DEVELOPMENT OF A PHASED ARRAY TOFD UT METHOD TO MEASURE THE DEPTH OF SCCS IN DISSIMILAR WELDS

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ABSTRACT
We have developed a phased array TOFD ultrasonic testing method to measure the depth of stress corrosion cracks (SCCs) in dissimilar welds on vessel nozzles. SCCs detected on nozzle welds of a reactor vessel in Japan in 2008 had a crack surface in the axial direction of the nozzle and an acute tip. It is not easy to measure the depth in such cases, so we simulated SCCs on Ni base alloy weld specimens. Since attenuation of the ultrasonic wave in the Ni base alloy welds is large, it is difficult to apply conventional TOFD by a single element probe to the welds. This phased array TOFD enables us to detect a tip echo from SCCs by focusing the ultrasonic beam on the crossing point of the transmitter and receiver probe. This paper presents the results of a depth sizing test of SCCs on Ni base alloy weld specimens by the phased array TOFD method.

INTRODUCTION
The TOFD method can precisely measure crack depth, but is not suitable for materials with high ultrasonic attenuation, such as stainless steel cast piping, austenitic stainless steel piping welds and dissimilar welds in vessel nozzles in nuclear power plant equipment.

The authors have developed a TOFD method with asymmetrical ultrasonic beams of a transmitter and a receiver (hereafter “phased array asymmetrical TOFD method”) to measure the depth of SCCs in dissimilar weld joints in the nozzle safe-end of the vessel. This method is characterized by (1) the use of 2D matrix array probes for the transmitter and receiver, (2) asymmetrical ultrasonic beams with different refraction angles and path lengths of the transmitter and receiver, and (3) synthesis of plural scanning data with different refraction angles and path lengths (hereafter “multi-angle synthesis method”).

We carried out experiments to measure the depth of SCCs in a specimen with dissimilar welds from the side of a crack.

MEASUREMENT METHOD
First, we decided to use the TOFD method with a transmitter and receiver set on both sides of a crack to measure the depth of the SCC from the side of the crack, because sometimes it is difficult to distinguish an echo from the tip of a crack and an echo from the crack bending surface.

Figure 1 illustrates a schematic diagram of the conventional TOFD method. Two probes with a single element are used for the transmitter and receiver. To change the refraction angle with a reflection source it is necessary to change the probes with another incident angle or the distance between the transmitter and receiver.

Figure 1 Conventional TOFD method

Figure 2 illustrates a schematic diagram of the phased array TOFD method. We can set the focus and convergence point of the ultrasonic beams of the transmitter and receiver at arbitrary different
positions in a material. However, to change the refraction angle with a reflection source it is necessary to change the distance between the transmitter and receiver.

![Figure 2 Phased array TOFD method](image)

Figure 2 Phased array TOFD method

Figure 3 illustrates a schematic diagram of the phased array asymmetrical TOFD method and our multi-angle synthesis method. Ultrasonic beams with different refraction angles and path lengths of the transmitter and receiver are set at an arbitrary focus and convergence point in the material in order to acquire the tip echo of the SCC with different refraction angles. Furthermore, the scanning data are synthesized with different refraction angles and different depths of focus point. This synthesis is expected to enable us to distinguish easily the echo from reflected sources and noise.

![Figure 3 Phased array asymmetrical TOFD and multi-angle synthesis method](image)

(1) Phased array asymmetrical TOFD
(2) Multi-angle synthesis method

Figure 3 Phased array asymmetrical TOFD and multi-angle synthesis method

**EXPERIMENTAL SETUP**

**Test Specimens**

Figure 4 shows a specimen with SCCs on an Ni base alloy weld. Stainless steel 316 plates are butt-welded with Inconel 600. SCCs were made with tetrathionic acid, tensile stress and an EDM slit starter.
Phased Array Probe
Figure 5 shows the phased array probes and wedges; their specifications are listed in Table 1. The probes’ frequency is 2.25 MHz, and the array of elements is 2×16 and 4×8. The probes are set on the surface of the specimen directly or with a wedge.

