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Ultrasonic Phased Arrays for Weld Testing

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INTRODUCTION

Conventional ultrasonic testing of welds is performed at fixed refracted angles, including 45, 60 and 70°. On the contrary, phased array ultrasonic testing sweeps a range of angles. Typically for shear wave testing, the scan range is from 35 to 75°. Sweeping the angles in real time is significant, as a single phased array test can cover all angles and display the image in real time. The real-time image is a direct superimposition of the ultrasonic illumination on the test piece. Phased array ultrasonic testing is highly effective for weld testing and results in highly reliable data.

In this paper, the ability of phased arrays to detect weld discontinuities was tested on specimens manufactured by a third party to assist technicians in preparing for ultrasonic testing qualification exams. These specimens include embedded discontinuities in plate and pipe samples. Tests were conducted using two phased array systems. The results of the tests showed that both phased array systems easily detected all of the discontinuities in the test plates.

PHASED ARRAY TECHNOLOGY

The laws of physics apply to phased array ultrasound in the same manner as they do to conventional ultrasonic testing. Ultrasonic phased array testing uses a multiple-element probe in which the output pulse from each element is time delayed in such a way as to produce constructive interference at a specific angle and a specific depth. These time delays can be incremented over a range of angles to sweep the beam over the desired angular range. For example, a 40 to 75° beam sweep would be produced by calculating the time delays to produce constructive interference at 40, 41, 42 ... 75°. Using the time delays on each element, constructive interference can be achieved at a desired angle and depth. Time delays are changed sequentially to sweep a range of angles. Figure 1 shows the focusing and beam sweep produced by the phased probe.

> ***The specimen plates were tested with both of the phased array ultrasonic testing systems.***

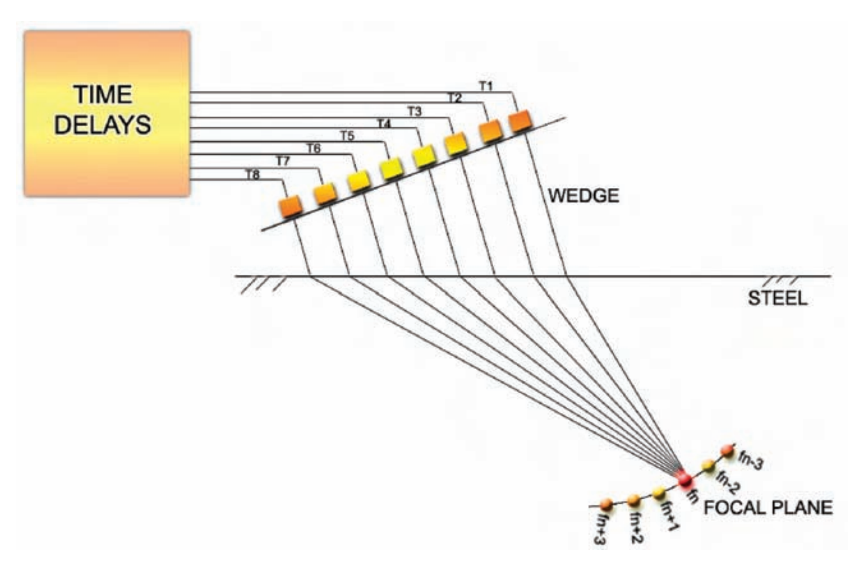

Figure 1 — Conceptual illustration of the phased array principle. Time delays to the eight elements control focusing and beam sweep (actual focal point spot size will not be as sharp as that shown, and its size will depend on the beam spread).

The maximum sweep range of phased arrays is determined by the element size and wavelength using the classical ultrasonic testing formula for calculating beam spread (Krautkramer and Krautkramer, 1990):

$$\sin \nu_6 = 0.51\frac{\lambda}{e} \tag{1}$$

where
ν_6 = the angle for the 6 dB decrease of echo relative to the axial position
λ = the wavelength
e = the element size.

The smaller the element size, the higher the sweep range. A phased array probe with 1 mm (0.04 in.) elements will result

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in a total beam spread of 74° (±37°) for L-waves in steel. This is what gives phased array technology the ability to sweep large angles.

The focal limit of the probe is the near field, which depends on the overall aperture size and the wavelength. No focusing is possible beyond the near field. The focal spot diameter of a phased array probe is calculated as it would be for conventional lens based probes. The focal spot size S_6 of the phased array probe is given by

$$S_6 = \frac{\lambda F}{D} \quad \text{for } F \leq N \tag{2}$$

where

S_6 is calculated at the 6 dB decrease of echo relative to the axial position
F = the focal length
D = the aperture
N = the near field.

