SMALL CRACK GROWTH BEHAVIOUR IN OIL ENVIRONMENTS

M. GOTO[1], N. KAWAGOISHI[2], H. MIYAGAWA[1] and H. NISITANI[3]
[1]:Department of Mechanical Engineering, Oita University, Oita 870-11, Japan [2]:Department of Mechanical Engineering, Kagoshima University, Kagoshima 890, Japan [3]:Faculty of Engineering, Kyushu-Sangyo University, Fukuoka 812, Japan

ABSTRACT

In the paper, the effect of oil environment on a small crack growth behaviour was investigated. Namely, rotating bending fatigue tests of annealed 0.34 % carbon steel plain specimens with a small blind hole were carried out in the paraffinic base oils having four viscosities, η. The cycle frequencies, f, used were 12.5, 25 and 50 Hz. The results showed that the effect of oil viscosity on the growth rate of a small crack depends on the cycle frequency. The relation between the crack propagation life and a term, ηf, is approximately by a smooth curve. The maximum propagation life was attained at around $\eta f = 2 \times 10^{-3}$ m^2/s^2. The existence of ηf which produce the maximum growth life seems to generate the dissimilar effect of η on dl/dN under the different values of f. The dl/dN of a small crack is determined uniquely by the term $\sigma_a^n l$ (σ_a:stress amplitude, l:crack length) .

KEYWORDS

Oil environment, small crack growth law, viscosity, cycle frequency, carbon steel

INTRODUCTION

Since oils with the most suitable characteristics for the performance of machines are used according to service conditions and service environments, the evaluation of the fatigue life in oils with different characteristics is an important task in order to design machines for use in such environments. Many studies concerning the fatigue damage of smooth specimens in oil environments have been reported. On the other hands, the fatigue life of a plain specimen is controlled mainly by the propagation life of a small crack. This indicates that the effect of oils on the small crack growth behaviour must be clarified to evaluate the fatigue life in oil environments. However, the studies which investigate the effect of oils on small crack growth are not abundant.

The present authors have carried out fatigue tests on plain specimens in oil environments and reported the effect of oils on the fatigue strength (Nisitani et al.,1986; Goto et al.,1988). From the results of the previous reports, oil has a limited influence on the fatigue limit of plain specimens and the microcrack initiation life, but has an observable influence on the small crack propagation life.

In the present study, by using a series of base oils of different viscosity grades, the effects of oil on the small crack growth law were investigated in rotating bending fatigue tests of an annealed 0.34 % carbon steel using plain specimens with a small blind hole. The cycle frequencies used were 12.5, 25 and 50 Hz. The relationship between the oil environments and small crack growth behaviour was studied.

EXPERIMENTAL PROCEDURES

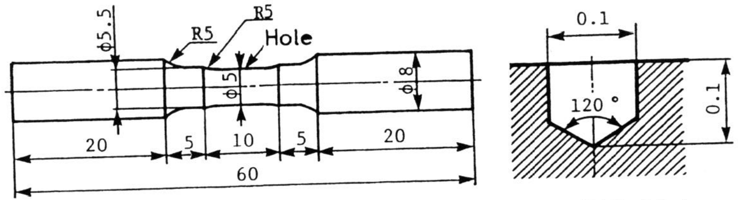
The material was a 0.34 % carbon steel in the form of rolled bar about 26 mm in diameter. The chemical composition (wt %) was 0.34 C, 0.34 Si, 0.74 Mn, 0.012 P, 0.016 S, 0.01 Cu, 0.02 Ni, 0.10 Cr, remainder ferrite. The specimens were machined from the bar after annealing for 60 min at 870 ℃. The mechanical properties were 306 MPa lower yield point, 546 MPa ultimate tensile strength, 952 MPa true breaking stress and 56.4% reduction of area.

