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LAMB-WAVE INSPECTION OF WELDS
IN STAINLESS STEEL TUBES

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U. S. ATOMIC ENERGY COMMISSION
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Quality
ENVIRONMENTAL TESTING AND
DEVELOPMENT LABORATORY

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SUBJECT DESCRIPTORS

Nondestructive Testing
Ultrasonics
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CONTENTS

Abstract	1
Introduction	1
Discussion	1
Ultrasonic Theory	1
Equipment	2
Shear-Wave Technique	2
Shear-Wave Results	3
Lamb-Wave Theory	3
Development of the Lamb-Wave Technique	5
Conclusion	5

LAMB-WAVE INSPECTION OF WELDS IN STAINLESS STEEL TUBES

Gerald W. Schrick

Abstract. An ultrasonic Lamb-wave inspection technique has been developed for use in inspecting the gas tungsten arc (GTA) welds in small diameter stainless steel tubes for lack of penetration. The particular technique was employed because of the ability to introduce the sound into the material a distance from the weld. A conventional shear-wave technique was tried without success.

INTRODUCTION

Problems were encountered in attempting to develop an ultrasonic testing technique capable of certifying a minimum of 85-percent weld penetration in small diameter stainless steel tubes. The components making up such a joint are a specified length of 0.125-inch diameter, a 0.028-inch wall Type-304 stainless steel tubing which is welded to a machined piece of Type-304 stainless steel (Figure 1). [For SI (metric) use: 1 inch = 25.4 millimeters.]

The initial test technique was a conventional shear-wave test. Ultrasonic results from transverse slots placed on the inside diameter (ID) of a piece of 0.125-inch diameter stainless steel tubing were favorable for a 45-degree, shear-wave test. When trying the technique on an actual part, problems were encountered which dictated the need of a

different inspection technique. Described herein are the problem areas encountered with shear-wave testing and the development of a Lamb-wave technique¹ which proved capable of performing the test.

DISCUSSION

Ultrasonic Theory:

Ultrasonic sound waves are generated when a piezoelectric element is caused to oscillate at its resonant frequency. The generated sound wave travels from the transducer through a coupling medium and into the material to be tested. When an ultrasonic sound wave strikes an interface between two media, a percentage of the wave will be transmitted through the media and a percentage will be reflected. The occurrence depends upon the acoustical impedances of the two media. At normal incidence, the ratio between reflected beam intensity, W_r , and incident intensity, W_i , is given by the reflection coefficient, R :

$$R = \frac{W_r}{W_i} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2 = \left(\frac{r - 1}{r + 1} \right)^2$$

Where, W_r = reflected beam intensity

W_i = incident beam intensity

Z_1 = acoustical impedance of medium one

Z_2 = acoustical impedance of medium two

$r = Z_2 / Z_1$

FIGURE 1. Typical Cross Section of the Weld Joint (inch dimensions).

¹Horace Lamb. "On Waves in an Elastic Plate." *Proceedings of the Royal Society A-93*, 114-128. 1917.

Equipment:

All testing was done with a Model-725 Immerscope used in conjunction with a Model-1508 Honeywell recorder. Test fixturing (see Figure 2) consists of a modified 10-inch Logan lathe. Mounted on the lathe are a stuffing box and transducer holder. The stuffing box acts both as a water reservoir and guide for the test parts. The transducer holder is designed to allow three axes of transducer movement.

Shear-Wave Technique:

Evaluation of the weld joint configuration suggested that the weld could be inspected with a shear-wave technique. The initial work was performed on a piece of 0.125-inch diameter, a 0.028-inch wall Type-304 stainless steel tubing with known depth transverse slots placed into the tube inside diameter (ID) (see Figure 3). These slots were made at

5- and 8-mil depths by an electron discharge machine (EDM). [For SI (metric) use: 1 mil = 2.5×10^{-5} meters.]

FIGURE 3. Stainless Steel Reference Piece (inch dimensions).

FIGURE 2. Ultrasonic Scanning Fixture.

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Lithium-sulfate transducers with frequencies from 5 to 25 megahertz (MHz) positioned at various angles of beam incidence were investigated to determine optimum sensitivity and resolution with minimum attenuation. A 15-MHz short focus 0.25-inch diameter crystal, incident to the test piece at an angle to produce a 50-degree refracted shear wave in the tube wall, showed optimum sensitivity to the slots.

Shear-Wave Results:

When trying the shear-wave technique on an actual weld, problems were encountered. The GTA weld of this joint is wider than the depth of the joint. In addition, considerable weld-crown build-up occurs on the OD. The width and build-up of the weld will cause direct interference with the incident sound wave (see Figure 4), regardless of the angle of the incident beam.

FIGURE 4. Shown Is Incident Wave on Material at an Angle to Produce a 60-Degree Refracted Shear Wave. (Note that the wave strikes partially on the weld surface.)

