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Fundamental Study on Nonlinear Ultrasonic Imaging Method for Closed Cracks Using Subtraction of Responses at Different External Loads

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ABSTRACT

To improve the selectivity of closed cracks with respect to linear scatterers or artifacts, we propose an extension of a novel imaging method, namely, SPACE (subharmonic phased array for crack evaluation) as well as another approach using subtraction of responses at different external loads. By applying external static or dynamic loads to closed cracks, the contact state in the cracks varies, resulting in the change in the responses at the cracks. In contrast, the linear scatterers other than cracks are independent of the external loads. Therefore, only the cracks can be extracted by subtraction of responses at different loads. In this study, we performed its fundamental experiments in a closed fatigue crack formed in an aluminum alloy A7075 specimen. Here we examined static-load dependence of SPACE images and dynamic-load dependence of linear phased array (PA) images by simulating the external loads by a servohydraulic fatigue testing machine. By subtracting the images at different external loads, we show that this method is useful in extracting only the variance in the responses related to closed cracks, with canceling the responses of other than cracks.

INTRODUCTION

Crack depth can be measured by ultrasound if they are open, since the ultrasound is strongly scattered by the crack tip.[1] However, the ultrasound is transparent through closed cracks whose faces are contacting each other because of residual stress[2,3] or by oxide films[4]. This causes the underestimation or overlook of the cracks. To solve this problem, nonlinear ultrasound is the most promising means of evaluating closed cracks.[5] Nonlinear ultrasound is based on the detection of nonlinear components, e.g., superharmonic waves ($2f$, $3f$,…)[6-8] or subharmonic waves ($f/2$, $f/3$,…),[9-13] generated by the interaction of large-amplitude ultrasound with closed cracks, where f is the input-wave frequency. Specifically, subharmonic waves are useful because of its selectivity for closed cracks. Thus far, we have developed a novel imaging method, subharmonic phased array for crack evaluation (SPACE), and demonstrated its performance in closed fatigue and stress corrosion cracks.[14-18] SPACE provides fundamental (f) and subharmonic ($f/2$) images by filtering received waveforms at each frequency. However, strong linear scatterers such as coarse grains, weld defects and back surfaces, sometimes appear in subharmonic images as a leak of the filter, since short-burst input waves are used to obtain high temporal resolution. The artifacts might degrade the performance of SPACE to identify closed cracks.

To improve the selectivity of closed cracks with respect to linear scatterers, some nonlinear ultrasonic imaging methods extracting responses at different loads have been proposed.[19-22] These demonstrated that linear and nonlinear scatterers in a plate can be discriminated and their in-plane positions can be located by extracting the change in the amplitude of high-frequency waves at different phase of low-frequency vibration. However, the measurement of closed-crack depths in the thickness direction has yet to be realized, although it is essential to evaluate material strength.

In this study, to measure closed-crack depths, we propose a precise nonlinear ultrasonic imaging method of an extension of SPACE as well as another approach of linear phased array (PA) using subtraction of responses at different external loads. We show its fundamental experiments in a closed fatigue crack by static-load dependence of SPACE images and dynamic-load dependence of PA images.

NONLINEAR ULTRASONIC IMAGING METHOD USING SUBTRACTION OF RESPONSES AT DIFFERENT LOADS

To improve the selectivity of closed cracks with respect to linear scatterers or artifacts, we propose a precisely nonlinear ultrasonic imaging method on the basis of subtraction of responses at different loads and phased array techniques. The schematic illustarion is shown in Fig. 1. In imaging welded parts by phased array, weld defects, back surface as well as crack are visualized in the images. By applying external static or dynamic loads to closed cracks, the contact state in the cracks varies. This results in the change in the responses at the cracks, since the scattering intensity at the tip strongly depends on the open/closed state of the crack. In contrast, the responses at the linear scatterers such as back surfaces and weld defects are independent of the external loads. Therefore, the subtraction of the responses at L1 and L2 enables to extract only the crack.