Figure 1 shows the shape of the specimen. Specimens used in the tests were plain specimens with 5 mm in diameter. A small blind hole (diameter:0.1 mm, depth:0.1 mm) was drilled at the surface of each specimen. Before testing, all the specimens were re-annealed in vacuum at 600 ℃ for 60 min to remove residual stresses, and were then electropolished to remove about 25 μm from the surface layer in order to facilitate observations of the surface state.

All the tests were carried out using a rotating bending fatigue machine. The cycle frequencies, f, used were 12.5, 25 and 50 Hz. In the experiment, four paraffinic base oils (P35, P60, P150 and P500) of different viscosity grades, η, with a molecular weight distribution over a narrow range, were used at 30 ℃ (±1 ℃). The characteristics of the oils are shown in Table 1. The oils were dropped continuously at a rate of 450 cc/min onto the midsection of the specimens during the tests.

Table 1 Characteristics of oils

Oil	Specific gravity,15/4℃	Kinematic viscosity x10⁻⁶ m²/s	
		40℃	100℃
P 35	0.844	2.4	1.0
P 60	0.863	7.8	2.2
P150	0.866	31.4	5.2
P500	0.877	106	11.4



Fug.1 Shape of the specimen and details of the small blind hole

The observations of fatigue damage on the specimen surface and the measurement of crack length were made via plastic replicas using an optical microscope at a magnification of ×400. The crack length, l, is the length along the circumferential direction on the specimen surface. The stress value referred to is that of the nominal stress amplitude, σ_a, at the minimum cross section.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 shows the S-N curves of drilled specimen in oils at the cycle frequency f=25 Hz. The S-N curves in air is shown by a dotted line. The oils do not affect the fatigue limit, σ_w, but an increase in the fatigue life at the stress beyond σ_w in the oil environments is observed. This increase tends to be larger in the high viscosity oils.

Figure 3 shows crack growth curves of nonpropagating cracks. In each environment, the crack is initiated from the hole, propagates for some period, and then its growth rate gradually decreases with repetitions of stress until propagation stops. In oil environments the propagation tends to stop suddenly compared to that in air. However, the stopping times of the propagation are hardly affected by the difference in the environments. The phenomenon that there is no effect of oils on fatigue limit can be explained by the following facts:

(1) The oil environments has little influence on the behaviour of crack initiation (Goto et al., 1988);

(2) The contribution of the hydrodynamic wedging action (Endo et al., 1986) to a non-

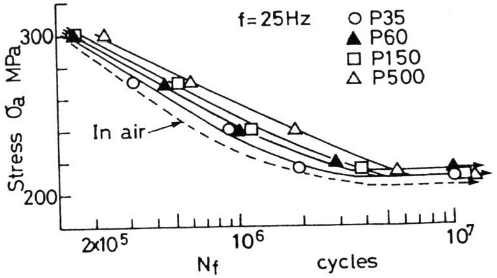


Fig. 2 S-N curves of the drilled specimens in air and in oils

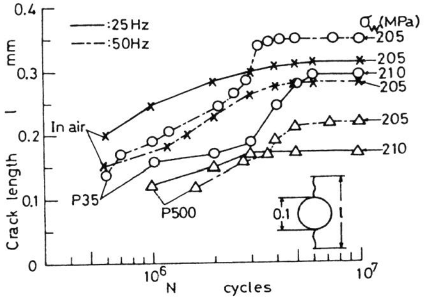


Fig.3 Crack growth curve of nonpropagating cracks

propagating crack seems to be small, because the penetration of oil inside the crack tip is more difficult to attain in a nonpropagating crack compared to a propagating crack.
(3) The oil-induced isolation from the atmosphere produces two opposite actions concerning the crack propagation; corrosion is prevented (this action makes the crack growth rate decrease), and the oxide debris, which forms as a result of fretting oxidation between the crack flanks, is suppressed (this action makes the crack growth rate increase). Tzou et al. (1985a) performed fatigue tests of the compact tension type using 2.25 Cr-1 Mo steel, and showed that the level of crack surface oxidation products at near-threshold stress intensity in air was larger than in oil environments.

