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Modelling the behaviour of titanium alloys at high temperature for gas turbine applications

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Abstract

Increased efficiency within the aero engine can be achieved through higher operating temperatures. In order to meet this requirement designers seek either to implement new alloys or show that existing alloys are capable of operating under more extreme conditions. At higher temperatures fatigue is no longer the sole damage mechanism and contributions from creep and environmental interactions must also be considered.
This paper seeks to address some of these issues within titanium alloys, and in particular how these high temperature interactions may affect stress concentrations which are often the source of potentially catastrophic fatigue cracks. The requirement to consider both the crack initiation and propagation phase under these conditions is addressed and a modelling capability is presented which shows the ability to predict some of these effects at high temperature.

Keywords: Fatigue, titanium, creep, environment

1. Introduction

As concerns grow about global warming, much focus has turned in recent years to the aero industry. ACARE (Advisory Council for Aeronautics Research in Europe) environmental goals for 2020 require a significant decrease in the production of greenhouse gases by the industry, with an 80% reduction in NOx required, along with 50% reductions in CO_2, fuel use and perceived noise [1]. To achieve these goals R&D efforts will need to be pushed faster and further than ever before. Whilst airframe design offers a clear opportunity to improve efficiency, many of these research opportunities relate to the gas turbine engine.

Titanium and nickel alloys are stalwarts of the gas turbine engine due to their contrasting properties. Titanium alloys offer an excellent strength to density ratio and account for approximately 40% of the material in the aeroengine by volume. Nickel superalloys by contrast have a significantly higher density but are capable of operating at temperatures far in excess of titanium alloys. With engine efficiency increasing as a function of temperature the importance of these alloys has become clear.
Whilst new nickel alloys are still being readily developed for high temperature applications, particularly in the field of single crystals, work on conventional titanium alloys has focussed on extending the operating conditions of existing alloys. Indeed probably the most popular titanium alloy, Ti6-4 (IMI318), has varied little from its original design in the 1950s[2].

Clearly to minimise weight it is preferable to utilise titanium alloys in preference to nickel alloys as extensively as possible. At low temperatures designers need only to consider fatigue damage processes. However as temperatures increase, a situation arises where creep and environmental damage mechanisms also begin to play an important role, and limit the use of $\alpha+\beta$ Ti alloys to approximately 500°C. Simple linear summation for these damage mechanisms is not adequate and a more holistic approach is required. A greater understanding of these interactions has led to a situation where both titanium and nickel alloys have been employed in the aeroengine, operating under such conditions.

Clearly, however, use of materials under these conditions requires a detailed understanding of their behaviour, a situation that can be complicated by the presence of stress concentration factors. In order to combat this, a modelling capability has been derived at the Rolls-Royce University Technology Centre in Swansea that allows for prediction of crack initiation lives and propagation rates under conditions where fatigue, creep and environmental damage mechanisms interact.

2. Experimental method

As stated above, prediction of material behaviour requires a detailed understanding of the stress-strain conditions that occur under fatigue loading of the material. The laboratories at Swansea UTC include two servo hydraulic test machines equipped with precision MTS extensometers. With a 12mm gauge length these extensometers allow for recording of the stress-strain conditions under strain control loading of plain 6mm diameter specimens, according to BS7270[3]. An R ratio of -1 was generally employed to produce open hysteresis loops that allowed for accurate modelling, although other R ratios were employed to evaluate mean stress effects that particularly became important at elevated temperatures. Dwell tests with a 2 minute hold at peak strain were employed in order to evaluate the effects of creep.

Crack growth behaviour was measured by standard DC potential drop techniques[4] on either square section 7mmx7mm or 10x10mm specimens with machined corner cracks of 0.35mm, or alternatively on Double Edge Notch (K_t=1.9) specimens, Figure 1, with either a 50µm centre hole or a 0.35mm corner crack. In house data logging allowed for the monitoring of voltage throughout complete waveforms from which crack closure rates could be calculated. Fatigue testing of DEN specimens was also undertaken over a range of temperatures. The strain control, crack propagation and notched load control (DEN) tests undertaken in air are summarised in Table 1, where "trap" refers to a trapezoidal 1-1-1-1 waveform and "dwell" refers to a 1-120-1-1 waveform.

