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# Basic Study on the Phased Array UT Technique for Crack Depth Sizing in Ni-Based Alloy Weld

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**ABSTRACT**

In recent years, it has been reported that primary water stress corrosion cracking (PWSCC) has occurred in Ni-based alloy weld components such as steam generator safe end welds, reactor vessel safe end welds, and so on, in PWR. Defect detection and depth sizing are important in order to ensure the reliable operation and life extension of nuclear power plants. In the reactor vessel safe end welds, it was impossible to measure the crack depth of PWSCC. The cracks have occurred in the axial direction of the safe end welds. Furthermore, the cracks had some features such as deep, large aspect ratio (ratio of crack depth and length), sharp geometry of crack tip, and so on. Therefore, development and improvement of crack detection and sizing capabilities for ultrasonic inspection technique have been required. Phased array UT technique for defect depth sizing was applied to the Ni-based alloy weld specimens with EDM notches. From the experimental results, superior performance of phased array UT at the inside inspection of Ni-based alloy weld was shown.

**KEYWORDS**

Ni-Based Alloy Weld, Phased Array UT, Crack Depth Sizing, Primary Stress Corrosion Cracking

**ARTICLE INFORMATION**

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## 1. Introduction

There have been many reports regarding the occurrence of PWSCC in Ni-based alloy weld of PWR in Japan [1]. The depth sizing of such cracks with high accuracy is important in order to ensure the reliable operation and life extension of the components in the nuclear power plant. The shape of PWSCC crack that had occurred in the reactor vessel nozzle safe end welds was large aspect ratio that is short in length but deep in depth. It is impossible to detect a tip diffraction echo from the crack tip by conventional UT [2]. In general, it has been considered that inspection of Ni-based alloy weld by conventional UT is difficult because of the anisotropy of the weld metal microstructure (columnar crystal microstructure). This is because of ultrasonic waves scattering and attenuation due to the weld metal microstructure. Furthermore, ultrasound noise echoes generated from the weld metal microstructure cause the decline of detection capability of the crack tip echo. Therefore, it is difficult to measure the defect depth of PWSCC cracks.

Phased array UT technique has been applied to many field inspections such as CRD housing-stub tube welds [3], core shroud welds [4] and so on. Phased array UT technique is capable of beam steering and focusing on objective regions. Real time images (A-scan, B-scan, C-scan and D-scan) are obtained from the electronic control of excitation pulses of each element without mechanical probe scanning. From these features of phased array UT technique, the optimization of inspection conditions and imaging of inspected data were carried out in Ni-based alloy weld in several institutions.

The purpose of this study is to establish a high accuracy defect depth sizing technique for SCC crack in Ni-based alloy weld (weld metal and buttering) by phased array UT. Especially, the study of the defect depth sizing in buttering by UT has not been enough. For the first step, the phased array UT technique was applied with regard to defect depth sizing capability at the inside inspection in

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Ni-based alloy weld specimen with EDM notches in weld metal and buttering. The report in this study has clarified the applicability of the phased array UT technique for defect depth sizing.

## 2. Experiment

### 2.1. Specimens

Two kinds of specimen were used in this study. One is a side drilled holes (SDHs) specimen for the determination of UT conditions. The material of this specimen is austenitic stainless steel SUS316L. The shape and dimensions are shown in Figure 1. On the specimen, SDHs of 3.2 mm in diameter were made at the following depth locations: Z = 5 mm, 10 mm, 15 mm, and 20 mm.

The other specimen is a Ni-based alloy weld specimen with EDM notches for defect depth sizing. The specimen was simulated weld of reactor vessel safe end. EDM notches were introduced in Ni-based alloy weld specimen to the perpendicular direction of weld line in weld metal and buttering. The shape and dimensions of these specimens are shown in Figure 2 and Figure 3. Overview of the specimen in weld metal is shown in Figure 4. Typical photograph of microstructure in Ni-based alloy weld is shown in Figure 5. From this photograph, it was observed that the columnar crystal microstructure in buttering is growing to the parallel direction in this paper. Table 1 shows the EDM notch conditions. Four EDM notches were introduced in weld metal as well as buttering respectively. The depth of these defects is equal to 2 mm, 5 mm, 10 mm and 20 mm, while the length of all the notches was 10 mm.

