Development of Simplified Ultrasonic CT System for Imaging of Weld Metal and It's Comparison with TOFD Method*

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In this paper, as a new measurement method to estimate the structure change of weld metal, the simplified ultrasonic CT system, which uses the information of three directions, that is, 90° , $+45^\circ$ and -45° about inspection plane is developed. Use of simplified ultrasonic CT system has two merits: Firstly, the measurement time is very short comparing with general CT. Secondly, it can detect sensitively very infinitesimal defect in vertical or slant direction about inspection plane because the obtained image is not C scan image but CT image calculated from three directions. From these merits, this method can be considered as a very effective method for the evaluation of material condition. In order to compare the performance of simplified ultrasonic CT, the CT image obtained from several specimens with several simple defects was compared with the D scan image obtained by TOFD (Time of Flight Diffraction) method. We can see simple defects more clearly by new proposed method. Experimental results on several kinds of specimen, having welded joint by electron beam welding, welded joint by electron beam welding and fatigue crack showed that the obtained C scan or CT image has better resolution than the D scan image by TOFD method and shows similar image to actual shape.

Key Words: Simplified Ultrasonic CT, C Scan Image, D Scan Image, TOFD Method

1. Introduction

Ultrasonic wave has been widely used in the field of nondestructive test of materials^{(1),(2)}. Specially, ultrasonic microscopy has a big role in the visualization of inner part of material⁽³⁾⁻⁽⁵⁾. However, most of these conventional methods for visualization are very sensitive to horizontally laid defects, but much less sensitive to vertically laid crack, slant crack or the change of material condition. Moreover, general crack in welded part is often found in slant direction according to welded line. Therefore, the development of a new method that can detect tiny crack in slant direction or material change in the welded part

becomes necessary.

Ultrasonic CT (Computerized Tomography) has been used to see into the inner part of human body in hospital and had made a big contribution to this field⁽⁶⁾⁻⁽⁹⁾. Also, in order to make the image of the inner part of the material or semiconductor, B, C and D scan (TOFD method) has been mainly used^{(3),(4),(10),(11)}. But, B and C scan using the transducer of longitudinal direction is very sensitive to the defect of horizontal direction about inspection plane and D scan method has difficulty in detecting the defect near the surface.

In this paper, as a new measurement method to estimate the welded part or change of material condition, a simplified ultrasonic CT system is developed and compared to TOFD method. The simplified ultrasonic CT system developed in this research uses the information of -45° and $+45^\circ$ direction about inspection plane as well as that of the perpendicular direction about inspection plane. So, we intend to make the simple CT image using only the information of 3 directions. Use of simplified CT has two merits:

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Firstly, the measurement time is very short in comparison with the general CT because this system requires only the information of three directions. Secondly, it can detect very tiny defect in vertical direction because the ultrasonic signal is obtained from three directions.

The basic performance of the proposed method was confirmed through specimens with simple defect. The obtained CT images about specimens with simple defect showed good agreement with actual shapes and had better resolution than D scan image by TOFD method. In order to know the applicability to actual welded part, CT images for welded specimens were obtained. The obtained results showed that the CT images measured by simplified ultrasonic CT had good agreement with the actual micro structural condition in welded part and had better resolution than D scan image by TOFD method.

2. The Principle of Simplified Ultrasonic CT and TOFD Method

2.1 The principle of simplified ultrasonic CT

CT is an acronym for computerized tomography and means the technique which represents the image of tomogram by computer. That is, CT is the technique to represent the cut surface by combining the information of each tiny point which is back projected from 360° direction in the object.

Figure 1 shows the principle of general CT. The received signal $p(r, \theta)$ which passes through the line SD, may be differently attenuated according to the condition of medium and is defined as

$$p(r, \theta) = \int_{SD} f(x, y) ds \quad (1)$$

using the x - y and r - θ coordinate system shown in Fig. 1, where $f(x, y)$ is an attenuation distribution coefficient and, for a point (x, y) on the line SD, $s = y \cos \theta - x \sin \theta$. The set of received signals with θ

Fig. 1 The principle of general CT

constant for a range r is called a projection at the angle θ . CT image is obtained by projecting inversely the information to the x - y coordinate from the 360° direction.

