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Applying Nonlinear Resonant Ultrasound Spectroscopy (NRUS) to Evaluating Fatigue Damage in a Pure Copper

純銅の疲労損傷評価への非線形超音波スペクトロスコピーの適用

Yutaka Ishii[1‡], and Toshihiro Ohtani [1] ([1]Department of Mechanical Engineering, Shonan Institute of Technology)
石井優 [1‡]，　大谷俊博 [1]（[1]湘南工科大　機械工学科）

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 non-contacting NRUS (Non-linear resonant ultrasound spectroscopy)[1)], which is a resonance-based technique exploiting the significant nonlinear behavior of damaged materials. 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 exhibits high sensitivity to microstructural change of the damaged material. It rapidly increases from 65 % of fatigue life to the fracture. This noncontact resonance-EMAT[2)] measurement can monitor the evolution of NRUS throughout the fatigue life and has a potential to assess the damage advance and to predict the fatigue life of metals.

2. Figures and Tables

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 %.

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 5 phases, the shift in the resonant frequency is measured. The quantity of the slope is defined as the nonlinearity in NRUS. These measurements were made possible using the system for nonlinear acoustic phenomena (SNAP) manufactured by RITEC.

We applied sinusoidal zero-tension–load at a frequency of 5 Hz. Three stress amplitudes, $\Delta\sigma$ = 100, 95 and 90MPa, were used with the stress ratio ($\sigma_{min}/\sigma_{max}$) of 0.01. The cycle to failure, N_F, was 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.

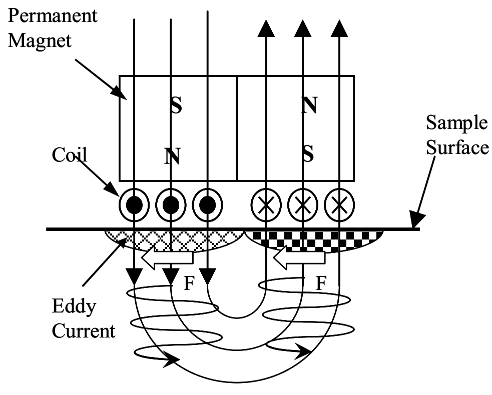

Fig. 1 Operation of the shear-wave EMAT. Lorentz force, F, excite the shear wave propagation in the thickness direction of the sample.

3. Results and Discussion

Figure 2 shows the amplitude dependence of resonant frequency of fifth resonant mode during fatigue progression. Little amplitude dependence is

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[1]ohtani@mech.shonan-it.ac.jp

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.

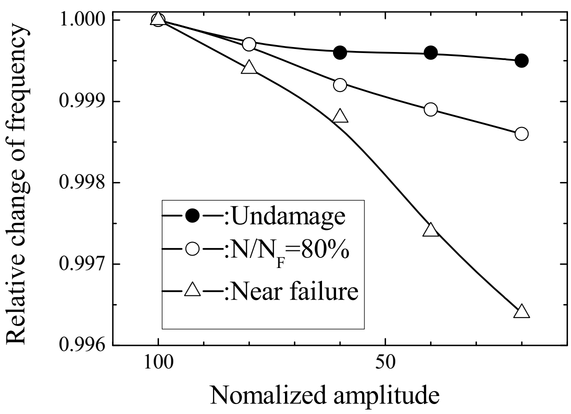

Fig. 2 Amplitude dependence of resonant frequency of fifth resonant mode at three different fatigue damage condition ($\Delta\sigma$=95MPa, N_F=163,307cycle).

Figure 3 shows typical evolutions of the attenuation coefficient α, and the nonlinearity for the fifth bulk-shear wave resonance around 2.3 MHz during fatigue. The nonlinearity exhibits much larger sensitivity to the damage accumulation. It rapidly increases from 65 % of fatigue life to the fracture. The attenuation shows the peak at 80 % of the life. These are no clear independence on the stress amplitude. The attenuation evolution as fatigue progress was related to the microstructure change, especially, dislocation mobility[3].

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[4]. 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[5].

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 (as a shift in the resonance frequency) in 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 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.

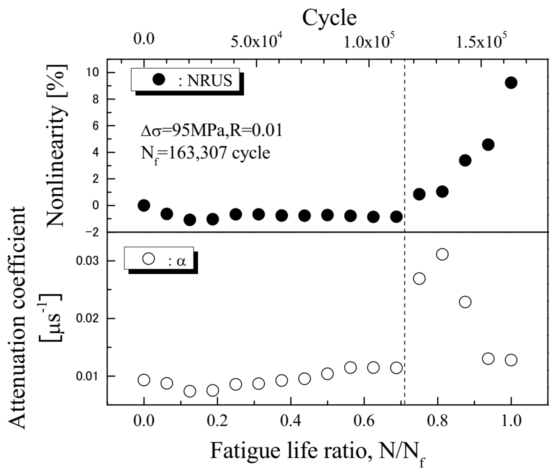

Fig. 3 Typical evolutions of the attenuation coefficient and the nonlinearity for the fifth bulk-shear wave resonance around 2.3 MHz.

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