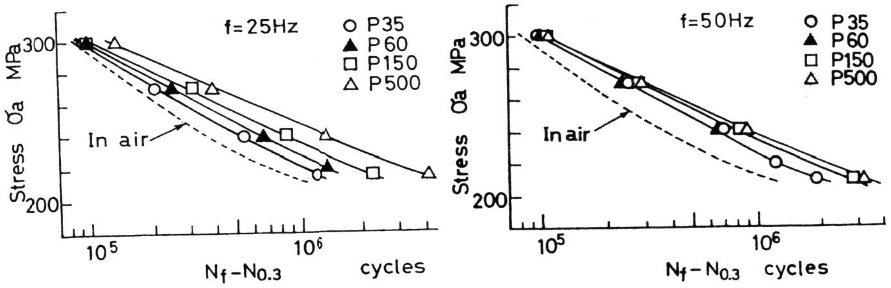
The authors have previously performed fatigue tests on various kinds of metals in air and showed that the growth rate of small crack was determined uniquely by Eq.(1) (Nisitani et al, 1986).

$$dl/dN = C\,\sigma_a^{\,n} l \qquad (1)$$

Moreover, a simpler method based on the small crack growth law and tensile strength used to predict the fatigue life was proposed (Nisitani et al, 1992; Goto et al.,1994). The validity of the method was confirmed by applying it to data published by other researchers. Recently, it was shown that for a specific oil the dl/dN of a small crack was determined by $\sigma_a^{\,n} l$ (Goto et al., 1988). However, the effect of oil properties and cycle frequency on the small crack growth law must be known in order to estimate the fatigue life in the oil environments because the machines usually operate under varying service conditions.

Considering the above-mentioned factors, the effect of the oil environment on the small crack growth behaviour is investigated, paying attention to the effect of oil viscosity and cycle frequency on the small crack growth behaviour. The measurements of dl/dN were made for a crack larger than 0.3 mm, because the propagation behaviour of a crack near the hole was affected by the existence of the hole (the 0.3 mm length was required for the crack front to cover the hole).

Figure 4 shows the $N_f - N_{0.3}$ versus σ_a relation for f=25 and 50 Hz. A term $N_f - N_{0.3}$ is the propagation period for crack between 0.3 mm in length to fracture. For both cycle frequency f, the propagation life in oils are larger than in air, and it tends to increase with an increase in oil viscosity η. Moreover, it is found that the effect of difference in viscosity on growth life is larger at f=25 Hz than f=50 Hz.



(a) case of f=25 Hz (b) case of f=50 Hz
Fig.4 Relation between the σ_a and $N_f - N_{0.3}$

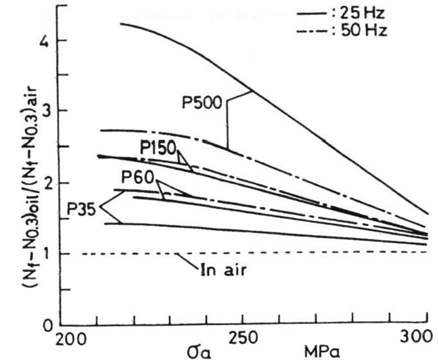


Fig.5 Relation between σ_a and $(N_f - N_{0.3})_{oil}/(N_f - N_{0.3})_{air}$

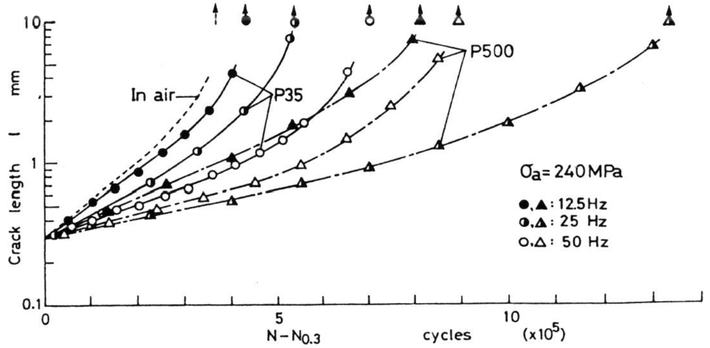


Fig.6 Crack growth curve in air, P35 and P500 (σ_a=240 MPa)

