Fracture mechanisms due to Fatigue, Creep and Environmental damage in titanium alloys

M.T. Whittaker, W.J. Evans, W Harrison
Swansea University, Singleton Park, Swansea. SA2 8PP

Abstract

Improved understanding of the interactions of fatigue, creep and environmental damage mechanisms has enabled design engineers to extend the operating temperatures of existing alloys. The current paper investigates these effects in the titanium alloy Ti6246 in terms of the growth of fatigue cracks from notched specimen geometries and plain samples. Partitioning of these damage mechanisms is shown to be possible, and the development of a modelling capacity which encompasses both fatigue crack intiation and growth is subsequently reported.

1. Introduction

The work reported here formed part of a major research programme aimed at evaluating fatigue, creep and environmental damage in the titanium alloy Ti6246. Much of that work has been reported previously [1, 2]. In particular, it has been shown that damage mechanisms can be partitioned into fatigue, creep and oxidation mechanisms at temperatures in the range 450 to 550ºC. On this basis strain control fatigue data have been used to predict not only notch fatigue performance at these temperatures [3] but also the observed fatigue crack propagation rates [4]. In many respects the observations and conclusions have built and extended on an earlier programme of work on Ti834.

The present paper addresses issues that were not covered in the previous publications. In particular it focuses on fatigue cracks within the highly stressed and plastically deformed root region of a double edge notch specimen geometry. Cracks often initiate and grow from 'hot spot' locations in structures and components where the stress is raised locally above the nominal design level. Accurate prediction of notch behaviour requires numerical models not only for crack initiation but also for subsequent crack growth through the highly stressed notch root region. At high temperatures, such growth will be affected by creep deformation, damage and relaxation processes, as well as environmental factors and conventional fatigue damage mechanisms. To quantify some of these issues, crack growth behaviour was measured for freely initiated cracks, cracks developing from centre-drilled holes and from machined corner slits in a double edge notch geometry. The DEN specimen had K_t=1.9 resulting from 3mm radius notches constructed around a 10x10mm centre section. The latter is identical to the 10x10mm corner crack (CC) specimen geometry used to establish crack growth rate data. The paper reports the information obtained and provides a direct comparison with the standard growth rate behaviour. The implications are discussed in relation to a previously published model for crack growth rates [5].

2. Experimental method

Crack propagation testing, whether using corner cracked or DEN specimens, was conducted on a Mayes screw test machine with a 100kN load capacity. For plain specimen crack propagation, corner crack (CC) propagation specimens, Figure 1, were used, with a corner slit of 0.35mm machined into one corner. A similar slit was machined into the DEN specimens, Figure 2, at the corner of the notch (DEN CC). For the centre holed notch specimens however (DEN CH), a 50µm diameter hole was drilled 50 µm deep into the centre of the notch to act as a crack initiator.

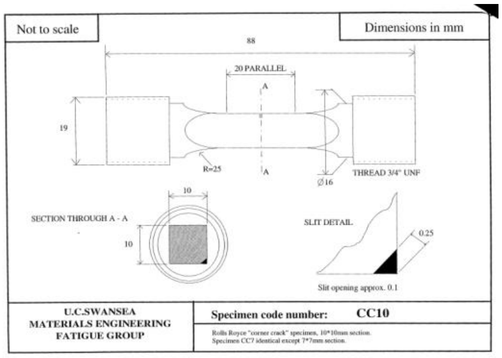


Figure 1: Corner crack specimen

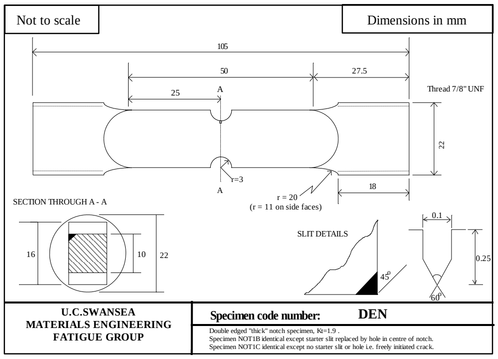


Figure 2: DEN specimen

Tests were undertaken at 20°C, 450°C, 500°C and 550°C, and included cyclic and dwell waveforms, at various R ratios. Previous data available for the programme also included cyclic and dwell data at these temperatures, in both air and high vacuum (10^{-6} Torr) conditions.

All testing was completed at R = 0, using a standard 1-1-1-1, 15cpm trapezoidal waveform for cyclic tests, and a 1-120-1-1 waveform for 120 second dwell tests.

