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Nonlinear ultrasonic induced by fatigue damage in a low carbon steel
炭素鋼の疲労損傷に起因した非線形超音波特性

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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 nonlinear ultrasonics for evaluation of fatigue damage, which is capable of probing the change of dislocation structure[1)]. Its sensitivity to microstructural evolutions during fatigue is often higher than that of linear properties. We elucidated the relationship between microstructural change and the evolutions of two nonlinear acoustic characterizations; resonant frequency shift [2)] and harmonic componets[3)], with electromagnetic acoustic resonance (EMAR)[4)] sduring fatigue in a low carbon steel, JIS-S45C.

2. Experimental method

The material of the specimens was commercially available JIS-S45C, which was heated at 1083 K for 90 min, water-cooling, and then, heated at 823 K for 90 min and air cooling. Fatigue specimens with 20mm in gauge length, 10 mm in diameter were cut from the material. We applied sinusoidal tension-compression–load at a frequency of 5 Hz. The stress amplitudes, $\Delta\sigma$ = 216 MPa, were used with the stress ratio ($\sigma_{min}/\sigma_{max}$) of -1.

We measured evolutions of the acoustic nonlinearities with the nonlinear resonant ultrasound spectroscopy (NRUS) [3)], and higher harmonic components[4)] by interrupting the cyclic loading with an electromagnetic acoustic transducer (EMAT) [5)]. As shown in **Fig. 1**, we used an axial-shear wave EMAT. Operating of EMAT is referred to Ref 4. Axial SH wave is a kind of surface waves, which propagates along the circumference of cylindrical rod or pipe with the axial polarization. Each resonant mode of the axial SH wave is described by the normal function of radius showing the peak amplitude at specific radius. The spatial resolution in the radial direction is determined by to the spacing of the meander line coil. The spacing used in this study is 0.9 mm and the resolution is 0.3 mm from the surface.

NRUS analyzed the dependence of the resonance frequency due to the strain amplitude

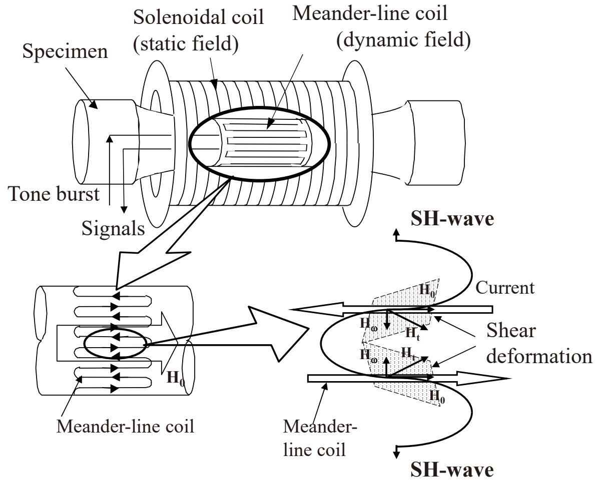

Fig. 1 Axial-shear-wave EMAT consisting of a solenoid coil and a meander-line coil surrounding the cylindrical surface. The magnetostrictive mechanism causes the axial surface SH wave.

while excitation the specimen at comparative low amplitude. The elastic nonlinearity brings about the resonance frequency shift with increasing the excitation force. By observing the relative frequency shift, it is possible to measure of internal degradation of the microstructural properties of the material. We applied the measurement of NRUS to the EMAR. We defined $\Delta f/f_0$ (resonance frequency shift: Δf, amplitude independent resonance frequency: f_0)[3)] to as the nonlinear acoustic parameter.

