EFFECT OF OVERLOAD RATIOS ON FATIGUE CRACK GROWTH BEHAVIOR IN Ti-6Al-4V ALLOY

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ABSTRACT

The effect of various overload ratios, Q_{01}=1.3~2.8 on the fatigue crack growth rate under single tensile overloading for a Ti-6Al-4V alloy was investigated. The variation of fatigue crack tip region and fracture surfaces as well as the dislocation substructures ahead of the crack tip within the plastic zone under different overload ratios was evaluated. From a close microscopic analysis of these specimens, it was found that the main causes of the retardation effect induced by the tensile overloading may be ascribed to the following factors: (a) the closure stress in the wake of the crack tip, (b) the compressive residual stresses ahead of the crack tip and (c) the strain hardening effect in the overload plastic zone. A schematic of the mechanism of crack growth retardation behavior under a tensile overload was proposed.

INTRODUCTION

It is well known that a tensile overload retards the fatigue crack growth rate and the overload ratio is one of the very important factors in affecting the crack growth retardation behavior for engineering materials[1~5]. In order to evaluate the crack growth retardation behavior, the nature and physical causes which induce the retardation effect, should be properly explored. In this respect, a number of semi-empirical models and mechanisms have been proposed[4,6~15). Recently, the authors have suggested a synthetic retardation mechanism caused by a number of factors, which composed primarily the closure stress behind the crack tip and the compressive residual stresses ahead of it[2]. The present investigation is to devote a further evaluation of the effect of various overload ratios on the fatigue crack growth behavior, hence the mechanism of the crack growth retardation effect could be properly revealed.

MATERIAL AND EXPERIMENTAL PROCEDURE

The material used was a mill-annealed Ti-6Al-4V alloy. The chemical composition and mechanical properties of the alloy have been described in Ref. 16. The centre-cracked-tension (CCT) specimens of 300×100×2 mm were machined in the longitudinal direction. The surface along the crack path of these specimens were locally polished. The test parameters are as follows: maximum constant amplitude cyclic load, P_{max}=15,690 N at a stress ratio, R=0.1 and a frequency, f=10 Hz; the ratios of single overload, $Q_{01}=P_{01}/P_{max}$=1.3, 1.4, 1.5, 2.0, 2.4, 2.66 and 2.8 at R=0.1 and f=0.03 Hz; the crack length at the overload 2a=32, 46 mm etc.

The microscopic studies of the crack tip regions, the fracture surfaces and the dislocation structures were preformed on optical microscope, micro-interferometer, SEM and TEM respectively.

EXPERIMENTAL RESULTS

It can be seen from Fig. 1 that different overload ratios give quite different retardation effects on the crack growth performance. As the crack length, 2a=32 mm and at Q_{01}=1.4, no appreciable influence on the crack growth was observed; at Q_{01}=2.0, the retardation effect is obvious, the number of delayed cycles, N_D, is about 15,000; at Q_{01}=2.8, the crack growth rate is very low and the crack is practically arrested.

As shown in Plate 1, the crack tip appears to be sharp after constant amplitude cyclic loading. There is little change of sharpness of the crack tip after overloading at Q_{01}=1.5, however, at Q_{01}=2.0, the crack tip becomes considerably blunted. After overloading at Q_{01}=2.4 and 2.8, the bluntness of the crack tips is very pronounced.

In Plates 1 and 2, it is obvious that under constant amplitude cyclic loading, the size and magnitude of plastic deformation near the crack tip is very small. At Q_{01}=1.5, some "wing-like" concentrated shear deformation bands can be observed in front of the crack tip. These bands stretched forward along two sides with an angle of about 120° apart. At Q_{01}=2.0, 2.4 and 2.8, they become larger and larger in size and the plastic zone

