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VARIABLE AMPLITUDE FATIGUE CRACK GROWTH IN TITANIUM ALLOY
Ti-4Al-4Mo-2Sn-0.5Si (IMI 550)

by

C. M. Ward-Close
R. O. Ritchie

March 1988

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SUMMARY

A study has been made of fatigue crack growth behaviour in the α/β titanium alloy Ti-4Al-4Mo-2Sn-0.5Si (IMI 550), subject to single tensile overloads and the FALSTAFF flight simulation loading spectrum. Fatigue overloads were found to produce crack growth rate acceleration, followed by delayed retardation. The transient changes in crack growth rates were associated with large changes in crack closure immediately behind the crack tip. For both single overloads and flight simulation loading, the greatest load-interaction effects were at the lowest load amplitudes. Microstructure had only a slight influence on load-interaction effects associated with single tensile overloads. However, at the higher stress amplitudes, the β annealed material showed greater retardation than the α/β material under simulated flight loading.

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ABSTRACT

A study has been made of fatigue crack growth behaviour in the α/β titanium alloy Ti-4Al-4Mo-2Sn-0.5Si (IMI 550), subject to single tensile overloads and the FALSTAFF flight simulation loading spectrum. Fatigue overloads were found to produce crack growth rate acceleration, followed by delayed retardation. The transient changes in crack growth rates were associated with large changes in crack closure immediately behind the crack tip. For both single overloads and flight simulation loading, the greatest load-interaction effects were at the lowest load amplitudes. Microstructure had only a slight influence on load-interaction effects associated with single tensile overloads. However, at the higher stress amplitudes, the β annealed material showed greater retardation than the α/β material under simulated flight loading.

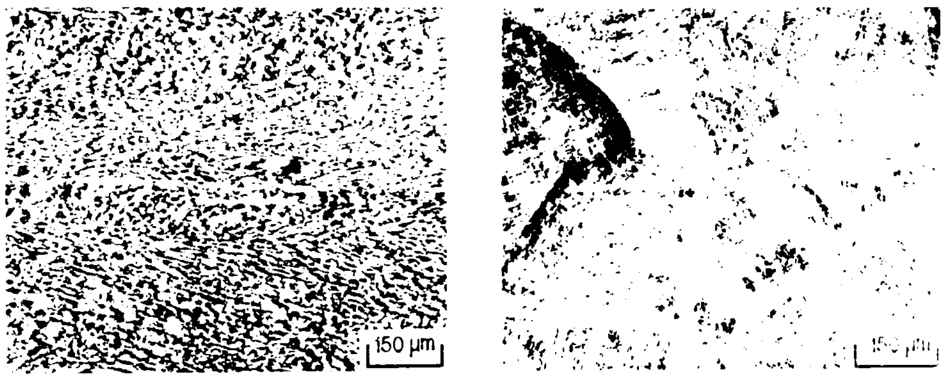
INTRODUCTION

Fatigue loading under service conditions normally involves variable amplitude, rather than constant amplitude, loading and it is known that under these conditions load history can have a major effect on fatigue crack growth rates. Various load-interaction effects have been reported, including both acceleration and retardation of fatigue crack growth rates compared with those expected under steady-state conditions. The most important effect appears to be that of crack growth rate retardation following an overload. Of the different models which have been proposed to account for this effect, the concept of plasticity induced crack closure appears to offer the best means of rationalising many of the load-interaction effects (1,2). A number of prediction models have been based on crack closure (3,4), and these have been reasonably successful at predicting crack growth rates for simple loading sequences. However, very little direct evidence for the role of crack closure exists, yet in order to model and predict crack growth behaviour in engineering structures under service-loading conditions, a thorough understanding of the mechanisms controlling load interactions will be required.

The objective of the work now reported was to investigate load-interaction effects and crack closure in fine-grained α/β annealed, and coarse-grained β annealed microstructures in IMI 550 titanium alloy, using single tensile overloads and the FALSTAFF flight simulation loading spectrum. Additionally the FALSTAFF results were compared with cumulative damage life predictions, based on constant amplitude fatigue data.

MATERIAL AND EXPERIMENTAL METHOD

The IMI 550 alloy studied was heat treated to two microstructural conditions, shown in Fig.1; mechanical property data are presented in Table 1.