The sharpness of the focus is improved by increasing aperture, increasing frequency and reducing focal length. Increasing the number of elements only refines the beam, but has minimal effect on focusing. Therefore, a 5 MHz, 16 mm (0.63 in.) aperture, 16-element probe will have sharper focus than a 5 MHz, 12 mm (0.47 in.) aperture, 32-element probe.

For phased array weld testing, refracted shear waves can be used in the range of 35 to 75°. Refracted longitudinal waves can be used from 0 to 80°. This is the same as in classical ultrasonic testing.

PHASED ARRAYS FOR WELD TESTING

A probe is selected that illuminates the weld as shown in Figure 2. In the direct mode, only the bottom half of the weld is illuminated. However, with reflection from the inner diameter surface, the entire weld is illuminated and the complete weld volume is tested. For example, the indication *a* in the weld is detected by the reflected sound and displayed as the mirror image *a–*. Similarly, other discontinuities are displayed in the image. Figure 3a shows the image of the weld root.

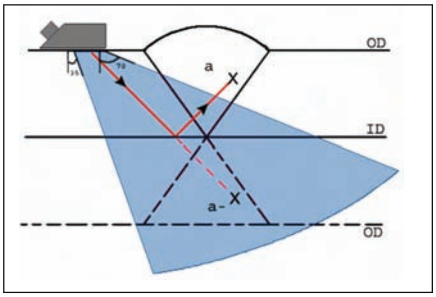

Figure 2 — Concept of phased arrays for weld testing. Indication a*, detected by the reflected beam, is displayed as a mirror image* a–.

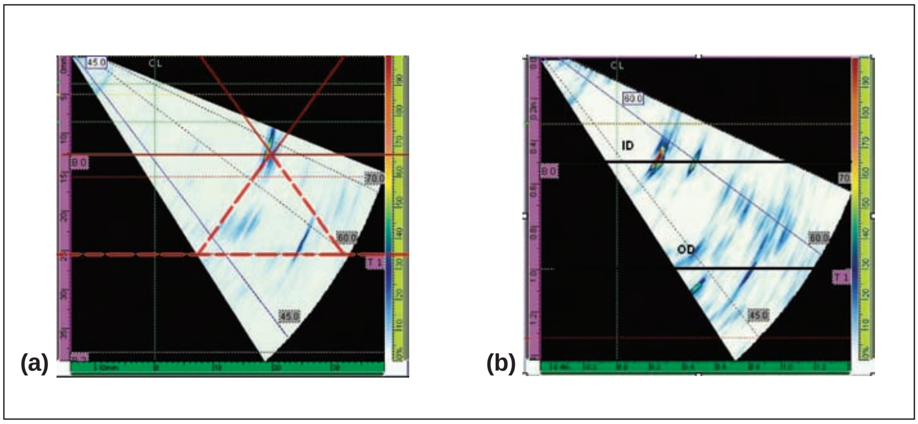

Figure 3 — Images of the 13 mm (0.5 in.) thick plate: (a) root; (b) inner diameter crack indication on the left, just ahead of the root. (Instrument: 5 MHz, 9.6 mm [0.38 in.] aperture, 16-element probe.)

PHASED ARRAY TESTS ON SAMPLES WITH DISCONTINUITIES

The ability of phased array ultrasound to detect discontinuities in weld samples was tested. These samples contain embedded discontinuities that include toe cracks, root cracks, lack of fusion, lack of penetration, slag and porosity. Eight samples with a total of 24 discontinuities were used in the test. The sample matrix is shown in Table 1.

Test Equipment

Tests were performed using the following commercially available equipment. Both machines have 16-channel phased array modules (N_{ss} denotes the near field distance of shear waves in steel):

- 5 MHz, 9.6 mm (0.38 in.) aperture, 16-element probe (N_{ss} = 36 mm [1.42 in.])
- 4 MHz, 8 mm (0.31 in.) aperture, 16-element probe (N_{ss} = 25 mm [0.98 in.]).

Calibration

Calibration was done on 10% deep notches in the test samples. Signals that exceeded 20% of the notch levels were evaluated.

Results

The specimen plates were tested with both of the phased array ultrasonic testing systems. Figures 3 and 4 show typical discontinuity indications detected by the phased array machines. Figure 3b shows an inner diameter indication at the weld root. The indication is just at the inner diameter surface line. Behind the inner diameter crack indication is the root. Figure 4b shows a lack of fusion indication. This indication is detected in the reflected mode and displayed as a mirror image. Slag is detected in both the direct and reflected modes. Tests showed that both systems successfully detected all 24 embedded discontinuities. The test results showed 100% detection of the discontinuities, thereby establishing the reliability of phased array ultrasound for the nondestructive testing of welds.