Fatigue tests were also carried out on DEN specimens without machined slits and centre holes. These tests were monitored by a standard DC potential drop technique. Although the accuracy of measuring the crack length was difficult due to the positioning of PD wires, qualitative information about the crack length was gained.

3. Results

3.1 Crack propagation testing on corner crack specimens

Extensive crack propagation testing on Ti6246 corner crack specimens has been previously reported [1] for air and vacuum conditions under cyclic and dwell waveforms at temperatures of 450°C, 500°C and 550°C. The present work extended that database through extended dwell waveforms, including a 300 second hold at peak stress (1-1-300-1) and temperatures of 20°C, 500°C and 550°C.

At 20°C, the 300 second dwell data and the previous cyclic results superimposed confirming a dwell insensitive fatigue response. However, at 500°C the data displays a significant dwell sensitivity. Figure 3 shows the crack propagation rates of cyclic (1-1-1-1), 120 second dwell (1-1-120-1) and 300 second dwell (1-1-300-1) tests. The material is now in a temperature regime where creep effects have a marked influence. The effects on the crack propagation rate are clear, with the cyclic data showing the slowest crack propagation rate, the 120 second dwell intermediate, and the 300 second dwell showing the fastest growth rate behaviour. The difference between the two dwell periods is interesting, since it seems to show the damage occurring during the dwell period to be continuous and not isolated to the early part of the dwell period.

Attempts were made to conduct the same 300 second dwell test at 550°C. Results however were difficult to achieve due to specimen necking, and deformation at regions other than the starter slit.

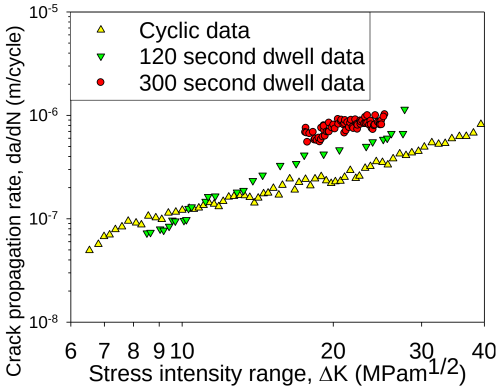


Figure 3: Growth rates at 500°C

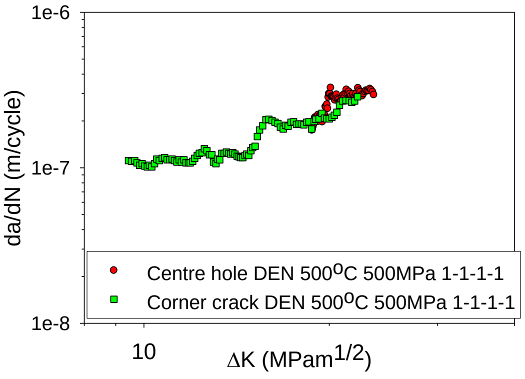


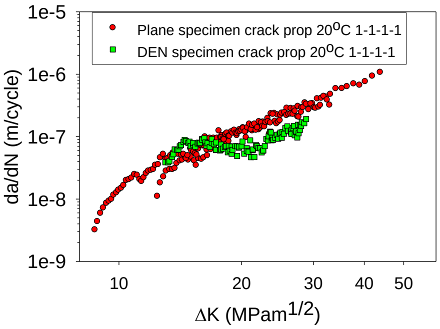
Figure 4: CH and CC DEN comparison

3.2 Crack propagation in pre-notched DEN specimens

Crack propagation in DEN specimens was undertaken using either a centre hole or a corner slit to initiate the crack. Initial testing was carried out to confirm that both methods were acceptable, and that calculated ΔK values were correct. Figure 4 compares corner crack and centre hole data for DEN specimens. The tests were conducted at R=0.1 and 500°C. The ΔK values for the centre hole crack were calculated both along and perpendicular to the notch root, and in the direction perpendicular to this. It was found that the growth rates varied considerably but along the notch root matched those of the corner cracked DEN specimens.

Figure 5 compares crack growth in DEN and CC specimen, both with corner crack initiation sites at room temperature. It can be seen that there is a good correlation between the DEN crack growth and the plane specimen crack growth, confirming the validity of the K calibration for the notch specimen. At 550°C, however, it is clear that at both R=0 and R=0.7 growth rates in the DEN CC specimen are faster at the lower stress intensity factors. It is likely that this is due to creep effects associated with plasticity at the notch root. Creep can be beneficial by encouraging stress relaxation but the accumulation of plasticity can promote creep damage. Previous work [1] has shown that creep is significant at

550°C through experiments carried out in high vacuum. Nevertheless, environmental effects cannot be ignored as the previous work conducted in air demonstrated. In the present case, however, it is difficult to believe that there will be significantly different environmental influences between the DEN and CC test programmes.