At this point, the need for a new technique became evident. Investigation of several techniques showed that a Lamb-wave technique could be used. A discussion follows on what Lamb waves are and how they work.

Lamb-Wave Theory:

In addition to the longitudinal, shear- and surface-waves, with which nearly all testing is done currently, another important but less known class of vibrational mode exists. The mode was theoretically discovered by Horace Lamb² who reported it to the Royal Society of London in 1916. The use of these waves in nondestructive testing was proposed some 30 years later. To date, only limited testing with these waves has been reported in practical testing.

Lamb waves consist of an infinite number of modes of vibration that can be generated in elastic materials. Lamb's grouping of these infinite number of modes into symmetric and asymmetric depended on the direction of particle displacement. In a given material, each mode has a different velocity of propagation. The phase velocity at which the various modes travel in a material depends on the the material thickness, the transducer wave frequency, the order of the mode, and the material in which the wave travels.

Figure 5 after Worlton³ illustrates the phase velocity-frequency thickness (Fd) relationship in stainless steel for the symmetric and asymmetric modes. (Frequency $\times$ depth = Fd .)

Lamb waves can be generated if the angle of incidence of a longitudinal sound wave is adjusted so that the phase velocity of the incident longitudinal wave equals the phase velocity of a particular type and mode of a Lamb wave.

The phase velocity of the incident longitudinal wave follows:

²*Ibid.*

³D. C. Worlton. *Lamb Waves at Ultrasonic Frequencies*. HW-60662. Hanford Atomics Products Operation, Richland, Washington. 1959. (Permission granted for use of Figure 5.)

FIGURE 5. Lamb-Wave Curves for Stainless Steel.

$$V_P = \frac{V_L}{\sin \phi}$$

Where, V_P = the phase velocity of the incident longitudinal wave

V_L = the group velocity of the incident longitudinal wave

$(\phi) \phi$ = the angle of incidence of the incident longitudinal wave

Note that the phase velocity refers to the rate of travel of a disturbance in an infinitely long-wave train and is to be distinguished from the more usual group velocity concept, which refers to the velocity of a short group of waves. In order to visualize this difference, consider an ocean swell moving in toward the shore, with the swell making a straight line parallel to the shore. Points along the wave front then arrive at the shore simultaneously. Alternately, if the wave approaches at an angle, any two given points along the swell arrive at different times and the point of contact of the wave runs along the beach at a rate dependent upon the angle of approach. This is called the phase velocity and is, of course, different in general with the velocity at which the swell moves through the water.

If the speed, V_P , is the same as the phase velocity of a Lamb-wave mode, the mode will be generated in the tube wall. Once a Lamb wave is generated, it will continue to travel down the tube, attenuated, but otherwise undisturbed until it reaches a discontinuity.

The wave is in part reflected from the discontinuity and travels back along the tube. It is radiated from the tube at an exit angle equal to the incident angle and can be detected by the transducer that was used to generate it.

Development of the Lamb-Wave Technique:

The Lamb-wave technique was first tried on the stainless-steel tube reference piece. As noted

earlier, this tube has 5- and 8-mil deep slots placed on the tube ID. With a 10-MHz, 0.25-inch diameter crystal having a short focus, best results were achieved. At 10 MHz, the frequency-thickness (Fd) product was 2.8×10^5 inches per second. Using the data in Figure 5, the 1A (asymmetrical) and 1S (symmetrical) modes can be generated when the incident beam angle is set at 32.2 degrees. Other incident beam angles giving the 2A and 2S modes were tried. The most favorable response from the slots was obtained with the 1A and 1S modes which, incidentally, have their angles of incidence so close as to make them indistinguishable from each other. A second tube, with identical depth transverse slots on the OD and ID, was checked.

Initial results showed the response to be considerably higher from the OD slot. Investigation revealed that the higher response was not from a Lamb wave, but from a direct surface reflection. Additional work revealed that the maximum signal response from an ID slot occurred when the incident beam was at a set distance from the slot. Using the same set distance from an OD slot, a response equal to that from an ID slot was obtained. When the incident beam was moved from this set point toward the OD slot, the Lamb-wave signal would decay and a new signal (direct surface reflection) would take its place. These two signals can be easily differentiated because of their difference in arrival time when viewed on an oscilloscope. Positioning of the flaw gate on the Immerscope to accept only the Lamb-wave signal eliminates the possibility of recording the wrong signal.

CONCLUSION

Several parts, ultrasonically rejected by the Lamb-wave technique for apparent lack of penetration, have been sectioned and the lack of penetration measured. Physical measurements compare favorably with predicted ultrasonic measurements.

The Lamb-wave technique has provided a means of testing a weld having a cross section which prevented the use of shear-wave testing.