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RECONSTRUCTION OF CRACK-TIP PROFILE OF SMALL FATIGUE CRACKS BY ULTRASONICS

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ABSTRACT

This paper describes the application of a newly developed ultrasonic method for the re-construction of crack-tip contours of small fatigue cracks under no-load conditions. The method uses the amplitude of a shear wave beam of 50 deg. incidence for the evaluation of surface connected cracks in steel specimens. This study also focuses on the determination of closure stress distribution along the crack length and on the effect of specimen sidewall on the evaluation of part through crack. The crack closure stress and the crack depth of an unknown crack are determined here by the inverse analysis of the measured response of the crack. To justify the capability of the NDE method, evaluation is done based on the ultrasonic measurement at different locations along the length of a fatigue crack under no-load condition. Evaluated crack-tip profile is compared with the actual profile observed on the fractured surface. The method demonstrates an excellent capability of quantitative characterization of small closed cracks.

Keywords: Small fatigue crack, Closure stress, Ultrasonics, Quantitative NDE.

1. INTRODUCTION

Testing the depth of tightly closed small surface cracks is an important issue. Recently, the ultrasonic technique has shown its potential for detecting, as well as characterizing, smaller tight cracks under a no load condition. By introducing a model of crack closure, Saka and Uchikawa [1,2] have developed a technique to evaluate the crack size quantitatively and crack closure qualitatively by using a normally incident longitudinal wave (LW) beam. In this technique an empirical calibration equation derived for the open cracks has been considered as the basis for evaluating the closed cracks in the size range of 3.5 - 14 mm by using an inverse analysis of the measured normal incidence response. Recently, introducing a small angle to the incident LW beam Ahmed and Saka [3-5] have extended the capability of the ultrasonic evaluation method to smaller closed cracks up to the smallest size of 0.5 mm. In a recent study, Akanda and Saka [6] have showed that shear wave can be a sensitive investigating agent for detection of smaller cracks. In the technique, only the sensitive crack echo is visible which also proves its superiority over the recent normal and small-angle incidence techniques, where the crack-echo signal is not that easy to distinguish from that of un-cracked part, especially for the smaller closed cracks. Later by a detailed study, Akanda and Saka [7] have showed that 50^0 incidence of SW against the back-wall cracks in steel material is the optimum angle for testing of smaller cracks. Further, from the study of the effect of crack closure on the echo response of 50^0 incidence of SW against back-wall crack in steel material [8], it was found that the ultrasonic response curves carry sufficient information of crack depth and closure stress for their evaluation. In the latest study, experimentally establishing a new model of crack closure, Saka and Akanda [9,10], have developed a method for quantitative evaluation of crack depth as well as closure stress of small fatigue cracks under no-load condition.

The present paper extends the capacity of the newly developed ultrasonic NDE method to reconstruct the crack-tip profiles of tightly closed small fatigue cracks, which is totally beyond the capacity of any other techniques developed so far. For the present analysis, back-wall small fatigue cracks developed in stainless steel specimens by tension-to-tension loading, have been considered. The large capacity of the method is also extended to evaluate the corresponding closure stress along the crack profile. The accuracy as well as reliability of the crack-tip profile reconstruction has been verified by comparing results with the actual crack-tip profile observed on the fractured surfaces.

2. SPECIMEN PREPARATION

Fatigue-cracked specimen, shown in Fig. 1, was prepared as plates having the initial dimensions of 60x330x15 mm. The large width (in this case 60 mm) was chosen intentionally to have the fatigue crack with non-uniform depth along the specimen width. The fatigue crack in the specimen was developed from the tip of a 3 mm depth starter notch by cyclically loading the plate in 4-point bending on the dynamic testing machine. To introduce the non-uniform crack depth along the specimen width the notch-tip was discretely sharpen by a knife-edge cutter before loading. During the process of fatigue, the crack growth was monitored from both sides of the specimen. Based on the crack depth observed in the sidewalls, the maximum stress intensity factor, K_{Imax} (= 22.0 MPa·m$^{1/2}$) and the stress ratio (i.e., the ratio of minimum to maximum stress intensity factors), K_{Imin}/K_{Imax} (=0.5), were maintained during the crack growth.

