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Evolution of Nonlinear Ultrasonics and Microstructural change during Fatigue in Metal
金属疲労中の非線形超音波と微細組織の関係

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1. Introduction

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 fatigue damage evaluation in A5052 plates subjected to zero-to-tension fatigue loading through monitoring of with three-wave interaction method[1)] and non-contacting NRUS (Nonlinear resonant ultrasound spectroscopy)[2)], which is a resonance-based technique exploiting the significant nonlinear behavior of damaged materials. Three-wave- interaction technique is based on the fact that material nonlinearities cause interaction between two intersecting ultrasonic waves [3)]. 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. The amplitude of incident wave is measured. In NRUS, the resonant frequency of an object is studied as a function of the excitation level. As the excitation level increases, the elastic nonlinearity is manifest by a shift in the resonance frequency. NRUS and nonlinear three-wave interaction 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[4)] measurement can monitor the evolutions of nonlinearities in NRUS and three-wave interaction 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 gage section, notch 1mm, radius 5mm. The specimens were rolled in longitudinal direction. The mechanical properties in A5052 were following; the tensile strength 205.5MPa, the elongation 26.4 %, Hardness 47 HB.

We used EMAT to monitor NRUS of bulk shear wave propagating in the thickness direction of the sample. The EMAT operated with the Lorentz-force mechanism and is the key to establish a monitoring for microstructural change during fatigue with high sensitivity, as shown in **Fig. 1**. The measurement setup of the zero-to-tension fatigue test was the same as that developed in our previous study[5)]. By increasing the excitation level of the EMAT to 10 phases, the shift in the resonant frequency was measured. The quantity of the slope is defined as the nonlinearity in NRUS.

In the three-wave interaction method, we used same components as the NRUS system and measured maximum amplitudes, A_1, A_2 of the two different fundamental resonance modes and the amplitude, A_3 of the incident wave. The nonlinearity in three-wave interaction was evaluated by ratio of these three amplitude ratio. We measured them by SNAP manufactured by RITEC.

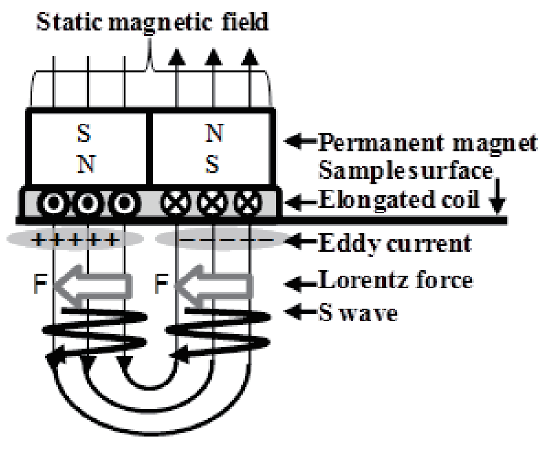

Fig. 1 Operation of the shear-wave EMAT. Lorentz force, F, excite the shear wave propagation in the thickness direction of the sample.

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We applied sinusoidal zero-tension-load at a frequency of 10 Hz. The stress amplitude, $\Delta\sigma$ is 75.8MPa, stress ratio, $R=\sigma_{min}/\sigma_{max}$, 0.01. 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. The polarization of shear wave is parallel to the stress direction.

3. Results and Discussion

Figure 2 shows the evolutions of the nonlinearity in three-wave interaction, $A_3^2/(A_1A_2)$ and nonlinearity in NRUS, $\Delta f/f_0$, ultrasonic attenuation,α, and relative velocity, $\Delta V/V_0$ during fatigue. A_1 is amplitudes at the 3th (f_3 around 1.39 MHz,), A_2 that at 8th (f_8 around 4.22 MHz), A_3that at incident wave (f_8-f_3). A_3^2/ (A_1A_2) increases rapidly from 60% of the life. $\Delta f/f_0$ slightly increased as fatigue progress. Evolutions of α shows the gradually increase of the life. The change of the $\Delta V/V_0$ is very small. The attenuation evolution as fatigue progress was related to the microstructure change, especially, dislocation mobility[6)]

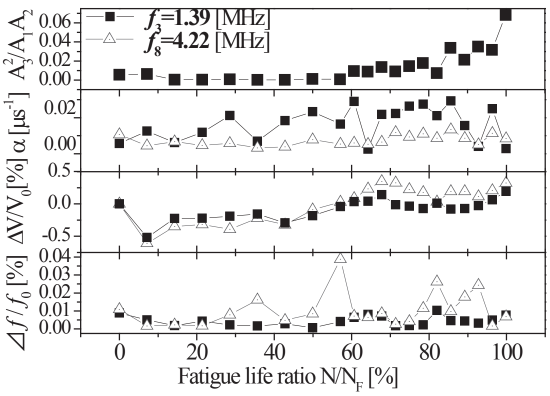

Fig. 2 Evolutions of nonlinearity in three-wave interaction, $A_3^2/(A_1A_2)$, attenuation coefficient, α, relative velocity, and NRUS nonlinearity in NRUS, $\Delta f/f_0$ during fatigue. ($\Delta\sigma$=75.8MPa, R=0.01, N=280,271cycle).

The change of the non-linearity by the three-wave 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, the nonlinearities of NRUS and the three-wave-interaction showed the same tendency but at the aluminum specimen, the result was different because aluminum sample is more sensitive to the change in temperature during NRUS measurement. The change of the nonlinearity in the three-wave interaction during fatigue undergoes the increase of the dislocation density[6)] and nonlinearity on crack opening and closure when an acoustic wave impinges on the crack faces.

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 interaction method and NRUS 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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