A FLAW SIZING TECHNIQUE FOR AUSTENITIC STAINLESS STEEL WELDS USING CREEPING WAVE PROBE

Satoru Shiroshita[1], Yoshikazu Yokono[2]

[1]Nondestructive Inspection Co.,Ltd., Osaka, Japan
[2]Pony Industry Co.,Ltd, Osaka, Japan

Abstract

One of the most important subjects in nuclear power plants is sizing of flaws which are detected during In-Service Inspection (ISI), since reliability of flaw sizing is very important to estimate the life of the structure or pressure equipment. The most difficult matter for applying the flaw sizing techniques mentioned above is how to identify the flaw tip signal, especially in the case of natural cracks such as stress corrosion cracking (SCC). At present, the identification of the flaw tip signal depends on technical skill, related knowledge and experiment of UT personnel. This paper proposes a new technique using echo locus curves on B-scan image for flaw sizing. The technique was applied to welds test specimens with simulated SCC and advantages of the technique were confirmed experimentally. As a result, it is clear that flaw sizing can be conducted with higher accuracy and misjudgment or measuring error due to personnel ability can be reduced.

1. Introduction

One of the most important subjects in nuclear power plants is sizing of flaws which are detected during In-Service Inspection (ISI). Although ultrasonic methods have been commonly applied for detecting and sizing flaws, there still remain some difficulties when austenitic stainless steel welds are inspected. These difficulties caused by high attenuation of signal amplitude during propagation and low SN ratio of echoes due to ultrasound scattering at grain boundaries. Anisotropy of ultrasound characteristics such as sound velocity is also problem to be considered. Therefore, it has been said that application of ultrasonic testing to such welds is so limited. Recently the following procedure has been provided to size the inner surface breaking flaws in the pipe welds by the Technical Recommendation of Japan Electric Association, JEAG 4207:2004[1].

Firstly, creeping wave technique should be used to confirm the existence of the inner surface breaking flaws detected by regular UT methods. Secondly, mode conversion technique is used to divide the size of the flaw into three categories: large, middle and small [2]-[3]. Thirdly, the combination of tip echo technique, TOFD technique and/or phased array probe technique should be applied to estimate the size of the flaws.

However, the fact is that the problems regarding UT for austenitic stainless steel welds are not being solved for all of these techniques. In this paper, flaw sizing technique using echo dynamics obtained by creeping wave probe is proposed in order to solve these problems.

2. Flaw sizing technique using ultrasonic methods

2.1. Present concerns on current flaw sizing techniques

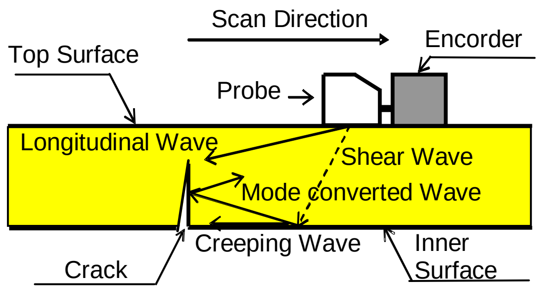
Tip echo technique and TOFD technique as commonly used for flaw sizing are based on flaw tip location estimated by probe position and time of flight. While phased array technique is based on imaging such as B-scan and/or C-scan presentation, it is regarded as one of the technique to obtain flaw tip indication in cross sectional B-scan image in accordance with JEAG4207 for flaw sizing.

The most difficult matter for applying these techniques is to identify the signal from flaw tip. Therefore high quality skills and much experience of UT personnel have been required for accurate evaluation when performing not only tip echo technique but also TOFD and phased array technique. It is not too much to say that to solve this problem is the best way to improve the accuracy of flaw sizing in austenitic stainless steel welds.

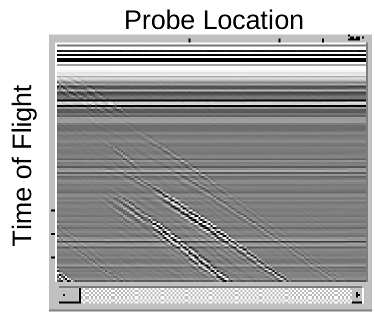
2.2. Flaw sizing technique using creeping wave probe

Creeping wave probe has been regarded as a powerful tool to detect and evaluate the opposite surface breaking flaw, but there remains some difficulties to analyze the obtained signals in A-scan presentation. On the other hand, not only creeping wave technique but also tip echo technique using longitudinal wave and mode conversion technique can be carried out by a creeping wave probe. In this paper, new approach to flaw sizing using creeping wave probe is proposed.