For a practical application of external loads to cracks, there are static and a dynamic loading. For the application of static loads, the method to utilize a hydraulic pump and a jig, e.g. for four-point bending test, would be effective. This can easily control external loads, while the apparatus is large. For quasi-static loading, the use of thermal stress induced by laser irradiation[23] and ice cylinder[24] have been reported. However, they can not be readily controlled. On the other hand, a low-frequency vibrator has been widely used to apply dynamic loads.[19-22,25-27] This can not easily control the load to the crack, while the apparatus is realatively small and easy to handle. In this study, as a fundamental experiment, we simulated a static and a dynamic loads by a servohydraulic fatigue testing machine, which was used to form closed fatigue crack.

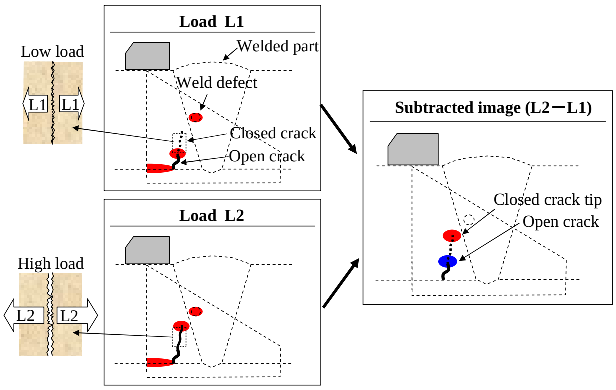

Figure 1. Nonlinear ultrasonic imaging method of closed cracks by subtraction of responses at different loads

SPECIMEN

We used a compact tension (CT) specimen of an aluminium alloy (A7075) to form a closed fatigue crack. The shape of the CT specimen (Fig. 2) was based on ASTM-E399. The distance between notch and top surface was 40 mm for ultrasonic diagnosis. To form closed cracks, the fatigue conditions were the maximum stress intensity factor of 9.0 MPa·m$^{1/2}$ and the minimum stress intensity factor of 0.6 MPa·m$^{1/2}$.[28] The crack was extended to the depth of approximately 10 mm on the side surface after 76,000 cycles.[18]

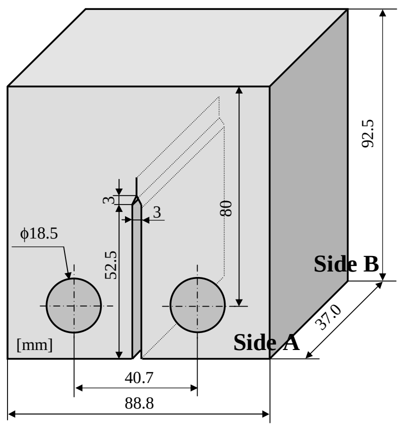

Figure 2. Shape of CT specimen

EXPERIMENTAL RESULTS

Static-load dependence of SPACE images

To demonstrate the proposed method, we imaged the closed crack in the CT specimen using SPACE with applying static loads by the servohydraulic fatigue testing machine. The schematic illustration of experimental configuration is shown in Fig.3. A LiNbO3 single-crystal (LN) transmitter with a polyimide was used for generating intense ultrasound, and an array sensor was used as a receiver for focusing on reception. An input wave emitted from the LN transmitter was 3-cycles burst wave with a center frequency of 7 MHz. Its displacement was measured to be 50 nm by laser interferometery.[11] The array sensor is 31 elements with a center frequency of 5 MHz to receive both fundamental (7 MHz) and subharmonic (3.5 MHz) components simultaneously. The received signals are digitally filtered at fundamental and subharmonic frequencies. Finally, they are phase-matched following the delay laws to create fundamental and subharmonic images, respectively.

