The Development of Simplified Ultrasonic CT System and Its Application to the Evaluation of Weld Metal

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In this paper, as a new measurement method to estimate the change of material condition, the simplified ultrasonic CT system, which uses the information of three directions, that is, 90°, +45° and -45° about inspection plane is proposed. Use of simplified CT system has two merits: Firstly, the measurement time is very short compared with general CT. Secondly, it can detect sensitively small defect in vertical or slant direction about inspection plane because the obtained image is CT image calculated from three directions. From these merits, this method can be considered as an effective method to evaluate material conditions. The basic performance of the proposed method was confirmed through several specimens with several simple defects. In order to confirm the applicability of actual NDT, several kinds of welded specimens are investigated. The result showed that the CT image obtained had good agreement with actual defect of specimens.

Key Words : CT(Computerized Tomography), Material Condition, NDT(Nondestructive Testing)

1. Introduction

Nowadays, the importance of detection of micro cracks or degradation of strength of materials at the early stage of fracture has been increased. Actually, micro cracks near welded part of pressure vessel, or aircraft parts have become social issues.

Ultrasonic wave has been widely used in the field of nondestructive test of materials. (Birks, 1991; Miyoshi et al., 1996) Specially, ultrasonic microscopy has a big role in the visualization of inner part of material. (Briggs, 1992; Hillger, 1998; Yamanaka and Enomoto, 1982) 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 has made a big contribution to this field(Comm and Mauseth, 1999; Choi et at., 1993; Romans, 1995; Williams ad Beck, 1995). 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. (Briggs, 1992; Hillger, 1998; Silk, 1996,; Bernard, 1987) But, B and C scan using the transducer of longitudinal direction is very sensitive to the defect of horizontal direction about inspect 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 proposed. The simplified ultrasonic CT system

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developed in this research uses the information of -45° and +45° 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: 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 small 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 and the obtained CT images about specimens with simple defect showed good agreement with actual shapes. 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 had good agreement with the actual micro structural condition in welded part.

2. 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.

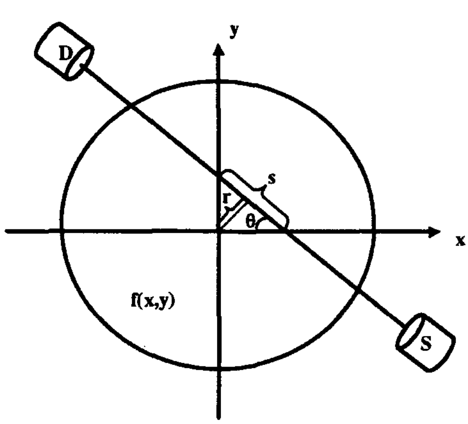


Fig. 1 Principle of general CT

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

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

using the x-y and r-θ coordinate system shown 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 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

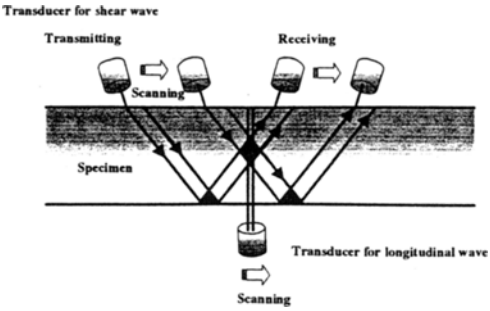


Fig. 2 Principle of simplified ultrasonic CT system

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.

