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Nonlinear Ultrasonic Imaging of Closed Cracks Using Subtraction of Responses at Different Loads

異なる荷重における応答の差分を用いた閉じたき裂の非線形超音波映像法

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1. Introduction

Nonlinear ultrasound has a potential of becoming a primary means of evaluating closed cracks, and subharmonic waves[1)] with half-frequency of input wave are particularly useful because of its excellent selectivity for closed cracks. Thus far, we have developed a novel imaging method, subharmonic phased array for crack evaluation (SPACE)[2)], and demonstrated its performance in closed fatigue cracks and stress corrosion cracks (SCCs) made in this laboratory[2-4)]. The SPACE fabricates fundamental (f) and subharmonic (f/2) images by filtering received waveforms at each frequency. However, in case of SCCs in a weld part or cracks near back surface, it is difficult to identify cracks because of strong liner scatterers such as coarse grain and back surface, which were visualized in subharmonic images as a leak of filter as well as fundamental images. In this study, to solve this problem, we propose a nonlinear ultrasonic imaging of closed cracks using subtraction of responses at different load. Then, we apply it to a closed fatigue crack formed in an aluminum alloy A7075 specimen as a fundamental experiment to prove its performance.

2. Nonlinear ultrasonic imaging method using subtraction of responses at different loads

By applying external static or dynamic loads to closed cracks, the contact state in the cracks varies as shown in **Fig. 1**. This changes the intensity and area of contact acoustic nonlinearity (CAN), whereas does not influence the other linear scatterers. Therefore, the changes in CAN can be extracted by subtraction of responses at different load as shown in **Fig. 2**. As the calculation methods, we consider intensity subtraction and waveform subtraction. The former is the subtraction of intensity of responses at each focusing point, providing not only amount of variations but also its increase and decrease. The latter is the subtraction of received waveforms, providing not only amount of variations but also phase variations.

For practical application of this method, the external loads can be applied with a bending jig and compact actuator, low-frequency vibrator, or the thermal stress[5)] , etc.

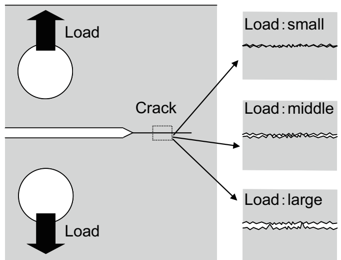

Fig. 1. Variance in contact state in closed crack.

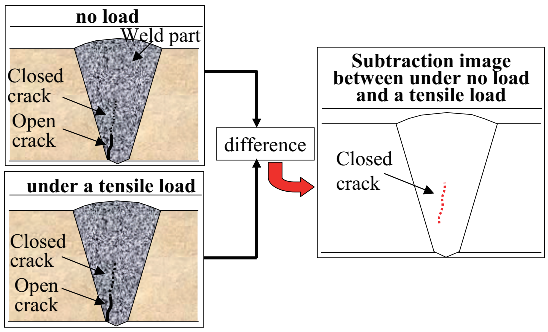

Fig. 2. Nonlinear ultrasonic imaging of closed cracks using subtraction of responses at different loads.

3. Specimen and experimental conditions

The fatigue crack was formed in an aluminum alloy A7075 compact tension (CT) specimen following ASTM-E399 with $K_{max} = 9.0\,\mathrm{MPa \cdot m^{1/2}}$ and $K_{min} = 0.6\,\mathrm{MPa \cdot m^{1/2}}$[6)]. After 87000 fatigue cycles, we visualized the crack with the configuration shown in **Fig.3**.

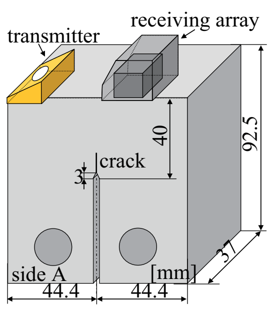

Fig. 3. Experimental setup

Here the input wave was a three-cycle burst of a 7 MHz sinusoidal wave with 50 nm_{p-p} amplitude. We used an array sensor of 31 elements with the center frequency of 5 MHz. In this study, as a fundamental experiment to prove the basic principle of this method, we applied tensile loads using tensile testing machine via a jig for CT specimen.