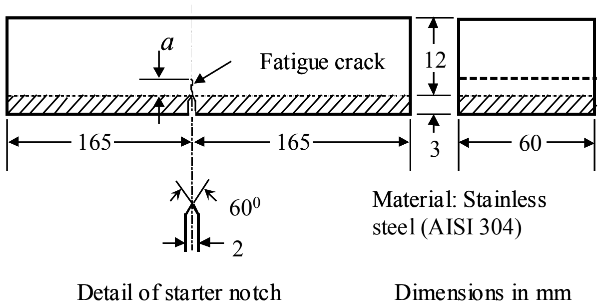


Fig. 1 Geometry of the specimen having a fatigue crack

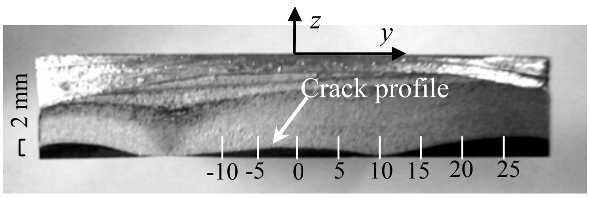


Fig. 2 Photograph of the crack on fractured surface

After producing the crack to the desired depth, the plate was machined and polished to remove the initial notch, thereby leaving a true fatigue crack in the remaining material. Then the specimen was ready to take ultrasonic testing. The ultrasonic measurements carried out have been discussed in the following article.

Table 1: Crack depth at different position along specimen width

Measurement position *y* (mm)	**Actual crack depth** (mm)
-10	0.82
-5	1.28
0	1.45
5	1.18
10	0.57
15	1.52
20	2.34
25	2.75

After finishing the ultrasonic testing the specimen was heat tinted and then 3-point bending fatigue load was applied until failure. The photograph of the crack on fractured surface has been shown in Fig. 2. Note that the crack depth along the specimen width was found non-uniform. The crack depths at every 5 mm along the specimen width measured on the fractured surfaces have been presented in Table 1.

3. MEASUREMENT PROCEDURE

In order to achieve better repeatability as well as fast and precise measurements, automatic linear scanning has been performed by a *xyz*-scanner using water immersion technique. The testing configuration is illustrated in Fig. 3. The crack inspected was situated vertically at the middle of the specimen back wall. All the measurements have been performed at room temperature. A single flat pulse-echo transducer (Panametrics *A310 S*) of diameter, d = 6.4 mm, transmitting a LW of nominal frequency 5 MHz has been used for both generating and detecting the elastic waves. The space between the transducer and the top surface of the specimen has been filled with water used as a medium for ultrasonic LW propagation. The distance between the probe and the specimen back wall was kept fixed at 30 mm, ensuring far-field measurements. The transducer was used to scan automatically over the top surface of the specimen. Measurements were performed in every 0.5 mm interval of the probe position. All the received signals have been post-amplified and then sent to the digitizing oscilloscope from where the digitized data were downloaded directly to a personal computer. For getting real fatigue crack data, experiments were performed under no-load condition. After finishing the experiment on closed crack, sufficient tensile load was applied on the same specimen to keep the crack open during the process of receiving open crack data.

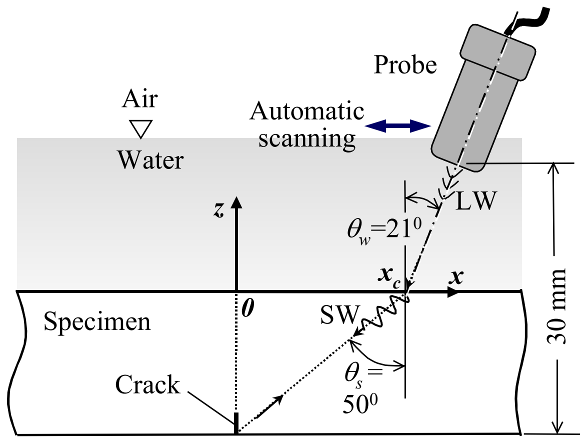


Fig. 3 Schematic diagram of ultrasonic testing

A Cartesian coordinate system (x, y, z) was chosen in such a fashion that the origin O is located at the intersecting point of the center line of the top surface of the specimen and the vertical crack plane as shown in Fig. 3. The specimen was scanned along different lines parallel to x-axis. The crack depths under the scanning lines of the fatigue-cracked specimen are shown in Table 1 and the corresponding positions are shown on the fracture surface by vertical ticks in Fig. 2.

The location on the top surface from which the probe can locate the crack is denoted by x_c corresponding to the incidence angle in water θ_w = 21^0 and angle in steel material $\theta_s \approx 50^0$ (see Fig. 3). In this technique, the crack-corner echo is received via the shear wave from the solid.