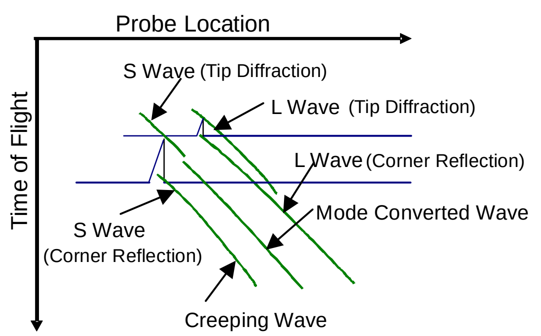
When the creeping wave probe is scanned to and fro on a test material as shown in Fig.1 (a), the echoes from some specific reflectors can be observed continuously moving right and left on the display. The feature of the echo pattern is recognized in the figure showing relations between amplitude, time of flight and probe position, that is to say, some locus curves in B-scan image are observed as shown Fig.1 (b). The analysis of the data to estimate the size of the reflector was carried out by interpretation of the signals as shown in Fig.1 (c). Some sizing techniques for opposite surface breaking flaw are followed using the analyzing the locus curves.



(a) Scanning creeping wave probe and ultrasound propagation



(b) Echo locus curves on B-scan image



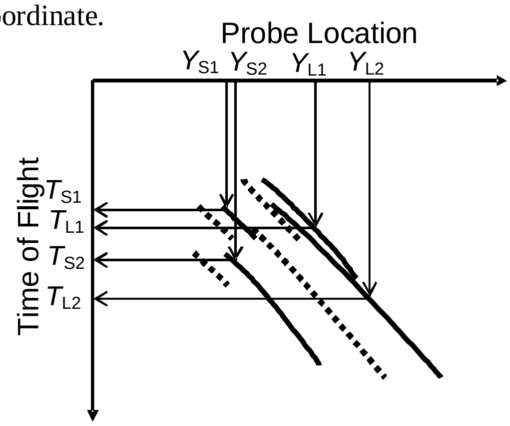
(c) Interpretation of the signals

Figure 1: *Relations between amplitude, time of flight and probe position*

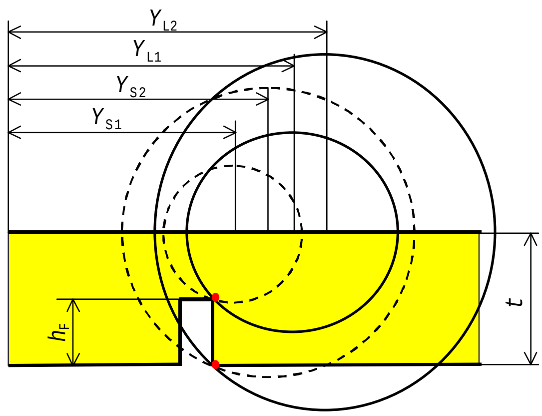
2.2.1. Advanced sizing technique using both longitudinal wave and shear wave

An example of echo locus curves on B-scan image of opposite surface breaking flaw is shown in Fig.2 (a). Four solid lines are generated by corner reflections and tip echoes of both longitudinal wave and shear wave. Two circles with its center at certain probe indexes, Y_{L2} and Y_{S2}, and with radius of beam path distances calculated from time of flight, T_{L2} and T_{S2}, respectively. The breaking point of flaw can be determined by intersections of the circles, as shown in Fig.2 (b). The location of the flaw tip can also be determined by intersection of two circles obtained from probe indexes, Y_{L1} and Y_{S1}, and time of flight, T_{L1} and T_{S1}, respectively, in the same manner. If the indication of shear wave is difficult to be observed due to attenuation of ultrasound, the data from only longitudinal wave can be used for drawing circles to locate the opposite surface breaking position and flaw tip.

The discernible part of locus curve can be used for estimating beam path distance at certain probe position. Accordingly, it is not necessary to obtain maximum echo for the case of tip echo technique. They can also be determined by calculation in x-y coordinate.



