Fatigue Strength of Mild Steel Specimens under Negative Mean Stresses

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Summary

Plane bending fatigue tests were carried out on plane specimens of mild steel with a hole or a pre-crack, under bending mean stresses, and fatigue limit diagrams were obtained especially for the range of partly repeated compressive stresses.

For pre-cracked specimens, the line of critical stress which propagates the crack, was obtained.

It was also found that, a crack propagates even when the maximum stress is negative, and the relation between the length of crack propagated and the maximum stress was cleared.

1. Introduction

Fatigue limit diagram which shows the effect of the mean stresses on the fatigue limit is already obtained in the case of mean stresses ranging from positive to negative for many materials(1). For the case of partly repeated compressive stresses where the maximum stress becomes negative, experimental results of cast-iron are found(2), but experimental results of the ductile materials such as mild steels are not published, because the fatigue test is impossible on acount of compressive yielding in the case of plane specimens. In the case of repeated plane bending of a notched plate specimen with mean stresses, however, and if stress concentration such as a hole or a pre-crack exist on the side of plate specimen where the maximum compressive stress is applied, the fatigue failure may initiate from the edge of notch because of the stress concentration by the hole or the pre-crack. And, it is necessary to clear the fatigue strength for such case. In the present study, the authors carried out plane bending fatigue tests under mean bending stresses on plane specimens of mild steel with a hole or a pre-crack, and fatigue limit diagram were obtained especially for the range of partly repeated compressive stresses. Fatigue crack propagation behavior was also cleared under the mean stresses.

2. Experimental Procedure

2. 1 Test Specimens

The material used in this experiment is mild steel S10C, the chemical compositions

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Table 1. Chemical compositions and mechanical properties

Chemical compositions %					Mechanical properties				
C	Si	Mn	P	S	Yield strength	Tensile strength	Elongation	Reduction of area	Hardness H_V
0.036	0.033	0.22	0.010	0.006	223 MPa	316 MPa	57.9%	73.2%	123

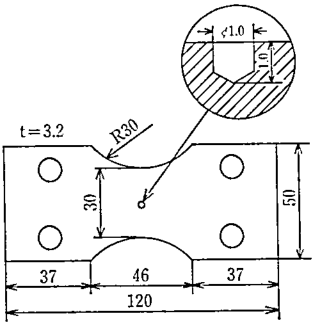

Fig. 1 Shape and dimensions of specimen

and the mechanical properties of which are shown in Table 1. Figure 1 shows the shape and dimensions of the specimen. Notch are drilled to open a hole 1 mm in diameter and 1 mm in depth, as shown in Fig. 1, at the center of the specimen, and finally the surface of the specimen is polished with emery paper of ♯07 in the longitudinal direction. The specimen is not heat treated.

2.2 Testing Apparatus

The testing machine used in this experiment is Simadzu type Bending-Torsion fatigue test machine (33.3 Hz, 98 N•m). The machine is constant load type.

2.3 Observation of Crack

The pre-cracks were initialed by the stress amplitudes above the fatigue limit of the notched specimen with a small hole. The primary stress amplitude (over-stress) is 177 MPa (mean stress $\sigma_m=0$), and the length of pre-crack is about 2 mm, including the diameter (1 mm) of a hole, and was read by a tool maker's microscope. In order to measure the fatigue crack length, a replica of a crack was taken by attaching an acetyl cellulose film 34 μm thick using methyl acetate as solvent.

3. Test Results

3.1 Fatigue Limit Diagrams of Smooth and Notched Specimens

The fatigue limit diagrams of smooth and notched specimens are shown in Fig. 2. In the figure, the stress amplitude σ_a is taken in ordinate and the mean stress σ_m in abscissa, both in natural scale. The mark □ or ■ shows that the smooth specimen is not broken or broken, and the mark △ or ▲ shows that the notched specimen is not broken or broken.

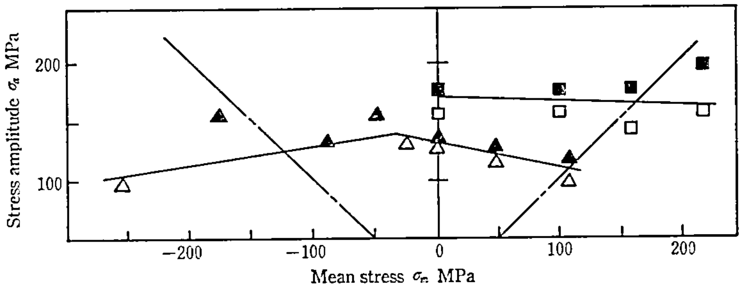

Fig. 2 Fatigue limit diagram of smooth and notched specimens

From Fig. 2, completely reversed fatigue limit of smooth specimens was 168 MPa and completely reversed fatigue limit of notched specimens was 132 MPa. Fatigue notch factor on completely reversed stress amplitude was 1.27. The effect of mean stress was learger for notched specimens than for smooth specimens. It was also cleared that the effect of mean stress was small compared with high hardness material, such as carburizing steel(3). In the notched specimens, the stress amplitude at fatigue limit increases as the mean stress decreases from 108 MPa to −30 MPa, but, the stress amplitude decreases as the mean stress decreases less than −30 MPa. It was found that even when the maximum stress is negative, the fatigue crack grew and the test specimen fractured.