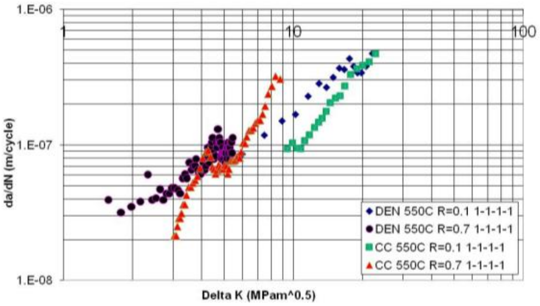
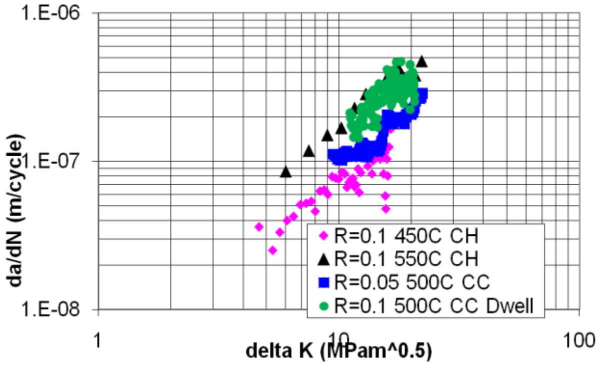


Figure 5: Comparison of plain specimen and DEN CP rates at 20°C

Figure 6: Comparison of CP rates in DEN and plain specimens

Further testing on corner cracked DEN specimens at R=0.05 and 500°C is reported in Figure 7. A comparison is made with previous data from DEN specimens. The previous tests were conducted using thinner (3mm as opposed to 10mm thick) specimens, with centre holes (CH) to initiate the crack. The graph also includes the results from a 120 second dwell test at 500°C on a corner cracked DEN specimen. The graph demonstrates consistency with the earlier work. It also confirms the earlier deduction that cyclically there is not a large difference between R=0.1, 450 and 500°C growth rates, but there is a significant increase in rates on raising the temperature to 550°C. Furthermore the data highlight the acceleration caused by a dwell period at 500°C



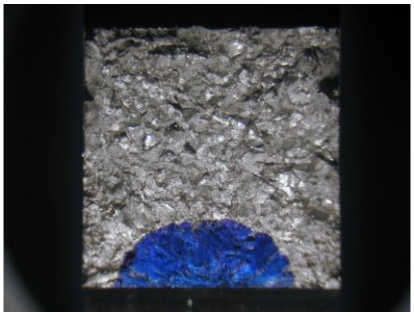


Figure 7: CP rates in DEN specimens

Figure 8: Crack detected in freely initiated specimen

3.3 Growth rates in plain DEN specimens

An important element of this activity was to produce fatigue curves on DEN specimens for both cyclic and dwell waveforms under vacuum and air conditions. PD monitoring was employed during the air tests of the DEN specimen in order to gain information about crack initiation and the early growth stages. Several tests were stopped to enable a correlation to be made between voltage changes and crack lengths, Figures 8 and 9. This enables a threshold to be defined for crack detection. It also produced a linear fit for a range of voltages over which a crack length can be determined. With this information appropriate da/dN vs. ΔK can be established.

PD wires were connected across the entire notch, since free initiation of cracks was important and hence some accuracy had to be sacrificed. However, consistent results were obtained, Figure 10. A small increase can be seen in growth rate as the temperature is increased from 500°C to 550°C. A marked difference is again seen at 550°C when the dwell period is added. These results are compared with crack propagation results from both corner cracked DEN and CC crack propagation tests, Figure 10.