(a) Echo locus curves on B-scan image



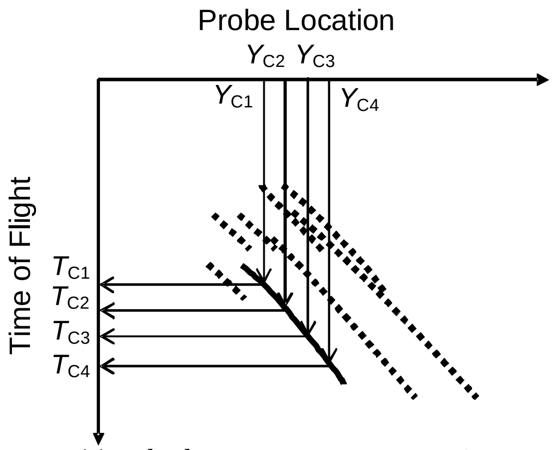
(b) Estimation of reflecting location

Figure 2: *An example result of sizing technique using both longitudinal wave and shear wave*

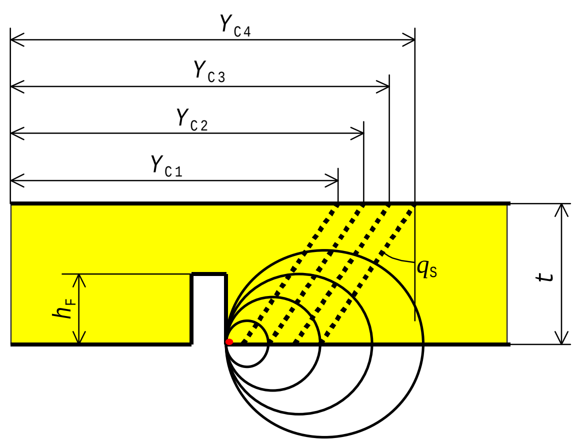
2.2.2. Estimation of surface breaking location using creeping wave

The solid line in Fig.3 (a) shows locus curve of creeping wave. Time of flight represented by vertical axis shown in the figure corresponds to total propagation time of shear wave and creeping wave as shown in Fig.3 (b). In this case, the refraction angle of shear wave q_S is determined as critical angle of shear wave. This estimation has a good correlation with actual flaw location experimentally.

The shear wave signal from corner of surface breaking flaw is sometimes observed very close to the creeping wave signal from breaking point of flaw simultaneously. In many cases these two signals are difficult to be distinguished each other on A-scope presentation. When the probe is moved backward away from flaw location, they could be separated and two locus curves can be observed as shown in Fig.4. The results obtained by calculations and experiments are shown in Fig.4 (a) and (b), respectively.