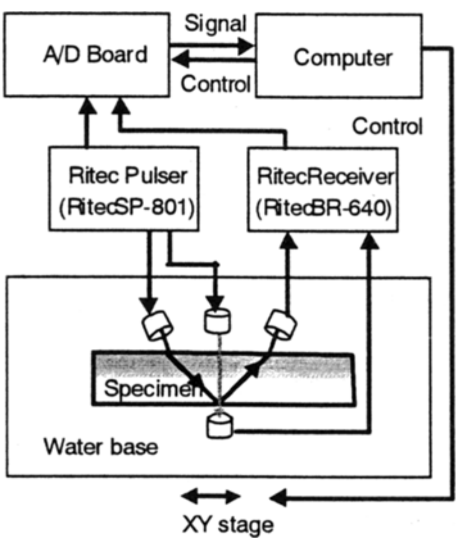


Fig. 3 Construction of simplified ultrasonic CT system

3. Design of Measurement System and Specimen

3.1 Design of measurement system

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

Fig. 4 View of the simplified ultrasonic CT system

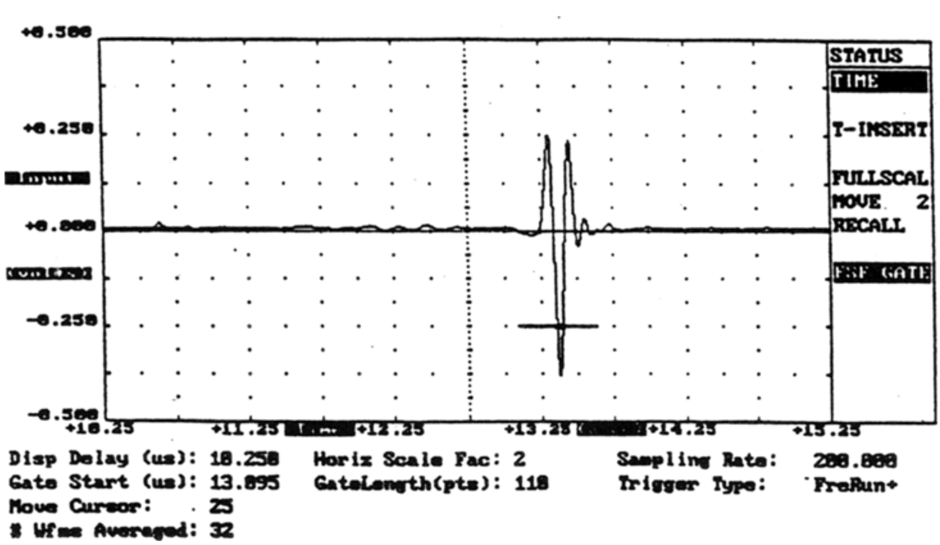


Fig. 5 Example of received waveform in simplified ultrasonic CT system

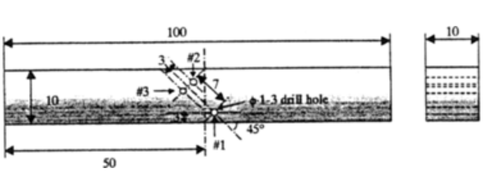
In Fig. 5, horizontal axis means the elapsed time from transmission of ultrasonic wave and vertical axis is the amplitude of waveform. The bar under waveform means the gate. In this case, the length of gate is composed by 110 points and can be adjusted.

Used transducer is focused type (focal length : 10mm) and has the frequency region of broad band (longitudinal transducer : 20MHz, shear transducer : 15MHz). X-Y-Z scanner(④ in photo. 1) and software for image processing are made by Sonix company and the software to convert the data into the CT image has been 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.

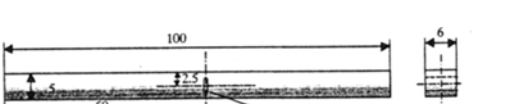
3.2 Specimen

Firstly, in order to confirm the reliability of the measurement system, the several specimens were prepared and showed in Fig. 6. Specimen is made by SUS304(JIS G 4304, 1999)(Han, 1999). 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 : 2mm). Also, specimens with drill hole ($\phi = 1$mm) or slit laid in 45° direction about inspection plane were prepared.

Next, in order to confirm the applicability to welded specimen, several welded specimens are prepared and showed in Fig. 7. Figure 7(a) shows specimen with welded part by electron beam welding. Also, in order to compare with Fig. 7(a), the welded specimen with higher energy than the case of Fig. 7(a) is prepared. Figure 7(b) shows the specimen with welded part by electron beam welding and drill hole. Figure 7(c) shows the specimen with welded part by arc welding. Then, only the material of the specimen with welded part by arc welding is made by SM50(JIS G 3106, 1999).



(a) Specimen for adjusting refraction angle



(b) Specimen for basic experiment

Fig. 6 Specimen for basic experiment

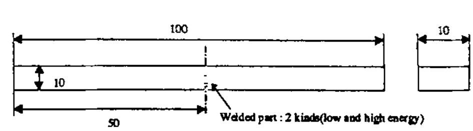
4. Experiment Results and Discussion

4.1 Adjustment of refraction angle

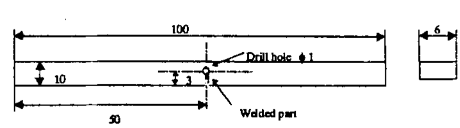
In order to adjust the refraction angle of transducer for shear wave as 45°, the specimen with 3 holes of Fig. 6(a) is used and Fig. 8 shows the echo signal when the refraction angle is properly adjusted. The waveform near 16 μsec is echo from the hole 1. If the refraction angle is not properly adjusted, the big echo from the hole 2 or 3 will be appeared near 11 μsec.