(a) (b)

Fig.1 (a) α/β annealed at 900° C, air cooled, aged 24 hrs at 500° C, and (b) β annealed at 1010° C, air cooled, aged 24 hrs at 500° C

Table 1 Room temperature Tensile Properties

Microstructure	Young's Modulus E (GPa)	0.2% Yield Strength (MPa)	Tensile Strength (MPa)	Elong. (%)	Redn. in Area (%)	K_{Ic} (MPa$\sqrt{m}$)
α/β annealed	107	984	1130	15	18	86
β annealed	107	874	1094	12	9	100

Single tensile overloads were carried out on 10mm-thick compact tension test pieces under 'constant K' conditions (baseline R-ratio 0.1, overload K max. 100% above baseline K max.); crack closure was measured using back-face strain compliance. The method of estimating the delay associated with tensile overloads is illustrated in Fig.2; 'delay cycles' represents the increase in total fatigue life due to the overload, and 'delay distance' is the equivalent amount of crack growth. FALSTAFF simulated-flight life tests were carried out on 10mm-thick pre-cracked single-edge-notch test pieces; FALSTAFF fatigue life predictions were made using a cumulative damage model without allowance for load interaction. Full experimental details are given elsewhere (5,6).

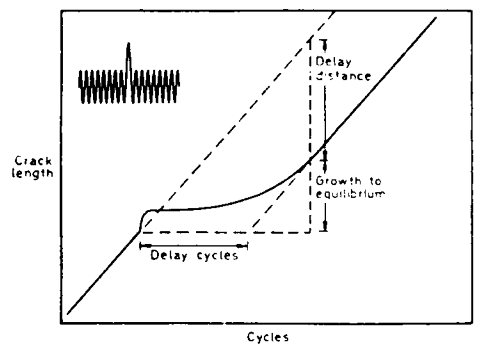


Fig.2 Curve of crack length vs. load cycles, under constant baseline ΔK conditions, illustrating definition of 'delay cycles' and 'delay distance'.

RESULTS

Constant Amplitude Fatigue

Constant amplitude fatigue crack growth tests were carried out at four R-ratios (min.load/ max.load) for each microstructural condition (R = -1,0.1,0.3,0.5). At every R-ratio, the β annealed material showed lower crack growth rates than the α/β annealed material, particularly at low ΔK levels. Fatigue fracture surfaces for the α/β annealed material were macroscopically smooth and featureless, whereas, fracture surfaces for the coarser-grained β annealed material were highly irregular and crystallographic (5,6).

Single Overloads

A series of single 100% tensile overloads tests were carried out with baseline ΔK values in the range from ΔK threshold to about 30 MPa$\sqrt{m}$. Figure 3 shows a typical fatigue crack growth curve for an overload in the α/β annealed material. After the overload on return to baseline load cycling, there was always a brief acceleration in crack growth rate compared with the pre-overload rate, followed by the well known delayed retardation of crack growth rates first reported by Schijve (1). The retardations associated with 100% tensile overloads are presented in Fig. 4 as a double logarithmic plot of baseline ΔK versus delay distance.

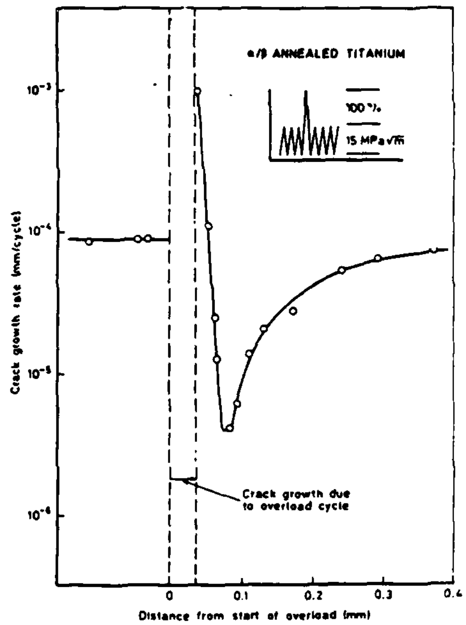


Fig.3 Typical crack growth rate curve, showing delayed retardation.