approaches to a circular shape when Q_{01} exceeds 2.4. A rather deep groove

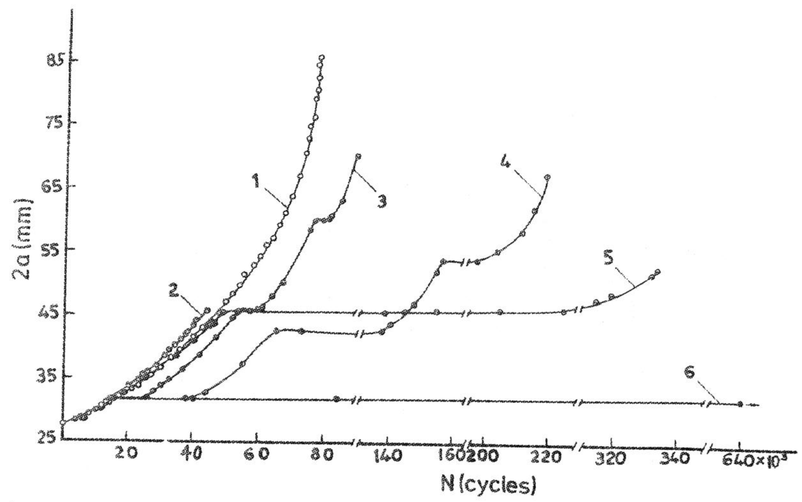


Fig.1 Effect of Q_{01} on da/dN. 1—Q_{01}=1.0, 2—Q_{01}=1.4, 3—Q_{01}=2.0 4—Q_{01}=2.4, 5—Q_{01}=2.66 and 6—Q_{01}=2.8

was gradually developed near the crack tip and the region of maximum deformation gradient, in turn, advanced forward, accompanied by an increase in its magnitude, as shown in Plate 2, in which the density of the interference fringes increases correspondingly.

Fig. 2 illustrates the plastic zone size and the amount of strain along the thickness of the specimen, ε_3. An increase of r_p and ε_3 with increasing overload ratio, Q_{01}, is noticeable.

The closure length and the extent behind the crack tip after a tensile overload increase remarkably with an increase of overload ratio. As shown in Plate 3, a section of the crack of about one fifth of the overload plastic zone size kept closed not only during its growing, but also after the crack has propagated over a certain distance into the plastic zone. No secondary deformation was observed along both sides of the crack. In this stage, the crack extended in a decreasing rate to a minimum and then grew in an increasing rate until the normal growth rate under constant amplitude cyclic loading was resumed. The new plastic zone ahead of the crack tip began to appear and to grow until the normal plastic zone size under constant amplitude cyclic load was acquired.

Some metal-foil specimens were prepared from the region within 0.3 mm from the crack tip and examined under a 200 KV transmission electron microscope. It was noted that the morphology of dislocation structures

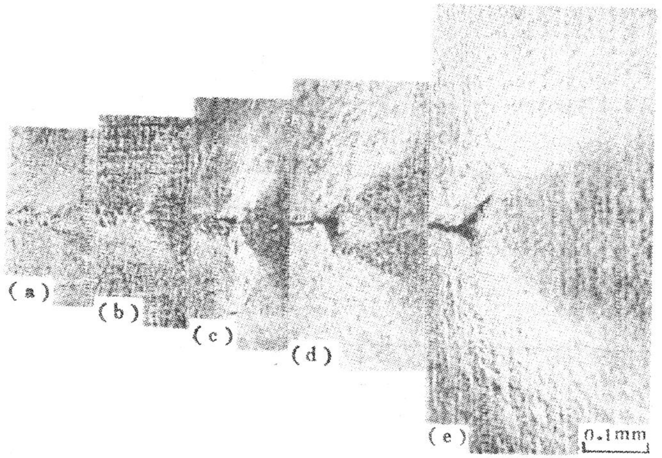
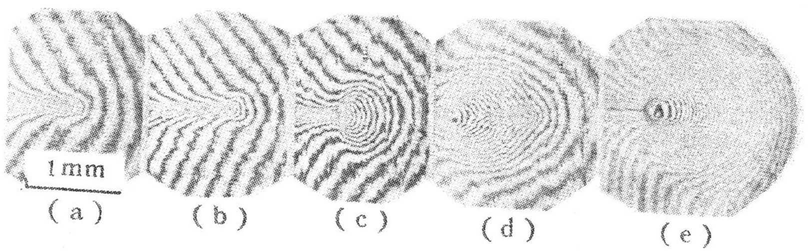


Plate 1 Macro-photographs of crack tip regions after overloading at different Q_{01}. (a) Q_{01}=1.0, (b) Q_{01}=1.5, (c) Q_{01}=2.0, (d) Q_{01}=2.4 and (e) Q_{01}=2.8



Palte 2 Configuration of plastic zone ahead of crack tip after overloading at different Q_{01}. (a) Q_{01}=1.0, (b) Q_{01}=1.5 (c) Q_{01}=2.0, (d) Q_{01}=2.4 and (e) Q_{01}=2.8