Figure 5 shows the relation between σ_a and $(N_f - N_{0.3})_{oil}/(N_f - N_{0.3})_{air}$ (the ratio of $N_f - N_{0.3}$ in air to that in oil). The action of oils on the crack propagation life is larger in high viscosity oils, and it increases with the decrease in the stress amplitude except when in the vicinity of the fatigue limit. On the other hand, the propagation life at f=50 Hz is larger than that at f=25 Hz, when the viscosity of oils is smaller than P150. For the P500, however, the growth life at f=50 Hz is smaller than that at f=25 Hz.

Figure 6 shows the crack propagation curves under a constant stress (σ_a=240 MPa) in each condition. Here, the comparison in growth curve between P35 and P500 is made, because the results for P60 and P150 exhibited the similar trend as P35. The crack growth rate in P35 increases with a decrease in f, however, P500 exhibits the different results; namely dl/dN is smallest at f=25 Hz and it is largest at f=12.5 Hz.

The decrease in growth rate in oil environments results from the wedging action caused by the oil penetrated into crack. When the oil fully penetrated into crack tip, the wedging action may increases with an increase in viscosity and cycle frequency. On the other hands, the penetration of oil inside the crack may be difficult for higher viscosity and higher cycle frequency. This indicates that the wedging action does not act fully in such a case and there is an optimum condition for producing the largest wedging action. Concerning the hydrodynamic wedging action caused by the penetration of oil inside the crack, an analysis has been performed by Tzou et al., 1985b; which indicated that the true stress at the crack tip under the crack closing process decreases with increases in viscosity.

Figure 7 shows the crack growth life, N_f -$N_{0.3}$ versus a term, ηf, relation. The symbol: ● shows the result for the base oil with tremendously large viscosity (η =460×10^{-6} m^2/s). The relation can be approximated by a smooth curved line independent of viscosity and cycle frequency. Moreover, there is a peak of growth life at around ηf=2×10^{-3} m^2/s^2. Similar results were also obtained from the experiments carried out at other stress amplitudes. The term ηf is proportional to the shearing force due to the viscosity, and accordingly it may be a parameter which approximately controls the wedging action in crack propagation.