4.2 Experiment Result for Simple Defect

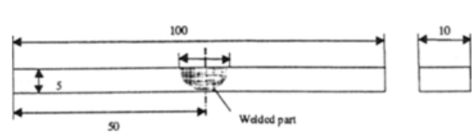
Experiment results for basic specimens with simple defects were obtained and showed in Fig. 9~11. Figure 9 shows the experiment result for the specimen with vertical slit of Fig. 6(b)



(a) Specimen with welded part by electron beam welding



(b) Specimen with welded part by electron beam welding and drill hole



(c) Specimen with welded part by arc welding

Fig. 7 Specimen with welded part

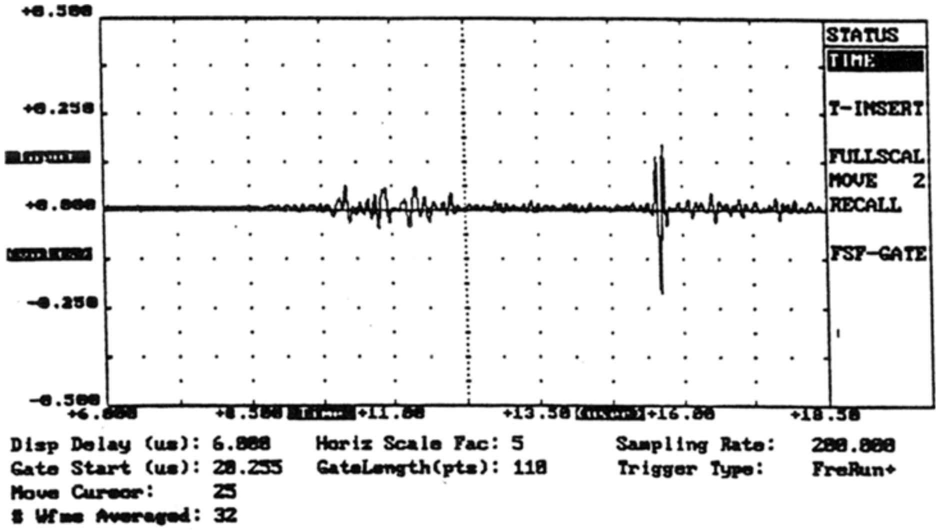
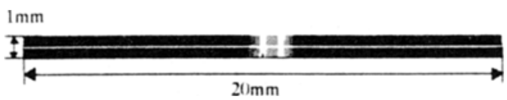
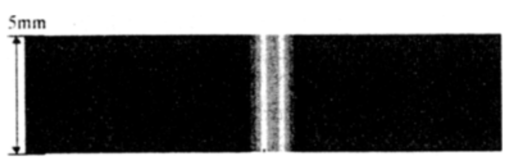


Fig. 8 Echo signal when refraction angle is adjusted

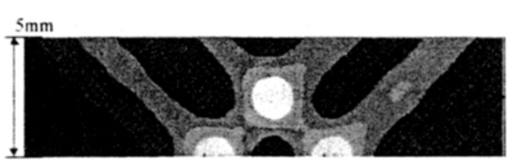


(a) The Cscan image for longitudinal wave

(b) The Cscan image for shear wave



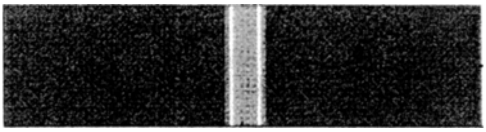
(c) The back projection image for longitudinal wave



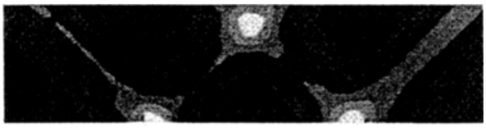
(d) The back projection image for shear wave

(e) The CT image for 3 directions

Fig. 9 CT image for specimen with vertical slit



(a) The back projection image for longitudinal wave

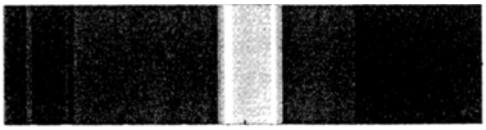


(b) The back projection image for shear wave

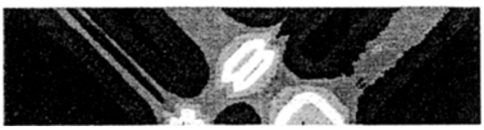
(c) The CT image for 3 directions

Fig. 10 CT image for specimen with drilled hole

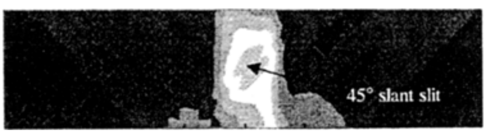
Figure 9 (a) and (b) show the C scan image or projection image for longitudinal and shear wave, respectively. In (a) and (b), the horizontal line shows the line to make the back projection image of (c) and (d). (c) and (d) show the back projection image of (a) and (b), respectively. (e) shows the CT image which is made by combining the images (c) and (d). Experiment result shows a good agreement with the actual shape of defect. Similarly, Fig. 10 and 11 show the result for specimen with drill hole (ϕ=1mm) and specimen with 45° slant slit, respectively.