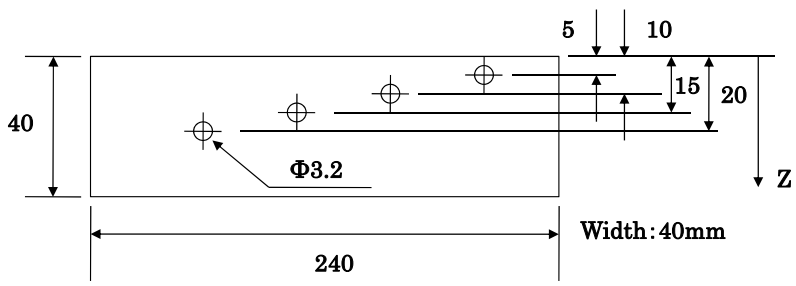


**Fig.1. Shape and dimensions of SDHs specimen**

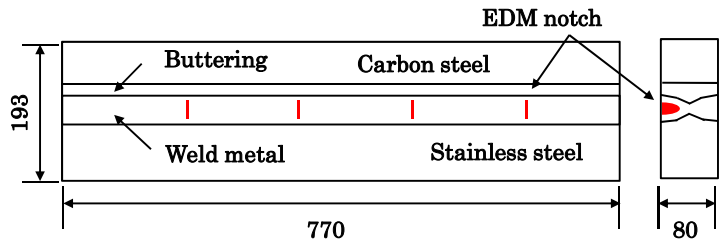


**Fig.2. Ni-based alloy weld specimen with EDM notches in weld metal**

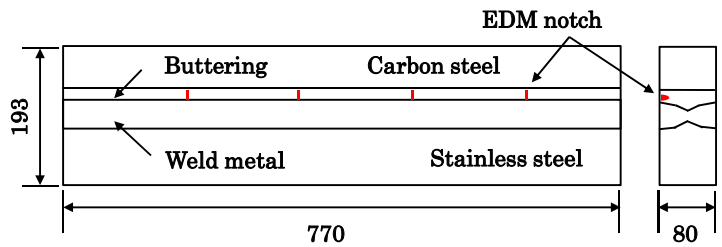


**Fig.3. Ni-based alloy weld specimen with EDM notches in buttering**

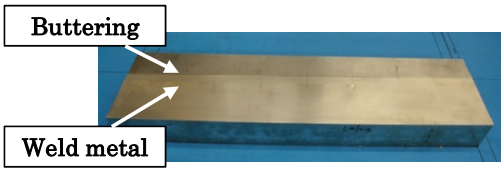


**Fig.4. Overview of Ni-based alloy weld specimen with EDM notches in weld metal**

**Table 1 EDM notch conditions of Ni-based alloy weld specimen**

| Specimen | Area | Direction | Flaw No. | Depth (mm) | Length (mm) | shape |
|---|---|---|---|---|---|---|
| EDM-1 | Weld metal | Axial | A | 2 | 10 | Semi-ellipse |
| | | | B | 5 | | |
| | | | C | 10 | | |
| | | | D | 20 | | |
| EDM-2 | Buttering | Axial | E | 2 | 10 | Semi-ellipse |
| | | | F | 5 | | |
| | | | G | 10 | | |
| | | | H | 20 | | |