4. ANALYSIS OF ECHO AMPLITUDE

Waveforms of the received echo for 50^0 (θ_s) incidence of shear wave against an open crack of depth 0.5 mm for three particular probe positions are shown in Fig. 4. The waveforms presented by solid curve, dotted curve and broken curve are denoted by A, B and C respectively. The waveforms A, B and C have been obtained for the probe positions, x = 14.67, $x = x_c$ = 17.87 and x = 21.07 mm, respectively. Therefore, the waveform B is for crack corner position and A and C are for equal distance left and right of the crack corner respectively. For these cases, projections of intensive part of the incident beam are schematically shown in Fig. 5. The height of waveform B is greater than that of A or C, see Fig. 4. This is due to the highest intensity of the center part of the incidence beam that takes reflection from the crack corner zone; see Fig. 5(b). The waveforms B and C are observed similar. This is due to the similar way of getting reflection of the incidence beam; see Figs. 5(b) and (c). The waveform A is different from B and C. This might be the simultaneous effects of crack tip and crack corner as the incidence beam covers both. Although the waveforms A and C have been taken equal distance left and right of the crack corner, respectively, the height of A is less than that of C. This attenuation of echo height might be due to crack tip diffraction. For the probe movement from crack corner zone to left, the received waveform changes continuously with decreasing its height.

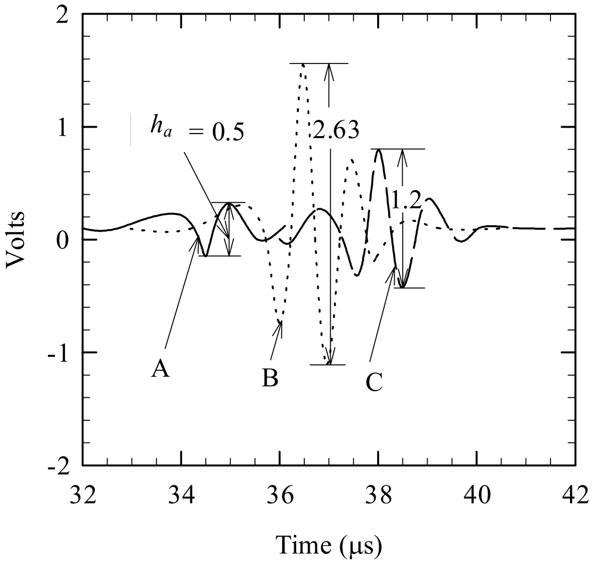


Fig. 4 Received waveforms obtained against an open crack of depth 0.5 mm

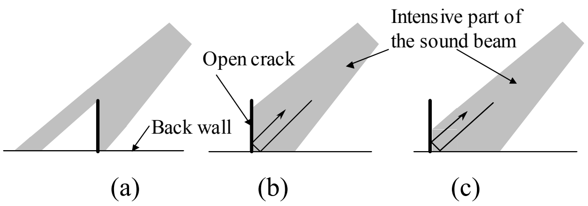


Fig. 5 Ultrasonic angle beam against the open crack, where the beam center line strikes at (a) left of the crack corner, (b) crack corner and (c) right of the crack corner (schematic presentation)

In the study having the method simple, attention has been paid only on the change in height of the received waveform for the probe movement across the crack. The difference between the maximum peak and the minimum peak of any waveform is called here peak-to-peak amplitude or simply amplitude of the received echo signal. The received amplitude is denoted by h_a. The h_a values of the waveforms A, B and C are found 0.5, 2.63 and 1.2 Volts, respectively, as shown in Fig. 4. The values of h_a for every 0.5 mm probe movement across the crack have been recorded. From the recorded data a curve is plotted as $h_a - x$ relation in Fig. 6. The amplitudes of the waveforms A, B and C are shown on the curve by the vertical arrows (Fig. 6). From the curve it is clear that when the probe moves far away from the crack i.e., a position of no crack it receives almost no echo rather than a negligible noise, see Fig. 6.

