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VISUALIZATION OF ULTRASONIC-BEAM DISTORTION IN ANISOTROPIC STAINLESS STEEL

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Abstract - The inspection of cast stainless steel and stainless steel piping with a weld overlay is an important nondestructive testing problem in the nuclear industry. The ultrasonic inspection of these components is complicated by their coarse-grain and textured microstructure, which distorts the ultrasonic beam. The distortion of pulsed ultrasonic beams produced by conventional piezoelectric transducers mounted on stainless steel samples was measured by scanning the back surface of the samples with a laser interferometer. The plots illustrate how the beam from a 6.3-mm-dia, 2.25-MHz longitudinal transducer can be skewed, focused, or defocused after passing through samples that are 3.2 or 19.0 mm thick. The crystallographic symmetry of the steel samples varied from isotropic to transverse isotropic.

I - INTRODUCTION

Cast austenitic stainless steel and weld metal are often formed with a distinct microstructure consisting of coarse columnar grains.1 These grains can be as large as a centimeter in length by 1-2 mm in diameter with the <100> direction along the axis of the grains and random orientations of the orthogonal axes. Material used in this study was found to have transverse isotropy when measured by x-ray and ultrasonic methods. Because of the texture, acoustic beams propagating in these transversely isotropic materials may be distorted, depending on the orientation of the beam relative to the grain axis. Gaussian beams from nondestructive testing transducers generally do not retain an asymmetrical Gaussian shape but can be skewed, and focused, along certain directions.2 These pernicious effects can make the interpretation of nondestructive tests difficult unless the beam deviations and distortion can be predicted and verified.

Laser detection of ultrasonic waves is becoming a popular method for applications where noncontracting measurements must be made or where high spatial resolution or quantitative measurements of displacement are required.3-5 A laser interferometric technique was used to map the ultrasonic displacement profile from a transducer beam that had propagated through centrifugally cast stainless steel pipe wall material. The laser interferometer was calibrated by a direct capacitance method, which allowed quantitative measurement of the surface displacement amplitude to 0.35Å.

II - EXPERIMENTAL TECHNIQUE

Shown in Fig. 1 is the experimental apparatus used to map the ultrasonic wave fronts. The laser interferometer is a Michelson quadrature interferometer manufactured by Sonoscan.6 The advantages of this system are good sensitivity (~0.3Å), compared with other optical methods; ability to detect short (<1 μs) pulses; and insensitivity to low-frequency vibrations (f < 100 kHz). The disadvantages of the system are that the signal voltage output is proportional to the square of the displacement and the apparent frequency of the waveform is doubled due to the electronic stabilization technique. The system has a frequency band pass (~3dB) of 150 kHz to 8 MHz, limited at low frequencies by laser noise and random vibrations...
and at high frequencies by the frequency response of the squaring and summing electronics. Because the sensitivity of the interferometer is proportional to the light intensity reflected from the surface to the photodiodes, a flat mirror-like sample surface is required for maximum sensitivity over the scanning area. As shown in Fig. 1, the sample, with the ultrasonic transducer affixed to the opposite face, is scanned in the x-y plane with mechanical stepping motors. Data were obtained at 760 µm increments with a beam diameter of 800 µm. (The beam could have been focused to a much smaller spot size but the larger spot size made the technique less sensitive to surface scratches or imperfections.) The scan area was approximately 1.7 cm by 1.5 cm. During the scan, data from the interferometer were digitized and stored for normalization and plotting.

As the sample moves in front of the laser beam there are small changes in reflectivity that occur due to scratches and misalignment of the sample surface. A normalizing signal at 2 MHz is applied to a piezoelectric crystal (mirrored reference transducer) in the reference arm, which provides a signal proportional to the surface reflectivity. This signal is then used to correct the amplitude of the signal received through the sample. This procedure eliminates asperity in the plots of the ultrasonic wave front and allows measurement of small changes in amplitude.

Quantitative measurement with the interferometer requires that the laser system be calibrated. The system can be roughly calibrated by use of the relation between the photodiode current $i_s$, and the light intensity in the reference arm and sample arm $I_r$, $I_s$, as shown below.

$$i_s = \delta \sin \omega t,$$

where $\delta \sin \omega t$ is the displacement and $\eta$ is the quantum efficiency of the photodiode. Use of Equation 1 implies that the photodiode current, light intensity, and quantum efficiency are known or can be measured accurately. Even if this were the case, the transfer function for the rest of the laser system electronics would have to be measured. To circumvent the difficulty of calibrating each individual component, a calibration device was constructed. The calibration device directly measures the time-dependent displacement of a mirrored fused quartz surface.