A custom built vacuum chamber was also employed for simple fatigue or fatigue crack growth tests. High vacuum conditions of approximately 10^{-6} Torr meant that environmental effects could be isolated through comparisons with standard air data. The crack propagation and notched load control (DEN) tests undertaken under vacuum conditions are summarised in Table 2.

3. Materials

Throughout the experimental programmes testing has focussed on the titanium alloy Ti6246, with specimens removed from a standard disc forging, the heat treatment and processing conditions of which are considered proprietary. Ti6246 is widely used in the aerospace industry due to its excellent strength to density ratio and good high temperature properties. An example of the microstructure of Ti6246 is shown in Figure 2. It shows a fine Widmanstätten microstructure and relatively random texture that would be considered typical of a material processed above the beta transus temperature.

4. Background

A previous research programme focussed on crack propagation rates in Ti6246 under conditions where fatigue, creep and environmental interactions become important[5]. Clear evidence is shown of how these damage mechanisms can interact in a way that leads to severe degradations in the life experienced in fatigue crack propagation. Figure 3 shows how these mechanisms can be isolated through strategic use of vacuum and dwell testing. These effects are demonstrated in Ti6246, at 550°C. The 'pure fatigue' response is shown by the 1Hz sinewave testing under high vacuum conditions. The introduction of a trapezoidal waveform with 1 sec and 120 sec hold times at peak stress respectively indicate that there is a significant amount of creep damage occurring ahead of the crack tip. Significant environmental damage is seen at this temperature in Ti6246, and this is reflected in a further increase in the crack propagation rate.

5. Results and Discussion

5.1 *Stress concentrations*

The current programme aimed to build on the experience of the previous work and extend its applications, particularly in the area of notched specimens. Notched specimens act as a laboratory representation of stress discontinuities which may occur in engineering applications. These discontinuities act as stress raisers which may lead to material in the locality exceeding the yield stress. Under cyclic loading this plasticity has the potential to initiate localized fatigue cracks, which in turn may cause catastrophic failure of critical components. In contrast to the previous work, the research detailed in this paper seeks to build towards a total life prediction methodology for notched specimen behaviour. In order to achieve this both the fatigue crack initiation and propagation phases must be considered for specimens tested under these arduous conditions.

5.1.1 Crack initiation

Previous work[6] has shown that material at the notch root tends to behave in an essentially strain control manner, due to restrictions imposed by the notch geometry, despite the specimen being cycled under load control conditions. It has also been shown that due to this loading state, strain control data can be used to predict the initiation lives of notched specimens through analytical approaches such as the Coffin-Manson method, or the Walker strain method[7]. It should be noted that test specimen data included in Figure 4 is the total notched fatigue life, whereas the predictions are intended only to indicate a life to crack initiation. In strain control specimens when a crack forms it will propagate quickly to failure through fatigue damaged material. Conversely in a notched specimen, the crack travels through material experiencing stresses considerably lower than the notch root. Consequently a significant propagation phase should be considered for the notched specimen. Figure 5 shows evidence of this through DCPD monitoring of a DEN specimen. Previous tests had been interrupted when a voltage change was detected and the detection threshold indicated on the graph illustrates the smallest voltage change achieved. A crack of 2.2mm was recorded for this specimen. Despite this high threshold brought about by the coarse nature of attaching DCPD wires across the notch, Figure 6, it is evident from the graph that the crack initiates at 40-50% of the total life[8].