In the case of ultrasonic C scan about plate, obtaining the C scan image for the defect of vertical direction about inspection plane is very difficult. For the C scan about plate, this point is a big fault. However, if we use the incident wave of the width direction or the direction corresponding to this direction, detecting the defect in vertical direction about inspection plane becomes possible. That is, if we have information for +45° and -45° direction about the width direction of plate, the simplified ultrasonic CT system which represents the condition of defects laid in vertical direction about inspection plane can be realized.

Figure 2 shows the principle of simplified ultrasonic CT system to detect the defect of vertical or slant direction. As shown in figure, CT scan is performed while the shear wave in the -45° and +45° direction about inspection plane is transmitted and received, respectively. So, the basic method of measurement system used in this research is V transmission method for shear wave. By reflecting the incident wave in the bottom of specimen, the object of measurement may be inspected with the difference of 90° angle as shown in figure. So, the dead zone which can not be scanned by longitudinal transducer can be measured. Also, the object of measurement can be inspected with difference of 45° by adding longitudinal transducer. By combining the waveform information from scanning of shear wave and longitudinal wave, CT image is made. Also, in order to do this experiment, it will be noticed that the position and acoustic axis of each transducer should be completely in accord.

2.2 Principle of TOFD method

TOFD technique is an ultrasonic NDT technique used in measuring the defect in welded part in the

Fig. 2 The principle of simplified ultrasonic CT system

(a) The principle of TOFD method

(b) The method to get D scan image

Fig. 3 TOFD method (a) The principle of TOFD method and (b) The method to get D scan image

field. This method relies on the diffraction of ultrasonic energies from 'corners' and 'ends' of internal structures (primarily defects) in a component being tested. Figures 3(a) and (b) show the principle of TOFD method and the method to get D scan image, respectively.

As shown in Fig. 3(b), the defect can be found by D scan method. That is, D scan image shows the shape of defect obtained from upper surface of specimen. Thus, TOFD method is different method with simplified ultrasonic CT in that the simplified ultrasonic CT can measure a kind of tomogram.

3. Construction of Measurement System and Specimen

3.1 Construction of simplified ultrasonic CT system

Figure 4 shows the design of measurement system and Fig. 5 shows the photo of measurement system. Firstly, the ultrasonic wave is transmitted from square wave pulser (Ritec SP-801, ① in Fig. 5) and received by broad band receiver (Ritec BR 640, ② in Fig. 5). This signal is A/D converted (Ritec STR 8100) and recorded in PC (IBM compatible, ③ in Fig. 5).

Used transducer is focused type (focal length: 10 mm) and has the frequency region of broad band (longitudinal transducer: 20 MHz, shear transducer:

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Fig. 4 The construction of simplified ultrasonic CT system

Fig. 5 View of the simplified ultrasonic CT system

15 MHz). X-Y-Z scanner (④ in Fig. 5) and software for image processing is made by Sonix company and the software to convert the data into the CT image is developed in this research. In this software, the C scan image is made by the absolute magnitude of the received signal. Using the C scan images of three directions, the CT image was calculated.

3.2 Specimen

Firstly, in order to confirm the reliability of the measurement system, the several specimens were

Fig. 6 Specimen for basic experiment

Fig. 7 Specimens with welded part

prepared and showed in Fig. 6. Specimen is made by SUS304 (JIS G 4304, 1999)⁽¹⁴⁾. In order to adjust the refraction angle of shear wave, specimen of Fig. 6(a) is prepared. In this specimen, 3 holes are drilled to adjust the refraction angle to 45°. For the left and right transducer, this adjustment is performed in order. Figure 6(b) shows the specimen with vertical slit (the height of slit: 2 mm). Also, specimens with drill hole ($\phi=1$ mm) or surface slit were prepared.