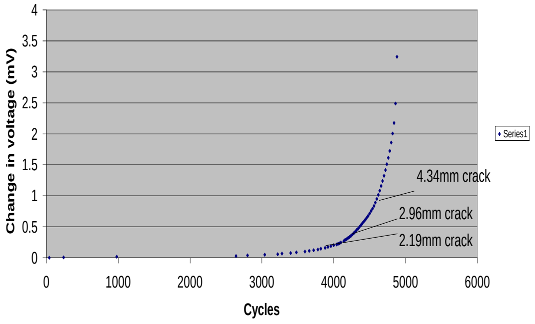


Figure 9: Crack size determined by stopped tests

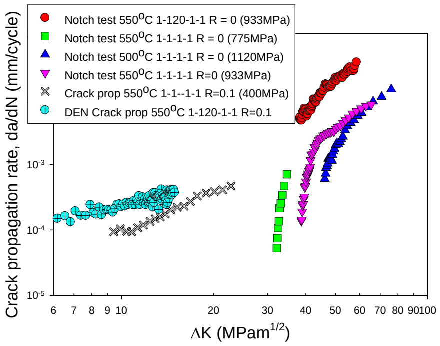


Figure 10: Comparison of freely initiated and CC/CH growth data

It is interesting that the freely initiating cracks appear to run to a threshold condition at ΔK values that are much larger than the ΔK values at which cracks grow in the DEN specimens with corner cracks. In assessing this observation, it is important to appreciate that the applied stresses in the latter are only 400MPa. This is essentially an elastic condition for the notch root. For the freely initiating cracks, the peak elastic stresses are 775, 933 and 1120MPa. Each will generate significant plasticity at the notch root. This plasticity will lead to geometry induced crack closure. In this respect, it is interesting that the apparent threshold at 550°C and a stress of 933MPa is higher than for 775MPa. This could be due to the greater level of plasticity and hence closure. The faster rate for the 933MPa dwell test could then be due to creep damage accumulation, relaxation of the residual compressive stress at the notch root or perhaps a combination of the two.

3.4 Creep and Environmental damage

The data presented and associated discussion has alluded to both creep and environmental influences on the observed crack propagation rates. To explore the relative contributions the freely initiating DEN specimens were tested under air and vacuum conditions. Some of these results are presented in Figure 11. This demonstrates that there is a reduction in life under dwell loading in vacuum. This strongly implies a creep influence. However, there is a further reduction in cyclic and dwell lives on testing in air. This must be associated with the environment which is probably dominated by oxygen [6]. Other researchers [7], however, have also invoked moisture for this effect. Figure 12 compares fracture surfaces in air at room temperature and 500°C. The secondary cracking at 500°C may be associated with an environmental influence. Creep damage has previously been related to localised interface cracking rather than the general effect apparent in Figure 12(b) [4].

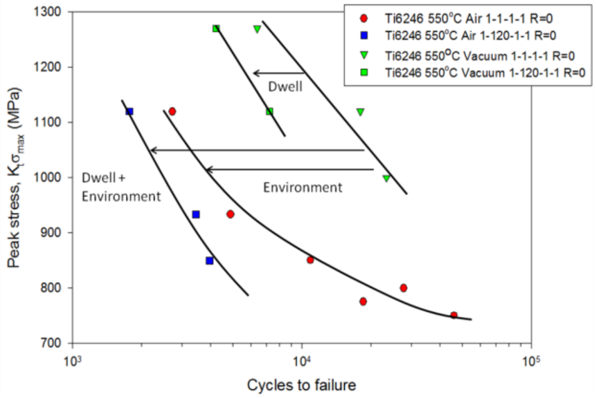


Figure 11: Dwell and environmental effects at 550°C

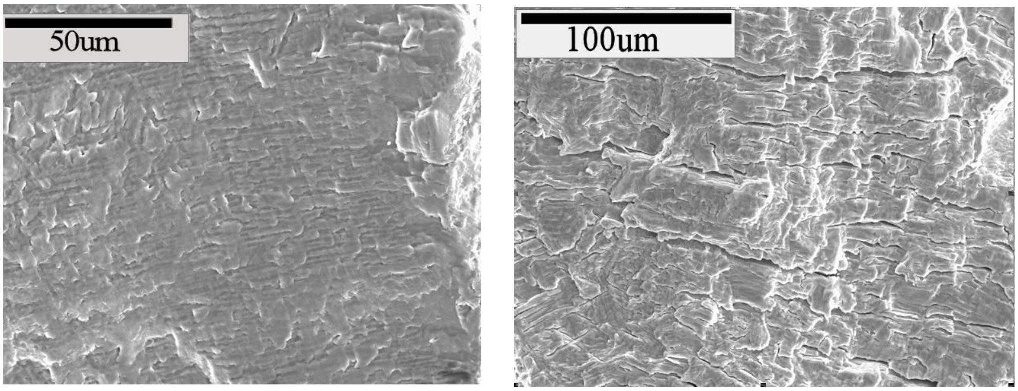


Figure 12: Fracture surface at a) 20°C and b) 500°C

3.5 Fatigue modelling

A key objective of the work was the prediction of notch fatigue behaviour at elevated temperatures based on the measured fatigue response of plain specimen strain controlled data. The Walker strain [10] is widely used as a method to handle mean stress effects in fatigue testing. It also formed the basis of the predictions carried out in this programme. Previous work has reported this in greater detail [4, 8]. Based solely upon strain control fatigue data, an ABAQUS based model encompassing a user-defined subroutine to implement the MRoz [9] multilayer kinematic hardening approach has been used to make predictions of both initiation life and propagation behaviour in this alloy at elevated temperatures. Figure 13 (a) shows predicted DEN fatigue lives at 450°C, using a Walker-strain based approach [10] to initiation life prediction based on strain control data, and Figure 13 (b) highlights similar predictions made at 500°C for fatigue crack growth rates. For the crack growth predictions a pure fatigue approach is shown to underpredict rates. An improved prediction, however, is made through the use of a loosely coupled fatigue-creep model as shown in Figure 13 (b).

