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Study on the characteristics of aluminum-alloy fatigue cracks and the behavior of subharmonic generation

アルミニウム合金の疲労き裂性状とサブハーモニック波発生挙動に関する検討

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1. Introduction

Crack depth measurement using ultrasound utilizes the waves scattered at the crack tip. However, such measurement might be difficult in complicated structures and highly scattering materials because the crack tip echo is often weaker than the other echoes, for instance, due to grain scattering. Our developed imaging method, subharmonic phased array for crack evaluation (SPACE)[1,2] can be a solution for such problems. SPACE has been verified in various crack samples, whereas the mechanism of the subharmonic generation has yet to be elucidated. To realize the industrial application of SPACE, we need to clarify the relationship between the subharmonic generation and crack characteristics.

In this study, we formed two fatigue cracks in aluminum-alloy samples under different fatigue conditions. Then, we examined the dependence of subharmonic generation on fatigue crack characteristics using SPACE. Furthermore, we discuss the results in terms of fracture mechanics.

2. SPACE

Figure 1 shows a schematic illustration of SPACE. A monolithic transducer with a wedge is used to input a large-amplitude ultrasound, which is essential to cause the contact vibration of crack faces. Here the transmitter is composed of soft PZT with a high piezoelectric strain constant and a wedge made of an aluminum alloy, which is the same material as the fatigue-crack sample. An SiC pulser is adopted to excite the soft PZT efficiently. By irradiating a large-amplitude longitudinal wave with a frequency of f onto cracks, linear scattering occurs not only at open cracks but also at the other linear scatterers such as coarse grains, bottoms. In contrast, nonlinear scattering at the subharmonic frequency ($f/2$) can occur only at a crack with a smaller crack opening displacement than the incident wave amplitude. The scattered waves are received at each element of an array transducer. The set of waveforms received are analog-to-digital converted and recorded. Subsequently, they are digitally filtered around f and $f/2$, respectively. Delay-and-sum (DAS) processing following delay laws[1)] is then carried out. Finally, the root-mean-square (RMS) value is calculated as the intensity at a focal point. This process is repeated over the imaging area to create fundamental and subharmonic images.

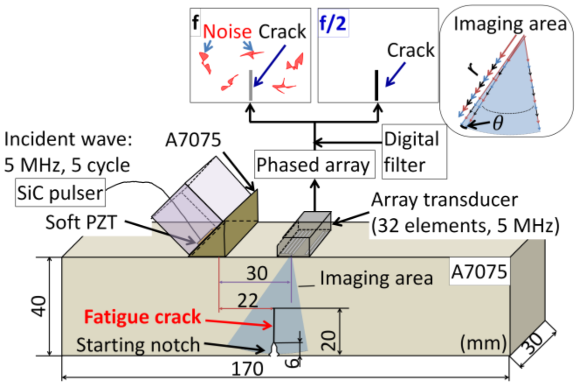

Fig. 1 Schematic illustration of SPACE.

3. Experimental conditions

To examine the dependence of subharmonic generation on crack characteristics, we made two kinds of fatigue cracks. The samples with the geometry shown in Fig. 1 were made of an aluminum alloy A7075. We respectively selected the fatigue condition that were stress intensity factor ranges ΔK=13 and 8.4 MPa·m$^{1/2}$ for a fixed stress ratio R=0.067. We extended fatigue cracks from the starting notch to a depth of approximately 20 mm by a three-point bending fatigue test. Here we refer to the samples as large and small ΔK samples.

We describe the imaging conditions by SPACE. The soft PZT transmitter was excited by a five-cycle burst with a frequency of 5 MHz at 300 Vp-p with an SiC pulser, where we confirmed by a laser-Doppler-vibrometer measurement[1)] that the incident wave amplitude at a crack position was 32.3 nm$_{p\text{-}p}$. As a receiver, we used a 32-elements array transducer (5 MHz, 0.5 mm pitch). Figure 1 illustrates the relative positions of the transmitter and receiver to the crack. A fast

Fourier transform filter was used to extract the fundamental (5.0 MHz) and subharmonic component (2.5 MHz) from the received waves, respectively. The scan area for focusing on reception was set to $\theta = -10$ to 35° (1° step) and r = 10 to 40 mm (4 mm step).