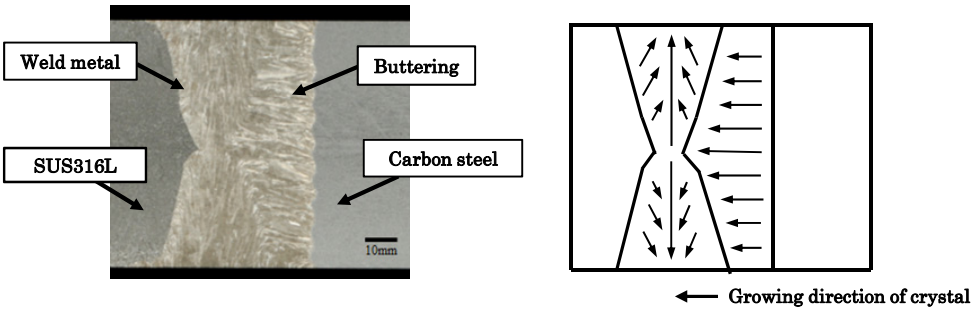


**Fig.5. Typical photograph in Ni-based alloy weld**

## 2.2. Equipment and phased array probes

Phased array UT equipment (Tomoscan III) and phased array probe were used in this experiment. The following two types of array probes were used for this examination from the inside surface: (1) a nominal frequency of 2 MHz, an element size of 10 mm x 0.8 mm, and the number of channels was 64ch (abbreviated as 2L(10)), (2) a nominal frequency of 2 MHz, an element size of 20 mm x 0.6 mm, and the number of channels was 64ch (abbreviated as 2L(20)). Array probe 2L(10) was selected for crack depth sizing of a shallow crack (about 10 mm in depth), and array probe 2L(20) was selected for crack depth sizing of a deep crack (about 20 mm in depth). The specification of phased array UT probes is shown in Table 2.

**Table 2 Specification of phased array UT probes**

| | Probe | Specification | Target |
|---|---|---|---|
| ① | 2L(10) | Type : Linear<br>Frequency : 2MHz<br>Mode : Longitudinal<br>Element size : 10 x 0.8mm<br>No. of channels : 64ch | for shallow crack |
| ② | 2L(20) | Type : Linear<br>Frequency : 2MHz<br>Mode : Longitudinal<br>Element size : 20 x 0.6mm<br>No. of channels : 64ch | for deep crack |

## 3. Results and Discussion

### 3.1. Determination of UT conditions

The UT conditions of phased array probes 2L(10) and 2L(20) were investigated. In order to determine the main UT conditions (active aperture size and focal depth), UT data of SDHs specimen was measured.

#### 3.1.1 UT conditions of array probe 2L(10)

An active element size of 2L(10) was investigated. In general, although the focal effect of ultrasonic beam increase with increasing active aperture size, surface dead zone of ultrasonic beam also increase. Therefore, detection capability of shallow crack is decreased. Then, in order to keep the surface dead zone within 2mm, the active aperture size of 10mm x 12.8mm at 2L(10) was selected.

The typical results of the echo height distribution by the array probe 2L(10) are shown in Figure 6. This figure shows the B-scan images (upper side of this figure) and SDHs echo height distributions (lower side of this figure). These results were obtained from an examination that was performed at a refraction angle of 45°, a focal depth of F = 10 mm, and a sensitivity of 42 dB for active aperture size of (a) 10 mm x 6.4 mm and (b) 10 mm x 12.8 mm. This figure shows that the active aperture size (b) 10 mm x 12.8 mm has steep echo height distribution width and a better focal efficiency on either of the SDHs at depth locations of Z = 5–20 mm, compared to the active aperture size of (a) 10 mm x 6.4 mm. From these results, the active aperture size of 10 mm x 12.8 mm was selected.

The effect of focal depth of the array probe 2L (10) was investigated. The typical results of echo height distribution in the three focal depth conditions, that is F=5mm, 10mm and 20mm, are shown in Figure 7. The distribution of the reflection echo from the SDHs, where the focal depth was changed in increments from F = 5 mm to 10 mm, to 20 mm, was examined with the active aperture size of 10 mm x 12.8 mm, and effect of focal depth of the array probe 2L (10) was evaluated. As a result, the spread of ultrasonic waves was equivalent at all the focal depth conditions, and no significant difference was confirmed in the echo height distribution. From this result, the focal depth was determined to be F = 10 mm, which is the same value as the shallow defect (10 mm in depth), which was the purpose of applying this array probe.

#### 3.1.2 UT conditions of array probe 2L(20)

The UT conditions of the array probe 2L(20) were investigated. The array probe 2L(20) was selected for crack depth sizing of a deep crack (about 20mm in depth). And then, maximum active channels of phased array UT equipment are 32chs. Thus, active aperture size of 20 mm x 19.2 mm (32ch) at 2L(20) was selected.