A cross section of the calibrator is shown in Fig. 2. A wideband (1.9 cm dia) piezoelectric transducer, epoxied to a fused quartz block (2.5 cm thick by 3.8 cm dia), is used as a source of 0.5-2 MHz longitudinal waves. Longitudinal wave pulses, after propagating through the fused quartz, are reflected off the end of the quartz block causing oscillatory surface displacement. The end of the fused quartz block is sputtered with a mirror-like layer of chrome 2500 Å thick. A small stainless steel electrode (1.27 cm dia) measures the average change in capacitance over the surface due to the displacement. A small hole (1 mm dia) in the center of the electrode allows the laser beam to measure the displacement at the center of the rear surface of the fused quartz block. The peak to average displacement factor (<5%) was calculated by determining the shape of the nearly Gaussian ultrasonic beam wavefront by scanning the laser over the back surface of the fused quartz block with the capacitor electrode removed.
Comparing the square root of the laser system output with the displacement as measured with the capacitor gave a sensitivity of $2.5 \times 10^{-4}$ A/$\text{Hz}^{1/2}$ or 0.35 A sensitivity in a 2 MHz bandwidth. This is approximately the sensitivity for other reported Michelson type interferometers. This sensitivity is far above the sensitivity that can be obtained with wideband piezoelectric probes such as the NBS acoustic emission sensor. A comparison of the spectral sensitivity of the laser to the NBS at 1 MHz indicated that the laser system is approximately the sensitivity for other reported Michelson type interferometers. This sensitivity is far above the sensitivity that can be obtained with wideband piezoelectric probes such as the NBS acoustic emission sensor. A comparison of the spectral sensitivity of the laser to the NBS at 1 MHz indicated that the laser system is 47 dB less sensitive than the NBS conical transducer.

An increase in the sensitivity of the laser probes could be obtained with lower noise preamplifiers or photodiodes. The predominant noise in the laser system was found to be the thermal noise inherent in either the photodiode or preamplifier. Higher power (5 mW) lasers were used with the system but they were found unsatisfactory due to excessive mode hopping noise. With improvements to the interferometric sensing system, it should be possible to achieve detection sensitivities comparable to wideband piezoelectric probes.

III - RESULTS

As shown in Fig. 1, a small (6.3 mm OD) longitudinal wave transducer was epoxied to various specimens of isotropic or transversely isotropic stainless steel. Shown in Fig. 3 are etched surfaces of samples with (a) isotropic grains and (b) transverse isotropy with the grain axis oriented in the $<100>$ direction as confirmed by x-ray diffraction analysis and ultrasonic velocity measurements.

A beam wavefront from the 6.3 mm transducer after passing through a 3.1 mm thick sample of isotropic steel with grains less than 2 mm dia is shown in Fig. 4. The beam shape is approximately Gaussian and symmetric about the center of the transducer. Note that the center of the transducer does not, in general, coincide with the center of the scan area of the three-dimensional plot. In addition, because of the perspective for Fig. 4, the contour plot looks elliptical rather than circular. The plots were constructed by pulsing the transmitting transducer with a 200 V, 0.2 $\mu$s unipolar pulse and subsequently detecting the peak laser signal at 2 MHz as a function of position and then converting to peak displacement in angstroms.
Several thicker samples with longer grains (2–3 mm dia by 1 cm in length) were also measured and show qualitatively the expected behavior for the orientation of the material that was selected. In Fig. 5 beam wavefronts originating from the 6.3 mm transducer are shown after passing through 1.9 cm of centrifugally cast austenitic steel. Shown in Fig. 5a is the wavefront for the longitudinal beam incident at a 45° angle to the grain axis. The beam should not be skewed by any significant amount but should be focused in the y direction indicated on the graph. This focusing effect results in an elliptical shape of the beam at the back wall.9,10 A calculation of the spreading of the beam as described in Reference 10 gives a beam diameter of 15 mm for an amplitude decrease of 50%. The measured beam diameter in the x direction is about 13 mm for a 50% decrease in signal level. In the y direction the beam has been focused down to 8 mm rather than the 11 mm expected.

The beam wavefront for longitudinal waves traveling normal to the axis of the grains is shown in Fig. 5b. In contrast to Fig. 5a, the beam has spread very little (3 mm dia for 50% decrease in amplitude), which is not the behavior predicted for propagation along this axis. This may be due to the relative sizes of the grains and transducer. Obviously when the grains are 2–3 mm dia and the beam is 6.7 mm in diameter, only a few local grains are averaged by the beam, which may negate the observation of global transverse isotropy.
IV - SUMMARY

A sensitive, calibrated, and wideband laser interferometer has been demonstrated as a useful tool for the detection of subtle spatial distortion of ultrasonic beams with a high resolution. Mapping of beam wavefronts with the laser have for the first time allowed quantitative two-dimensional measurements of beam distortion so that it can be compared with theory. Predictions of the beam shape based on transverse isotropy are generally consistent with observations of beam distortion for longitudinal waves.

REFERENCES

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