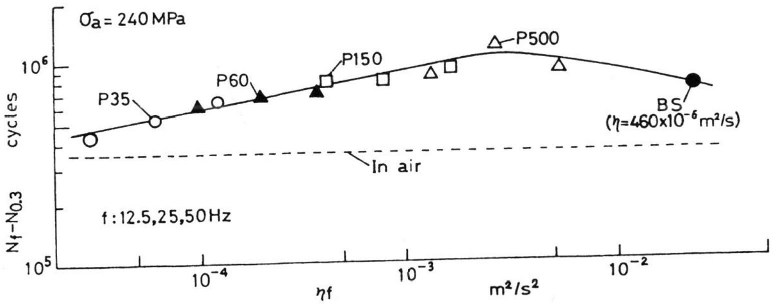


Fig.7 Relation between the crack growth life, N_f -$N_{0.3}$, and ηf

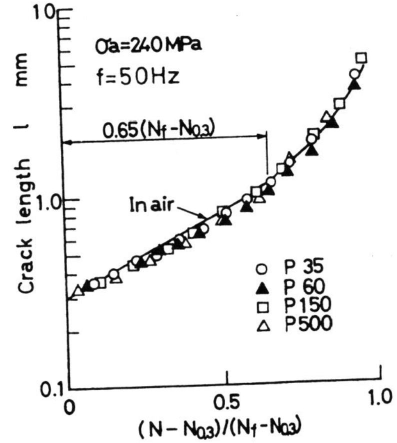


Fig.8 The ln l vs. $(N$-$N_{0.3})/(N_f$ -$N_{0.3})$ relation

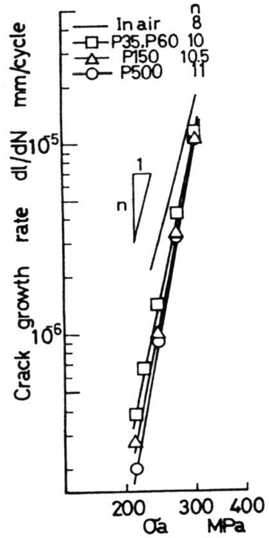


Fig.9 The dl/dN vs. σ_a relation

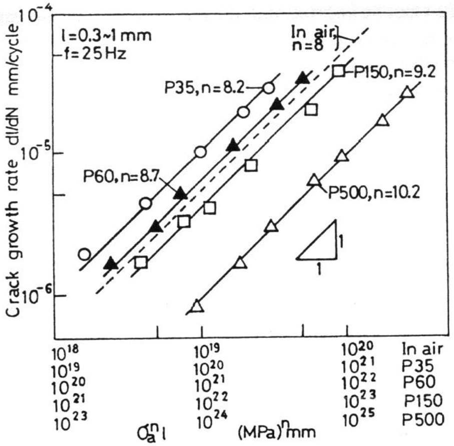


Fig. 10 The dl/dN vs. $\sigma_a{}^n l$ relation

Table 2 Values of n in Eq.(1)

Environment	Value of n	
	f=25Hz	f=50Hz
In air	8.0	
P 35	8.2	10
P 60	8.7	10
P150	9.2	10.5
P500	10.2	11

Figure 8 shows the relation between the logarithmic crack length, $\ln l$, and the relative number of cycles, $(N$-$N_{0.3})/(N_f$ -$N_{0.3})$, at f=50 Hz. The relation is approximated by a curved line and is independent of the environments (it was confirmed that this relation holds at other stress amplitudes and cycle frequencies). Moreover, we can recognize that about 65 % of N_f -$N_{0.3}$ is occupied by the propagation of cracks smaller than 1 mm, and a straight line can be approximated for those small cracks. The straightness property in the ln l versus N relation means that the crack growth rate is proportional to the crack length : $dl/dN \propto l$.

Figure 9 shows the dependency of dl/dN on the stress amplitude under the constant crack length (l=0.5 mm). For each environment, the dependency is expressed by the relation $dl/dN \propto \sigma_a{}^n$.The n takes different value in accordance with the viscosity and cycle frequency. Table 2 shows the value of n for each condition.

Putting the results of Figs.8 and 9 together, we obtain the small crack growth law; Eq(1). Figure 10 shows the relation between dl/dN and the term $\sigma_a{}^n l$. For each condition, the growth rate of a small crack is determined uniquely by Eq.(1).

CONCLUSIONS

The following results were reached with regard to the effect of oil environments on the fatigue limit and the small crack growth behaviour in rotating bending fatigue tests of an annealed 0.34 % carbon steel plain specimens with a small blind hole.

(1) The fatigue limit of drilled specimens is not affected by the oil viscosity, η, and cycle frequency, f.

(2) The crack growth rate under constant f increases with an increase in oil viscosity. On the other hand, the growth rate in P35, P60 and P150 increases with an decrease in f. However, the opposite relation between dl/dN and f was obtained in P500.

(3) The crack growth life versus ηf relation can be approximated by a smooth line independent of oil viscosity and cycle frequency. There is a peak in the relation at around $\eta f = 2 \times 10^{-3}$ m^2/s^2.
(4) The growth rate of a small crack is determined by a term $\sigma_a^n l$, note that the n takes different values in accordance with viscosity of oils and cycle frequency ($n \fallingdotseq 8$ - 11).

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