The effect of focal depth by the array probe 2L(20) was investigated in the three conditions of focal depth (F=10mm, 20mm and 30mm). The typical results of the echo height distribution by the array probe 2L(20) are shown in Figure 8. This figure also shows the B-scan images (upper side of figure) and the distribution of the reflection echo from the SDHs (lower side of figure) where the refraction angle was 45° and the sensitivity was 34 dB. As shown in Figure 8, the significant difference in the echo height distribution at the three focal conditions was not recognized. From this result, the focal depth was determined to be F = 20 mm, which is the same depth as the defect depth of 20 mm that was the purpose of applying this array probe.

#### 3.1.3 UT conditions of Ni-based alloy weld specimen

From the above results, the phased array UT conditions for the Ni-based alloy weld specimen were investigated. These conditions are described below. Automatic UT of the direct contact method was applied to the near surface inspection in both directions towards the defect.

The sector scanning operation method was used. The range of the refraction angles was set from 30 to 80 degrees, and the scanning pitch was set to 1 degree.

Mechanical scanning of the array probe was applied to rectangular scanning by using the X-Y

scanner. As for the scanning area, the parallel direction of weld line (direction Y) was set at Y = 80 mm or more, and the perpendicular direction of weld line (direction X) was set at X = 30 mm. The scanning pitch was set at 0.5 mm for direction Y and at 1 mm for direction X.

Data analysis was performed by converting the sector scanning data into linear scanning data. The data analysis was performed by the UT data of 45° and 60°. The defect depth sizing was performed by tip echo method.