3.2 Fatigue Limit Diagram of Pre-Cracked Specimens

Fig. 3. shows the fatigue limit diagram of pre-cracked specimens.

In the figure the stress amplitude σ_a is taken in ordinate and the mean stress σ_m in abscissa, both in natural scale. In the figure, the mark × shows the fracture, the mark ● shows the growth of non-propagating crack, and the mark ○ shows that crack did not initiate. The thick line is the limitting line of the fracture and

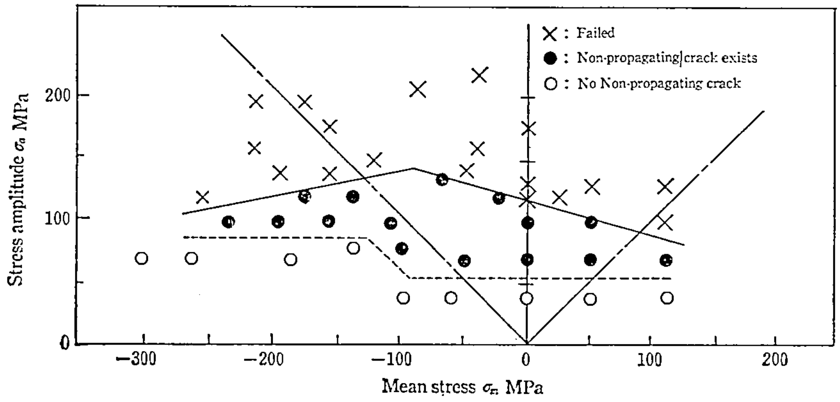

Fig. 3 Fatigue limit diagram of pre-cracked specimens

the growth of non-propagating crack. The completely reversed fatigue limit of pre-cracked specimens is 116 MPa.

From the figure, it is found that the stress amplitude decreases as the mean stress increases above −95 MPa, and decreases as the mean stress decreases below −95 MPa. Even when the mean stress decreases, and the maximum stress becomes negative it was found that the fatigue crack propagates and the test specimen fracture. The crack propagation rate in the case of negative maximum stress was much more slow than that in the case of positive maximum stress and some test pieces failured after 10^8 stress cycles in the former case. Non-propagating crack grew by the stress amplitude below the fracture fatigue limit (understress).

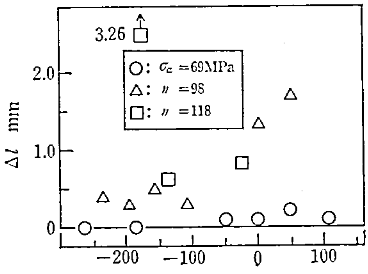

Fig. 4 Effect of mean stress on the non-propagating crack length

Fig. 4. shows the relation between the length of crack propagated at understresses Δl and the mean stress σ_m for various stress amplitude σ_a. In the figure, the mark ○ shows the case in which stress amplitude $\sigma_a = 69$ MPa, the mark △ $\sigma_a = 98$ MPa, the mark □ $\sigma_a = 118$ MPa. When the stress amplitude $\sigma_a = 69$ MPa, the effect of the mean stress on crack length Δl is littlle. When the stress amplitude $\sigma_a = 98$ MPa, the negative mean stress does not affect the length of crack, but the positive mean stress increase the non-propagating crack length Δl. When the stress amplitude $\sigma_a = 118$ MPa the effect of the mean stress upon crack length is the same with that of the stress amplitude $\sigma_a = 98$ MPa, exsept the experimental point when $\sigma_m = -177$ MPa.

If the stress amplitude is decreased moreover, the non-propagating crack is not observed (conf. Fig. 3). The authors named this limitting stress as crack non-propagating fatigue limit $(\sigma_{w1})_l$. Then, the effect of the mean stress on $(\sigma_{w1})_l$ is not observed at the mean stress between 108 MPa and −95 MPa, and the value $(\sigma_{w1})_l$ is 54 MPa constant (Fig. 3). But, $(\sigma_{w1})_l$ is increased to 85 MPa and kept this value when the mean stress is decreased below −95 MPa.

The experimental result that the crack non-propagating fatigue limit is independent of the mean stress, was obtained by Kakuno and Kawada(4) in the case of torsion.

When the mean stress becomes less than −310 MPa, pre-cracked specimens are deformed largely and the experiment becomes impossible.