(a) The back projection image for longitudinal wave



(b) The back projection image for shear wave



(c) The CT image for 3 directions

Fig. 11 CT image for specimen with 45° slant slit

Experiment result for the specimen with drill hole shows a good agreement with the actual defect. Then, in case of the specimen with 45° slant slit, the obtained CT image shows two defect. This is due to the fact that the incident direction of ultrasonic wave is the same as the direction of defect. That is, the bottom echo was deivded into two parts when shear wave faces to the defects. In this case, in gate, two waveforms was appeared. This is because that, in center of defect, ultrasonic wave is reflected completely and, in the edge of defect, ultrasonic wave is transmitted partially. If we make CT image using only waveform of one part in gate, we can get exact CT image.

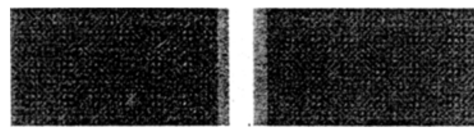
From these results, we can confirm that the simplified CT system is properly constructed.

4.3 Experiment result for specimen with welded part

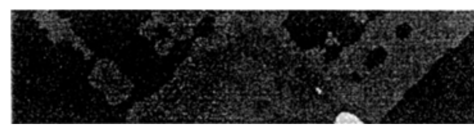
In order to confirm the applicability of the simplified CT system to the evaluation of welded specimen, the CT images of several welded specimens were obtained and showed in Figs. 12~15. Firstly, in order to know the possibilty of application to welded part, the CT image for the specimen with welded part by electron beam welding of Fig. 7 (a) was obtained and showed in Fig. 12. In this case, two kinds of welding intensity, that is, high energy and low energy welding were applied. Figure 12 shows low energy welding and Fig. 13 shows high energy welding.

(a) The Cscan image for longitudinal wave

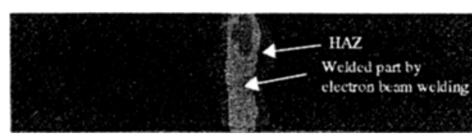
(b) The Cscan image for shear wave



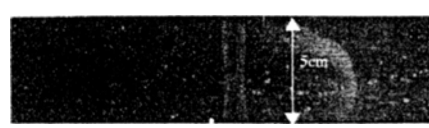
(c) The back projection image for longitudinal wave



(d) The back projection image for shear wave



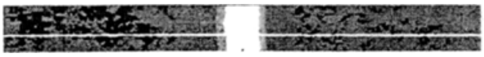
(e) The CT image for 3 directions



(f) The photo of specimen

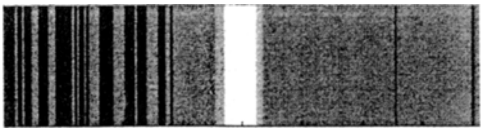
Fig. 12 CT image for specimen with welded part by electron beam welding (low energy welding)

Experiment results represent 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. 12 and Fig. 13 show this condition well. By comparing two figures, we can notice the energy used in welding is different. Also, we can see the faint part in the border line between welded part and



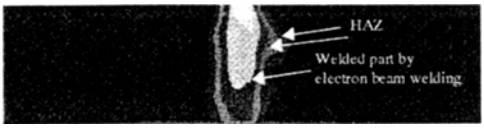
(a) The Cscan image for longitudinal wave

(b) The Cscan image for shear wave

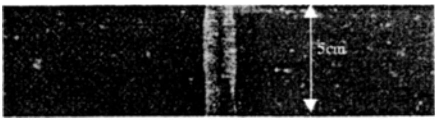


(c) The back projection image for longitudinal wave

(d) The back projection image for shear wave

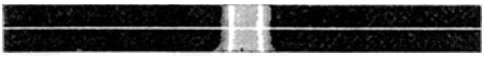


(e) The CT image for 3 directions



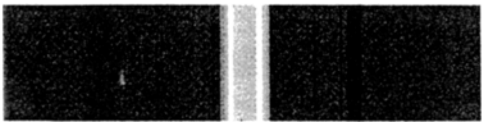
(f) The photo of specimen

Fig. 13 CT image for specimen with welded part by electron beam welding (high energy welding)