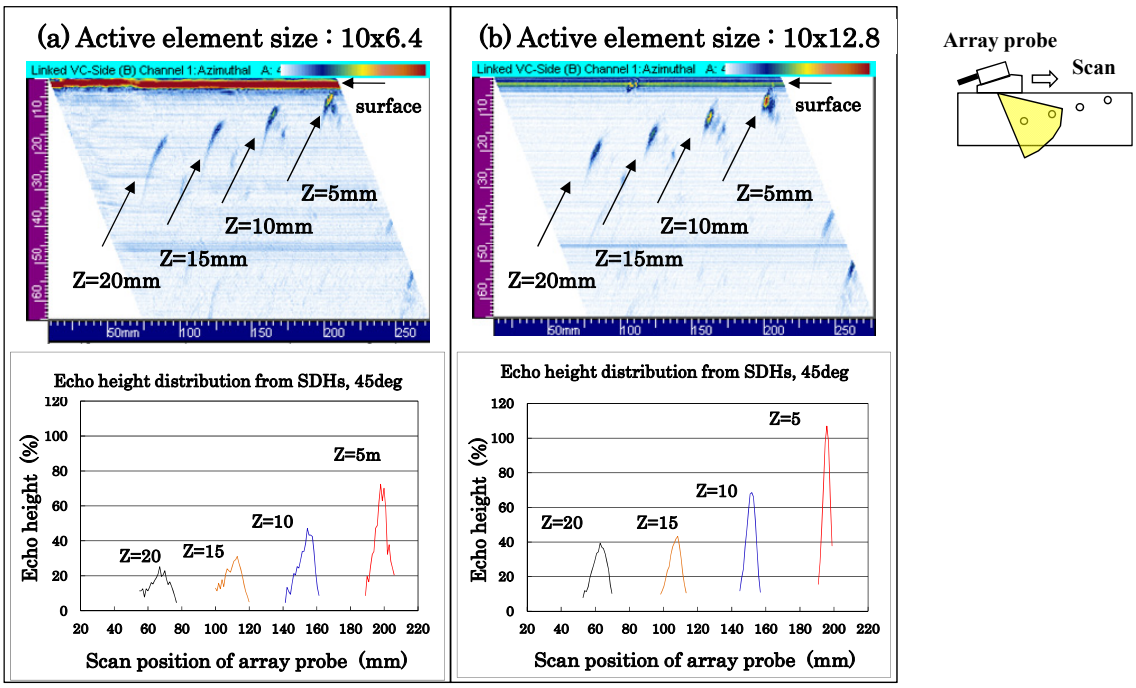


**Fig.6. Effect of active element size by the array probe 2L(10)**

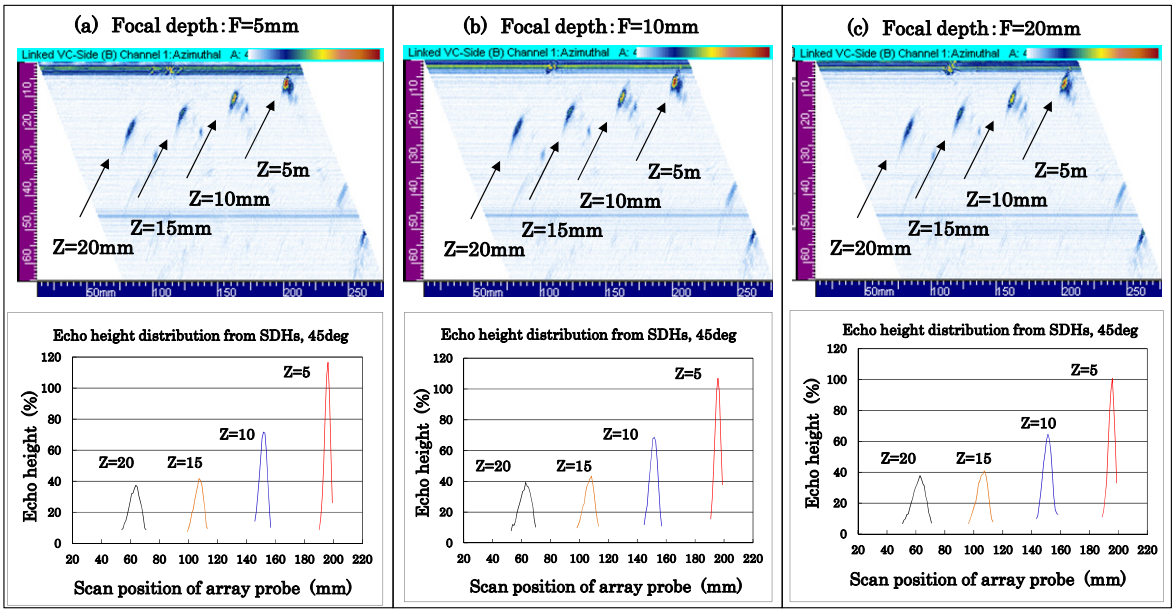


**Fig.7. Effect of focal depth by the array probe 2L(10)**

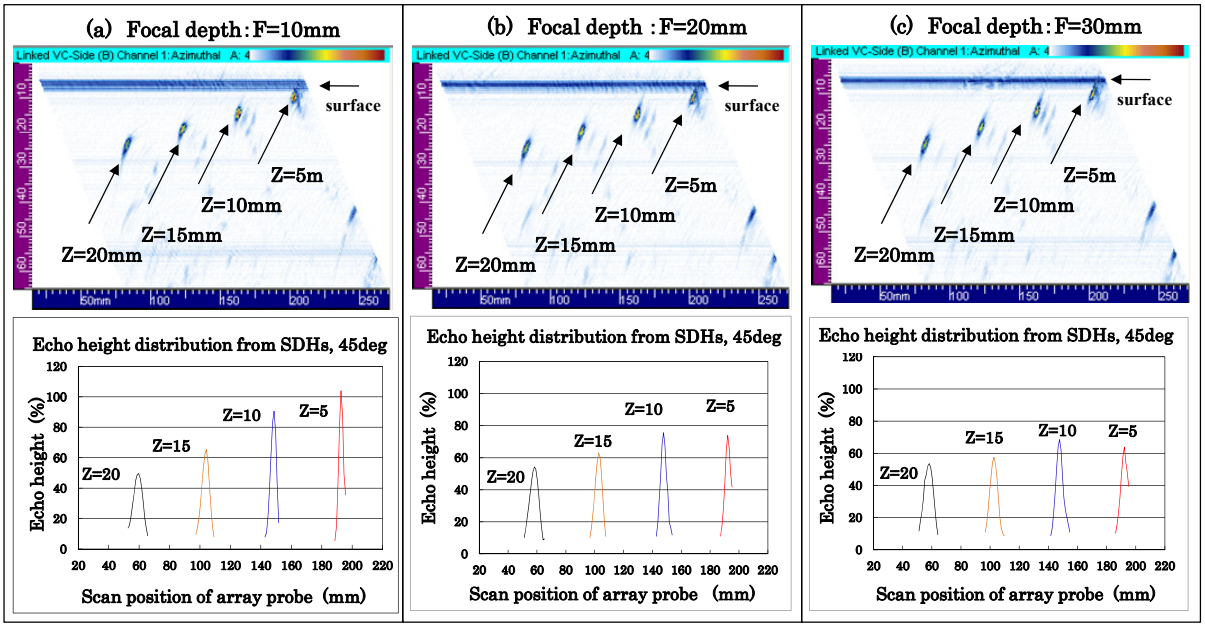


**Fig.8. Effect of focal depth by the array probe 2L(20)**

## 3.2. Depth sizing in weld metal

The results of phased array UT on the specimen (specimen name: EDM-1) with EDM notches in weld metal are in Figure 9. This figure also shows the B-scan images for each notch depth. As shown in Figure 9, corner echoes, denoted surface breaking defect echoes, and tip echoes are indicated with an arrow and a circle. The corner echoes can be observed in all the EDM notches.

On the other hand, the tip echoes can be clearly observed in the notches with depth of 5 mm, 10 mm and 20 mm. In the defect of 2mm depth, the tip echo was buried in the surface dead zone due to the notch being a shallow defect, and was not detected. The results of depth sizing in these notches are shown in Table 3. In this Table, the measured depth by phased array UT was evaluated within an error of 3 mm.

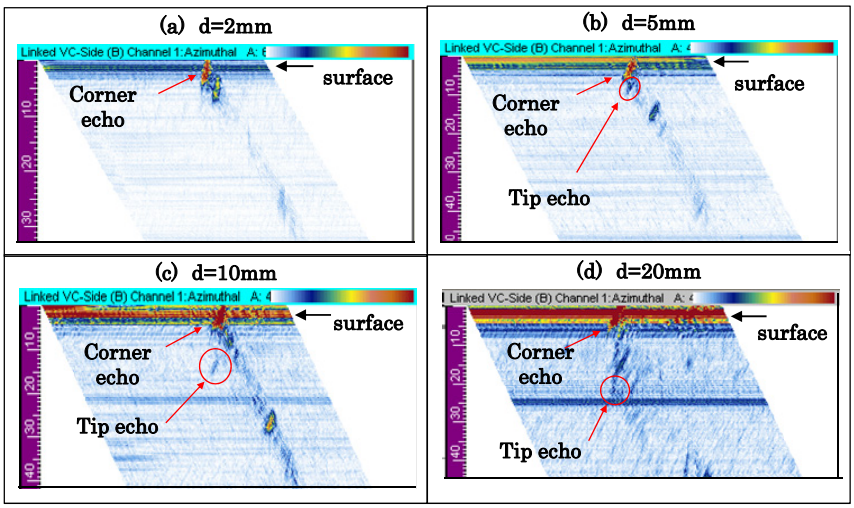


**Fig.9. B-scan images of weld metal with EDM notch by phased array UT**

**Table 4 Defect depth sizing accuracy of weld metal with EDM notch by phased array UT**

| EDM notch depth (mm) | 5 | 10 | 20 |
|---|---|---|---|
| Measured depth by UT (mm) | 6.6 | 12.7 | 21.1 |

### 3.3. Depth sizing in buttering

The results of the phased array UT for the specimen (specimen name: EDM-2) with EDM notches made in buttering are shown in Figure 10. This figure shows B-scan images similar to the previous section. In this figure, the corner echoes and the tip echoes are indicated with an arrow or a circle. According to this figure, the corner echoes, denoted the surface breaking defect echoes, can be observed in all the defects. Then, the tip echoes were observed in the three notches except the defect of 2mm depth. The tip echo of this defect was buried in the surface dead zone and was not detected.

The results of depth sizing in buttering are shown in Table 4. In this table, the measured depth by phased array UT was evaluated within an error of ±2 mm. From these results, it was obtained the significant defect depth sizing data in buttering. The study with regard to defect depth sizing capability in buttering is very few. Therefore, in future, it is necessary to evaluate for the many defect depth sizing data.

