MICROWAVE NDE OF A SMALL 3-D CRACK ON THE SURFACE OF STAINLESS STEEL

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ABSTRACT
A method to evaluate the shape and size of a small 3-D crack by microwaves was demonstrated. A component named interference waveform, which is based on the amplitude of the reflection coefficient measured at two different frequencies, was obtained. On the other hand, based on the interference model, a corresponding interference waveform, which can be calculated from the assumed shape and size of a 3-D crack, was also introduced. By comparing these two interference waveforms, the evaluation of the shape and size of a 3-D crack was carried out. The shape and size of the crack were estimated well by using the proposed method.

1 INTRODUCTION

As a tool of nondestructive testing, microwave enables us to detect small cracks without bringing a sensor into contact with the surface of inspected material and also without coupling medium between the sensor and material surface. However, it had been hard to detect small cracks, especially closed cracks, on the metal surface. Cracks are often closed under a no load condition (Elber [1]), and this phenomenon makes detection and evaluation of the cracks difficult (Buck and Skillings [2] and Clark et al. [3]). Since the 1970s, some researchers had attempted using microwave to detect surface cracks in metallic components (Hruby and Feinstein [4] and Auld [5]). In recent years, some researchers had further promoted such researches by using an open-ended rectangular waveguide in a near-field fashion (Qaddoumi et al. [6]). However, the detection of closed cracks had not been succeeded. Just recently, a highly sensitive open-ended coaxial line sensor was developed and it became possible to detect closed cracks by microwaves (Ju et al. [7]). Also, a noteworthy technique, that is called microwave dual frequency technique, was developed for quantitative nondestructive evaluation of small cracks, irrespective of crack closure, and had been verified by using 2-D closed cracks (Saka et al. [8]). Moreover, by investigating the relationship between the load applied to a cracked material and strain measured straddling the crack, the limit of the absolute value of crack closure stress to the dual frequency technique was evaluated (Saka et al. [9]). However, when the dual frequency technique was directly applied to a 3-D crack, the shape of the crack could not be evaluated correctly, since the amplitude of the reflection coefficient measured at different position of the sensor in the direction of the crack length showed a fluctuation. The reason is due to the interference of microwave occurring at the sensor aperture, which was not considered in the usual dual frequency technique. In the present paper, we report a method to solve an inverse problem in order to evaluate the shape and size of 3-D cracks correctly.

2 EXPERIMENTAL PROCEDURES

The configuration of the microwave inspection system is shown in Fig. 1 The network analyzer is a microwave receiver designed to process the magnitude and phase of the transmitted and reflected waves from the network. It was used to generate a continuous wave signal which was fed to an open-ended coaxial line sensor and to measure the amplitude of the reflection coefficient, A, at

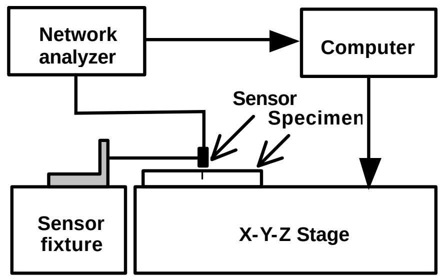

Figure 1: Configuration of the microwave inspection system

Figure 2: Photograph of the open-ended coaxial line sensor

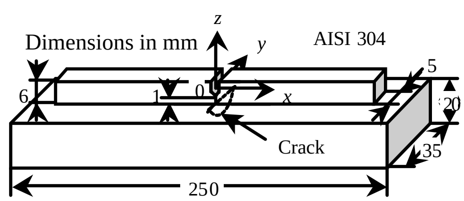

Figure 3: Descriptive geometry of the specimen used to introduce a 3-D crack

the sensor aperture. The photograph of the sensor is shown in Fig. 2. The sensor has an inner and outer conductor with a radius of 0.1 and 0.5 mm, respectively. The spatial resolution of the sensor was evaluated to be 125 μm when the standoff distance was 500 μm at the operating frequency of 110 GHz (Ju et al. [10]). A 3-D fatigue crack was introduced in a specimen. The specimen was machined from austenitic stainless steel, AISI 304, of which initial shape is shown in Fig. 3. The dimensions of the bed-plate were $250 \times 35 \times 20$ mm, on which a narrow strip having the dimensions of $200 \times 5 \times 6$ mm was remained. A Cartesian coordinates system (x, y, z) was chosen such that the origin 0 was located at the center of the specimen width on the surface of the bed-plate. To introduce a fatigue crack, an initial notch was introduced in the strip, where the direction of crack growth was considered perpendicular to the longitudinal rolling direction, L, and parallel to the short transverse direction, S, of the material (ASTM designation for crack plane orientation ASTM E399-90 [11]). The fatigue crack was grown from the tip of the initial notch by cyclically loading the plate in four-point bending of tension and tension on the dynamic testing machine. During the process of fatigue, crack growth was monitored from the side surfaces of the strip and also from the top surface of the bed-plate. Stress ratio R was maintained during the crack growth. After the crack length on the surface of the bed-plate reached the desired value, the specimen was machined and polished to remove the narrow strip, leaving a true 3-D fatigue crack in the remaining bed-plate. After the microwave measurement was carried out, the specimen was fractured for observing the shape and the size of the crack. The value of the crack depth at the deepest penetration point was 3.0 mm.