By applying Neuber's rule that the product of stress and strain is constant at the notch root, the Coffin-Manson equation can be utilized to make excellent predictions about the behaviour of Double-edged notch specimens (K_t = 1.9) under fully reversed loading conditions. However when mean stresses are introduced in the form of R=0 testing it is clear that the method overpredicts the lives of the specimens, Figure 4 (a). This is due to the fact that the Coffin-Manson equation that has been derived is based on R=-1 data and does not account for mean stresses. Although in an R=0 test redistribution of stress and strain at the notch root leads to a compressive minimum stress, the mean stress is still positive and leads to a reduction in life. It is interesting to note that for a sharper notch, such as a V-cylindrical (VCN, K_t=2.8) notch, the higher applied stresses at the notch root tend to lead to a closer approximation of fully reversed loading, and the predictions are more accurate.
Figure 4 (a) shows that a modified version of the Coffin-Manson equation is able to more accurately predict the R=0 data, since a mean stress dependence is now considered. However, as temperatures are increased to regimes where additional failure mechanisms become important (450°C), it can be seen, Figure 4 (b), that the modified Coffin-Manson technique begins to significantly underpredict the material behaviour. As such it was decided that the best prediction method for implementation into a fatigue model would be the Walker method.

5.1.2 Modelling damage mechanisms

With the fatigue, creep and environment damage mechanisms isolated in the experimental test programme, further work has concentrated on the generation of a predictive model. To accurately determine the stress-strain characteristics of the material R=-1 strain control testing was employed for the generation of open hysteresis loops. These loops formed the basis of predictive sub-routines developed in ABAQUS[9]. Work was initially based in air conditions so that interactions between fatigue and environment and fatigue/creep/environment could be modelled.

The model was based on the fact that under strain control conditions, localized stress redistribution allows the bulk stress in the specimen to stabilize to essentially constant peak and minimum stress conditions. From the experimental data on plain specimens the required cyclic stress-strain behaviour of the material was defined. The model used the Mroz[10] multilayer kinematic hardening approach through application of a user subroutine within ABAQUS. A series of finite element (FE) simulations of the strain control specimens were run using the subroutine to demonstrate how the initial loading ramp and the stabilised hysteresis loops may be modelled with sufficient accuracy at ambient and elevated temperatures. Figure 7 shows an example of these simulations and the ability of the method to account for the Bauschinger effect evident in this material. It should be noted, however, that the current fatigue model does not allow for time dependent effects due to creep at the higher temperatures. Whilst creep would not be expected to greatly affect the shape of the loops it would have a large effect in the presence of mean stresses. Modelling of the Double Edged Notch (K_t = 1.9) specimen was achieved through the construction of a three dimensional 1/8 symmetrical FE model using 20-noded isoparametric rectangular elements (C3D20) with 18833 nodes and 4032 elements. The element size was reduced closer to the notch root so that the mechanical response could be more accurately described in this region. Fatigue calculations were based on the stabilised stress-strain conditions at the node adjacent to the centre of the notch root.

Analytical prediction techniques showed that the Coffin-Manson equation was unable to make accurate predictions for the DEN specimen when mean stresses were involved. Instead the Walker strain technique was utilized to predict the behaviour at the notch root, with accurate descriptions of the stress and strain state produced by the FEA provided by ABAQUS. Figure 8(a) shows the predictions made using Walker and other previously documented techniques[11] for notched life prediction at 20°C. The good correlation between the differing techniques gave the confidence to extend the predictions to higher temperatures, Figure 8(b). However, it becomes clear that a method based solely on fatigue was unable to make accurate predictions, most likely due to miscalculation of the von Mises stress when creep has a significant effect on the material at the notch root.

5.1.3 *Crack propagation modelling*

A simple damage accumulation model has been constructed for predicting fatigue crack propagation in Ti 6246. The model takes a different approach to many previous studies in that rather than assuming that the process zone comprises only a fraction of the cyclic plastic zone, as is generally the case in most damage accumulation models, the process zone was assumed to be equivalent to the cyclic plastic zone. This assumption is based on the fact that damage accumulation within the cyclic plastic zone is consistent with the processes leading to crack initiation in smooth specimens, which results from the accumulation of plastic strain within the gauge cross section. This is a similar concept to that used in the calculation of fatigue lives of notched specimens, described earlier. It should be noted that the methodology does not necessarily imply that physical crack growth occurs via increments equal to the size of the cyclic plastic zone, only that the "life" of the cyclic plastic zone ahead of a crack is equivalent to that of a smooth specimen tested under identical stress–strain conditions. Calculations of damage in the process zone are based on the stress–strain conditions prevailing at the crack tip at each stage of incremental growth, which are, in turn, determined using nonlinear finite element analysis. No previous information on the fatigue crack growth rate characteristics is required. Further details of this model can be found in a previous publication[12].