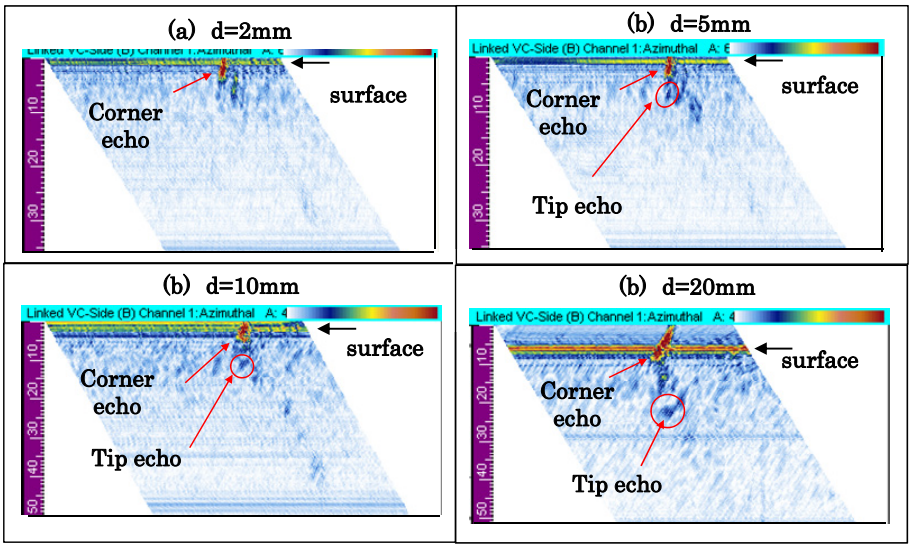


**Fig.10. B-scan images of buttering with EDM notch by Phased Array UT**

**Table 4 Defect depth sizing accuracy of buttering with EDM notch by phased array UT**

| EDM notch depth (mm) | 5 | 10 | 20 |
|---|---|---|---|
| Measured depth by UT (mm) | 6.5 | 9.9 | 18.7 |

### 3.4. Depth sizing of EDM notch

The results of depth sizing of the EDM notches in Ni-based alloy weld (weld metal and buttering) by phased array UT are shown in Figure 11. Although the amount of data obtained was less, a statistical error evaluation was attempted and resulted in the average error of 0.92 mm and the RMS error was 1.58 mm. Therefore, it can be say that this RMS error of 1.58 mm was evaluated as having better accuracy than the RMS error of 3.2 mm, which is the acceptance criteria of performance demonstration, as defined in ASME Code Sec. XI App. VIII.

From the above results, the phased array UT technique is an effective technique for defect depth sizing in nickel based alloy welds (weld metal and buttering).

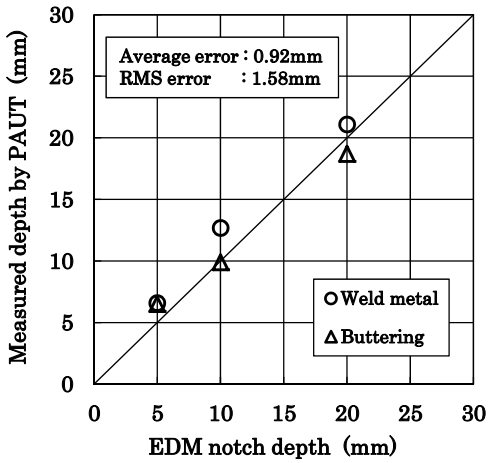


**Fig.11. Defect depth sizing accuracy of EDM notches in Ni-based alloy weld by phased array UT**

### 3.5. Noise echo in Ni-based alloy weld

It has generally been considered that the defect detection and depth sizing in Ni-based alloy weld by conventional UT are difficult. This is because that the noise echoes are generated from the columnar crystal microstructure in Ni-based alloy weld. Therefore the tip echo is buried in the material noise echo, and then defect detection capability decrease.