The 3-D crack was scanned under a no-load condition in the x-direction with a pitch of 0.04 mm and the standoff distance (between the sensor and the specimen) of 60 μm, by using two frequencies (f_1 and f_2) of 105 and 110 GHz, respectively. The amplitude of the reflection coefficient A was continuously recorded corresponding to the measurement position, and the amplitude difference, ΔA, in the cases of crack being absent and present under the sensor, was obtained from the measured A distribution along the x-axis. Such scanning was repeated in the y-direction with a pitch of 0.2 mm. Finally, a distribution of ΔA along the y-axis was obtained.

3 INTERFERENCE WAVEFORM OBTAINED FROM EXPERIMENT

By considering the sensor position, y_s, along the direction of crack length and the interference of microwave, and by referring Saka et al. [8], the crack depth, d, at $y=y_s$ can be expressed as (Ju et al. [12])

$$d(y_s) = \frac{\Delta A(f_1, y_s) - \dfrac{G(f_1, y_s)}{G'(f_2, y_s)}\Delta A(f_2, y_s)}{S(f_1, y_s) - \dfrac{G(f_1, y_s)}{G(f_2, y_s)}S(f_2, y_s)}, \tag{1}$$

where ΔA, in decibel, is the amplitude difference of the reflection coefficient in the cases of crack being absent and present under the sensor; $S(f, y_s)$ and $G(f, y_s)$ are constants determined by the operating frequency, f, and y_s. The numerator of eqn (1) was denoted by $I(y_s)$, which is called interference waveform (Ju et al. [12]), as

$$I(y_s) = \Delta A(f_1, y_s) - \frac{G(f_1, y_s)}{G(f_2, y_s)}\Delta A(f_2, y_s), \tag{2}$$

and

$$\frac{G(f_1, y_s)}{G(f_2, y_s)} = \frac{G(f_1)}{G(f_2)}. \tag{3}$$

Therefore, the value of I can be calculated by using the ratio of G obtained from 2-D cracks (Saka et al. [8]). It was known that I is a quantity including the effects both of the shape and size of the 3-D crack and the interference of microwave, but is independent of crack closure stress (Ju et al. [12]).

4 INTERFERENCE WAVEFORM OBTAINED FROM THEORETICAL MODEL

On the other hand, the interference of microwave in the crack can be considered theoretically by assuming a model of the crack as a parallel plate waveguide. Figure 4 shows a conceptional diagram of a 3-D crack. In Fig. 4, y_s expresses the position of the sensor where microwave signal is radiated and received. Let us consider that microwave is radiated within a small angle dq, and is reflected at the front of the crack. Here, we assumed that the reflection at the crack front will not induce the change of the amplitude and phase of the microwave signal. Therefore, the amplitude of the received signal will be $1/\sqrt{r}$ due to the radiation, where r is the distance between y_s and an arbitrary point on the crack front and is a function of y_s and q, see Fig. 4. Therefore, the returned signal, the x component of the electric field, E_{xq}, at the sensor aperture can be expressed as

$$E_{xq}(y_s) = C_0 \frac{1}{\sqrt{pkr}} \cos\left(2kr - \frac{p}{4} - wt\right) dq \quad , \tag{4}$$

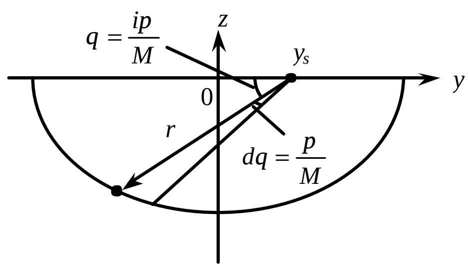

Figure 4: Conceptional diagram of a 3-D crack

where C_0 is the amplitude of the incident wave at y_s, and w the radian frequency, k the wavenumber, t the time coordinate. By integrating eqn (4) with respect to q, the microwave signal measured by the sensor, E_x, including the interference effect, can be written as

$$E_x\left(y_s\right) = C_0 \int_0^p \frac{1}{\sqrt{pkr}} \cos\left(2kr - \frac{p}{4} - wt\right) dq \quad . \tag{5}$$

To calculate the amplitude of the received signal, eqn (5) is written as

$$\left.\begin{aligned}
&E_x\left(y_s\right) = C_0 \sqrt{p''^2 + q''^2}\ \sin\left(\frac{p}{4} + wt + r\right)\\
&p'' = \int_0^p \frac{1}{\sqrt{pkr}} \cos\left(2kr\right) dq\\
&q'' = \int_0^p \frac{1}{\sqrt{pkr}} \sin\left(2kr\right) dq\\
&r = \tan^{-1}\frac{p''}{q''}
\end{aligned}\right\} \quad . \tag{6}$$

