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Ultrasonic Fatigue Test of Mild Steel*

By Ken TERA0**, Takahiko KUNO***,

Toshio ONO***, Masao MIZUNO****

In an ultrasonic fatigue test of mild steel, the authors investigated the effects of strain amplitude, mean stress, and pre-strain on the changes of resonant frequency, and found a close relationship between the reduction of resonant frequency due to ultrasonic fatigue and the change of the microscopic structure.

"The yield point for the stress of vibration" was defined by a strain amplitude which causes a rapid decrease of resonant frequency. Moreover, from an ultrasonic fatigue test with mean stress, a fatigue limit diagram was made for practical use.

1. Introduction

In ultrasonic fatigue tests, longitudinal resonant vibration is used (resonant frequency is about 20 kHz). This type of test is characterized by its easiness. It takes only about 85 minutes for 10^8 times vibrations, in comparison with conventional fatigue tests. For this reason, it has been drawing great attention recently. However, many difficulties are involved in high speed cycles of stress, such as: measuring method of stress of vibration; corrosion caused by coolant used to keep constant temperature; changes of dynamic modules of elasticity; limitation in size and shape of samples due to the resonant system. In recent days, despite such difficulties, various studies have been made, on changes in mechanical properties due to ultrasonic fatigue, (1)(2) mechanism of fatigue, (3) the effect of velocity in cycles of stress on fatigue limits, (5)~(7) the effect of corrosion, (5) internal frictions (3)(8)(9)(10) and so on.

In this paper, frequency changes due to ultrasonic fatigue were investigated in detail, and the effects of strain amplitude, mean stress and pre-strain on the changes of resonant frequency were made clear. Moreover, ultrasonic fatigue test with mean stress was done to make the method practically applicable and a fatigue limit diagram was obtained.

2. Frequency Changes due to Fatigue

2.1 Apparatus

In the present ultrasonic fatigue test, mean stress was given by a dead load as shown in Fig. 1. Resonant frequency was set at approximately 20 kHz. The displacement amplitude, which is considered to be proportional to stress, was detected by the output voltage of a bolted Langevin-type transducer. The ultrasonic generation system consists of an oscillator (for 9 - 55 kHz), a wide range amplifier (for 10 - 100 kHz, 2 KW), a transducer (the ferrite type, for 20 kHz), and horns (for 20 kHz). The dead load is applied at the node of the horn through a triple-point supporter shown in Fig. 2. The automatic control measuring system proposed by Kikukawa et al. (5) was used in order to follow the changes of resonant frequency and displacement amplitude in progress of fatigue. The cooling system of test pieces is shown in Fig. 3, which avoids the temperature increasing by internal frictions of materials. The coolant is water.

Fig. 1 Ultrasonic fatigue testing apparatus

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** Graduate Student, Keio University, Yokohama.

*** Associate Professor, Faculty of Engineering, Keio University, Yokohama.

**** Professor, Faculty of Engineering, Keio University, Yokohama.

Fig. 2 Supporting jig

Fig. 3 Cooling system

Fig. 4 Test pieces

S10C (wt. %)					
C	Si	Mn	P	S	Cu
0.10	0.01	0.38	0.008	0.010	0.03

2.2 Test Pieces

The size and chemical composition of test pieces are shown in Fig. 4. Test pieces were machined from cold drawn rods (S10C) of 6 mm diameter. The specimen used for the fatigue test has a notch as shown in Fig. 4, but the one for the test of frequency changes due to fatigue has no notch. The length of test pieces should be a half of wave length if the strain of vibration is purely elastic. In practice, however, we can not neglect the effect of inelasticity and additional masses, so we examined the effect of the length of test pieces on the displacement amplitude and resonant frequency under the condition of

Fig. 5 Distribution of displacement amplitudes

Fig. 6 Output voltage and resonant frequency with length of test piece

constant input (see Fig. 6). Based on the results, the total length of test pieces including the connecting screw part was determined to be 135 mm.

The variation of displacement amplitude along the axial length presents a cosine curve as shown in Fig. 5, which means the design of the vibration system is possible under the assumption of elastic vibration.