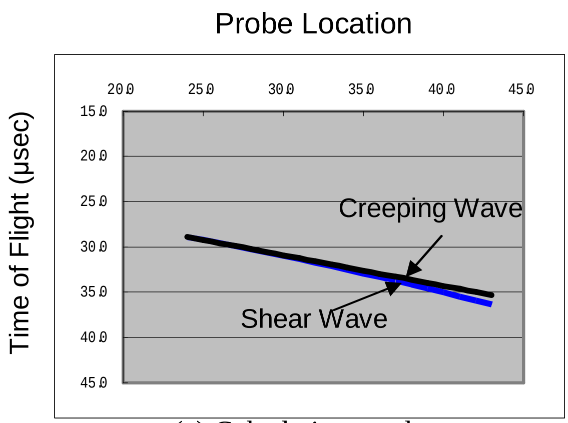


(a) Echo locus curves on B-scan image

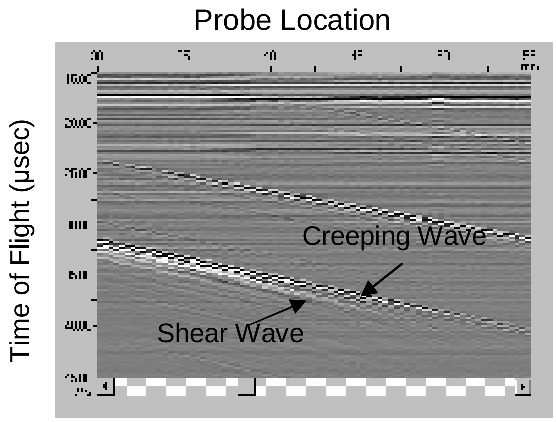


(b) Estimation of reflecting location

Figure 3*: An example result of creeping wave technique*



(a) Calculation result



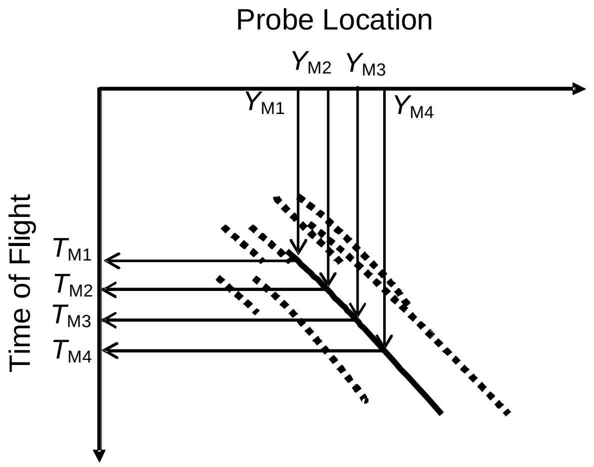
(b) Experimental result

Figure 4*: Separation of creeping wave signal and shear wave signal on locus curves*

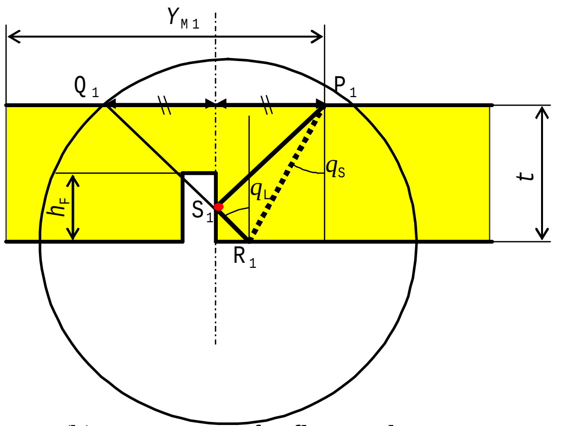
2.2.3. Categorization of flaw using mode conversion technique

The solid line in Fig.5 (a) shows locus curve obtained by mode conversion technique. Shear wave propagates along the line of P_1-R_1 with beam angle of q_S and longitudinal wave propagate along the lines of R_1-S_1-P_1 with beam angle of q_L as shown in Fig.5 (b), since mode conversion occurs at the position of R_1. The line of R_1-S_1 is extended to Q_1 so that the length between R_1 and Q_1 become same as the propagation path length of longitudinal wave. In this case beam angle of shear wave, q_S is defined as the angle between the central axis of the beam and normal line of test surface. A perpendicular bisector of P_1-Q_1 corresponds to reflector face. This proves that there exists a reflecting point S_1 and the flaw is higher than the depth of S_1 from the back surface.

This technique can also be used for the inclined flaw as shown in Fig.6. Inclined angle, α is determined by the breaking point of flaw and flaw tip location estimated by sizing technique using both longitudinal wave and shear wave as described before.



(a) Echo locus curves on B-scan image



(b) Estimation of reflecting location

Figure 5*: An example result of mode conversion technique*

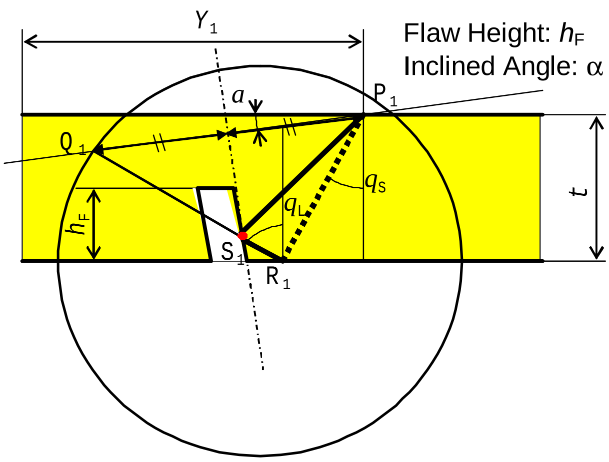
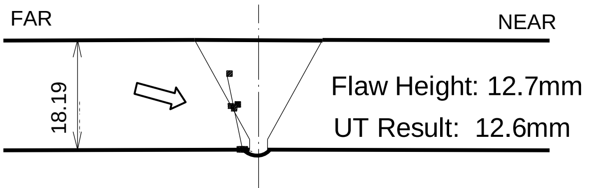