4. Experimental result

The fundamental and subharmonic images at $K = 5.0$ and $1.3\,\mathrm{MPa \cdot m^{1/2}}$ are shown in **Fig.4**. At $K = 5.0\,\mathrm{MPa \cdot m^{1/2}}$, the fundamental image (a) indicated the middle part B and the notch C. This suggests that B and C are distinct discontinuities and thus become a linear scatterer. Contrary to this, the subharmonic image (b) indicated overall crack containing crack tip A. This result suggests that crack was overall closed. On the other hand, at $K = 1.3\,\mathrm{MPa \cdot m^{1/2}}$, C diminished in the fundamental image (c). This suggests that the bottom part was opened by the increase in the tensile loads. In the subharmonic image (d), the intensity in the crack was decreased. This result suggests that the closed region were reduced.

Using these results, we performed intensity and waveform subtraction of $K = 5.0$ and $1.3\,\mathrm{MPa \cdot m^{1/2}}$. The images by intensity subtraction are shown in **Fig. 5(a,b)**. The fundamental subtraction image (a) indicated the increase at B and the decrease at C. In addition, the artifacts appeared in the upper left of **Fig.4(a, c)** were canceled. This suggests that only the variance in linear scatterers was extracted. The subharmonic subtraction image (b) mainly indicated the decrease around the crack tip.

The images by waveform subtraction are shown in **Fig.5(c, d)**. The fundamental subtraction image (c) was almost the same as (a). On the other hand, the subharmonic subtraction image visualized the decrease in overall the crack. This is different from (b). This shows that the waveform subtraction extracted the phase change due to change in CAN, which can not be extracted by the intensity subtraction. Thus, we showed that the subtraction method has a potential to visualize open and closed behaviors of cracks with high selectivity.

5. Conclusion

In this study, we proposed a nonlinear ultrasonic imaging using subtraction of responses at different loads, and performed fundamental experiment with a closed fatigue crack. As a result, we showed that this method can extract only the variance in open and closed behaviors of crackcancel the responses without cracks with high selectivity. As a nest step, we will apply this method to SCCs in a weld part with coarse grains.

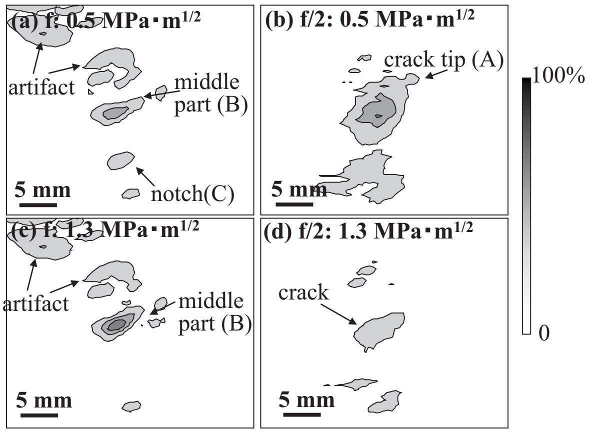

Fig. 4. Load dependence of SPACE images: (a) fundamental and (b) subharmonic images at $K = 0.5\,\mathrm{MPa \cdot m^{1/2}}$, (c) fundamental and (d) subharmonic images at $K = 1.3\,\mathrm{MPa \cdot m^{1/2}}$.

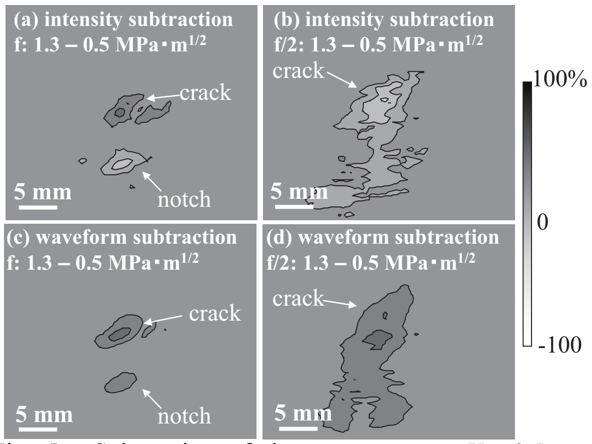

Fig. 5. Subtraction of the responses at $K = 0.5$ and $1.3\,\mathrm{MPa \cdot m^{1/2}}$; (a) fundamental and (b) subharmonic images by intensity subtraction, (c) fundamental and (d) subharmonic images by waveform subtraction.

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