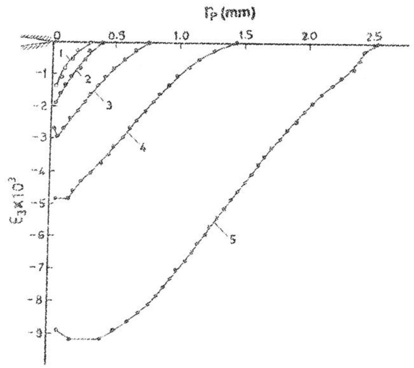


Fig.2 Distribution of ε_3 ahead of the crack tip after overloading at various Q_{01}. 1—Q_{01}=1.0, 2—Q_{01}=1.5, 3—Q_{01}=2.0, 4—Q_{01}=2.4 and 5—Q_{01}=2.8

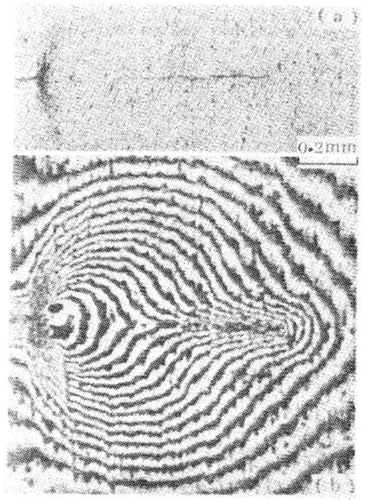


Plate 3 The crack closure behavior within plastic zone at Q_{01}= 2.4. (a) Macrophotograph and (b) Interference pattern of the plastic zone

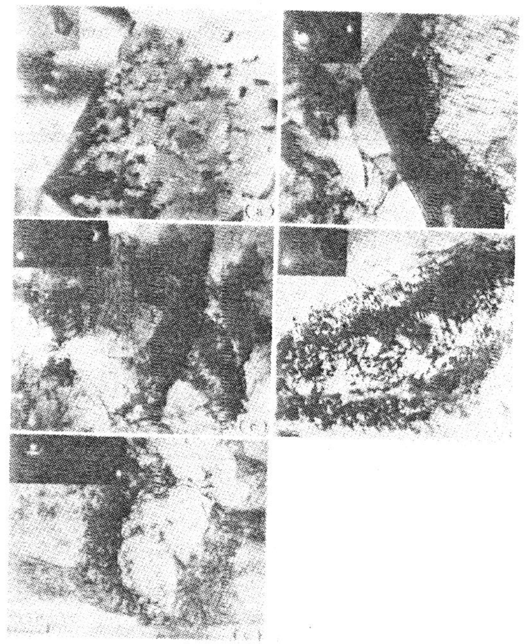


Plate 4 Dislocation morphology within 0.3 mm from crack tip inside plastic Zone. (a) Original state; (b) Q_{01}=1.0; (c) Q_{01}=1.5; (d) Q_{01}=2.0 (e) Q_{01}=2.8

changes substantially under different overload conditions, as shown in Plate 4. In the annealed specimen, only a few dislocation arrays were observable (Plate 4,a). After constant amplitude cyclic loading, some bands of line dislocations appear locally (Plate 4,b). As the overload ratio increases, the morphology changes from patches of dislocation networks (at Q_{01}=1.5), to embryonic dislocation cells (at Q_{01}=2.0) and finally to nearly perfect cell structures (at Q_{01}=2.8). In addition, the density of dislocations increases correspondingly.

DISCUSSION OF RESULTS

As mentioned above, it is evident that the plastic zone size, the magnitude of plastic strain ahead of the crack tip and the length of crack closure increase with increasing overload ratio. These factors would enhance both the closure stress behind the crack tip and the compressive residual stresses, consequently reduce the amplitude of the effective stress intensity range. It is believed that the crack closure stress primarily prevents the crack tip from opening and the residual stresses mainly resist the crack for further extension, hence both of them decrease the crack growth rate. As the overload ratio increases, the stress intensity

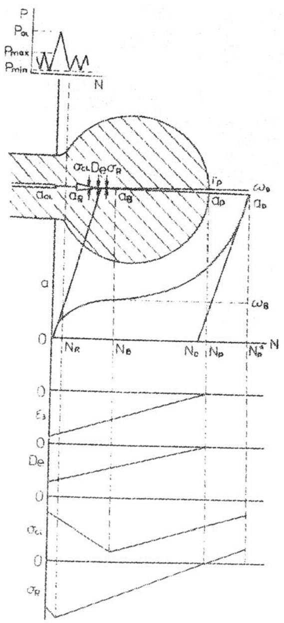


Fig.3 Schematic of the mechanism of crack growth retardation behavior after A tensile overload.

