EFFECT OF YOUNG'S MODULUS ON FATIGUE CRACK PROPAGATION UNDER VARIABLE LOADING

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ABSTRACT

In order to predict the most reliable fatigue life under variable loading conditions such as the service environment, we have developed a new fatigue test method, and by using it the fatigue crack propagation properties were studied for SM50B steel, Ti-6Al-4V alloy and 5083 Al alloy. The test results showed that the acceleration of the crack propagation rate occurred on all alloys especially at low ΔK regions when the intermittent compressive overload was applied. The maximum acceleration of crack propagation was dependent on the alloy. When the intermittent compressive overload is applied, the crack propagation rate becomes proportional to the second power of ΔK and the ΔK_{th} decreased. The crack propagation rate under intermittent compressive overloading conditions is expressed as $da/dN = C(\Delta K^2 - \Delta K_{th}^2)$ $(C=10/E^2)$ independent of alloys. This crack propagation behavior is easily derived from the theory if CTOD is the critical factor for the fatigue crack propagation. These accelerations of the crack propagation rate under intermittent compressive overloading conditions were discussed with the deformation mode at the crack tip.

KEYWORDS

Fatigue crack propagation, intermittent compressive overload, deformation mode, Young's modulus.

INTRODUCTION

The fatigue crack propagation behavior is usually expressed by Paris's law, $da/dN = C \Delta K^m$ (C, m :constant). According to the in situ observation by Neumann (1974), the fatigue crack propagates by alternating slip at the crack tip under Mode I loading conditions. That is, the crack growth occurs only during the loading process and the amount of the crack growth is

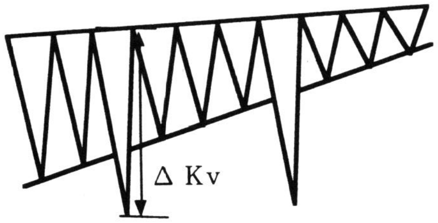

Fig.1 Test loading sequence .

dependent on the crack tip opening displacement proportional to the second power of ΔK. If the crack propagates according to this mechanism, the value of m should be 2. However for various alloys the value of m is not equal to 2 even if the crack closure effect is removed by using the high load ratio. The meaning of the value of m has been one of the unknown matters for the fatigue crack propagation. One of the reasons that the value of m is not equal to 2 is considered to be due to the change of the crack tip deformation mode. Paying attention to this, we have developed a new fatigue crack propagation test method (Masuda and Matsuoka, 1989) to get an ideal crack propagation and confirmed the crack propagation rate becomes proportional to second power of ΔK in both air and 3%NaCl solution for steels (Masuda and Matsuoka, 1990). In this paper the effect of Young's modulus on the crack propagation rate is studied to confirm whether the crack propagation rate becomes proportional to second power of ΔK.

EXPERIMENTAL METHOD

The test materials used were 3 different structure alloys, SM50B steel (bcc), 5083 Al alloy (fcc) and Ti -6Al-4V alloy (hcp). The chemical composition and mechanical properties of test materials are given in Table 1. Fatigue tests were performed by using the computer system (Masuda et.al, 1988) with the compact type specimen of 50 mm width in air at room temperature. The crack length and crack closure level were derived from calculating the elastic compliance of load vs. back-face strain. The tests employed where intermittent compressive overload is applied are done under ΔK decreasing condition where initial $K_{min}/E \geqq 3\times10^{-5}\sqrt{m}$ and K_{min} and K_{max} were increased with the crack length for preventing the crack closure and constant amplitude compressive overload ΔK_v was applied at each certain cycles (Figure 1).

Table 1 Chemical composition and mechanical properties of materials.

Material	Chemical composition	σ_y (MPa)	σ_B (MPa)	E (GPa)
SM50B	0.15 C, 0.37 Si, 1.36 Mn, 0.02 P, 0.03 Ni, 0.02 Cr, 0.01 Cu, Bal. Fe	372	530	208
Ti-6Al-4V	6.20 Al, 4.06 V,0.074 Fe, 0.0081N, Bal. Ti	921	980	103
5083	4.51 Mg, 0.14 Si, 0.63 Mn, 0.04 Zn, 0.04 Cu, 0.12 Cr, 0.02 Ti, 0.23 Fe, Bal. Al	147	325	71