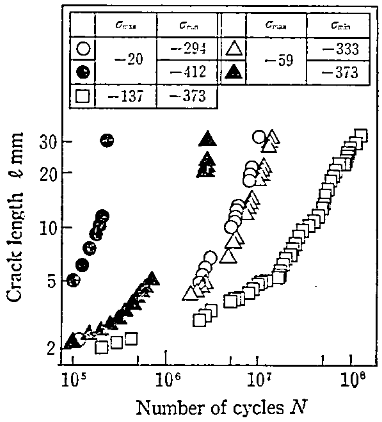

Fig. 5 Crack propagation in the case of negative maximum stress

3.3 Fatigue Crack Propagation Behavior for Negative Maximum Stress

Fatigue crack propagation behavior when maximum stress is negative is shown in Fig. 5. In the figure, the crack length l is taken in ordinate and the number of cycles N in abscissa, both in logarithmic scale.

Fig. 5 shows that the fatigue life becomes shorter when the maximum stress $\sigma_{max} = -20$ MPa and -59 MPa, for small minimum stress (mark ● and ▲), compared

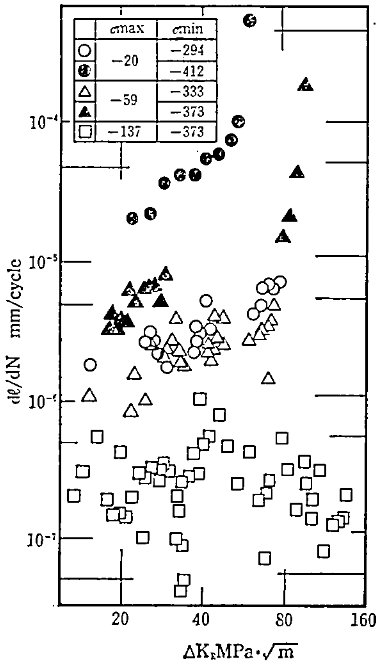

Fig. 6 Relation between ΔK_E and dl/dN in the case of negative maximum stress

with the life for large minimum stress (mark ○ and △). When the maximum stress is decreased to $\sigma_{max}=-137$ MPa (mark □), the number of cycles to failure is increased to 10^8.

The above mentioned fatigue crack propagation behavior was expressed in the relation between the rate of crack propagation dl/dN and the stress intensity factor ΔK_R, both in logarithmic representation as shown in Fig. 6, where, $\Delta K_R=2\sigma_a\sqrt{\pi l/2}\times\sqrt{\sec(\pi l/2W)}$. In Fig. 6, when stress amplitude is large (mark ● and ▲), the rate of crack propagation dl/dN increase with the increase of the stress intensity factor ΔK_R, but, when stress amplitude is small (mark ○ and △), the rate of crack propagation dl/dN do not increase with the increase of the stress intensity factor ΔK_R. When the maximum stress $\sigma_{max}=-137$ MPa (mark □), the rate of crack propagation dl/dN does not vary with the increase of the stress intensity factor ΔK_R, and dl/dN was about 2×10^{-7} mm/cycle.

From the above-mentioned results, it was found that a crack propagates and specimen fractures even when the maximum stress is negative.

4. Consideration

Using electron microscopy, Forsyth(5) showed that both silp band intrusions and extrusions occur on the suface of materials when they are subjected to cyclic loading. A slip band occurred on the suface of materials is primarily controlled by shear stresses rather than normal stresses. Fatigue cracks initiate in local slip bands and initially tend to grow in a plane of maximum shear stress. This growth is quite small, usually of the order of several grains (slip band crack).

This stage of fatigue crack growth is called Stage I. As cycling continues, the fatigue crack tend to coalesce and grow along plane of maximum tensile stress.

In the present study, fatigue crack grew as shown in Fig. 5 and 6 even when the maximum stress is negative.

When negative maximum stress is applied, many cracks which grew by shear stress near the crack tip is considered to be coalesced by the repetition of shear stress and grow along plane of maximum compressive stress. In this case, the rate of crack propagation is very slow and fatigue life is very long.

5. Conclusions

Bending fatigue tests were carried out on plate specimens with a circular hole or pre-cracks made of mild steel, under bending mean stresses, and fatigue limit diagram covering the mean stress from positive to negative was obtained. It was found that the fatigue crack grow and test specimen fracture, even when the maximum stress is negative. Fatigue crack propagation behavior under negative maximum stress was cleared.

Acknowledgements

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References

(1) Nishihara, T. and Endo, K., Trans. Japan Soc. Mech. Engrs., 17, 146 (1951)
(2) A. Pomp, Kaiser-Wilhelm-Inst. f. Eisenforsch., Düsseldorf, Mitt. 169 (1940)
(3) Hayama, T. and Yoshitake, H., Trans. Japan Soc. Mech. Engrs. 37, 650 (1971)
(4) Kakuno, H. and Kawada, Y., Fatigue of Engineering Materials and Structures, 2, 229, (1979)
(5) P. J. E. Forsyth, Acta, Metallurigica, 11, 730 (1963)