Next, in order to confirm the applicability to welded specimen, several welded specimens are prepared and showed in Fig. 7. Figures 7(a) and (b) show specimen with welded joint by electron beam welding. Also, in order to compare with the specimen of Fig. 7(a), the welded specimen with higher energy than the case of Fig. 7(a) is prepared. Figure 7(c) shows the specimen with welded joint by electron beam welding and fatigue crack. The original size of this specimen was 17 mm $\times$ 17 mm $\times$ 100 mm. After electron beam welding, this specimen was fatigued in

Fig. 8 The construction of D Scan system by TOFD method

Machine Test System (MTS). After fatigue experiment, this specimen was cut as same size with another specimen. Figure 7(a) is made by SUS304 (JIS G 4304, 1999)⁽¹⁴⁾. Then, the material of (b) and (c) is made by SM50 (JIS G 3106, 1999)⁽¹⁵⁾.

3.3 Construction of D Scan system by TOFD method

Figure 8 shows the design of D scanning system by TOFD method. In the simplified ultrasonic CT, we removed longitudinal transducer and changed the refraction angle as about 60°. Used transducer is a wide band normal probe (Sonix PR 35 with nominal frequency of 25 MHz).

As shown in figure, the wave reflected in the upper surface of specimen is used a standard instead of lateral wave.

4. Experimental Results and Discussion

4.1 Adjustment of refraction angle in simplified ultrasonic CT

In order to adjust the refraction angle of transducer for shear wave as 45° in simplified ultrasonic CT, the specimen with 3 holes of Fig. 6(a) is used and Fig. 9 shows the echo signal when the refraction angle is properly adjusted. The waveform near 17 μ sec is echo from the hole 1. If the refraction angle is not properly adjusted, the big echo from the hole 2 or 3 will be appeared near 13 μ sec.

4.2 Experimental result for simple defect

Experimental results for basic specimens with simple defects were obtained by simplified ultrasonic

Fig. 9 The echo signal when refraction angle is adjusted

Fig. 10 The CT image for specimen with vertical slit

Fig. 11 The CT image for specimen with (a) surface slit and (b) drill hole

CT and showed in Figs. 10 and 11. Figure 10 shows the experimental result for the specimen with vertical slit of Fig. 6(b).

Figures 10(a) and (b) show the C scan image or projection image for longitudinal and shear wave, respectively. In (a) and (b), the horizontal line shows the line to make the back projection image of (c) and (d). (c) and (d) show the back projection image of (a) and (b), respectively. (e) shows the CT image which is made by combining the image (c) and (d). Experimental result shows good agreement with actual shape of defect. Similarly, Figs. 11(a) and (b) show the result for specimen with surface slit

Fig. 12 D scan image for the specimen with (a) surface slit and (b) drill hole

and drill hole ($\phi=1$ mm), respectively.

Experimental result for the specimen with surface slit and drill hole shows good agreement with the actual defect. From these results, we can confirm that the simplified CT system is properly constructed.

For comparison with this result, the experimental results for specimen of Figs. 6(b) and (c) were obtained by TOFD method. Figures 12(a) and (b) show the D scan image for specimen with surface slit and drill hole, respectively.

From Fig. 12, we can reconfirm that TOFD method is not effective method to measure the defect near the surface.

If we compare Fig. 11 with Fig. 12, we can know that the simplified ultrasonic CT has better resolution than D scan image. To draw CT or D scan image, the maximum amplitude of received waveform was used. In CT image of Fig. 11, the magnitude difference between maximum and minimum value is almost 100. Then, the magnitude difference is almost 30 in the case of D scan image of Fig. 12. Because the CT image is the summation of 3 direction information, the resolution will be about 3 times. This is why the simplified ultrasonic CT has better resolution than D scan image. Also, we can not know the shape of defect in the D scan image.