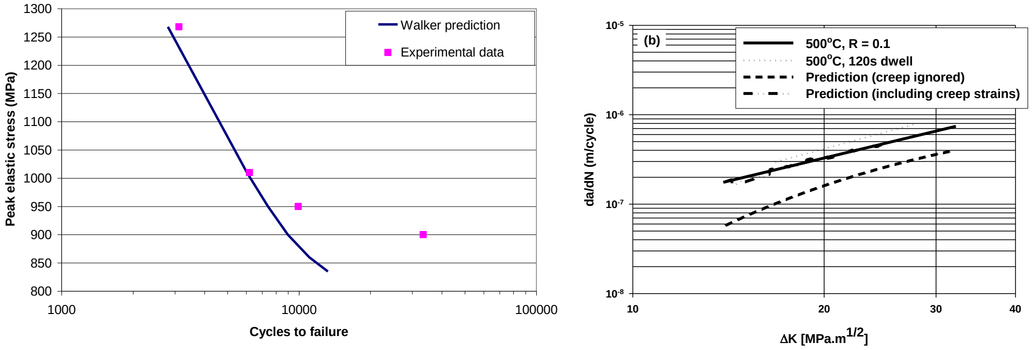


Figure 13 (a): Fatigue life predictions at 450°C and (b) Crack growth rate predictions at 500°C

4. Concluding remarks

The information presented confirms earlier observations that fatigue crack growth rates in Ti6246 at temperatures of 450, 500 and 550°C are strongly influenced by both creep and environmental damage mechanisms. Particularly important in this work is the role of notch root geometry in DEN specimens. When a crack ‘starter’ mechanism is introduced into the DEN specimen in the form of a corner slit or drilled hole, the stresses for growing the crack are comparatively low. In this case the correlation between conventional corner crack testpieces and the DEN is good although rates in the latter tend to be slightly faster. However, for freely initiating cracks, the growth rate data display apparent thresholds at ΔK values considerably higher than the ΔK for crack growth in corner slit or centre holed DEN specimens. This difference is attributed to the much higher stresses, the occurrence of plasticity and induced compressive stresses that cause geometry induced closure.

5. Acknowledgements

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6. References

[1] WJ Evans, JP Jones, S Williams, “The interactions between fatigue, creep and environmental damage in Ti6246 and Udimet 720Li”, International Journal of Fatigue 27 (2005) pp1473-1484
[2] WJ Evans, “High temperature fatigue/creep/environment interactions at notches in titanium and nickel disc alloys”, 11th Portuguese Conference on Fracture, 2007
[3] MT Whittaker, PJ Hurley, WJ Evans, D Flynn, “Prediction of notched specimen behaviour at ambient and high temperatures in Ti6246”, International Journal of Fatigue, Vol 29 (9-11) pp 1716-1725,
[4] PJ Hurley, MT Whittaker, PJ Webster, WJ Evans, “A Methodology for Predicting Creep/Fatigue Crack Growth Rates in Ti6246”, International Journal of Fatigue, Vol 29 (9-11) pp 1702-1710,
[5] P.J. Hurley, W.J. Evans “A new method for predicting fatigue crack propagation rates” Materials Science and Engineering: A, Volume 466, Issues 1-2, 25 September 2007, pp 265-273
[6] Foerch R, Madson A, Ghonem H. Met Trans A 1993;24A:1321–31.
[7] Petit J, Mendez J, Bevata W, Legendre L, Muller C. Short fatigue cracks, vol. 13. EMAS; 1992. pp. 235–50.
[8] Prediction of fatigue initiation lives in notched Ti 6246 specimens, International Journal of Fatigue, Volume 30, Issue 4, April 2008, Pages 623-634 P.J. Hurley, M.T. Whittaker, S.J. Williams, W.J. Evans
[9] Z Mroz, “An attempt to describe the behaviour of metals under cyclic loads using a more general work-hardening model”, Acta Mechanica., 7, pp199-212, 1969.
[10] K Walker, “Effects of Environment and Complex Loading History on Fatigue Life”, ASTM STP 462, 1-14, 1970