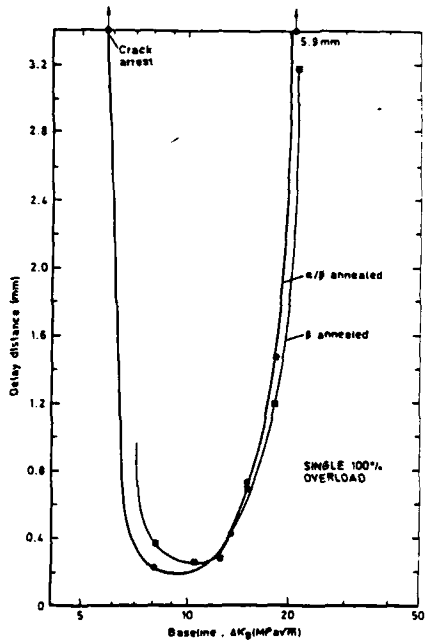


Fig.4 Curves of 'delay distance' vs baseline ΔK for the two microstructural conditions.

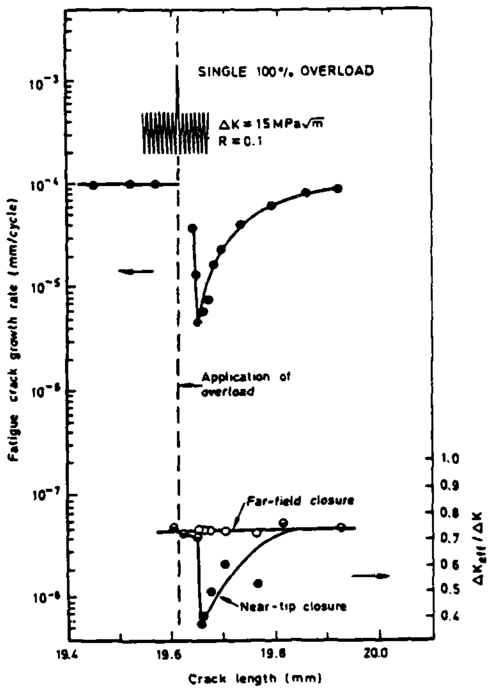


Fig.5 Variation in crack growth rate and corresponding changes in crack closure following a 100% overload in α/β annealed material.

Metallographic sections of cracked test-pieces indicated that a tensile overload blunted the normally sharp crack, and increased crack opening such that it remained open for some distance behind the tip, even at zero load.

Crack closure loads were monitored at intervals throughout the overload tests by back-face strain compliance. Under constant amplitude conditions, the closure load was indicated by a sharp change in slope of the load/displacement curve. For both microstructures under steady-state conditions, closure occurred at about 0.35 of the maximum load, regardless of crack length. Immediately following the overload, a slight decrease in the closure load was noted, particularly at high ΔK levels. During subsequent delayed retardation, a second slope change appeared on the load/displacement curve, indicating a large increase in the closure load. This second closure point is thought to correspond to closure of the post-overload fatigue crack immediately behind the crack tip, termed near-tip crack closure. Figure 5 shows variation in crack propagation rate and the associated changes in both 'near-tip' closure and that generated along the main crack length, which has been termed 'far-field' closure.

Simulated flight fatigue loading

The results of simulated flight fatigue life tests on pre-cracked test pieces are presented in Fig. 6 together with life predictions based on constant amplitude data. The predicted lives were all conservative compared with the measured lives, and accurate within a factor of approximately two.

FALSTAFF fatigue fracture-surfaces for the α/β annealed material were characterised by 'beach marks' which were parallel to the crack front, and up to several millimetres in depth. Scanning electron microscope examination showed that these marks were highly ductile in appearance, and are thought to correspond to crack extension during the largest excursions of the FALSTAFF loading spectrum.

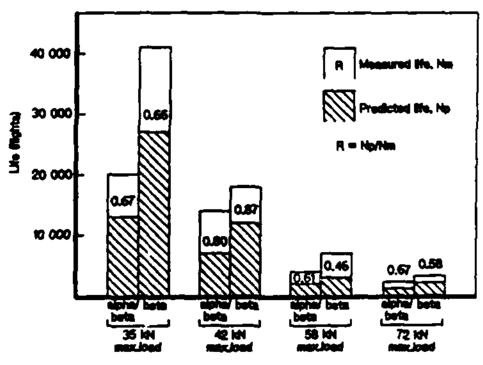


Fig.6 FALSTAFF fatigue lives for two microstructures at various load amplitudes.

DISCUSSION

The results for single tensile overloads suggest that transient fatigue crack growth rates associated with variable amplitude fatigue are primarily controlled by the magnitude and location of crack closure. One way of accounting for crack closure in terms of stress intensity factor is to use the closure load as a lower cut-off for the load cycle, and to calculate ΔK for the crack open part of the cycle only, this is normally termed the effective ΔK.

