STRAIN RATE DEPENDENCE ON SURFACE CRACK PROPAGATION IN ELASTO/VISCO-PLASTIC MATERIAL

Hidetoshi SAKAMOTO* and Hiroyuki SAIKI*

Effect of stress frequency on fatigue surface crack propagation in commercial pure titanium, which has remarkable strain rate dependence in plastic region, was studied by experiment and FE analysis. Surface crack propagation tests were carried out under two different loading frequencies. In this analysis, 3D-elasto/visco-plastic FEM-code was used. A comparison between surface crack propagation rate and behaviors of crack front by analysis was made.

INTRODUCTION

Many materials in machines and structures have strain rate dependence at room temperature. In such material, fatigue strength, that is, fatigue crack initiation and propagation rate more or less depend upon stress frequency. However, in many cases, the effect of stress frequency was almost all ignored and fatigue strength was evaluated by the results of fatigue test under a constant loading frequency. This conventional evaluation is likely to over/under estimate fatigue strength(1)-(5).

So, in strain rate dependence materials, present study made clear the effect of stress frequency on surface crack propagation by following experiments and analysis. (1) Evaluation of strain rate dependence of material. (2) Making clear the effect of loading frequency on surface crack propagation by fatigue tests and observation of fracture surface by SEM. (3) 3D-elasto/visco-plastic FEM simulation of surface crack propagation. (4) Comparison of the experimental results with the calcu-

*Department of Mechanical Engineering, Faculty of Engineering, Kumamoto University

lated ones(by FEM),and propose an evaluation's parameter of effect of stress frequency on surface crack propagation.

SURFACE CRACK PROPAGATION TESTS

Specimen and Experimental Method

The material used in this study was commercial pure titanium bar,which has remarkable strain rate dependence. The geometry and dimensions of surface crack propagation test is shown in Fig.1. A circular hole of 0.5mm in diameter and 0.5mm depth was made at the center of specimen surface to serve as a crack starter. All specimens were annealed under argon atmosphere at 540°C for 1.5 hours after machining. The surfaces of the specimens were polished with No.1500 emery paper and alumina polishing suspension for microscopic observation.

Before fatigue tests, the strain rate dependence of material was made clear by monotonic and cyclic tensile tests under different constant tensile speeds by using Instron-type testing machine.

Fatigue tests were performed in hydraulic servo-type fatigue testing machine. In order to observe the effect of loading frequency on surface fatigue crack propagation, pulsating loads in tension ($\Delta\sigma$ = 157, 176 MPa) with two different constant frequencies (f=0.02, 20 Hz), were applied. The growth of the fatigue crack was observed with a travelling microscope (x50). In the case of 20 Hz, crack length was measured by synchronizing a stroboscope. After this tests, fracture surface was observed by Scanning electron microscope (SEM) and striation spacing was measured.

Experimental Results

The stress-strain relations obtained by cyclic tensile tests are shown in Fig.2. It is found that the stress level increased with higher strain rate in the plastic region. Monotonic ones also show similar tendency. Both of ratio of strain rate dependence were approximately same. Figure 3 shows an example of beach mark on fracture surface. The crack front propagated toward concentric ellipse. From this figure, aspect ratio, b/a= 0.9 was obtained, where a is half surface crack length and b is crack depth.

Relations between surface crack propagation rate dl/dN and stress intensity factor ΔK is shown in Fig.4. From this figure, it is observed that crack propagation rate depend upon stress frequency. For a low frequency f, a high crack propagation rate dl/dN was obtained for same ΔK value. On the fracture surface, striations were observed by SEM and relation between striation spacing s and ΔK also shows same tendency of dl/dN–ΔK relations.

ANALYSIS OF SURFACE CRACK PROPAGATION

For the purpose to introduce strain rate dependence and the Baushinger effect in plastic region, 3D- Elasto/visco-plastic overlay-model was employed, which applied the Perzyna equation(6) and overlay model proposed by Zienkiewic. et al.(7). The constitutive relation is as follows:

$$\begin{aligned} \{\varepsilon\} &= \{\varepsilon^{e}\} + \{\varepsilon^{vp}\} \\ \{\varepsilon^{e}\} &= [D^{e}]^{-1}\{\sigma\} \\ \{\dot{\varepsilon}^{vp}\} &= \gamma \langle \Phi(F) \rangle \frac{\sqrt{3}}{2} \frac{1}{\sqrt{J'_2}} \frac{\partial J'_2}{\partial \sigma} \end{aligned} \qquad (1)$$

The dot denotes partial differentiation with respect to time, γ, E, ν are coefficient of viscosity, Young's modulus and Poisson's ratio, respectively The symbol $<\Phi(F)>$ is defined as follows:

$$\begin{aligned} \langle \Phi(F) \rangle &= 0 \qquad (F \leq 0) \\ \langle \Phi(F) \rangle &= \Phi(F) \qquad (F > 0) \\ F &= (\overline{\sigma} - \sigma^{*}) / \sigma^{*} \end{aligned} \qquad (2)$$

and $F=0$ denotes the von Mises yield surface, σ is the equivalent stress and σ^* is quasi-static stress which was obtained from the cyclic stress-strain relation in the case of smallest strain ($\dot{\varepsilon}=2.47\text{x}10^{-5}$ 1/s).