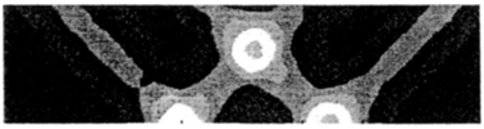


(a) The Cscan image for longitudinal wave

(b) The Cscan image for shear wave

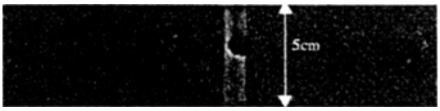


(c) The back projection image for longitudinal wave



(d) The back projection image for shear wave

(e) The CT image for 3 directions



(f) The photo of specimen

Fig. 14 CT image for electrically welded specimen with drill hole

base metal. This seems to be HAZ(heat affected zone) by welding.

Next, the CT image for the specimen with welded part by electron beam welding and drill hole is obtained and showed in Fig. 14.

Also, the CT image of this specimen shows good agreement with actual defect. In this case, the HAZ was not represented because the difference of brightness between the hole and welded part are very big. Lastly, we applied this system to the specimen of arc-welded part. Figure 15 shows the experiment result.

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

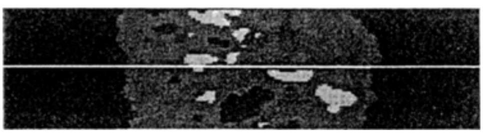
5. Conclusion

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 $+45°$ 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

(a) The Cscan image for longitudinal wave

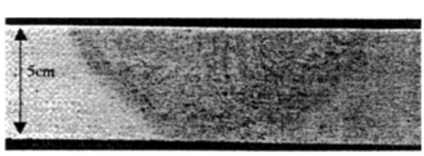


(b) The Cscan image for shear wave

(c) The back projection image for longitudinal wave

(d) The back projection image for shear wave

(e) The CT image for 3 directions



(f) The photo of specimen

Fig. 15 CT image for actual welded specimen

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 a good agreement with the actual defect of specimens.

So, we can confirm that the proposed simplified CT system can be applied to the dection of change of material condition.

In the future, the research on the enhancement of image resolution and the characterization of grain size will be performed.

References

Bernard, L., 1987, "Time of Flight Diffraction Technology for Ultrasonic Inspection of Piping and Pressure Retaining Components," *Materials Evaluation*, Vol. 45, No. 5, pp. 506~507.

Birks, A. S., 1991, Nondestructive Testing Handbook 7 : Ultrasonic Testing, ASNT.

Briggs, A., 1992, *Acoustic Microscopy*, Clarendon Press, Oxford

Cho, Z. H., Jones, J. P. and Singh, M., 1993, *Foundation of Medical Imaging, New Imaging*, New York, John Wiley and Sons

Comm, T. J. and Mauseth, J. A., 1999, "State of the Technology: Ultrasonic Tomography," *Materials Evaluation*, Vol. 57, No. 7, pp. 747~752.

Han, S. M., 1999, "A Comparison of Ultrasound and Computed Tomography in Evaluation the Mechanical Properties of Trabecular Bone," *KSME International Journal*, Vol. 39, No. 3, pp. 101~108.

Hillger, W., 1998, "Ultrasonic Imaging of Defects in Sandwich Composites from Laboratory Research to In-Field Inspection," *Proceedings of the 7th European Conference on Non-Destructive Testing*, pp. 26~29.

JIS G 3106, 1999, Rolled Steels for Welded Structures.

JIS G 4304, 1999, Hot Rolled Stainless Steel Plates, Sheets and Strip.

Miyoshi, S., et. al, 1996, Ultrasonic Technology Handbook, Nikkan Kogyo Newspaper Co. (In Japanese).

Romans, L. E., 1995, *Introduction to Computed Tomography*, Baltimore, Williams & Wilkins

Sharpe, R. S., 1982, *Research Technique in Nondestructive Testing*, Academic Press, Vol. 6, pp. 255~287.

Silk, M. G., 1996, "Estimates of the Probability of Detection of Flaws in TOFD Data with Varying Levels of Noise," *INSIGHT*, Vol. 38, No. 1, pp. 31~36.

Williams, R. A. and Beck, M. S., 1995, *Progress Tomography : Principles, Techniques and Applications*, Oxford, England, Butterworth-Heinemann.

Yamanaka, K. and Enomoto, Y., 1982, "Observation of Surface Cracks with Scanning Acoustic Microscope," *J. Appl. Phys.*, Vol. 53, No. 2, pp. 846~850.