Figure 6*: Mode conversion technique for the inclined flaw*

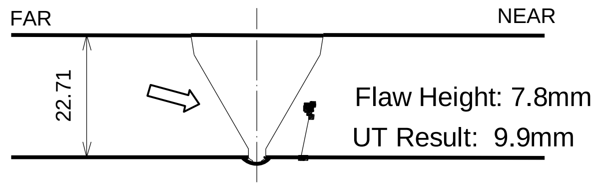
3. Experimental investigation into applicability

Some experiments using test specimens with embedded fatigue cracks are carried out to demonstrate the accuracy of this technique. Typical examples on estimating flaw size on cross sectional view are shown in Fig.7. All flaws having several sizes ranging from small (about 10% of thickness) to large (larger than 50% of thickness) can be evaluated accurately comparing with the designed values of flaw height.

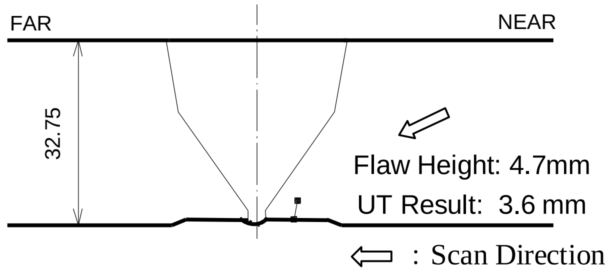
Test specimens with several slits of 1mm to 19mm in height were also used for the experiments. Estimated values by this technique as a function of actual flaw height are shown in Fig.8. As a result, flaw size can be estimated with the average error of -0.19mm and the standard deviation of 0.31mm.



(a) 6” Sch160, Flaw Location: 40°



(b) 8” Sch160, Flaw Location: 170°



(c) 12” SCH160, Flaw Location: 310°

Figure 7*: Results of flaw reconstruction on cross sectional view*

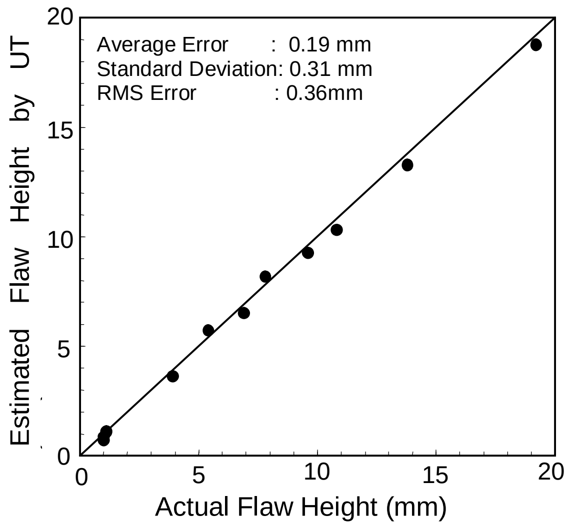


Figure 8*: Estimated values by UT as a function of actual flaw height*

4. Instrumentation for field application

4.1. Portable X-Y scanner

Portable X-Y scanner was developed to acquire the data of time domain signal and probe position as shown in Fig.9. The scanner having centering function module can be applied ranging from circumference welds of 4B piping to but welds of flat plate. Wheels which contact to test surface have grooves to avoid slipping due to couplant.

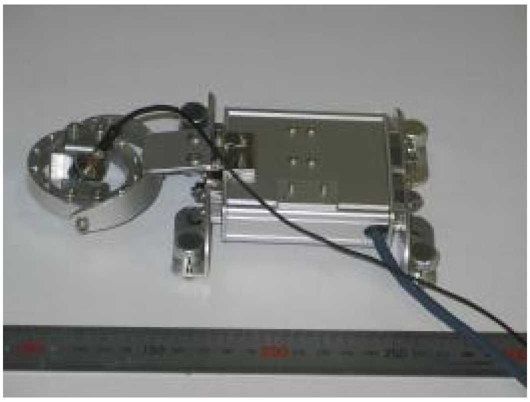


Figure 9*: Portable X-Y scanner*

4.2. Data analyzing system

Software for flaw reconstruction was developed to make it easier to apply this technique to field inspection. The software includes calibration of encoder equipped with scanner and imaging of cross sectional view. When moving a cursor and clicking it on the specific locus curve, location of reflector is pointed on cross sectional presentation.