Table 1 Specifications of the probes

<table>
<thead>
<tr>
<th>Type</th>
<th>2 × 16 probe</th>
<th>4 × 8 probe</th>
</tr>
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<tbody>
<tr>
<td>Frequency</td>
<td>2.25MHz</td>
<td>2.25MHz</td>
</tr>
<tr>
<td>Number of elements</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Element array (width × length)</td>
<td>2×16</td>
<td>4×8</td>
</tr>
<tr>
<td>Aperture dimension (mm × mm)</td>
<td>31.8 × 14.9</td>
<td>15.8 × 15.8</td>
</tr>
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</table>
**Experimental Method**

An XY scanner is used to move the probe in two-dimensional directions on the surface of the specimen. The direction of the ultrasonic beam and the movement of the transmitter and receiver are set in a direction perpendicular to the crack surface. The Dynaray phased array UT system with Ultra Vision was used for the experiments.

**RESULTS AND DISCUSSION**

**Phased Array Asymmetrical TOFD**

Figure 6 indicates the test results of SCC-A by the phased array asymmetrical TOFD, using a B, C, D-scope display by Ultra Vision: (1) 2×16 probe without wedge, (2) 2×16 probe with wedge, (3) 4×8 probe without wedge, and (4) 4×8 probe with wedge. These displays are for a focus depth of 8 mm, which corresponds to the estimated depth of SCC-A. Five kinds of display with different refraction angles of -30, -15, 0, 15, 30 degrees are shown in the horizontal direction. The refraction angle is defined as the angle of a line from the center between the transmitter and receiver to the focus point (convergence point).

Table 2 lists depth measurements of SCC. These measurements were evaluated with measured echo path and incident point position calculated by Ultra Vision for scanning data with a refraction angle of 0 degree.

**Multi-angle Synthesis**

Figure 7 indicates B-scope displays synthesized with the different refraction angle results shown in Figure 6 by the multi-angle synthesis method.

Figure 8 indicates B-scope displays synthesized with the different focus depth results shown in Figure 7 by the multi-angle synthesis method. We can obtain a single display with different refraction angle and focus depth results.

<table>
<thead>
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<th>Table 2 Depth measurement of SCC</th>
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<tbody>
<tr>
<td>Probe</td>
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<td></td>
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<tr>
<td>Depth Measurements (mm)</td>
</tr>
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</table>
(1) 2x16 probe without wedge

(2) 2x16 probe with wedge

Figure 6 (continued)
Figure 6 Test results of SCC-A by the phased array asymmetrical TOFD (focus depth 8 mm)

(3) 4×8 probe without wedge

(4) 4×8 probe with wedge
Figure 7 Synthesis in refraction angle by the multi-angle synthesis method (focus depth 8 mm)

Figure 8 Synthesis in refraction angle and focus depth by the multi-angle synthesis method

SCC Destructive Evaluation

Figure 9 shows the results of the SCC-A destructive evaluation, for sections perpendicular to the crack surface. We can recognize several cracks and the depths are 6–7 mm. The depth measurements by UT correspond to those by destructive evaluation.
We can also find several weld defects such as porosities and hot cracks below the SCC. In the display in Figure 10, we can detect a few echoes below the SCC. However, we judged that these are not cracks on the upper surface, because with the method using a transmitter and receiver, the crack surface interferes with the detection of several tip echoes of cracks. We can verification these evaluations by SCC destructive evaluation.

(1) 2×16 probe without wedge
CONCLUSION
We have developed a phased array asymmetrical TOFD method which uses two matrix array probes as the transmitter and receiver for measuring the depth of SCCs in dissimilar welds of the nozzle safe-end of the vessel. This method has the following characteristics:

1. use of 2D matrix array probes for the transmitter and receiver,
2. asymmetrical ultrasonic beams with different refraction angles and path lengths of the transmitter and receiver,
3. synthesis of plural scanning data with different refraction angles and path lengths.

We have measured the depth of SCCs in dissimilar welds on the crack surface of specimens with this method and tested its effectiveness.

In future, we will acquire more test data of flaws, conduct tests on the surface opposite to the crack, conduct tests on cylindrical surfaces, and so forth.