2.3 Heat Treatment of Test Pieces

Test pieces were annealed in vacuum at 900°C for 3.5 hours, given tensile pre-strain and low annealed at 100°C for 1.5 hours for a stabilizing treatment. The tensile pre-strain eliminates the Magneto-Mechanical Damping (M.M.D.) and makes the input-output relation linear. Annealed mild steel usually has internal frictions which become maximum at 10^{-4} strain amplitude. Such internal frictions are considered to be caused not by dislocation but by M.M.D. One of the authors reported that M.M.D. comes from the movement of

magnetic wall in α -Fe and disappears by the tensile strain of 2 - 3%. (8)-(10) Low-annealing is done to prevent the change of internal frictions, as proposed by one of the authors. (8)-(10)

2.4 Results and Discussion

The output voltage of the bolted Langevin-type transducer (B.L.T.) represents the relative displacement amplitude which is determined by use of Fig. 7. Fig. 8 shows the relationship between displacement amplitude and strain amplitude. The stress amplitude can be calculated under the assumption of elastic vibration, but it is not always accurate as pointed out by B. Wielke and others. (11)

2.4.1 Changes in Resonant Frequency

Fig. 9 shows frequency changes with time, where the tensile pre-strain was 3.75% and the output voltage was 6.0 V. It shows that resonant frequency steadily decreases.

2.4.2 Effect of Pre-strain

Frequency decrease is affected by the internal frictions, which depends on the pre-strain. Fig. 10 shows the value of frequency decrease, Δf , with time where output voltage was 6.2 V (strain amplitude was 4.2×10^{-4}). Fig. 11 shows effects of pre-strain on Δf at the time of 5-, 10- and 15-minutes.

The ratio of input voltage to output voltage is considered to be an index of internal frictions in materials. Fig. 12 shows the dependence of this ratio on the pre-strain. The results in Figs. 11 and 12 can be interpreted as follows. A large pre-strain causes the multiplication and entanglement of dislocations, making their movement difficult. This means a small internal friction and a small frequency decrease.

Fig. 7 Output voltage and displacement amplitude

Fig. 8 Relation between stress and strain amplitude and displacement amplitude

Fig. 9 Change of resonant frequency with time

Fig. 10 Change of decrease of resonant frequency with time

2.4.3 Effect of Dead Load

Fig. 13 shows the relationship between Δf at the time of 10 minutes and dead load, where the pre-strains are varied from 2.0% to 9.4%. We can see Δf has a minimum value at a specific dead load.

Fig. 11 Rate of working and decrease of resonant frequency

Fig. 14 Change of decrease of resonant frequency with time

Fig. 12 Rate of working and internal friction

Fig. 15 Change of decrease of resonant frequency with time

Fig. 13 Mean stress and decrease of resonant frequency

Fig. 16 Change of decrease of resonant frequency with time

2.4.4 Effect of Strain Amplitude

Figs. 14~16 show the variation of Δf vs t curve due to output voltage (strain amplitude). These figures are rewritten as Figs. 17 and 18. Fig. 17 shows the existence of threshold to output voltage in annealed specimens, where Δf increase linearly. On the other hand when pre-strain is given, the relation between Δf and output voltage makes a hooked line as Fig. 18 shows.

Figs. 14~16 are rewritten again into Figs. 19~21. These figures show that the volume of output voltage at the refraction point becomes larger with pre-strain and is not affected by the sampling times. In Fig. 22, these values of output voltage at the refraction are converted to the values of stress amplitude using the curve of Fig. 8.

According to Granato-Rücke's theory, internal frictions increase sharply at a

Fig. 17 Decrease of resonant frequency and output voltage

Fig. 19 Decrease of resonant frequency and output voltage

Fig. 18 Decrease of resonant frequency and output voltage

Fig. 20 Decrease of resonant frequency and output voltage

certain strain amplitude. The stress corresponding to that point is named "break-away" stress and is considered to be a microscopic yield point. If the refraction point of Δf is caused by a breaking away of dislocations from constraint, stress at the refraction point corresponds to the break-away stress, namely, the microscopic yield point, which is denoted by σ_d hereafter. Fig. 23 shows the relation between σ_d and flow stress, σ_s , where these stress values are made dimensionless by use of the static yield stress $\sigma_Y = 14.2 \text{ Kg/mm}^2$. We can see σ_d is proportional to σ_s and $\sigma_d/\sigma_s = 1/3$.

The authors believe the microscopic yield point has some important meaning in ultrasonic fatigue tests.