Figure 9 indicates the accuracy with which the model is able to predict fatigue crack growth rates at room temperature in Ti6246, although it should be noted that at this temperature creep and environmental damage mechanisms are expected to have a negligible influence.

5.2 Observations of additional failure mechanisms

Clearly in attempting to build a total life prediction methodology at high temperatures it is necessary to describe the effects of creep and environmental damage in both initiation and propagation phases.

5.2.1 Crack initiation phase

Strain control testing was undertaken on Ti6246 samples at temperatures ranging from 20°C to 550°C. Figure 10 illustrates the influence of creep effects at the higher temperatures when a 2 minute dwell period is introduced at peak strain. Minimal relaxation is seen at 450°C but when the temperature is increased to 500°C and then to 550°C significant effects are seen. It has been shown however that any damage incurred by creep in these strain control tests appears to be offset by the associated stress relaxation in the fatigue process, resulting in a similar life to cyclic (1 sec at peak strain) tests. However, it should be noted that the case of strain control samples, where the crack propagation phase is extremely limited, may differ significantly from a notched sample, where, as described earlier, a significant propagation phase occurs. As such, consideration of creep damage ahead of the fatigue crack, shown in Figure 11, can have a more significant effect on notched specimen behaviour.

Clear evidence of the effects of creep in the notched specimens can be seen in Figure 12. The combination of fatigue and creep however does not necessarily act in a simple manner. The curves illustrate the fatigue response of the DEN specimen at 450, 500 and 550°C. The fatigue response at 550°C is clearly the poorest, but it is interesting to note that there is an improvement in life at 500°C when compared to the 450°C data. Figure 7 illustrated that at 500°C creep has begun to have a major influence. The stress relaxation associated with creep results in a situation where the peak elastic stresses at 500°C are lower than at 450°C. Consequently an increase in fatigue life occurs. At 550°C the increased creep rate is now more damaging and a reduction in fatigue life is evident.

Previous data[5] has shown the influence of environment on Ti6246 and how a clear transition is seen between lives below 10^4 cycles and those above. The transition is attributed to the cracking of an oxide layer that forms on the surface of the specimens[13]. Vacuum data in the previous work has indicated the inherent fatigue response of the material when this oxide layer is unable to form. It is interesting to compare this with the current work. Exactly the same trend is seen in the material with a marked transition at approximately 10^4 cycles in the high temperature notched specimen data, Figure 13. At 20°C however environmental interactions are minimal and the material behaves in the same manner as the previously reported vacuum data[13]. It is interesting to note that the environmental effects seemed to be apparent at temperatures as low as 80°C in the previous data.

Further evidence of these environmental effects can be seen in Figure 14. At 20°C the fracture surface of the specimen is relatively featureless, with striations marking the fatigue process. As the temperature increases however, sub-surface cracking becomes more evident. This cracking appears to be related to the increased environmental influence brought about by the higher temperatures and seemingly occurs at the interface of the α and β microstructures.

It is also useful to consider the interaction of all three damage mechanisms, Figure 15. At 550°C it may have been expected that creep damage would be the dominant mechanism. However, it can be seen that at this temperature environmental damage is actually far more significant than creep. It is also useful to acknowledge that whilst the combination of these damage mechanisms may show some cumulative effect.

Whilst it is clear from Figure 15 that environmental effects exert a greater influence on the fatigue life at these temperatures than creep, it has been shown that the response in notched specimens differs significantly from strain control plain specimens, with dwell now having a significant effect on life. This would seem to indicate that creep influences on life are mainly exerted during the propagation stage. Evidence of this interaction can be seen in Figure 11, which shows creep damage occurring ahead of the tip of the fatigue crack.