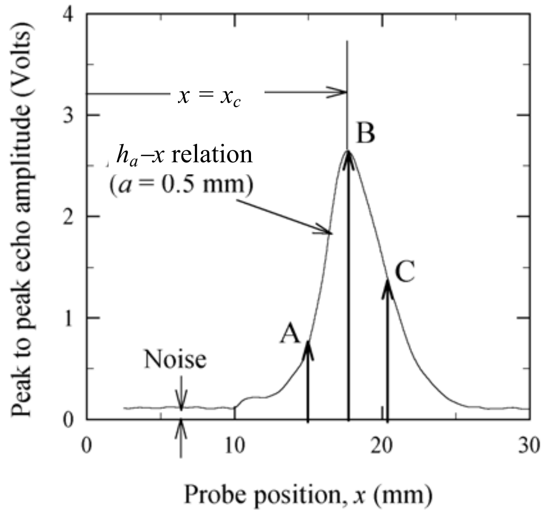


Fig. 6 Peak to peak echo amplitude obtained against an open crack of size 0.5 mm

For ease of analysis of the change in amplitude of the received waveforms, results have been prepared by normalizing the echo height and the probe position. The measured amplitudes have been normalized by an amplitude drop of 10.1 volts obtained in normal beam as:

$$p^{ex} = h_a/10.1 \quad (1)$$

The symbol p^{ex} in Eq. (1) is the normalized amplitude of the first back-wall echo, measured for the specimen containing the crack at every 0.5 mm gap of the transducer position.

For the present incidence technique, the received first back wall echo amplitude, p^{ex}, obtained for the plate containing a closed crack on the back wall, is given by [9,10]

$$p^{ex} = \gamma\, p_c^{ex} \quad (2)$$

where p_c^{ex} is the amplitude due to the reflection experienced at the open crack surface. The coefficient γ is defined by the ratio of the amount of wave reflection at closed crack surface to that at open crack surface.

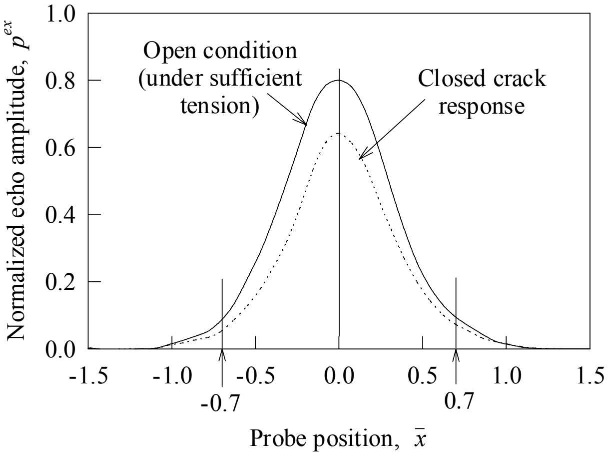


Fig. 7 Ultrasonic response as a function of probe position

For getting real fatigue crack data, experiments were performed under no load condition. After the experiment on closed crack had been performed, sufficient tensile load was applied on the same specimen to keep the crack open during the process of receiving open crack data. To observe how the experimental response varies with probe position, the results for a crack size, a = 1.82 mm, obtained under open as well as no load conditions, are presented as a function of probe position, $\bar{x}$ (=$(x-x_c)/d$), in Fig. 7. At no load condition, the response is much less than that of open condition. Therefore, the ultrasonic response is highly sensitive to crack closing stress. In Eq. (1), coefficient γ is determined by the ratio of echo amplitude of closed crack to that of open crack for each measurement position in the range of $-0.7 \le \bar{x} \le 0.7$.

5. CALIBRATION EQUATIONS

By testing a number of cracks under closed and open conditions the reflection coefficient γ has been calibrated [9,10] as a function of closure stress σ_p and the probe position $\bar{x}$, that is

$$\gamma = f_1\left(\sigma_p, \bar{x}\right) \tag{3}$$

By testing several open cracks the open crack echo response has been estimated as a function of crack depth (a) and the probe position as [9,10]

$$p_c^{es} = f_2\left(a, \bar{x}\right) \tag{4}$$

Therefore, the closed crack echo response can be estimated as

$$p^{es} = \gamma \cdot p_c^{es} = f_3\left(\sigma_p,\, a,\, \bar{x}\right) \tag{5}$$

For a given values of crack depth and closure stress the ultrasonic response curve across the crack can be estimated from Eq. (5). Note that the symbol p^{es} refers the estimated response from the calibration equation and the symbol p^{ex} refers the response obtained by experiment.

6. INVERSE SOLUTION

The essential feature of the ultrasonic evaluation method is to determine simultaneously the closure stress and the crack size, by comparing the estimated and the measured amplitudes of the echo signals. For the best estimate of the true values, a suitable optimization algorithm is used to minimize an objective function, F, which is defined as follows:

$$F = \sum_{j=1}^{m} \left\{\left(p^{ex}\right)_j - \left(p^{es}\right)_j\right\}^2 \tag{6}$$

where m is the total number of measurements corresponding to the discrete probe position, $(\bar{x})_j$. For easy understanding a flow diagram of inverse analysis is shown in Fig. 8.