4. Experimental results

Figure 2 shows the fundamental and subharmonic images obtained at the large and small ΔK samples. In the large ΔK sample, the fatigue crack was visualized in the fundamental image (Fig. 2(a)). In the subharmonic image (Fig. 2(b)), the crack response was weak. This shows that the crack opening displacements of the large ΔK sample were larger in most crack regions than the incident wave amplitude. On the other hand, in the small ΔK sample, the crack response was weak in the fundamental image (Fig. 2(c)). Note that and the crack tip was absent. In contrast, the crack tip appeared with a sufficient signal-to-noise ratio in the subharmonic image (Fig. 2(d)). This shows that the crack opening displacement of the small ΔK sample was smaller at the crack tip than the incident wave amplitude, resulting in the subharmonic generation due to the contact vibration of the crack faces. Note that the subharmonic response increased with decreasing ΔK. This may suggest that the subharmonic response has a relationship to the parameters (e.g., ΔK) studied in fracture mechanics.

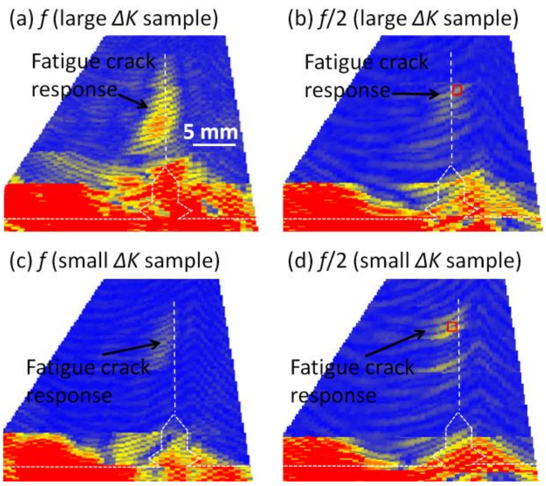

Fig. 2 Imaging results obtained by SPACE. (a) Fundamental and (b) subharmonic images of the large ΔK sample. (c) Fundamental and (d) subharmonic images of the small ΔK sample.

5. Discussion

We discuss the relationship between the subharmonic response and the parameters studied in fracture mechanics. A fatigue crack growth (FCG) rate is one of the important parameters not only in fracture mechanics but also for the maintenance of aging structures. It is well known that Paris' law[3] gives an FCG rate as a function of the ΔK:

$$da/dN = C(\Delta K^{m}), \quad (1)$$

where C and m are the so-called Paris' constants, a is the crack depth, and N is the number of fatigue cycle. As shown in Fig. 2, the intensities of the subharmonic response changed depending on ΔK. This may suggest that there is a relationship between the FCG rate and the subharmonic generation. We quantitatively examined the intensity of the subharmonic response in Figs. 2(b) and 2(d). Here the intensity was measured as mean value in the region surrounded by the red square. **Table 1** shows the relationship between the FCG rate and the intensity of the subharmonci response. In these samples, the FCG rate was inversely proportional to the I_C. This may suggest that a subharmonic image can provide information on FCG rate as well as an accurate crack depth.

Table I Relationship between FCG rate and subharmonic generation.

ΔK (MPa·m$^{1/2}$)	da/dN (mm/cycle)	I_C (arb. units)
13	4.5×10^{-3}	56
8.4	4.6×10^{-6}	82

6. Conclusions

We examined the dependence of subharmonic generation on fatigue crack characteristics using SPACE. The fundamental and subharmonic images markedly changed depending on the kinds of fatigue cracks. We also found that subharmonic response increased with decreasing ΔK. It may suggest that SPACE can provide information on an FCG rate as well as an accurate crack depth.

Aknowledghments

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