5.2.2 Modelling creep damage

In order to extend the modelling capabilities to these regimes where fatigue, creep and environmental damage mechanisms interact, it was decided that within the scope of this work to combine a fatigue damage model based on air data with a suitable creep model. To achieve this a creep model was constructed, based on the theta projection method[14]. A constitutive relationship based on the theta projection method was already available, with creep behaviour evolving with the accumulation of state variables based on dislocation hardening, dislocation recovery and internal material damage. An Abaqus-based user subroutine for this relationship was compiled which included creep rupture based on a Kachanov type failure process. Further details of this method can be found in an alternative publication[15].

Validation testing of the creep model for Ti6246, shown in Figure 16, indicate that, within the bounds of test-to-test variation, extremely accurate representations of the creep curve shape are made.

5.3 Modelling Fatigue/Creep interactions

Clearly, the measured fatigue performance at temperature highlights a combined fatigue-creep interaction. The model addresses this combined damage accumulation through a linear summation of the form:

$$\left(\frac{da}{dN}\right) = \left(\frac{da}{dN}\right)_f + \int\left(\frac{da}{dN}\right)dt$$

in which the first term on the right hand side represents crack growth due to pure fatigue while the second term provides the additional time dependent contribution due to creep damage[16]. To predict fatigue crack growth rates at high temperatures, the fatigue and creep damage models described above were integrated to form a loosely coupled model with the effects of creep and fatigue calculated separately and then combined at each time increment. The problem with combining the creep model with a fatigue model of this type is that the state variables required to store the creep data are not transferable to subsequent analysis once the crack is incremented to a new length, ($a + \Delta a_i$) since the nodal coordinates in the component differ between the two meshes. Therefore, an interpolative routine was developed to extrapolate creep damage in the specimen onto the continuously changing fatigue crack mesh method[17].

Figure 17 shows predicted fatigue crack propagation curves for two different modelling scenarios at 500°C in Ti 6246 at R=0.1 together with experimentally measured crack growth rates. In the first case, creep strain accumulation and damage were ignored so that crack propagation rates were predicted in the similar way to ambient temperature. It is evident that the model does not provide an adequate prediction of fatigue crack growth rates when creep effects are ignored. However, when both creep and fatigue damage are considered the predicted fatigue crack growth rate is considerably higher and it can be seen that the predicted behaviour overlays the experimental data extremely accurately. In this case, crack growth rate calculations were based on the total accumulated strain after creep (during the aggregate hold period at maximum load for the crack increment) and creep damage calculated using the model described above. The accuracy of the prediction is highlighted by comparison with the measured cyclic and dwell growth rates. Clearly the integration of the two damage mechanisms has considerably improved on capability for predicting fatigue crack growth behaviour at high temperatures. Ongoing application to other titanium alloys such as Ti6-4 also shows promise for the technique.

6. Conclusions

Clear evidence has been presented of the interactions of fatigue, creep and environmental damage mechanisms in titanium alloys. In Ti6246 this results in two separate regions in the fatigue curve for specimens tested in air, due to the formation of a protective oxide layer. This division does not occur in either room temperature data or specimens tested under high vacuum conditions, providing evidence of an environmental interaction that becomes important for temperatures as low as 80°C. This interaction results in subsurface cracking of the test specimens at $\alpha+\beta$ interfaces, and an increase in crack propagation rate as a consequence.

In plain specimens creep is shown to have a minimal effect on life, although its effects can be seen in the form of creep voids forming ahead of the fatigue crack tip. In notched specimens, which showed a significant crack propagation phase, the addition of a 2 minute dwell period to promote creep resulted in a decrease in fatigue life, indicating that it is during the propagation phase where this creep interaction is most significant. It is shown, however, through vacuum testing that environmental effects are more damaging than creep at temperatures up to 550°C.