4.3. Recommended procedure for flaw sizing

After the creeping wave probe is scanned to and fro to obtain echo locus curves on B-scan presentation at the objective position of welds, the following procedure is recommended for flaw sizing.

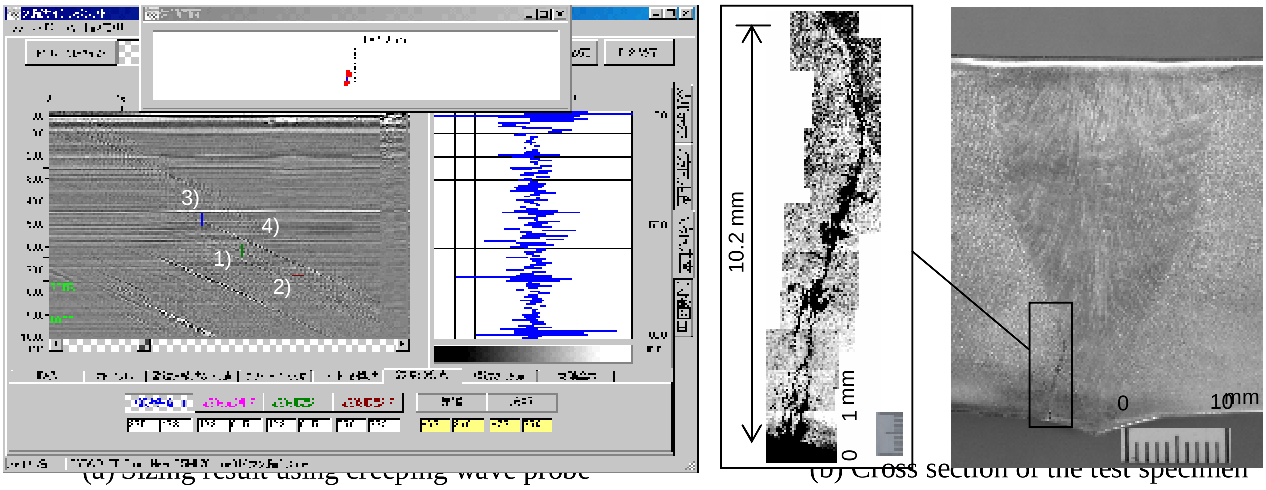
First, location of flaw tip is estimated as intersection of longitudinal wave and shear wave in accordance with 2.2.1. If there is no shear wave signal, then intersection of only longitudinal wave can be used. Second, location of surface breaking point is confirmed by creeping wave technique in accordance with 2.2.2. It can be estimated by drawing or calculation using locus curve of creeping wave. Third, middle position of flaw is determined by mode conversion technique in accordance with 2.2.3.

5. Experimental results for SCC in stainless steel welds

The procedure for sizing flaw mentioned above was tried to apply for stainless steel pipe welds with stress corrosion cracking (SCC). Test specimen having the diameter of 609.6mm and thickness of 35.2mm were prepared and some SCCs of different height were installed. To acquire the data creeping wave probe, 3.5MHz in frequency, 12.7mm in crystal size and 70 degrees in refraction angle of longitudinal wave, was scanned to and fro on the test surface using the above mentioned scanner shown in Fig.9. Data analyzing software was used to estimate the height of SCC. A typical example of the display obtained through the experiment is shown in Fig.10 (a). After the estimation, metallographic observation was carried out to verify the actual height of SCC in the test specimen. The cross sectional observation of the specimen corresponding to the result in Fig.10 (a) is shown in Fig.10 (b).

Since signals of interest indicated as inclined lines can be easily distinguished from unnecessary noise signals indicated as horizontal lines as shown in B-scan image of Fig.10 (a). As analyzing software includes advanced sizing technique, mode conversion technique and creeping wave technique, the technique to be applied can be selected by click the tab on the display. The example of the data shown in Fig.10 (a) was obtained by scanning the probe on the right side upper surface shown in Fig.10 (b). The data were analyzed by advanced sizing technique of longitudinal wave, since tip echo of shear wave cannot be identified. Two cross marks denoted by 1) and 2) were clicked on the indication line of inner surface breaking point and the location of crack bottom could be estimated. Also other two cross marks denoted by 3) and 4) were clicked on the tip echo line and the location of crack tip could be estimated. The sketch shown in the top of the figure illustrates the estimated crack location on the cross sectional image. The depth of the crack can be determined to be 9.3mm by considering all plots shown in the figure. When the probe was scanned on the left side upper surface, the height of SCC was estimated to be 9.6mm. As shown in Fig.10 (b), it can be supposed that the height of crack is 10.2mm which is corresponds to the height estimated by the sizing technique proposed here.