Measurement method of harmonics at the axial-shear wave has shown below [4)]. After driving the EMAT at the fundamental resonance frequency f_1, we measured the maximum amplitude of the resonance peak, A_1. We then excited the axial shear wave by driving the EMAT at half of the resonance frequency ($f_1/2$), keeping the input power unchanged. In this case, the driving frequency does not satisfy the resonance condition and the fundamental component does not produce a detectable signal. However, the 2nd harmonic component having double frequency (f_1) satisfied the resonance condition and the resonance spectrum of the received signal contained a peak at the original resonance frequency. We defined this peak height as the 2nd

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harmonic amplitude, A_2, to calculate the 2nd harmonic nonlinearity A_2/A_1. We defined the 3rd harmonic nonlinearity, A_3/A_1, in the same way. We used the systems for a nonlinear acoustic phenomenon (SNAP) manufactured by RITEC.

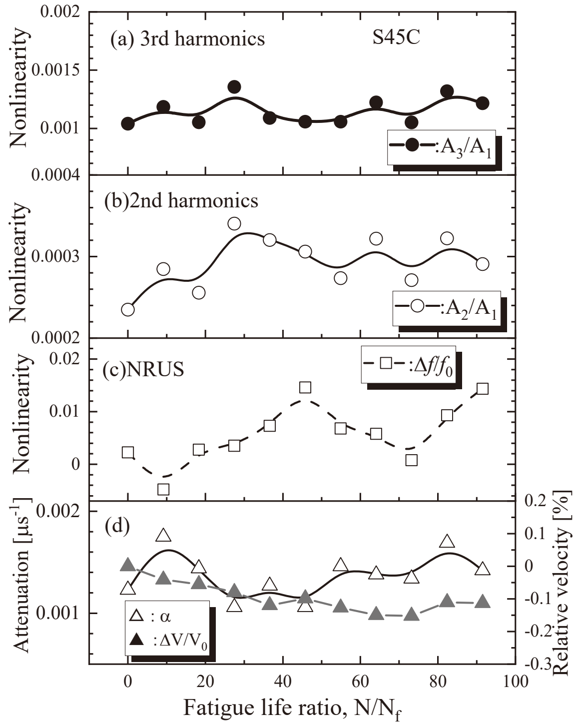

Fig. 2 Evolutions of (a) the nonlinearity in 3rd harmonics, (b) the nonlinearity in 2nd harmonics, (c) the nonlinearity with NRUS, and (d) attenuation coefficient and relative velocity in S45C during fatigue test ($\Delta\sigma$ = 216 MPa, R=-1).

3. Results and discussion

The number of cycle until fracture was 109,261 cycles. Resonant frequency is around 3.9MHz. **Figure 2** shows evolutions of (a) the nonlinearity in 3rd harmonics, (b) the nonlinearity in 2nd harmonics, (c) the nonlinearity with NRUS, and (d) attenuation coefficient and relative velocity in S45C during fatigue test. The harmonic amplitude ratio A_2/A_1 increases from the initial stage to around 30% of the fatigue life, then decreases to 55%. The attenuation coefficient, α also shows a similar tendency. From the results of previous studies[5)], it is known that the change of attenuation coefficient is caused by dislocation motion and lattice defects[3,5)], and its relationship can be explained by Granato-Lücke's string model [6)]. One of the material factors that influence nonlinear ultrasonic waves is nonlinearity caused by defects and cracks existing in solids due to dislocation motion[7)]. The attenuation coefficient is due to the stress and strain hysteresis generated by ultrasonic waves, and is caused by dislocation motion [2)]. The area of the hysteresis loop shows the absorption rate of ultrasonic energy per one cycle, which is observed as ultrasonic attenuation. The changes in A_2/A_1 in this study were found to capture the changes in dislocation structure. In the future, we would like to investigate the change in fatigue process due to the difference in heat treatment using test pieces with different heat treatment.

4. Conclusion

We investigated evolutions of the acoustic nonlinearities with the nonlinear resonant ultrasound spectroscopy (NRUS), and higher harmonic components by interrupting the cyclic loading with an electromagnetic acoustic transducer. The nonlinearity shows rapid increase from approximately 60% of the lifetime. We interpreted these phenomena in terms of dislocation mobility and restructuring. 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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