Finally, a modelling capability is presented, which is based on a loose coupling between a fatigue model and creep model. The fatigue model is based on the Walker strain parameter, Mroz method for establishing hysteresis loops and a damage parameter calculated using Walker strain for notch geometries and fatigue crack propagation. The creep model is based on the theta projection method which has previously been shown to accurately describe creep rates in Ti6246.

The model shows good results in many areas. Accurate predictions are made for notched initiation lives at low temperatures, although it is clear that further development including creep effects at higher temperatures are necessary to more accurately describe the stress state at the notch root, allowing for more accurate predictions. In terms of crack propagation however, coupling of fatigue and creep models has shown the ability to make accurate predictions about the propagation rate at temperatures where creep and environmental effects are having a significant influence.

7. Acknowledgements

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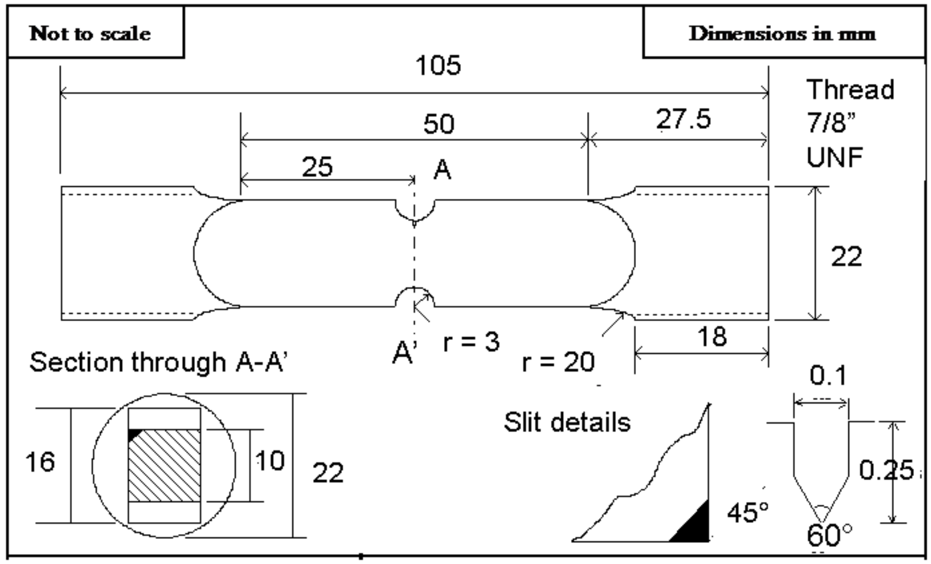
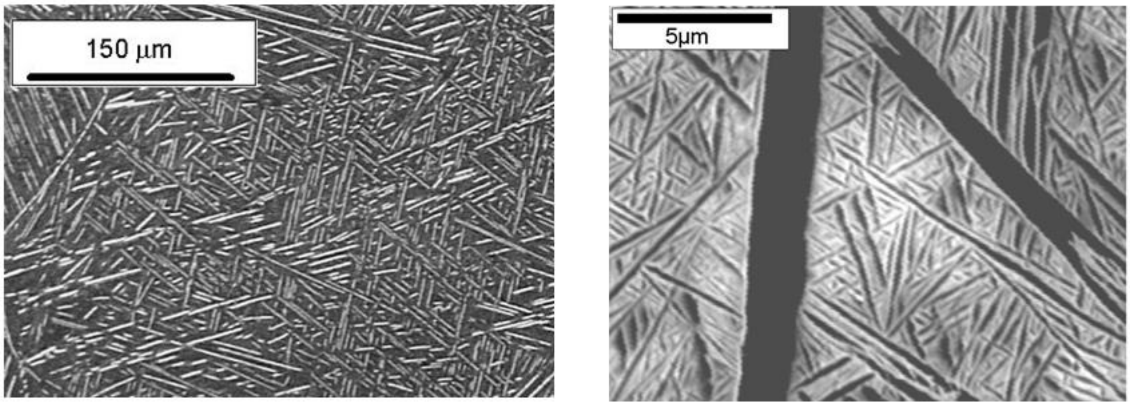


Figure 1: Double edged notch (DEN) specimen used for fatigue and crack propagation testing. Diagram is not to scale.



