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Non-contacting in-situ evaluation of torsional fatigue damage of carbon steel using axial-shear-wave resonance

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1. Introduction

Electromagnetic acoustic resonance (EMAR) is useful due to its non-contacting, accurate measurement of velocity and attenuation, and its application to fatigue evaluation has been conducted[1-3]. In this study, we applied EMAR using the axial-shear-wave resonance, which can sense different depth information, to non-contacting in-situ evaluation of torsional fatigue damage of a carbon steel rod. The previous studies have shown that as fatigue damage progresses, the ultrasonic velocity decreases monotonically and the attenuation peaks before failure. However, we here find that the velocity increases initially, which has never been reported. We discuss its mechanism.

2. Principle and experimental setup

Ultrasound has sensitivity to dislocation-structure change due to metal fatigue, and the following equations are known at ~MHz frequencies[4].

$$\alpha \propto \Lambda L^4 \qquad (1)$$

$$\frac{v_0 - v}{v_0} \propto \Lambda L^2 \qquad (2)$$

Here, v is the ultrasonic velocity, v_0 is the ultrasonic velocity independent of dislocations, α is the attenuation coefficient, Λ is the dislocation density, and L is the length of the dislocation loop. Note that these equations can apply only to dislocations responding to low stress by ultrasound.

Figures 1 and 2 show the specimen and the experimental setup, respectively. The specimen was a carbon steel (S45C) rod of 20 mm diameter. The torsional fatigue testing was performed under ±350 N·m torque at 3.5 Hz frequency, and we monitored the change in the ultrasonic velocity and attenuation using axial-shear-wave resonance by a magnetostrictively-coupled electromagnetic acoustic transducer (EMAT)[1-3]. The number of cycles to failure, N_f, was 82,295.

The EMAT consists of a solenoid coil which generates the static magnetic field in the axial direction and a meander-line coil which generates a fluctuating magnetic field in the circumferential direction. In the non-contacting manner using magnetostriction effect, it can excite and detect

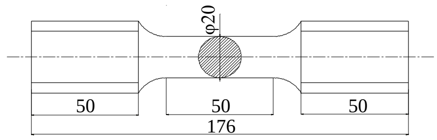

Fig. 1 Specimen. (Unit: mm)

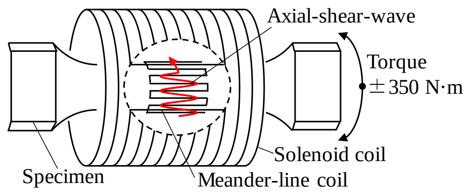

Fig. 2 Experimental setup.

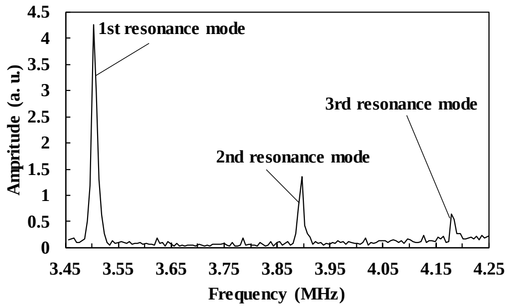

Fig. 3 Example of measured resonance spectrum.

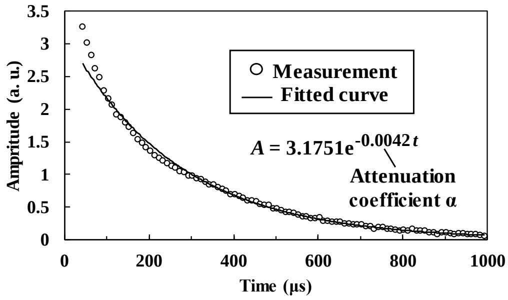

Fig. 4 Example of measured attenuation curve of standing waves by the first mode resonance.

axial-shear waves, which are polarized in the axial direction and propagate in the circumferential direction. The axial-shear waves are excited under each segment of the meander-line coil, and the resonance occurs when the wavelength coincides with the period of the meander-line coil. In this experiment, a meander-line coil with a period of 1 mm, 65 turns, and an axial length of 10 mm was developed. By sweeping the driving frequency of the coil and measuring the amplitude of the received signals, several peaks are observed (**Fig. 3**). The peak frequencies are the resonance frequencies. The ultrasonic velocity can be calculated from the measured resonance frequency and specimen

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diameter. In detail, there are several resonance modes satisfying the resonant condition, $nJ_n(kr) - krJ_{n+1}(kr) = 0$. Here, J_n is the Bessel function of the first kind of order n, and r is the radius of the rod. $n \simeq 2\pi r/d$, where n and d are the number of turns and the period of the meander-line coil, respectively. $k=2\pi f_m^n/C$, where f_m^n is the mth resonance frequency and C is the shear-wave velocity.

