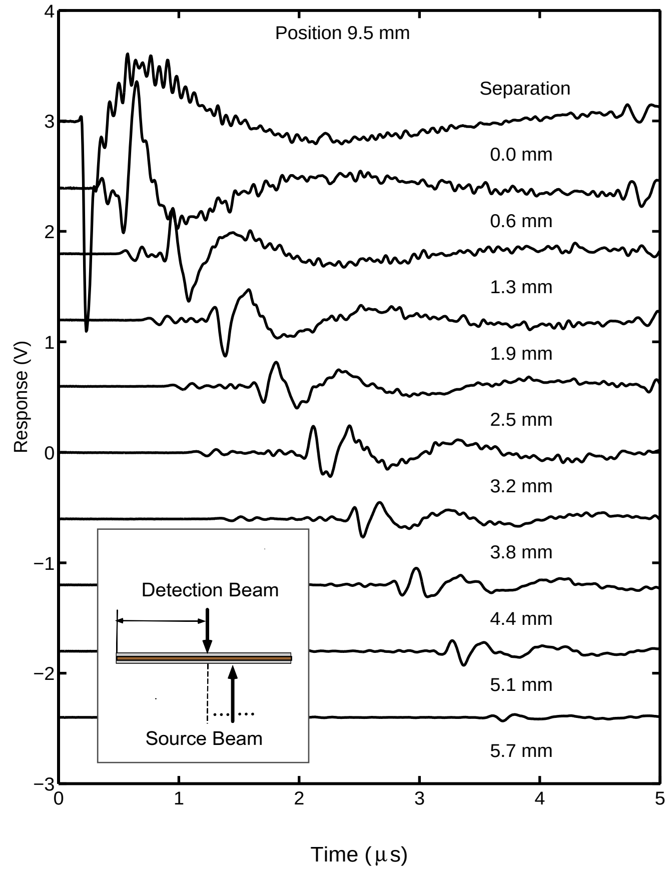

Fig. 5. Laser ultrasonic measurements on a BSCCO tape sample with a total thickness of 0.11 mm at a detection point well away from the tape end where the BSCCO layer thickness is approximately 0.03 mm.

speeds and dispersion, which separate the two modes as the pulse travels. Both the wave speeds and dispersive effects are consistent with the known properties of Lamb waves in stainless steel plates. Additional waveforms are seen that involve higher traveling modes. These data, as shown in Fig. 3, can be used to determine plate thickness and elastic constants through deconvolutions with the known elastic mode dispersion relations for this plate.

Laser ultrasonic waveforms taken at two points along a Ag/clad BSCCO-2223 tape are shown in Figs. 4 and 5. The results are similar to those seen for the stainless steel plate. When the source and detection beams are coaxial, the predominant effects are initial thermal expansion followed by through-thickness longitudinal resonance. The HTS tape is multicomponent and, therefore, additional signals are also seen. Larger separations between source and detection points again show dispersive traveling Lamb wave-like modes. The presence of the BSCCO layer complicates the waveform in a manner that will require detailed calculation of the anisotropic layered tape elastic mode spectrum. Fig. 4 is from a detection point near one end of the tape where, from sections of similar specimens, the BSCCO layer is known to vanish [2]. Comparison of the two figures shows that differences come about through small changes in the wave speeds and the effects of higher mode signals that come after the initial waveforms. Eventually, although not shown, reflections from the tape side boundaries also appear for large source to detector separations..

The longitudinal resonance through the tape thickness is seen immediately following the initial thermal expansion. Fig. 6 shows this region in more detail and compares different detection points, beginning from the tape end. The corresponding signal power spectra are shown in Fig. 7. The resonance peak is seen to shift to lower frequencies as the detection point is moved further inward from the tape end. To calculate the resonant mode frequency, the grain orientation within the tape must be known. Large critical current capacity in tapes demands that a high degree of grain alignment be established with the c-axis perpendicular to the tape surface. Tapes produced by the "powder-in-tube" method, as used here, have approximately this type of alignment. The first longitudinal mode frequency, using the c-axis longitudinal wave speed of 2670 m/s, is shown in the inset to Fig. 7 as a function of BSCCO layer thickness. The calculation predicts that the resonant frequency decreases from 16.6 MHz for an all Ag tape to 11.5 MHz when the BSCCO layer is 0.03 mm thick. This is supported by the experimental measurements; at the tape end, 2.6 mm, the resonant frequency is about