The crack propagation rate at a certain ΔK, da/dN, is given by equation (1):

$$da/dN = (1+V_F)\, da/dN_A - V_F\, da/dN_v \qquad (1)$$

where da/dN_A is the apparent crack propagation rate, da/dN_v is the crack propagation rate at $\Delta K = \Delta K_v$ and V_F is the frequency of the compressive overload. The tests employed where intermittent overload was applied were the ΔK decreasing method (load ratio R= 0.17 ～ 0.95) at $d\Delta K/(da \cdot E) = -10^{-2}/\sqrt{m}$ and $dK_{max}/(da \cdot E) = 10^{-2}/\sqrt{m}$. The frequency of the compressive overload V_F is 1/30 and ΔK_v is 30 MPa·$\sqrt{m}$ for SM50B, 20 MPa·$\sqrt{m}$ for Ti-6Al-4V alloy and 7 MPA·$\sqrt{m}$ for 5083 Al alloy. The tests employed where no overload was applied were the ΔK decreasing method (load ratio R= 0.3 ～ 0.93) at $\Delta K/E \leqq 7\times10^{-5}\sqrt{m}$, $d\Delta K/(da \cdot E) = -10^{-2}/\sqrt{m}$ and $dK_{max}/(da \cdot E) = 10^{-2}/\sqrt{m}$ and the constant stress ratio ΔK increasing method (R = 0.3) at $\Delta K/E \geqq 7\times10^{-5}\sqrt{m}$.

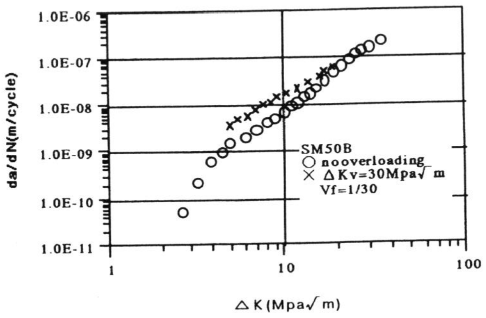

Fig.2 Crack propagation curve of SM50B steel.

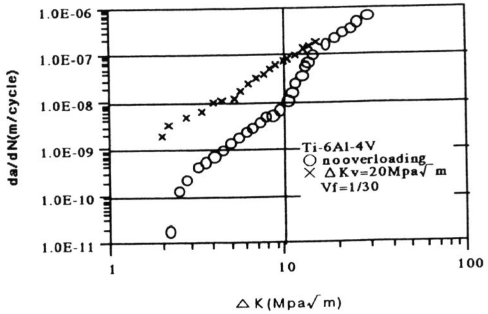

Fig.3 Crack propagation curve of Ti-6Al-4V alloy.

EXPERIMENTAL RESULTS

Fig.2 ～ Fig.4 show the crack propagation curves for the tested alloys. The absence of crack closure was confirmed by the crack closure curve. The shape of crack propagation curves under no overloading conditions were similar to each other (S curve) and the value of m was nearly equal to 2 at $\Delta K \geqq 30$ MPa·$\sqrt{m}$ for SM50B steel, at $\Delta K \geqq 20$ MPa·$\sqrt{m}$ for Ti-6Al-V alloy and at $\Delta K \geqq 7$ MPa·$\sqrt{m}$ for 5083 Al alloy. When the compressive overload was applied, the acceleration of the crack propagation occurred on all tested alloys especially at low ΔK regions and the crack propagation rate became proportional to the second power of Δ K. Δ Kth of 5083 Al alloy under compressive overloading condition was apparently lower than that under no overloading conditions. The accelerations of the crack propagation at Δ K/E = $4\times10^{-5}\sqrt{}$ m are 2 times for SM50B steel, 12 times for Ti-6Al-4V alloy and 4 times for 5083 Al alloy. Fig.5 and Fig.6 show the summary of crack propagation rates of tested alloys vs. Δ K/E. The crack propagation curves under no overloading conditions are different from each other especially at low Δ K/E regions. The crack propagation rate of SM50B steel is more than 6 times than that of Ti-6Al-4V alloy at Δ K/E = $4\times10^{-5}\sqrt{}$ m. While The crack propagation curves under overloading conditions are almost the same and can be expressed as:

$$da/dN = 10/E^2(\Delta K^2 - \Delta K_{th}^2) \quad (2)$$

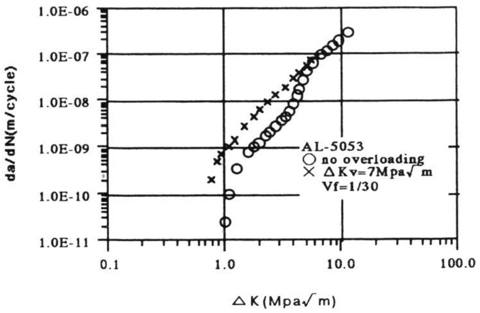

Fig.4 Crack propagation behavior of 5083 Al alloy.

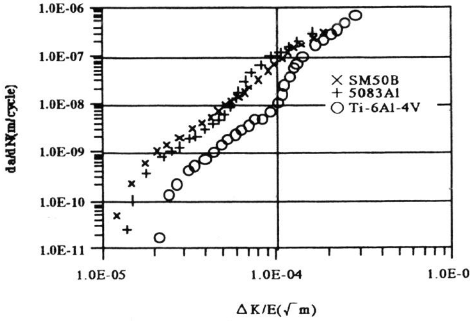

Fig.5 da/dN vs Δ K/E under no overloading.