In EMAR, the attenuation coefficient is measured by driving the EMAT at the resonance frequency for a certain time and measuring the attenuation curve of standing waves generated by the resonance (**Fig. 4)**. The higher the resonance order, the more the vibration area penetrates into the specimen, providing more interior information. In this experiment, the vibration area of the first resonance mode is from the surface to approximately 1 mm, and that of the second is from the surface to approximately 2 mm.

3. Experimental results

Figures 5 shows the measured change in the attenuation coefficient with the progress of torsional fatigue. It increased gradually in the early stages of fatigue and increased rapidly after N/N_f=60%, which is typical behavior reported in many previous studies[1-3]. The rapid increase in the attenuation was caused by the sudden increase in dislocations with the propagation of microcracks in the surface area (See the equations (1) and (2)). The first resonance mode is more sensitive to the surface and therefore it changed more significantly.

Figures 6 shows the measured change in the velocity with the progress of torsional fatigue. Although the specimen temperature increased during the fatigue test, it remained constant (~70°C) after $N/N_f \simeq$ 5%. The specimen diameter did not change before and after the fatigue test, measured at the same temperature. Therefore, it was normalized by the velocity measured at $N/N_f \simeq$5%.

For the first resonance mode, the velocity increased in the early stages, peaked at $N/N_f \simeq$57%, and then rapidly decreased. For the second resonance mode, it peaked at $N/N_f \simeq$75%. In previous studies conducted on rotary bending fatigue[1,2], tensile/compressive fatigue[3] and so on, it has been reported that the velocity always typically decreases as fatigue damage progresses, and we consider that the initial increase in the velocity is unique to torsional fatigue.

The decrease in the velocity after the peak is due to the dislocation-structure change in the surface area since it was larger for the first resonance mode, and it is consistent with the behavior of the attenuation coefficient. On the other hand, the increase in the velocity in the early stage is difficult to explain only in terms of the dislocation structure, because the increase in dislocations, indicated by the

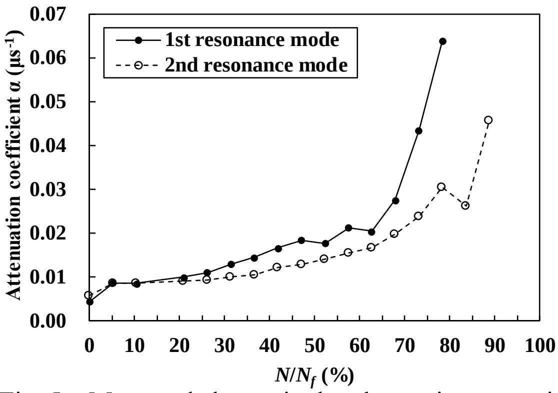

Fig. 5 Measured change in the ultrasonic attenuation coefficient, α, with the progress of torsional fatigue.

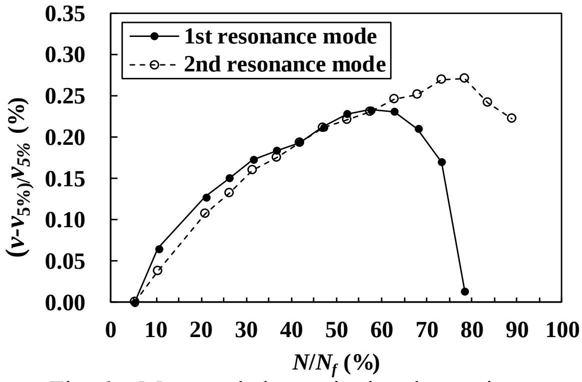

Fig. 6 Measured change in the ultrasonic velocity, v, with the progress of torsional fatigue.

change in attenuation coefficient, should have decreased the velocity. So, it is considered that some other factors may have increased the elastic constants or decreased the material's density, resulting in the increase of the ultrasonic velocity. In addition, the ultrasonic velocity increased similarly for each resonance mode, indicating that the material's changes occurred over a relatively large area near the surface.

4. Conclusions

We conducted the non-contacting in-situ evaluation of torsional fatigue damage of a carbon steel rod using axial-shear-wave resonance. The ultrasonic attenuation increased rapidly before failure, as in previous studies on other types of fatigue. In contrast, we found the ultrasonic velocity increased initially, which has never been reported.

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