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Measuring acoustic nonlinearity using three wave mixing in metals during fatigue

疲労した金属材料中の 3 波相互作用による非線形音響性の測定

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1. Introduction

The fatigue damage evaluation is an important goal in the non destructive inspection technology. Fatigue would often cause serious damage in materials and fracture all of sudden. Fatigue damage has gradually induced the change of material properties and led to final fracture.

In this study, we applied nonlinear three-wave mixing method[1)] to fatigue damage evaluation in an aluminum alloy, A5052, plates subjected to zero-to-tension fatigue loading. This method was based on the fact that material nonlinearities cause interaction between two intersecting ultrasonic waves [1)]. Under certain conditions, this can leads to the generation of a third wave with a frequency and wave-vector equal to the sum or difference of the incident wave frequencies and wave-vectors. Three wave mixing methods nonlinearity is obtained incident wave and third wave amplitude ratio. The amplitude of incident wave is measured those amplitude was decrease during the fatigue progress, but third waves amplitude was rise gradually. These phenomenon was imaged of follow to the wave form distortion from micro-cracks opening and closure or crystalline-interface.

Nonlinear three-wave mixing method exhibits high sensitivity to microstructural change of the damaged material. They rapidly increase from 60 % of fatigue life to the fracture. This noncontact resonance-EMAT[2)] (electromagnetic acoustic transducer) meaurement can monitor the evolutions of nonlinearities in three-wave mixing method throughout the fatigue life and have a potential to assess the damage advance and to predict the fatigue life of metals.

2. Experimental

We performed fatigue test of the plate specimen in air. Its dimension was 160 mm long, 22 mm wide and 3 mm thick. We provided stress concentration area in gauge section. Its notch depth was 1mm, radius 5mm. Rolling direction was parallel to longitudinal direction of specimen. The mechanical properties in A5052 were following; the tensile strength 205.5MPa, the elongation 26.4 %, Hardness 47 HB.

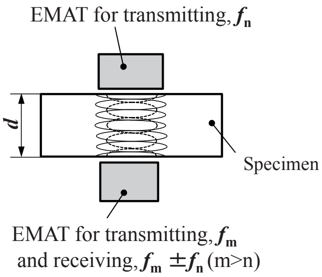

Fig.1 Experimental arrangement for nonlinear three wave mixing method.

We applied this three wave mixing method to electromagnetic acoustic resonance (EMAR)[2)], which was a combination of the resonant acoustic technique with EMAT. We used bulk-shear-wave EMAT which transmitted and received shear wave in the thickness direction of the sample, which operated with the Lorentz-force mechanism and is the key to establish a monitoring for micro-structural change during fatigue with high sensitivity.

Figure 1 shows the basic experimental arrangements. Two EMATs were faced and set in the thickness direction of the sample. Different resonance frequencies; f_n, f_m (*n, m*: resonant modes *m>n*) were generated by two EMAT, respectively. The difference or sum frequency, $f_n \pm f_m$ or $f_{m\pm n}$ was measured by one EMAT. Because material nonlinearity showed independence of the excitation level, the amplitude of the interaction resonant wave A_3, at $f_n \pm f_m$ was normalized to the product of the two input resonant amplitudes A_1 and A_2 measured.

$$\chi = A_3/(A_1A_2) \tag{1}$$

In this study, we measured the amplitude, A_3, at the resonant frequency, f_{n-m}. In selection of resonance mode, *n, m*, the numbers were prime numbers or not with common divisor or common multiple. We

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measured them by SNAP manufactured by RITEC.

We applied sinusoidal zero-tension-load at a frequency of 10 Hz. The stress amplitude, $\Delta\sigma$ was 76MPa, stress ratio, R ($=\sigma_{min}/\sigma_{max}$) =0.01. The cyclic stress direction was parallel to the longitudinal direction of specimen. We measured the nonlinearity, ultrasonic attenuation, and phase velocity of the bulk shear wave by interrupting the cyclic loading and releasing the cyclic tensile stress[3)]. The polarization of shear wave was parallel to the stress direction.

3. Results and Discussion

Figure 2 shows the evolutions of attenuation coefficient, α, nonlinearity in three-wave mixing, $A_3/(A_1A_2)$, and relative velocity, $\Delta V/V_0$ during fatigue. Horizontal axis is fatigue life ratio N/N_F (N: number of fatigue cycle, N_F: number of the cycle, when visible crack was observed). N_F was 200,000-cycle. A_1 is amplitudes at the fifth resonant mode, f_5 (around 2.65 MHz,), A_2 that at seventh resonant mode, f_7 (around 3.70 MHz), A_3 that at incident wave (f_7-f_5). $A_3^2/(A_1A_2)$ was decrease around the 60% life time, before the increases rapidly from 60% of the life. Evolutions of α shows the gradually increase of the life. The change of the $\Delta V/V_0$ is very small. The attenuation change as fatigue progress was related to the microstructure change, especially, dislocation mobility[4)].

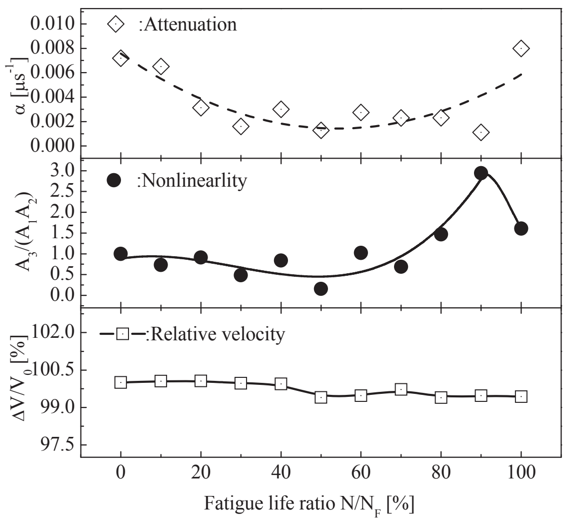

Fig. 2 Evolutions of attenuation coefficient, α, nonlinearity in three-wave mixing, $A_3/(A_1A_2)$, relative velocity, $\Delta V/V_0$ during fatigue. ($\Delta\sigma$=76MPa, R=0.01, N_F=200,000cycle).

The change of the non-linearity by the three-wave mixing method, which combined EMAT showed the tendency which is similar to as the results of the pure copper. As for these results of the pure copper, we interpreted that the evolution of the nonlinear quantity was caused by dislocation mobility and rearrangement during fatigue, which was supported by the TEM observation. In the results of the pure copper[5)], the nonlinearities showed the same tendency of the nonlinearity in the three wave mixing method. Therefore the change of the nonlinearity in the three-wave interaction during fatigue undergoes the increase of the dislocation density[4)] and nonlinearity on crack opening and closure when an acoustic wave impinges on the crack faces[6)]. As for any result of the specimen of the pure copper and A5052, the shown higher sensitivity of three-wave mixing method. This tendency was shown in three-wave mixing of the different frequency mode.

4. Conclusion

We summarize our conclusion as the following,

1) A combination of the EMAT and resonance method enables us to detect the acoustic nonlinearity in three-wave mixing method during fatigue progress without contact.
2) The nonlinearity shows rapid increase from approximately 60% of the lifetime. We interpreted these phenomena in terms of dislocation mobility, restructuring and micro-cracks opening and closure when an acoustic wave impinges on the crack faces.
3) The change in nonlinearity is synchronized with the change in attenuation coefficient with fatigue progression.
4) Assessment of damage advance and prediction of remaining fatigue life of metals may potentially be facilitated by nonlinear acoustics measurement with EMAR.

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