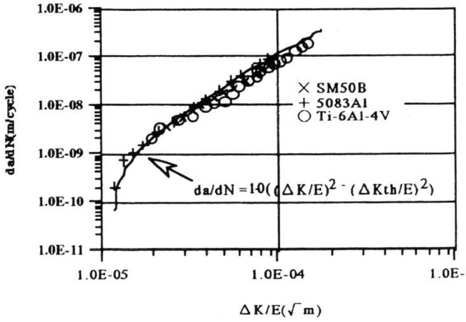

Fig.6 da/dN vs Δ K/E under compressive overloading.

DISCUSSION

If the fatigue crack propagates by the alternating slip at the crack tip, the mechanism of the crack propagation under compressive overloading condition can be considered as follows (Fig.7). The crack closes at stage (a). The crack opening and growth corresponding to the compressive overload amplitude occur at stage (b). The crack tip closes by the reversal slip but the main crack still opens at stage (c). The crack tip opening and crack growth corresponding to the small load amplitude occur at stage (d). The crack tip closes by the reversal slip at stage (e). The crack closes by the reversal slip at stage (f). According to this model, the crack growth occurs only during the loading process and the crack propagation rate is dependent on the crack tip opening displacement proportional to the second power of Δ K. Since the crack propagation rate under compressive overloading condition is proportional to the second power of Δ K, the mechanism of the crack propagation was found to obey the mechanism shown in Fig.7.

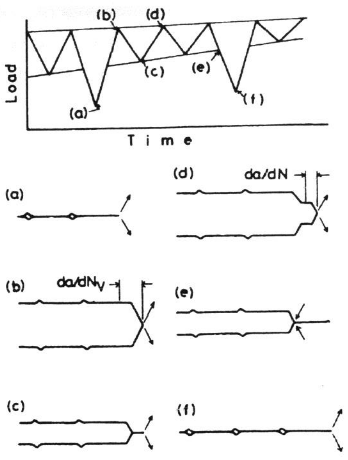

Fig. 7 Mechanism of crack propagation under compressive overloading.

According to Irwin (1957), the crack tip opening displacement (CTOD) in Mode I for plane strain condition is given as:

$$CTOD = 4(1 - \nu^2)K^2/(\pi\sigma_y E) \quad (3)$$

where ν is Poisson's ratio (=1/3) and σ_y is yield stress. If the crack propagates according to CTOD model, the crack propagation rate (not including ΔK_{th} effect) is expressed as:

$$da/dN \fallingdotseq \Delta K^2/\sigma_{yc}E \quad (4)$$

where σ_{yc} is yield stress under fatigue crack propagation. Our experimental results show that $da/dN \fallingdotseq 10\Delta K^2/E^2$ and $\sigma_{yc} \fallingdotseq E/10$. From these results the CTOD behavior of alloys under the fatigue crack propagation is as if they were ideal strength material ($\sigma_y \fallingdotseq E/10$).

Since the acceleration rate of the crack propagation under the compressive overloading condition is dependent on the metal structure of alloys, the frequency and amplitude of the overload (Masuda and Matsuoka, 1989) and Δ K, the acceleration factor of the crack propagation rate under the compressive overloading condition is considered to be related to the crack tip deformation mode. That is, the crack tip deformation is considered to be the mixed mode of the tensile mode (Mode Ⅰ) where many slip systems operates and the in-plane shear mode (Mode Ⅱ) where only the slip system closes the maximum shear stress plane operates at $\Delta K \leqq 30\ \mathrm{MPa}\cdot\sqrt{\mathrm{m}}$ for SM50B steel, $\Delta K \leqq 20\ \mathrm{MPa}\cdot\sqrt{\mathrm{m}}$ for Ti-6Al-4V alloy and $\Delta K \leqq 7\ \mathrm{MPa}\cdot\sqrt{\mathrm{m}}$ for 5083 Al alloy under no overloading condition. The operating ratio of Mode Ⅱ increases as ΔK decreases and the crack tends to propagate crystallographically and change direction. If the compressive overload amplitude which is big enough to deform the crack tip as Mode Ⅰ is applied frequently, the crack propagates only by Mode Ⅰ. This seems to be the reason why the crack propagation rate accelerates to become ideal and proportional to the second power of ΔK. The effect of the compressive overload amplitude can be explained in terms of the mixture ratio of Mode Ⅰ and Mode Ⅱ : the operating ratio of Mode Ⅱ increases as the compressive overload amplitude decreases to result in the decrease in the acceleration of crack propagation.

CONCLUSION

The fatigue crack propagation behavior of SM50B steel, Ti-6Al-4V and 5083 Al alloy in air were studied by using the newly developed variable loading ΔK-decreasing method. The test results show that the crack propagation behavior under intermittent compressive overloading conditions can be expressed as $da/dN = 10/E^2(\Delta K^2 - \Delta K_{th}^2)$ independent of alloys. From these, it can be said that this fatigue test method is the best method to predict the most reliable fatigue life under variable loading condition.

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