Figure 4 shows the images obtained in the stress intensity factors K =0.5 MPa·m$^{1/2}$ and K =1.3 MPa·m$^{1/2}$, respectively. Crack B was imaged in the fundamental images of (a) and (c). The intensity increased with increase in K . On the other hand, some artifacts deteriorated the signal-to-noise ratio (SNR). In subharmonic images of (b) and (d), the crack tip A was visualized. The intensity decreased with the increase in K . These results show that the crack became open with the increase in K . Then we subtracted the fundamental and subharmonic images between K =1.3 MPa·m$^{1/2}$ and K =0.5 MPa·m$^{1/2}$, respectively. As a result, the subtracted subharmonic image of (f) shows the decrease in the response at the crack tip A. The subtracted fundamental image of (c) was eliminated the artifacts and thereby succeeded in extracting only the increase in the response at the crack B.

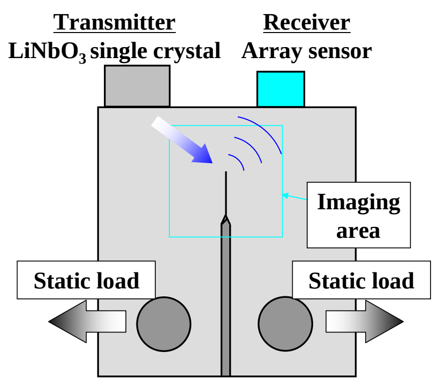

Figure 3. Schematic illustration of experimental configuration for SPACE and static loading

Dynamic-load dependence of PA images

As a fundamental experiment, we simulated dynamic loading by the servohydraulic fatigue testing machine instead of a compact low-frequency vibrator. The schematic illustration of experimental configuration is shown in Fig.5. We recorded the dynamic change in the closed crack in PA images, in real time, under the sinusoidal loading with K =0 MPa·m$^{1/2}$ to 7 MPa·m$^{1/2}$ with a frequency of 0.1 Hz. Here we used an array sensor of 32 elements with a center frequency of 5 MHz for PA. The typical snapshots of the recorded movie at K =0 MPa·m$^{1/2}$ and K =7 MPa·m$^{1/2}$ are shown in Fig. 6(a) and (b). The crack was unobservable in (a), whereas it was obviously observed in (b). This shows that the closed-crack tip was opened by the loading. Then we precisely examined the change in the intensity of responses at crack tip at the interval of 0.25 s (Fig.7). The intensity was not varied at $K \leq 0.5$ MPa·m$^{1/2}$ (region I). Within K =2.4 MPa·m$^{1/2}$ of K =0.5 MPa·m$^{1/2}$ (region II), the intensity increased linearly with K . Above K =2.4 MPa·m$^{1/2}$ (region III), the intensity was saturated. This suggests that the crack was closed in region I, it gradually became open at region II, and then it was completely opend in region III. Accordingly, the closure stress can be estimated to be approximately K =2.4 MPa·m$^{1/2}$. By subtraction of Fig.6 (b) and (a), the corner on the left side of notch, which was the strong linear scatterer, was eliminated, although the tip and the corner on the right side of the notch were visualized because they were affected by the crack opening/closing behaviour. Consequently, we succeeded in imaging the increase in the intensity at crack tip and the decrease in that at root of the crack, as shown in Fig.6(c). We demonstrated that the subtraction method can extract the parts related to closed crack.