CONCLUSION

Weld testing evaluation showed that both the system with a 5 MHz, 9.6 mm (0.38 in.) aperture, 16-element probe and the system with a 4 MHz, 8 mm (0.31 in.) aperture, 16-element probe detected all the discontinuities in the samples. The discontinuities included typical weld discontinuities (inner diameter cracks, outer diameter cracks, lack of fusion, lack of penetration, slag and porosity). When compared to A-scan ultrasonic testing, the phased array image output was easy to interpret for discontinuity detection and characterization.

Table 1 Samples used in this study

Sample	Weld Type	Number of Samples	Number of Discontinuities	Discontinuity Types
13 mm (0.5 in.) thick plate	vee	2	2 × 3	root crack, lack of fusion, slag
25 mm (1.0 in.) thick plate	double vee	2	2 × 3	toe crack, center line crack, lack of penetration, lack of fusion
203 mm (8 in.) diameter, 13 mm (0.5 in.) T pipe	vee	2	2 × 3	inner diameter crack, lack of fusion, porosity, slag
305 mm (12 in.) diameter, 18 mm (0.7 in.) T pipe	vee	2	2 × 3	outer diameter crack, inner diameter crack, lack of fusion, lack of penetration, porosity

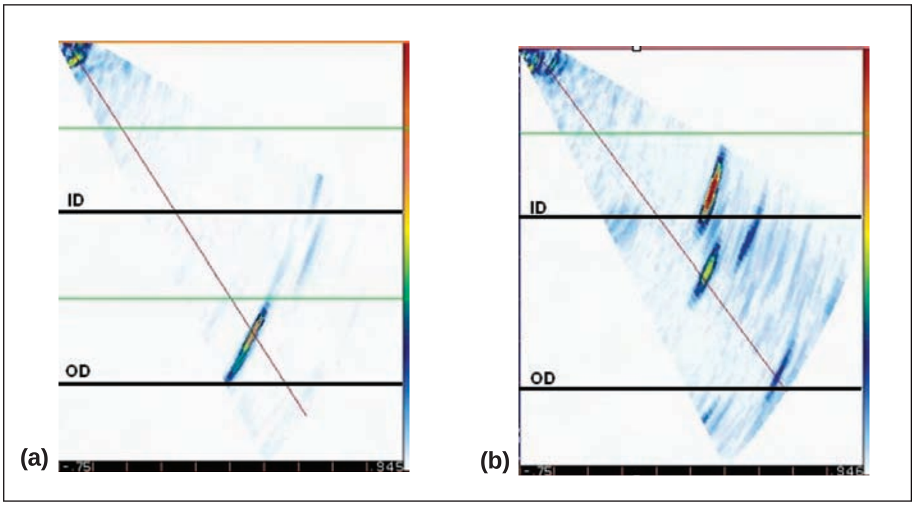

Figure 4 — Weld sample discontinuity images: (a) lack of fusion in a 13 mm (0.5 in.) plate detected in the reflected mirror image; (b) slag in a 13 mm (0.5 in.) thick, 203 mm (8 in.) diameter pipe detected in both the direct and reflected mirror image. (Instrument: 4 MHz, 8 mm [0.31 in.] aperture, 16-element probe.)

Recommendations

Tests have shown that a 16-channel phased array system is adequate for basic weld testing and will result in superior testing compared to the basic A-scan testing. However, it is recommended that any system used for weld testing as per testing codes must incorporate angle correction both for time delays and gain. For example, a 15 mm (0.6 in.) deep, 1.5 mm (0.06 in.) diameter side drilled hole in an IIW block, when scanned in the entire sweep angle range, must measure to the correct depth and same amplitude for all angles. The depth of the hole selected to establish these corrections must be in the depth range of the weld thickness testing. One has to note that while this adjustment will meet code requirements for shear wave ultrasonic testing, gain corrections will distort focusing at higher angles. However, for the size of discontinuities in the test samples, any distortion in focusing does not adversely affect discontinuity detection.

While the present test evaluations were limited to the 8 mm (0.31 in.) and 9.6 mm (0.38 in.) aperture probes on samples with a thickness range of 13 to 25 mm (0.5 to 1.0 in.), larger aperture probes will be necessary when performing testing on thicker material. Small aperture probes have limited focal depth because of the shorter near field. Focusing improves discontinuity detection sensitivity.

REFERENCES

Krautkramer, J. and H. Krautkramer, *Ultrasonic Testing of Materials*, fourth edition, New York, Springer-Verlag, 1990.

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