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Effect of load frequency on high cycle fatigue strength of bullet train axle steel

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ABSTRACT

A middle carbon steel is used for the axle of Japanese bullet train "Shinkansen". In order to clarify the effect of load frequency on the high cycle fatigue strength for this material, a series of high cycle fatigue tests were performed under the load frequency of 10 Hz, 400 Hz and 19.8 kHz up to 10^9 cycles. As a result, the fatigue limit of tests performed at 10 Hz was almost equal to that of tests performed at 400 Hz, whereas that of tests performed at 19.8 kHz was much higher than that of tests performed at 10 Hz or 400 Hz. The increase of fatigue limit in tests performed at 19.8 kHz may be mainly due to the increase of lower yield strength by the rapid straining in an ultrasonic fatigue test. In addition, it seems that the fatigue limit for the cyclic softening material corresponds to the proportional limit in the cyclic stress–strain curve.

1. Introduction

A cyclic loading is applied to a train axle every rotation of a wheel. Generally, the number of cycles is known to reach 10^9 cycles until retirement of a train axle. Therefore, the effect and mechanism of high cycle fatigue for train axle steel should be clarified in order to insure the safety of a train.

Recently, the ultrasonic fatigue test machines and very high cycle fatigue tests have been using as it can save time due to very high load frequency. However, it is reported in some materials that the fatigue strength obtained from tests performed at ultrasonic fatigue test machine is higher than that obtained from tests performed at conventional fatigue test machine [1].

In this study, a series of high cycle fatigue tests were performed under the load frequencies of 10 Hz, 400 Hz and 19.8 kHz in order to clarify the effect and mechanism of load frequency on the fatigue strength for Japanese bullet train axle steel and then the mechanism of load frequency effect was also discussed.

2. Material and test procedure

2.1. Material

Tested material is the middle carbon steel (JIS S38C) used for the axle of Japanese bullet train "Shinkansen". Chemical composition is shown in Table 1. Heat treatment is quenched and tempered. Microstructure is 50% ferrite and 50% pearlite as shown in Fig. 1. Mechanical properties are shown in Table 2.

2.2. Test procedure

Three kinds of axial fatigue test machines were used with different load frequencies. The first was the servo hydraulic one with the frequency of 10 Hz in Tohoku University. The second was also the servo hydraulic one with the frequency of 400 Hz in Technische Universität Darmstadt, as shown in Fig. 2. The third was the ultrasonic one with the frequency of 19.8 kHz in Tohoku University, as shown in Fig. 3.

Specimen geometries are shown in Fig. 4. Unnotched specimens with 5 mm length of diameter were used for servo hydraulic fatigue tests, whereas hourglass specimens with 3 mm length of diameter were used for ultrasonic fatigue tests.

All tests were performed at room temperature in air. The servo hydraulic fatigue tests were load controlled, while the ultrasonic fatigue test was displacement controlled. Load wave form was sinusoidal and stress ratio was −1.

In an ultrasonic fatigue test, the displacement of specimen end was measured with the eddy current type sensor, and then the stress at the center of specimen was calculated from the above mentioned displacement based on the resonance theory. However, the applied stress amplitude was calculated from the product of Young's modulus and the output obtained from a strain gage glued on the center of specimen, as it was 1.24 times as large as theoretical one. Cold air was blown on the specimen and an intermittent

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Table 1
Chemical composition of tested material (in weight %).

C	Si	Mn	P	S
0.35–0.41	0.15–0.35	0.60–0.90	~0.030	~0.035

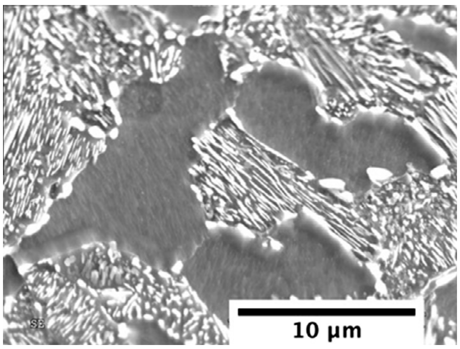

Fig. 1. SEM microstructure of tested material.

Table 2
Mechanical properties of tested material.

Lower yield strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation (%)
374	603	206	31

Fig. 2. Servo hydraulic fatigue test machine (f = 400 Hz).

Fig. 3. Ultrasonic fatigue test machine (f = 19.8 kHz).

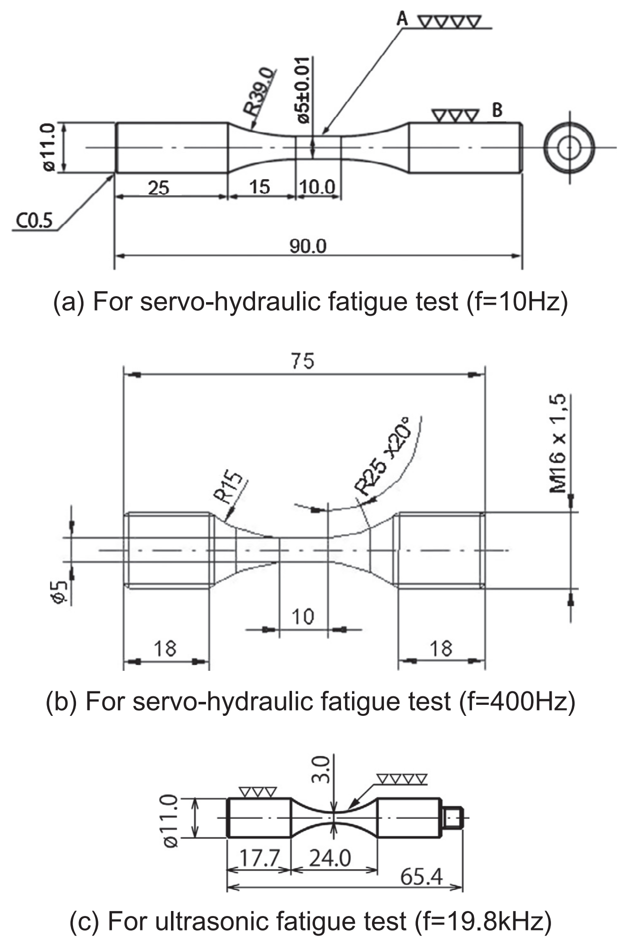

Fig. 4. Specimen configuration.

load was applied to prevent the heating of the specimen due to the plastic deformation and high frequency. As a result, the specimen temperature was controlled under 35 °C. In an intermittent load, loading period was 35–150 ms and pausing one was 3–10 s, as shown in Fig. 5.

3. Test result

3.1. S–N curve

Fig. 6 shows the S–N curves under the load frequency of 10 Hz, 400 Hz and 19.8 kHz.

The fatigue limit investigated at 10 Hz was 250 MPa and it was almost equal to that investigated at 400 Hz, whereas that investigated at 19.8 kHz was higher than that investigated at 10 Hz or 400 Hz by 120 MPa. It may be due to the difference of loaf frequency and specimen geometries etc. among three kinds of different tests. The cause of the increase of fatigue limit in an ultrasonic fatigue test will be discussed in the following chapter.

The number of cycles at the knee point investigated at 10 Hz or 400 Hz was about 7.0×10^5 cycles, whereas the number of cycles at the knee point investigated at 19.8 kHz was about 2.0×10^7