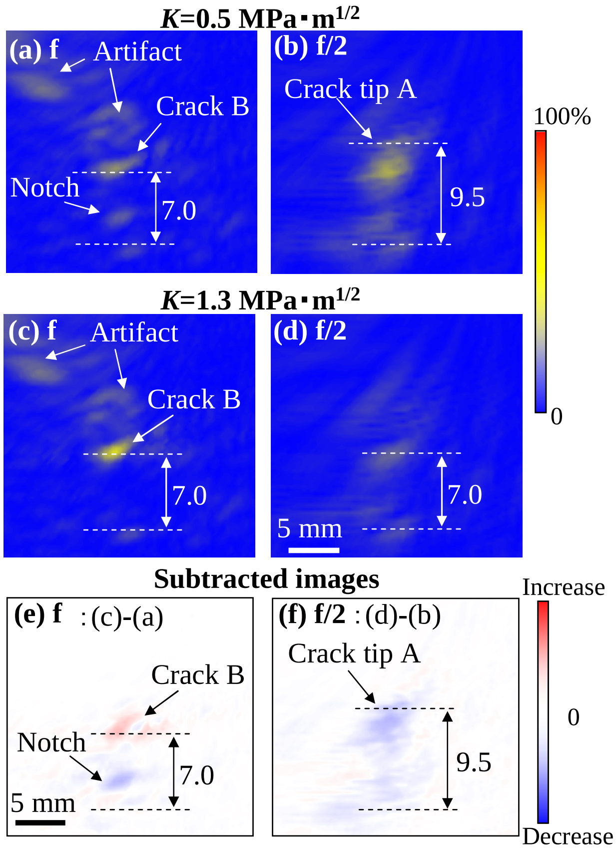

Figure 4. Static-load dependence of SPACE images and their subtracted images.

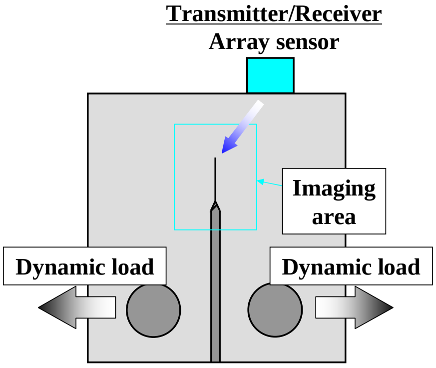

Figure 5. Schematic illustration of experimental configuration for PA and dynamic loading

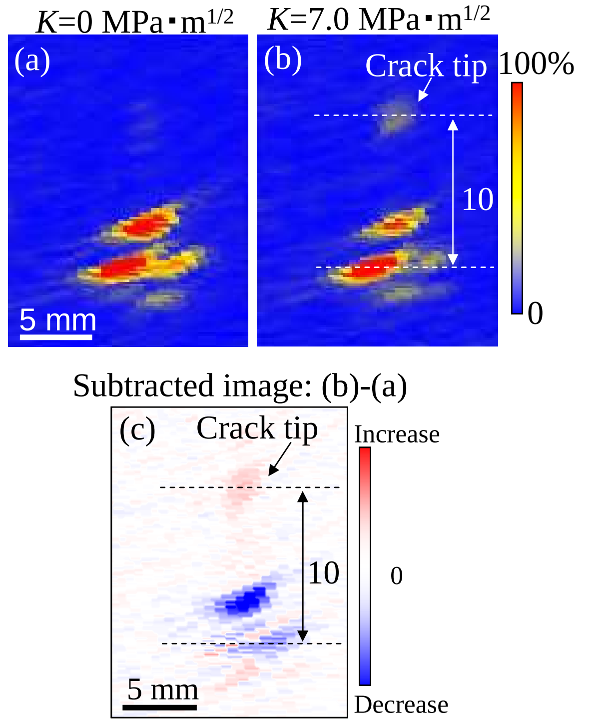

Figure 6. Typical snapshots of dynamic-load dependence of PA image and their subtracted images.