Then, from eqn (6), the amplitude of the reflection coefficient, in decibel form, can be written as

$$\left.\begin{aligned}
&I'_c\left(y_s\right) = 20\log_{10}\sqrt{p'^2 + q'^2}\\
&p' = \frac{p}{M}\sum_{i=0}^{M} \frac{1}{\sqrt{pkr}} \cos\left(2kr\right)\\
&q' = \frac{p}{M}\sum_{i=0}^{M} \frac{1}{\sqrt{pkr}} \sin\left(2kr\right)
\end{aligned}\right\} \quad , \tag{7}$$

where M is an integer dividing angle p around the sensor position y_s. Finally, the theoretical interference waveform could be written as

$$\left.\begin{aligned}
&I_c(y_s) = C_1 + C_2 \log_{10}\sqrt{p^2 + q^2}\\
&p = \frac{1}{M}\sum_{i=0}^{M} \frac{1}{\sqrt{kr}} \cos(2kr)\\
&q = \frac{1}{M}\sum_{i=0}^{M} \frac{1}{\sqrt{kr}} \sin(2kr)
\end{aligned}\right\} \quad , \tag{8}$$

where C_1 and C_2 are constants introduced to calibrate the difference between the theoretical model and the actual measurement. In order to include information of two frequencies in the equation, the average of f_1 and f_2 is used. Therefore, k is equal to $\pi(f_1+f_2)/c$, where c is the velocity of light. In addition, p and q in eqn (8) are divergent at $r \rightarrow 0$. By considering $1/k$ as a standard, eqn (8) can be used for $r>1/k$.

5 EVALUATION AND RESULTS

In order to predict the shape and size of the 3-D crack, first, the shape and size of the crack are assumed, where the length of the crack can be obtained directly from the measurement. Then, the comparison between the interference waveforms I and I_c obtained from the experiment and calculation, respectively, is carried out repeatedly by changing the assumed shape and size of the crack. Finally, the evaluated results are output when the difference between I and I_c becomes the minimum. The evaluation function B is given by

$$B(I,I_c) = aU(I,I_c) + bV(I,I_c) + gW(I,I_c) \quad . \tag{9}$$

Function B expresses the similarity of I and I_c. They are similar when B takes a minimum value. Here, the interference waveform is characterized by the number, the size, and the position of the peaks included in the waveform. In eqn (9), U, V, and W are functions which give the differences of the number, the size, and the position of the peaks in I and I_c. Symbols a, b and g are weight of the functions, respectively.

The interference waveform I was obtained from ΔA by using eqns (2) and (3). Here, $G(f_1)/G(f_2)$=0.82 obtained from 2-D crack measurement (Saka et al. [8]) was used. Crack length was measured by scanning the crack in the specimen. Referring the crack length, a semi-elliptical crack was assumed as initial crack. Some calculating points were arranged on the front of the semi-elliptical crack. The number of points was fixed independent of crack length. The positions of the points were arranged in the same pitch along the crack length. The initial value of the assumed crack depth was determined to satisfy the condition that B takes a minimum value under the assumption of semi-elliptical crack. Interference waveform I_c and function B were

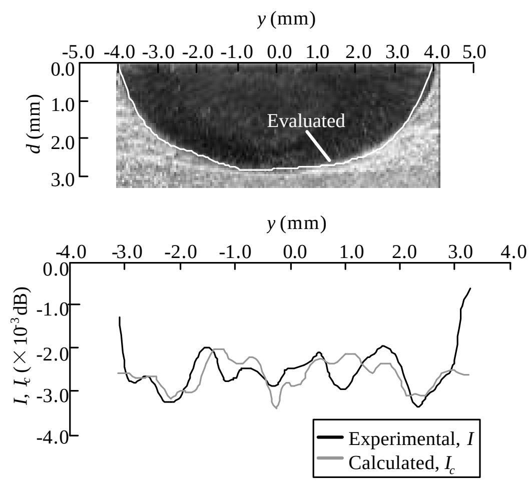

Figure 5: Evaluated distribution of crack depth

calculated by moving the points on the front of the assumed crack, and all the combinations of each point were calculated. The evaluated results are shown in Fig. 5, where I_c shows the result under the condition of B taking the minimum value. Both shape and size of the 3-D crack were estimated correctly.

6 CONCLUSIONS

A method to evaluate the shape and size of a small 3-D crack by microwaves was demonstrated. The technique was applied to a 3-D fatigue crack; both the shape and size of the crack were evaluated successfully. The promising technique has a great significance for the integrity assessment of metallic structures.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. M. Mikami for his help in preparing the specimen. This work was partly supported by The Ministry of Education, Culture, Sports, Science, and Technology under Grant-in-Aid for Specially Promoted Research (COE) (2) 11CE2003, and by Japan Society for the Promotion of Science under Grant-in-Aid for Scientific Research (B) (2) 14350050.

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