3. Ultrasonic Fatigue Test with Mean Stress

Most of the other ultrasonic fatigue tests have been done under the condition of zero mean stress, i.e. alternating loading. This study aims to find out the effect of mean stress on ultrasonic fatigue.

Fig. 21 Decrease of resonant frequency and output voltage

Fig. 22 Stress at refraction point and rate of working

Fig. 23 Stress at refraction point and flow stress

3.1 Test Pieces

Notched specimens of S10C of Fig. 4 were used. The heat treatments were similar to 2.3. The value of pre-strain was fixed at 3%. Two kinds of treatments to stabilize dislocations were employed; low annealing at 100°C for 1.5 hours and aging at room temperature for 100 hours. To investigate the effect of coolant, three kinds of coolants were employed; air, water and Valatile Corrosion Inhibitor (V.C.I.) proposed by Kikukawa et al.⁽⁵⁾ In the calculation of stress from displacement amplitude, the effect of notch was not taken into consideration.

3.2 Result and Discussion

3.2.1 Frequency Changes of Notched Specimens

Fig. 24 shows frequency decrease Δf of notched specimens, where coolant was water. If we assume that Δf corresponds to elongation and output voltage to temperature, this figure seems to show a trend similar to the creep curve. It has been reported that there is a dynamic creep phenomenon⁽⁴⁾ in the ultrasonic range and that an increase of logarithmic decrement and a decrease of modulus of elasticity due to fatigue also exhibit a very similar trend to the creep curve.⁽¹²⁾ The results of Fig. 24 may confirm these reports. It should be noted that a rapid decrease of frequency occurs just before rupture (mark of X in the figure indicate rupture).

Fig. 24 Change of decrease of resonant frequency with time

Fig. 25 Ultrasonic fatigue test (influence of coolant)

3.2.2 Effect of coolant

Fig. 25 shows the effect of coolant in an ultrasonic fatigue test, where the stabilizing treatment of dislocations was low annealing and the mean stress was 0.08 Kgf/mm² caused by the weight of measuring horn. The air cooling could not eliminate the temperature increase and the water cooling was affected by corrosion. On the other hand, the V.C.I. cooling at 4°C has no effects of temperature increase and corrosion and gives the most excellent result of fatigue limit.

3.2.3 Effect of Stabilizing Treatment

The fatigue tests with two kinds of heat treatments, low annealing at 100°C for 1.5 hours and 100 hours aging, were done. The results are shown in Figs. 26 and 27 respectively, where V.C.I. cooling at 4°C was applied. The fatigue limit is higher for low annealing than for aging. Moreover we see a large scattering of data for aging. Thus low annealing can stabilize dislocations more rapidly and surely than aging. Fig. 28 shows an input-output diagram for specimens without notch under various stabilizing treatments, from which

Fig. 26 Ultrasonic fatigue test (low annealing)

Fig. 27 Ultrasonic fatigue test (100 hours aging)

Fig. 28 Input and output voltage

we see the best linearity for the curve of low annealing.

3.2.4 Fatigue Limit Diagram

Apparatus is shown in Fig. 29 where the constant load is applied by an Amsler universal testing machine to produce large load. Fig. 30 shows S-N curves for various mean stresses. When mean stress exceeded 16 kgf/mm², stress of vibration decreased and it was difficult to maintain a constant amplitude level. Fig. 31 illustrates a fatigue limit diagram. While the ultimate strength of this material is 65.2 kgf/mm² and its yield stress is 14.2 kgf/mm², an extension of the fatigue limit line meets the abscissa at 36.2 kgf/mm². It is considered that the effect of mean stress is greater in ultrasonic fatigue tests than in conventional fatigue tests.

Fig. 29 Ultrasonic fatigue testing apparatus

Fig. 30 Ultrasonic fatigue test

Fig. 31 Fatigue limit diagram

4. Conclusions

- (1) In mild steel, the resonant frequency decreases as the fatigue advances. The rate of frequency decrease is affected by amplitude, pre-strain and mean stress.
- (2) The relationship between frequency decrease and output voltage (strain amplitude) has a refraction point and the output voltage corresponding to this point becomes greater with pre-strain.
- (3) The ultrasonic fatigue test with mean stress enabled us to get an ultrasonic fatigue limit diagram.

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