Utilizing symmetry, 1/4 region was analyzed; 8-node complex element was used and the least side length around crack propagation front is 0.2mm.

ANALYTICAL RESULTS AND DISCUSSION

Figures 5 and 6 show σ and $\overline{\varepsilon}^{vp}$ distributions of crack front element at cycle 7, respectively. The σ in the case of 20Hz becomes larger than that in the case of 0.02Hz and inversely $\overline{\varepsilon}^{vp}$ for 0.02Hz is larger than that for f=20Hz. These phenomena are due to material viscosity in plastic region.

Figure 7 shows relation between the stress intensity factor range ΔK and equivalent visco-plastic range $\Delta\overline{\varepsilon}^{vp}$ of crack front obtained by the elasto /visco-plastic analysis. The $\Delta\overline{\varepsilon}^{vp}$–$\Delta K$ relations are straight lines which correspond well with the tendency of dl/dN–ΔK relations shown in Fig.4. The facts mentioned above suggest that there is a probability of expressing methodically the fatigue surface crack propagation rate in terms of $\Delta\bar{\varepsilon}^{vp}$.

Figure 8 shows the relation between *dl/dN* and $\Delta\bar{\varepsilon}^{vp}$. If *dl/dN* is plotted against $\Delta\bar{\varepsilon}^{vp}$, the relation follows a straight line in logarithmic coordinates and the data fall in narrow range regardless of loading frequency and stress amplitude. From this figure, we conclude that the experimental surface crack propagation rate is closely related to visco-plastic strain range at the crack front, $\Delta\bar{\varepsilon}^{vp}$ and the dependence of the fatigue crack propagation rate on difference of loading frequency, where there is no environmental effect, is well explained by variations of $\Delta\bar{\varepsilon}^{vp}$ at the crack front based on visco-plasticity of the material.

CONCLUSIONS

(1) It was found from this experiment that the surface crack propagation rate and striation spacing on fracture surface depend on loading frequency. For lower frequency, higher crack propagation rate and large striation spacing were obtained.
(2) The experimental surface crack propagation rate, *dl/dN*, is closely related to $\Delta\bar{\varepsilon}^{vp}$ obtained by 3D-elasto/visco-plastic analysis. If *dl/dN* is plotted against $\Delta\bar{\varepsilon}^{vp}$, the relation can be expressed by a straight line in logarithmic coordinates for any loading frequency and stress amplitude.
(3) A parameter closely related to fatigue surface crack propagation rate is the equivalent visco-plastic strain range based on the material viscosity.

REFERENCES

(1) Yokobori T. and Sato K., Engng. Fract. Mech., Vol.8, 1976, pp.81-90.
(2) Strova E.N., Zavodskaya Laboratoriya, Vol.46, 1980, pp.660-662.
(3) Takezono S. and Satoh M., J. Engng. Mater. Tecnol. Vol.104,1982, pp.257-261.
(4) Sakamoto, H. and Takezono S., Engng Fract. Mech., Vol.31, No.3, 1988,pp.463-474.
(5) Sakamoto H. and Takezono S., Engng Fract. Mech., Vol.31, No.3, 1988, pp.463-474.
(6) Perzyna P., Adv. appl. Mech., Vol.9, 1976, pp.243-377.
(7) Zienkiewicz O.C., Nayak G.C. and Owen D.R.J., Int. Sym. on Foundations of Plasticity, 1972, pp.107-123.