The noise echoes were investigated in Ni-based alloy weld (weld metal and buttering). The B-scan images of weld metal and buttering by array probe 2L (10) are shown in Figure 12. In the weld metal, the structural noise echo is small. On the other hand, structural noise echo in the buttering was relatively large. The examination results of the array probe 2L (20) are shown in Figure 13. A slight structural noise echo was observed at a high sensitivity of 58 dB in the weld metal. However, structural noise echo was large in the buttering at 48 dB (10 dB lower than weld metal sensitivity).

As shown in Figure 5, it was observed that the columnar crystal microstructure in buttering is growing to the parallel direction in this paper. The structural noise echo in buttering was large compared to the structural noise echo in weld metal. The reason for this is that the ultrasonic wave was transmitted to the perpendicular direction of the columnar crystal microstructure.

It is generally considered that the tip echo of SCC crack is a weak signal. In order to detect the tip echo with high sensitivity, it is important to enhance the signal to noise ratio (SN ratio) and to distinguish the tip echo from the structural noise echo.

In this study, it could be detect the tip echo of EDM notch in Ni-based alloy weld because of the optimization of inspection conditions by phased array UT. On the other hand, there is concern related to the decline of the defect detection capability for SCC crack. Therefore, it is important to develop the advanced techniques such as matrix array UT, combined technique with linear and matrix array UT, and so on, for defect depth sizing.

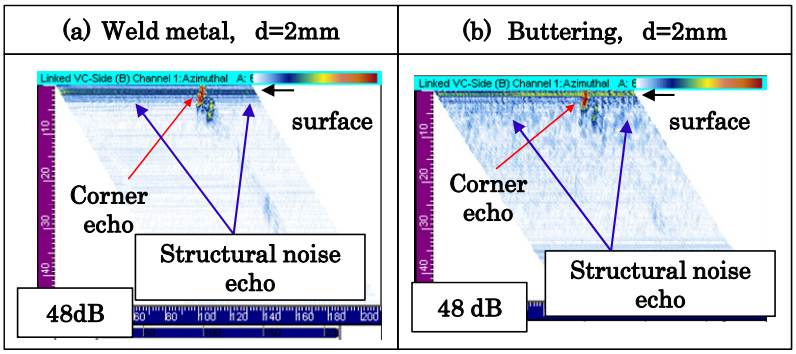


**Fig.12. Comparison of structural echoes between weld metal and buttering using array probe 2L(10)**

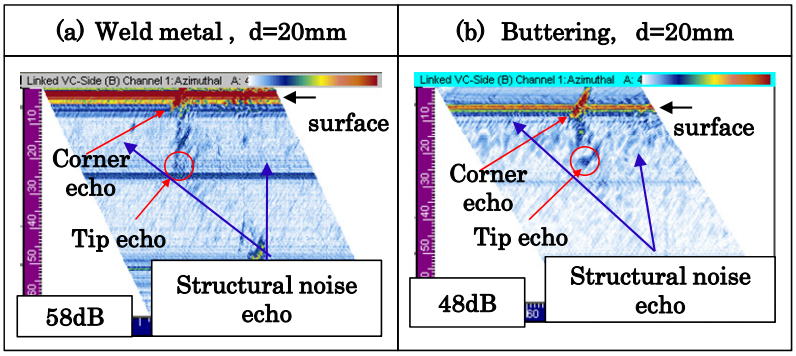


**Fig.13. Comparison of structural echoes between weld metal and buttering using array probe 2L(20)**

## 4. Conclusion

In order to establish the advanced depth sizing UT technique for SCC crack in Ni-based alloy weld, the phased array UT technique was applied to the Ni-based alloy weld specimen with EDM notches made in weld metal and buttering. From the experimental results, there was evaluated to the defect depth sizing capability. It was concluded as follows.

(1) Phased array UT conditions of the active aperture size and focal depth were optimized from the results of echo height distribution for SDHs specimen.
(2) Phased array UT technique was applied to Ni-based alloy weld specimen in weld metal and buttering with EDM notches. The superior performance of the phased array UT technique was shown for defect depth sizing, and could be evaluated with good accuracy with the average error of 0.92 mm and the RMS error of 1.58 mm.
(3) From these results, it was shown that the phased array UT technique is an effective technique for the defect depth sizing in Ni-based alloy weld.

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