However, it is evident from back-face strain compliance measurements, and from metallographic sectioning, that rather than there being a single load at which the crack closes completely, there can be several stages of crack closure, depending upon the loading history. It seems likely that it is closure very close to the crack front (probably within 500 μm) that controls the overload response. This suggestion is consistent with work on modelling the effect of fracture-face asperity contact (7), where it has been shown that closure close to the crack tip has a much greater influence on the effective crack driving force than does contact remote from the crack tip.

The acceleration in crack growth rates which was observed following tensile overloads is thought to result from the increase in crack opening brought about by the overload, which would reduce crack closure in the near tip region, and thus give an increase in the effective ΔK. Subsequent delayed retardation in crack growth rates was found to be associated with crack closure in the residual compressive region created by the overload, ahead of the crack front. As the post-overload crack extended, it would experience an increasing effect of crack closure in this region. The crack would eventually run clear of the compression zone, but plastic deformation in the wake would continue to give premature closure at that point. However, as the crack tip moved further away, the effect on the crack driving force would gradually diminish. This is supported by observations in this study that retardation would affect crack growth for distances up to eight times the maximum size of the overload plastic zone.

The delay caused by 100% tensile overloads was found to increase when the base-line ΔK was either decreased towards the ΔK threshold, or increased towards instability, (Figure 4). This was true whether delay was expressed in terms of fatigue cycles (delay cycles) or as equivalent crack growth (delay distance). This behaviour may be seen as a balance between the various mechanisms controlling the overload response. Clearly, increasing baseline ΔK increases the size of the crack-tip plastic zone created by the overload, and thus the retardation in crack growth rates would be expected to increase. Correspondingly, at low ΔK levels, near the threshold ΔK, the relationship between ΔK and crack growth rate is very acute, and any change in effective ΔK brought about by crack closure following an overload would have a severe effect on crack growth rate.

FALSTAFF test results suggest that retardation of crack growth rates under simulated flight loading follows a similar trend to constant amplitude loading. This is illustrated by the prediction ratios shown in Figure 6. If the ratio of test life against predicted life is taken as a measure of the degree of load interaction, the retardation effect under FALSTAFF shows a minimum in the intermediate stress range. The principal difference between the effect of single tensile overloads, and flight simulation loading appears to be the behaviour at very high loads. Whereas, increasing the stress intensity factor of single tensile overloads increased the magnitude of the delay, for FALSTAFF the retardation effect was reduced at the highest load amplitude (72 kN maximum load). This difference is probably due to the repetitive nature of the FALSTAFF loading. The total effect of a fatigue overload consists of that increment of crack growth actually occurring at the overload, combined with the effect of that overload on subsequent crack growth rates. For the overload levels used in this study, it was found that the overload crack-growth-increment for single overloads was always insignificant compared with the effect of the subsequent delayed retardation on crack growth rates. However, in FALSTAFF loading, it is likely that at high load amplitudes the large number of overload crack-growth-increments may contribute significantly to the average crack growth rate.

Microstructure also has a major effect on fatigue crack growth in α/β titanium alloys, and in the present study this was reflected both in constant amplitude and variable amplitude crack growth behaviour, where the β annealed material gave consistently lower fatigue crack growth rates than the α/β annealed material. However, the effect of microstructure on overload retardation appears to have been slight. When compared in terms of delay distance, there was almost no difference between the response of the two microstructures to single tensile overloads (Fig. 4). The FALSTAFF fatigue tests indicated that at the higher load amplitudes, load-interaction effects were greater in β annealed microstructure, compared with α/β annealed material. This was probably a result of the higher fracture toughness of the β annealed material leading to smaller overload crack-growth-increments compared with the α/β annealed material.

CONCLUSIONS

1 Transient crack growth rates associated with tensile overloads were found to correspond to large changes in crack closure immediately behind the crack tip (near-tip closure).

2 For both single overloads and flight simulation loading, the greatest load-interaction effects were at the lowest stress amplitudes. Load interaction was also very severe following single overloads at high stress amplitudes, whereas, under flight simulation loading, the highest stress amplitude produced only moderate retardation of crack growth rates. This was thought to be due to the contribution of overload crack-growth-increments in flight simulation loading at high stress amplitudes.

3 Microstructure had only a slight influence on load-interaction effects in the IMI 550 alloy. At the higher stress amplitudes, the β annealed material showed greater retardation than the α/β annealed material under flight simulation loading; an observation attributed to the higher fracture toughness of the β annealed material

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