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Nonlinear Ultrasound characterization of Fatigue Damage in Pure Copper
純銅の疲労損傷中の非線形超音波特性

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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 pure copper plates subjected to zero-to-tension fatigue loading through monitoring of with three-wave interaction method and non-contacting NRUS (Non-linear resonant ultrasound spectroscopy)[1)], which is a resonance-based technique exploiting the significant nonlinear behavior of damaged materials. In nonlinear three-wave interaction method)[2)], two intersecting ultrasonic waves produce a scattered wave when the resonance condition is satisfied. The wave amplitude 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[3)] measurement can monitor the evolution of NRUS and nonlinear 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. Experiment and Configuration

We performed fatigue test of the plate specimen in air. Its dimension was 140 mm long, 24 mm wide and 3 mm thick. The specimens were rolled in longitudinal direction. The material was 99.9 % pure copper, JIS-C1100, which was heated at 473 K for 1.5 h, furnace-cooled to relieve the residual stress. At room temperature, the 0.2% proof stress of the material was 256.2 MPa, the tensile strength 274.1MPa, the breaking elongation value 15.8 %.

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We use EMAT to monitor NRUS of bulk shear wave propagating in the thickness direction of the sample. The EMAT operates 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[3)]. By increase the excitation level of the EMAT to 10 phases, the shift in the resonant frequency is measured. The quantity of the slope is defined as the nonlinearity in NRUS.

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

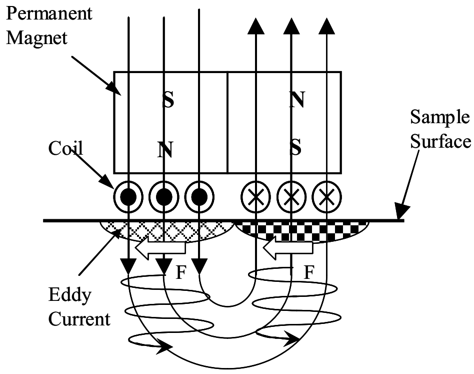

Fig. 1 Operation of the shear-wave EMAT. Lorentz force, F, excite the shear wave propagation in the thickness direction of the sample.

We applied sinusoidal zero-tension–load at a frequency of 10 Hz. Three stress amplitudes, $\Delta\sigma$ = 95,96MPa, were used with the stress ratio ($\sigma_{min}/\sigma_{max}$) of 0.01. The cycle to failure, N_F, was of the order of 10^5. We measured the nonlinearity, 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

We measured NRUS Nonlinearity, the amplitude dependence of resonant frequency of fifth resonant mode during fatigue progression. Little amplitude dependence is shown before fatigue. With progression of fatigue, the dependence became large. Note that, as the excitation level increases, a shift resonant frequency increases as fatigue progress. **Figure 2** shows evolutions of the attenuation shows the peak at 80 % of the life. Nonlinearity rises dramatically 70% of lifetime. The attenuation evolution as fatigue progress was related to the microstructure change, especially, dislocation mobility[4)]

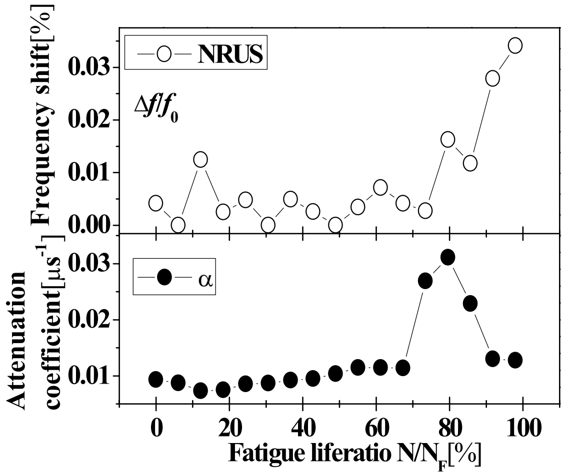

Fig. 2 Evolutions of the resonant frequency of 5th resonant mode NRUS nonlinearity ($\Delta f/f_0$) and ultrasound attenuation coefficient (α) to the failure. ($\Delta\sigma$=95MPa, R=0.01, N_F=163,307cycle).

Figure 3 shows evolutions of three amplitudes, A_1, A_2, A_3, at the 5 th (f_5 around 1.84 MHz,), 7th (f_7 around 2.64 MHz) resonant modes and interaction wave (f_7-f_5) and the ratio, $A_3^2/(A_1A_2)$ during fatigue. Two fundamental amplitudes of A_1 and A_2 decrease gradually to the damage accumulation. A_3 is fluctuates in the life time. $A_3^2/(A_1A_2)$ increases rapidly from 60% of the life. The trend is similar to change in attenuation in Fig.2.

In metals without cracks, the possible factors contributing to the nonlinearity in NRUS arise nonlinear elasticity due to lattice anharmonicity and inelasticity due to dislocation movement. These two effects are inseparable in actual nonlinear measurements[5)]. Both generate the nonlinearity in NRUS. This is supported by TEM observation for dislocation structure. This evolution of acoustic nonlinearity during fatigue was observed in creep progression in a Cr-Mo-V steel[6)].

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 NRUS and nonlinear three-wave interaction 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 and restructuring, with support from the TEM results.
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.

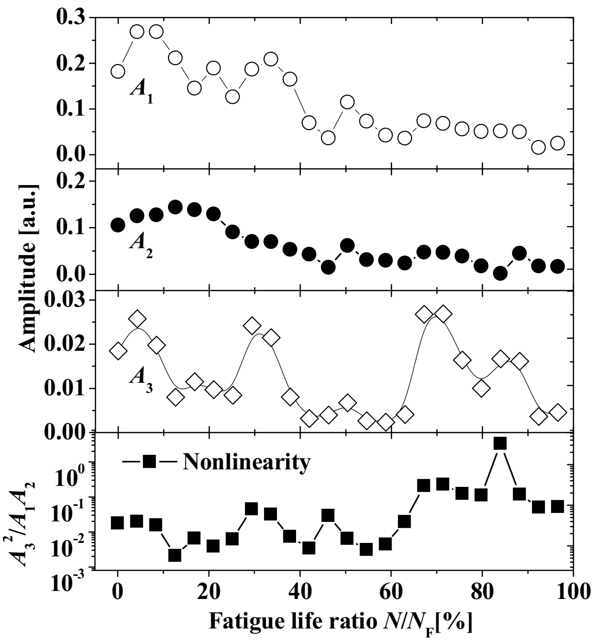

Fig. 3 Typical evolutions of the amplitudes for the A_1 at 5th(f_5), A_2 at 7th(f_7) resonance, A_3 at the interaction wave between f_5 and f_7 and the ratio, A_3^2/A_1A_2 during fatigue. ($\Delta\sigma$=96MPa,R=0.01, N_F=238,115cycle).

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