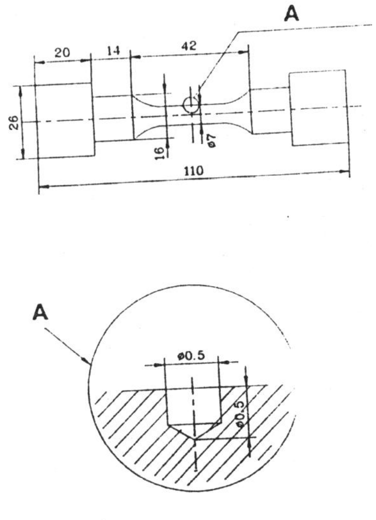

Fig.1 Geometry and dimensions of specimen

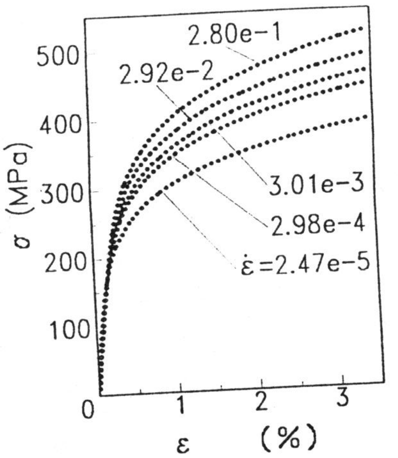

Fig.2 Cyclic stress-strain curves

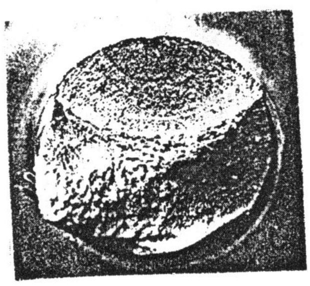

Fig.3 Fracture surface

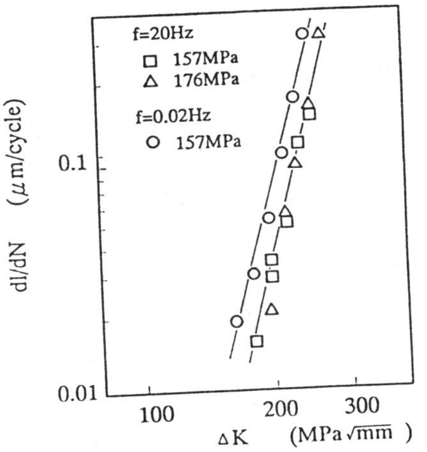

Fig.4 dl/dN-ΔK relations

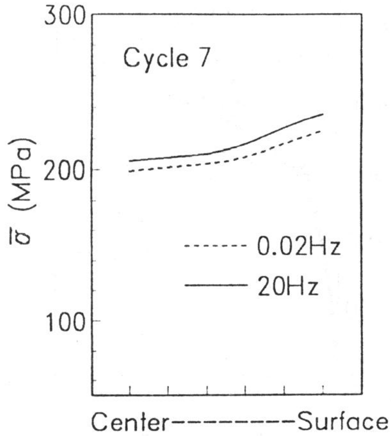

Fig.5 $\overline{\sigma}$ distributions of crack front

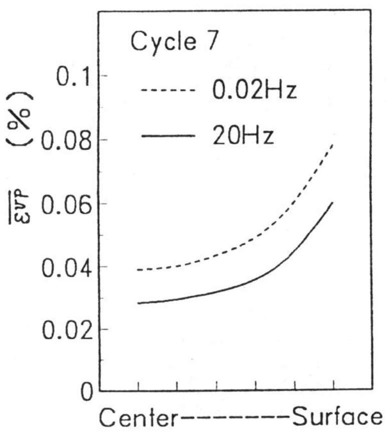

Fig.6 $\overline{\varepsilon}^{vp}$ distributions of crack front

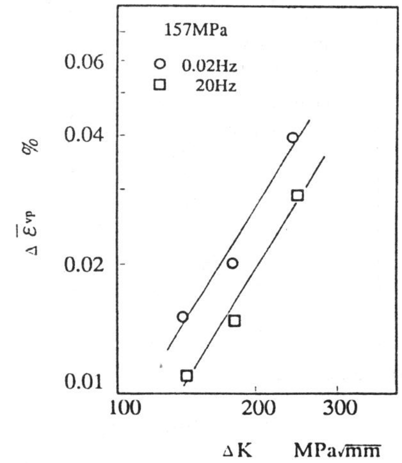

Fig.7 $\Delta\overline{\varepsilon}^{vp}$ - ΔK relation

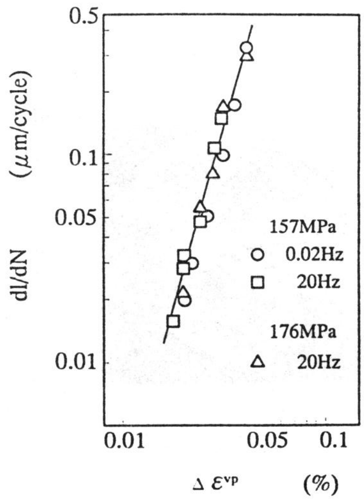

Fig.8 dl/dN - $\Delta\overline{\varepsilon}^{vp}$ relation