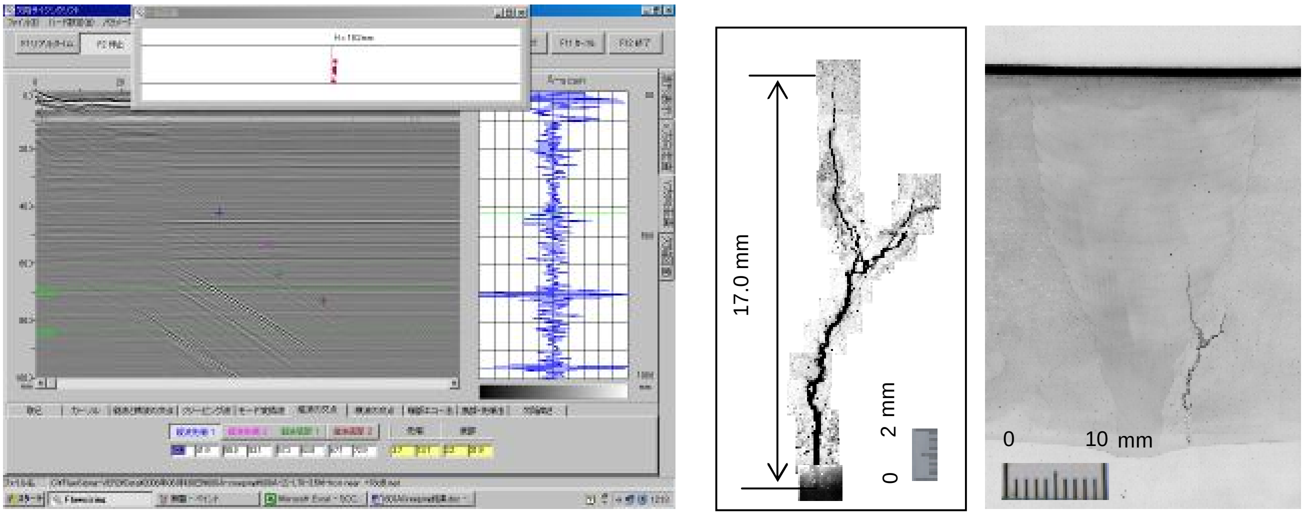
Another example is shown in Fig.11. The height of SCC was estimated to be 18.2mm by this technique and the actual height was confirmed to be 17.0mm, as shown in the figure.



(a) Sizing result using creeping wave probe (SUS316, 600A)

(b) Cross section of the test specimen with SCC

Fig.10: *The example of the sizing result of UT and cross section of the test specimen (1)*



(a) Sizing result using creeping wave probe (SUS316, 600A)

(b) Cross section of the test specimen with SCC

Fig.11: *The example of the sizing result of UT and cross section of the test specimen (2)*

6. Conclusions

A flaw sizing technique in austenitic stainless steel welds using creeping wave probe is investigated. The following results are obtained through this study.

(1) It was clear that not only creeping wave technique but also tip echo technique using longitudinal wave and mode conversion technique can be carried out by a creeping wave probe.

(2) Drawing locus curves when the probe is scanning to and fro is very effective to identify each signal and analyze reflection signals to estimate the flaw location.

(3) Portable X-Y scanner and software for flaw sizing are developed for field inspection.

Finally, the procedure of the flaw sizing technique was proposed and it has potential ability to reduce measuring error and misjudgment due to UT personnel proficiency. It is expected that the technique can contribute to improve the reliability of flaw sizing.

7. References

[1] JEAG 4207-2004, “Ultrasonic Examination for In-Service Inspection of Light Water Nuclear Power Plant Components”, Japan Electric Association, 2004.

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[3] Peter Hayward, “Detection and Sizing of Cracking from the Inner Surface using ID Creeping Waves”, 10th Asia-Pacific Conference on Non-Destructive Testing, Brisbane, Australia, 2001.