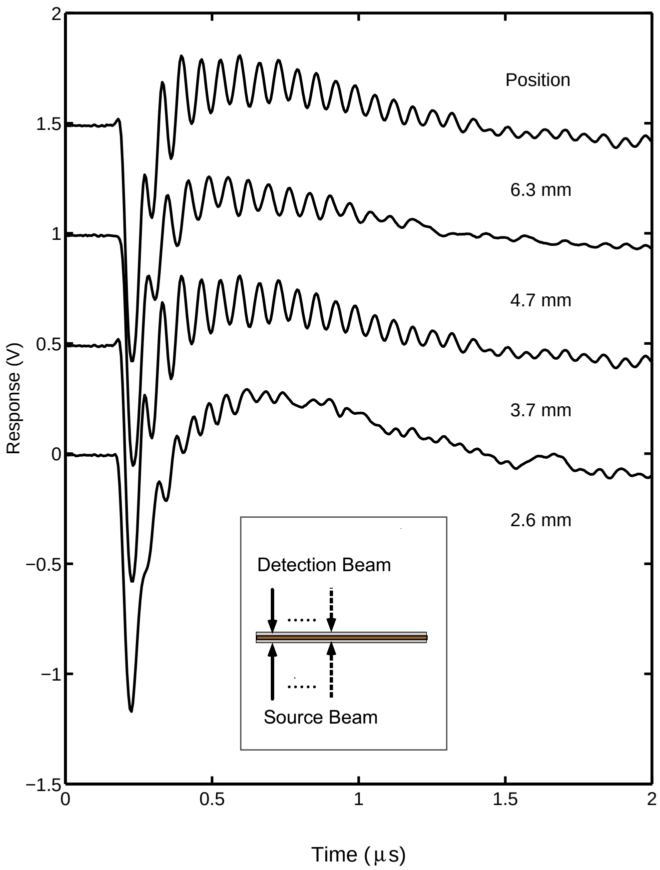

Fig. 6. Epicenter laser ultrasonic waveforms at different detection points along the tape, starting near one end.

15.2 MHz and at 9.5 mm it is about 13.3 MHz. Fig. 7 shows that the lowest longitudinal mode frequency decreases and then increases as a function of BSCCO layer thickness. The multivalued behavior shown in Fig. 7 will present problems for tapes in which the BSCCO layer is more than 60% of the total thickness.

SUMMARY

The results presented show some of the difficulties and potential of two noncontacting NDE measurement methods that can be applied to HTS tapes, both techniques are amenable to *in situ* application during manufacturing. The electromagnetic method depends on one of the most important parameters to be optimized in tape production, critical current, but yields only the product of critical current density and layer thickness. In contrast, the laser ultrasonic approach can provide thickness information if the tape microstructure and the elastic constants are known.. The results presented show that measurement of the thickness longitudinal resonance is an effective means of obtaining local BSCCO layer thickness in a tape of otherwise uniform total thickness. Further analysis and measurement of higher frequency modes

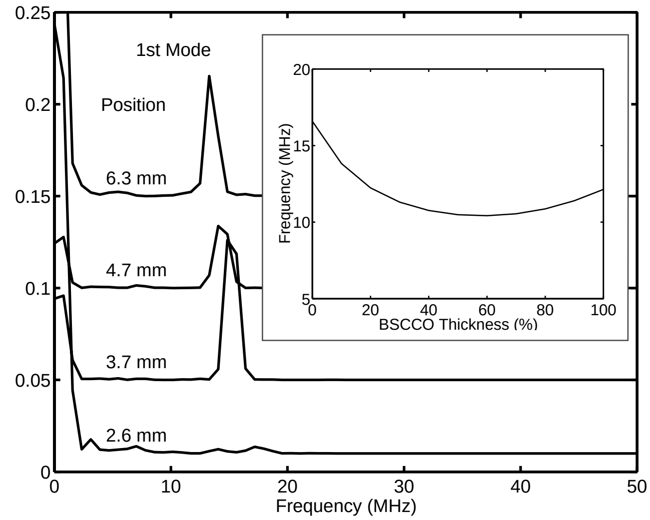

Fig. 7. Resonance power spectra at various detection points showing a decrease in resonant frequency as the detection point is moved to thicker BSCCO regions. The inset shows the calculated resonance frequency for different layer thicknesses compared to the total tape thickness.

may provide independent determination of thickness, elastic constants, and anisotropy.

ACKNOWLEDGMENT

The authors thank M.T. Lanagan and K.C. Goretta of Argonne National Laboratory for the Ag/clad BSCCO tape samples and information on the elastic constants of 2212 and 2223 BSCCO.

REFERENCES

[1] K. L. Telschow and T. K. O'Brien, "Noncontacting Alternating Current Surface Probe Measurements of Transport Critical Currents in a Slab Geometry," Appl. Phys. Lett. 59 (6), 1991, 730-732.

[2] K. L. Telschow, T. K. O'Brien, M. T. Lanagan and D. Y. Kaufman, "Local Critical Current Measurements on BiSrCaCuO/Ag Tape with an Electromagnetic Probe," IEEE Trans. Appl. Superconductivity 3(1), March 1993, 1643-1646.

[3] K. L. Telschow and L. S. Koo, "An Integral Equation Approach for the Bean Critical State Model in Demagnetizing and Nonuniform Field Geometries," Phys. Rev. B, 50(10), 1994, 6923-6928.

[4] K. L. Telschow and L. S. Koo, "Determination of the Critical State Response of High Tc Superconductors Including Demagnetization," IEEE Trans. Appl. Superconductivity, 5(2), June 1995, 1375-1378.

[5] L. S. Koo and K. L. Telschow, "A Method for Determining the Critical State Response of Superconductors in Tape Geometry," Phys. Rev. B 53, 1996, 8743-8750.

[6] C. B. Scruby and L. E. Drain, *Laser Ultrasonics*, (Adam Hilger, New York, 1990).

[7] K. L. Telschow and R. J. Conant, "Optical and Thermal Parameter Effects on Laser Generated Ultrasound," J. Acoust. Soc. Am. 88(3), 1990, 1494-1502.

[8] F. Chang, et al., "Anisotropic Elastic and Nonlinear Acoustic Properties of Very Dense Textured $Bi_2Sr_2CaCu_2O_{8+y}$," Supercond. Sci. Techol., 6, 1993, 484-489.