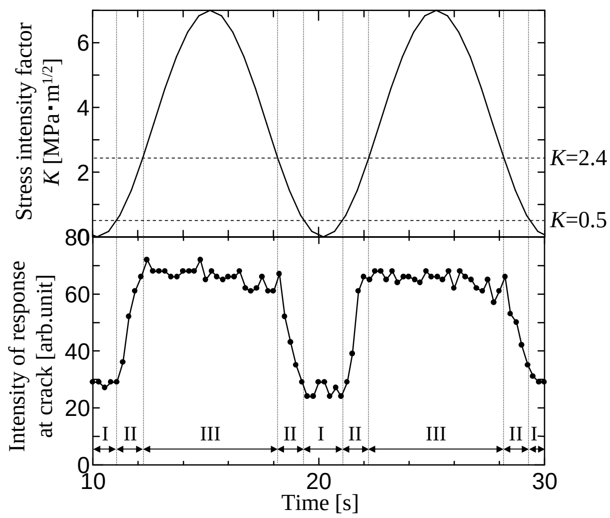

Figure 7. Dynamic change of load measured by load cell attached to servohydraulic fatigue testing machine and the intensity of response at the crack tip.

DISCUSSION

To validate the proposed method, we examined the improvement of selectivity of cracks quantitatively. As an indication of the selectivity, the intensity ratio of cracks and linear scatterers or artifacts is difined as

$$S = I_c / I_l \,, \qquad (1)$$

where I_c is the intensity at crack and I_l is that at linear scatterers or artifacts, which are unrelated to the crack opening/closing behaviors induced by external loads. Figure 8 shows S in the SPACE and PA images before and after the subtraction. Here, for SPACE images of Fig.4, I_c was the intensity at the crack B and the crack tip A in the fundamental and subharmonic images, respectively, and I_l was the maximum intensity among some artifacts. For PA images of Fig.6, I_c was the intensity at the crack tip and I_l was that at the corner on the left side of notch which was the strong linear scatterer unrelated to the crack opening/closing bahavior. As a result of the subtraction, S in the SPACE images were improved by 3.6 times and 3.3 times by cancelling the artifacts, respectively. For PA images, S was markedly improved by 24 times by cancelling the strong linear scatterer. Thus, we demonstrated that this method is very useful in improving the selectivity of closed cracks with respect to linear scatterers or artifacts.

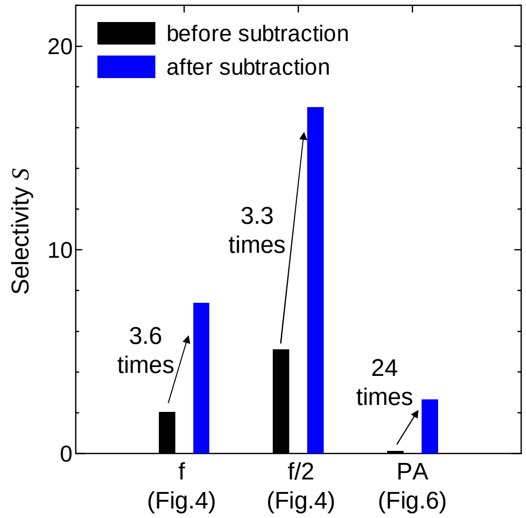

Figure 8. Selectivity of closed cracks with respect to linear scatterers or artifacts

In this study, we used servohydraulic fatigue testing machine to apply external loads to cracks. However, this is not practical because of the size and weight. In future works, we will construct the system consisting of a compact low-frequency vibrator (of the order of 10 Hz to 10 kHz), e.g. of giant magetostrictive actuators and piezostack transducers, and phased array techniques which are synthesized.

CONCLUSIONS

To improve the selectivity of closed cracks with respect to linear scatterers or artifacts, we proposed a nonlinear ultrasonic imaging method on the basis of the subtraction of responses at different loads and phased array techniques. We performed its fundamental experiments in a closed fatigue crack using static-load dependence of SPACE images and dynamic-load dependence of PA images. Here we simulated the external loads by a servohydraulic fatigue testing machine. By subtracting the images at different external loads, only the variance in the responses related to closed cracks was extractedn with canceling the responses of other than cracks. Thus, we demonstrated that this method is very useful in improving the selectivity of closed cracks with respect to linear scatterers or artifacts.

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