4.3 Experimental result for specimen with welded part using simplified ultrasonic CT

In order to confirm the applicability of the simplified CT system to the evaluation of welded specimen, the CT images of several welded specimens

Fig. 13 The experimental result for specimen with welded part by electron beam welding (low energy welding and welded joint is rectangle)

Fig. 14 The experimental result for specimen with welded part by electron beam welding (high energy welding and welded joint is rectangle)

Fig. 15 The CT image for specimen with welded part by electron beam welding (welded joint: triangle)

were obtained and showed in Figs. 13 - 16.

Firstly, in order to know the possibility of application to welded part, the CT image for the specimen with welded part by electron beam welding of Fig. 7

Fig. 16 The experimental result for the specimen with welded joint by electron beam welding and fatigued crack

(a) D scan image for the specimen with electron beam welding (rectangle)

(b) D scan image for the specimen with electron beam welding (triangle)

(c) D scan image for the specimen with electron beam welding and fatigue crack

Fig. 17 D scan image from the specimen with (a) electron beam welding (welded part: rectangle), (b) electron beam welding (welded part: triangle) and (c) electron beam welding and fatigue crack

(a) was obtained and showed in Fig. 13. In this case, two kinds of welding intensity, that is, high energy and low energy welding were applied. Figure 13 shows the experimental result for specimen welded by low energy welding and Fig. 14 shows the experimental result for specimen welded by high energy welding.

Each CT image represents well the condition of welded part. By electron beam welding, because the grain size will be changed largely, the changed part by welding will have another grain size according to the energy intensity of welding. In the welded region, the attenuation coefficient is bigger than that of base metal. So, the amplitude of received signal used to make the C scan image becomes small. The CT images of Fig. 13(e) and Fig. 14(e) show this condi-

tion well. By comparing two figures, we can notice the energy used in welding is different.

Secondly, Fig. 15 shows the CT image for the specimen with welded part by electron beam welding of Fig. 7(b). Similarly, experimental results represent well the condition of welded part.

Next, the experimental result for the specimen with welded joint by electron beam welding and fatigue crack of Fig. 7(c) is obtained and showed in Fig. 16.

In Fig. 16(a), the thick line in the center shows welded joint. This part is faintly represented. And, the fatigued part is seen in near the border line of welded joint. The degree of fatigue seems to be big in upper part. So, the fatigued crack can be surely seen by this ultrasonic CT.

The experimental result shows good agreement with actual shape of micro structure difference in welded zone. So, we can confirm that the proposed simplified CT system can be available in the evaluation of welded part.

4.4 Experimental result for specimen with welded part using D Scan system

In order to compare the image obtained by simplified ultrasonic CT with D scan image by TOFD method, we obtained D scan image for the specimen of Figs. 7(a), (b) and (c).

Figures 17(a), (b) and (c) show D scan image obtained by the specimen of Figs. 7(a), (b) and (c), respectively.

From these three figures, we can know that it is difficult by TOFD method to examine the structure change of material. TOFD method will be only effective to detect defect.

5. Conclusion

As a new measurement method to estimate the welded part or change of material condition, the simplified ultrasonic CT system which uses the information of -45° and $+45^\circ$ direction about the inspection plane as well as that of the vertical direction is developed.

The performance of the proposed method was confirmed through several simple specimens and the obtained CT images of specimen with simple defect show a good agreement with actual image.

In order to know the applicability to welded part or the change of material condition, CT images of several specimens with partially welded part are obtained. The obtained CT images showed that the CT image measured had good agreement with actual defect of specimens.

By changing a little the simplified ultrasonic CT, D scanning system by TOFD method was constructed and used to get D scan image. By this TOFD method, we can not detect the defect on surface. Also, this D scanning system by TOFD method was not proper to the evaluation of structure change of weld metal.

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