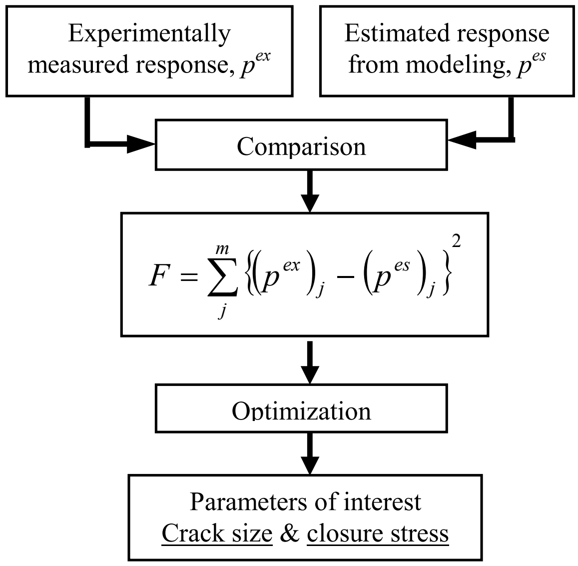


Fig. 8 Flow diagram of inverse solution

7. STUDY OF SIDEWALL EFFECT

A two-dimensional part through open crack (machine slit) was used to study the effect of sidewall on the evaluation of crack depth. The 2-D crack in a specimen of 35 mm width and 12 mm thickness was scanned along different lines of 1 mm apart and parallel to x-axis. As discussed earlier the open crack response shown in Fig. 7 apparently looks like a normal distribution having maximum amplitude at the middle. The similar response curves obtained for the aforesaid specimen at different measurement locations in central region of the specimen are found exactly same. The height of these response curves decrease if the scanning line moves towards the sidewall of the specimen. The maximum echo amplitudes of these curves are plotted against the specimen width as shown in Fig. 9. From the figure it is observed that the maximum ultrasonic response for crack in side the material gives uniform distribution for most part of the crack length. In the distribution the sidewall effect is observed for a distance of 5 mm on each side. Moreover, the nature of received waveforms presented in Fig. 4 found affected by the sidewall echo. The shape of the typical peak-to-peak amplitude curve discussed by Fig. 6 also found to be affected by the sidewall echo.

Their detail analysis is omitted here rather the distance along which the received echo amplitude does not vary is important for this study. Therefore, in this study to estimate the crack-tip profile for a part through crack, ultrasonic measurements closest to the sidewall was kept 5 mm away from the sidewall as shown in Fig. 2. Note that in the present case the incidence angle in solid is 50 degree. If this angle increases the affected length also increases. Similarly if the specimen thickness increases the affected length also increases. This study is limited to constant specimen thickness of 12 mm.

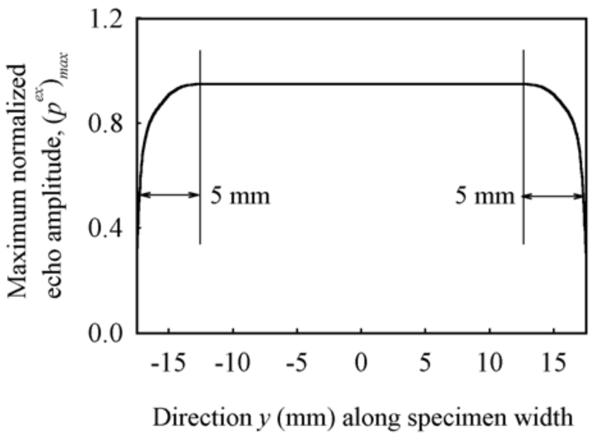
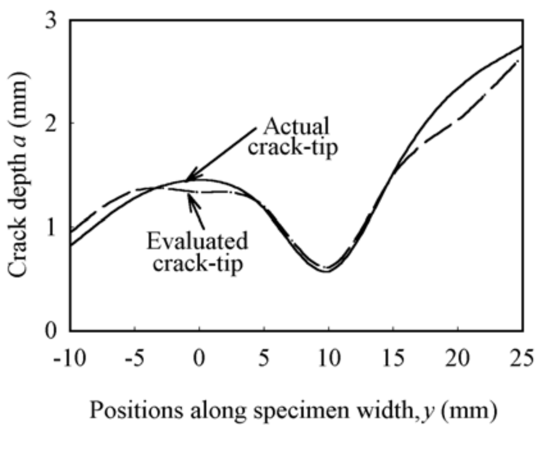