(a) Main affecting factors inducing the retardation effect;

(b) The a-N curve;

(c) Distribution of plastic strain, ε_3;

(d) The acting process of the affecting factors:

D_e—dislocation density

σ_{cl}—crack closure stress

σ_R—compressive residual stresses

range and the plastic zone size increase concurrently. The amount of plastic strain and the length of crack closure would increase as well, hence an

increase of the crack growth retardation effect with increasing overload ratio would be expected. Furthermore, the change of morphology of dislocation structures and dislocation density in the overload plastic zone increases the dislocation stress field which prevents the crack from further extension.

According to the present results and analyses of crack closure stress and compressive residual stresses by previous investigators[8,10] a schematic diagram showing a general mechanism of crack growth retardation effect by a tensile overload is proposed, as shown in Fig. 3.

Fig. 4 shows that the plastic zone size, r_p, the magnitude of the plastic strain, ε_3, and the number of delayed cycles, N_D, increase in an exponential function with the overload ratio, Q_{01}. It is also interesting to note that the variation of the maximum plastic strain, ε_3 with overload ratio is fairly consistent with that of the plastic zone size, r_p, hence it is resonable to suggest:

$$\varepsilon_{3max} = k \cdot r_p \qquad (1)$$

where k denotes an experimental constant related to the material and specimen geometry, here $k = -4\times10^{-3}$ mm^{-1}; r_p is the plastic zone size, $r_p = 2\frac{1}{\alpha\pi}(\frac{\Delta K}{\sigma_y})^2$.

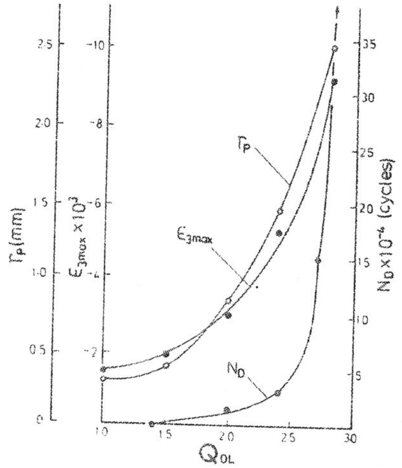


Fig.4 Effect of Q_{01} on r_p, ε_{3max} and N_D

Refer to Fig. 4, it may be suggested that the retardation effect is closely related to the plastic zone size after overloading or the ratio of the overload plastic zone size to that under constant amplitude cyclic loading, i.e.

$$r_{p(01)}/r_{p(ca)} = \frac{2}{\alpha\pi}(\frac{\Delta K_{01}}{\sigma_y})^2 / \frac{2}{\alpha'\pi}(\frac{\Delta K}{\sigma_y})^2 = m \cdot Q_{01}^2$$

then, an empirical expression can be obtained:

$$N_D = N_0 \exp(m \cdot Q_{01}^2) \quad (2)$$

where N_0 and m denote the experimental constants.

In addition, the crack tip blunting, the change of crack growth direction after overloading and the protuberance of fracture surfaces induced by overloading may have some additional effects on the crack retardation behavior.

CONCLUSIONS

1. The effect of various overload ratios on the fatigue crack growth retardation behavior is quite different. As $1.0<Q_{01}<1.5$, there is some retardation effect, but it is too low to be measured exactly. As Q_{01} approaches 3.0, the crack could be fully arrested.

2. The main causes of retardation effect induced by overloading are the crack closure stress, the compressive residual stresses and the strain hardening produced by overloading. The closure stress in the wake of crack tip prevents the crack from opening; the compressive residual stresses ahead of the crack tip resist the crack from extension; the strain hardening is to increase the stress intensity level for further deformation and growth.

3. The maximum plastic strain ahead of the crack tip, ε_{3max}, and the number of delayed cycles, N_D, after a tensile overload may be calculated by empirical expressions proposed.

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