Fig. 9 Distribution of maximum echo amplitude of a 2-D open crack of depth 2 mm along specimen width

8. EVALUATION RESULTS AND DISCUSSION

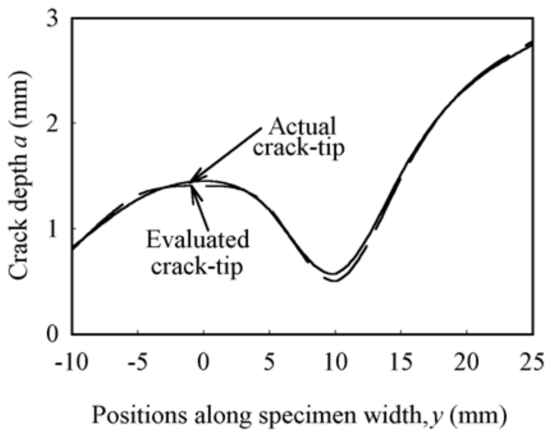
The results for crack-tip profile estimated under closed and open conditions are presented in Fig. 10. Figure 10(a) describes the comparison of actual crack-tip profile with that estimated for the crack tested under closed condition. The similar comparison for the results of crack under open condition is presented in Fig. 10(b).



(a) under no-load condition

Fig. 10 Comparison of evaluated crack-tip profiles of the fatigue crack with the actual ones

The evaluated results evidently verify that the crack size of smaller closed cracks as well as the open crack can successfully be determined using the proposed technique. The evaluated closure stress distribution is shown in



(b) under open condition

Fig. 10 *Continued*

Fig. 11. From the figure it is observed that the closure stress distribution for the non-uniform crack profile is also non-uniform. The evaluated closure stress for the open cracks are found zero thus they are not presented here. Note that the crack depth as well as the closure stress for the measurement position $y = 25$ mm have been successfully determined. The measurement position $y = 25$ mm is 5 mm away from the sidewall of the specimen.

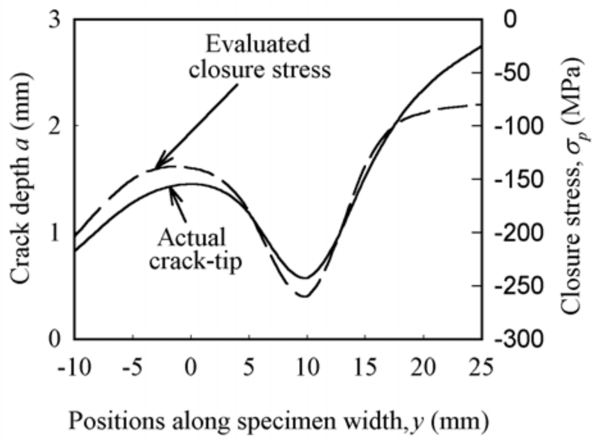


Fig. 11 Closure stress distribution along the crack length

9. CONCLUSION

The precise evaluation of crack-tip contours for both the open and the closed cracks evidently verifies the capability of the method. As observed in Fig. 2 the middle potion of the crack profile is almost a 3-dimensional. This profile is re-constructed accurately by the present NDE method. Therefore, this study extends the capability of the method for the evaluation of 3-dimensional narrow crack. The closure stress distribution as well as the crack-tip profile for specimen of 12 mm thickness (as studied here) can be determined up to a distance of 5 mm close to the sidewall for part through crack.

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NOMENCLATURE

Symbol	Meaning	Unit
K	Stress intensity factor	(MPa.m$^{1/2}$)
a	Crack depth	(mm)
θ_w	Incidence angle in water	(deg.)
θ_s	Incidence angle in material	(deg.)
x_c	Position on top surface from which crack corner is focussed	(mm)
γ	Wave reflection coefficient	(volt/volt)
p^{es}	Estimated echo amplitude for closed crack	(volt/volt)
p_c^{es}	Estimated echo amplitude for open crack	(volt/volt)
p^{ex}	Measured echo amplitude for closed crack (normalized)	(volt/volt)
p_c^{ex}	Measured echo amplitude for open crack	(volt/volt)
σ_p	Crack closure stress	(MPa)
$\bar{x}$	Normalized probe position	(mm/mm)
F	Objective function	(-)
m	Number of data points in the range of calibration equation	(-)