(a) (b)

Figure 2: Micrographs showing the microstructure of Ti6246. Discontinuous needles of alpha phase material can be observed on both large and small scales.

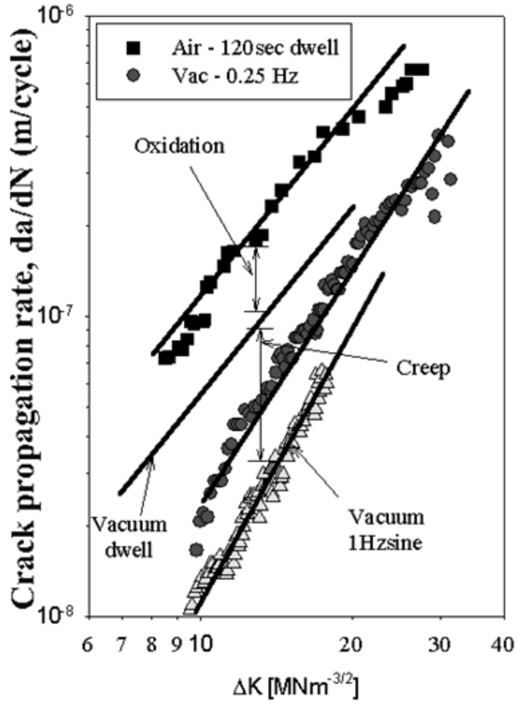


Figure 3: Fatigue, creep and environmental interactions in Ti6246 at 500°C, R=0.1. The vacuum 1Hz sin test indicates a crack propagation rate for 'pure fatigue'. The addition of dwell periods introduces creep damage, whereas testing in air introduces environmental damage

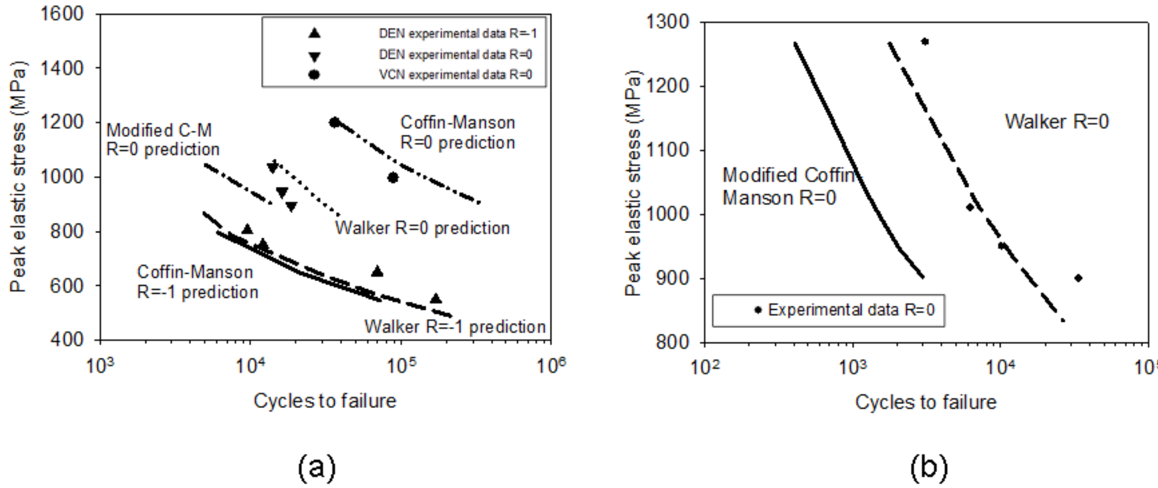


Figure 4: Methods of predicting notch initiation lives at (a) 20°C and (b) 450°C including Walker, Coffin-Manson and a modified Coffin-Manson approach which seeks to account for mean stress effects

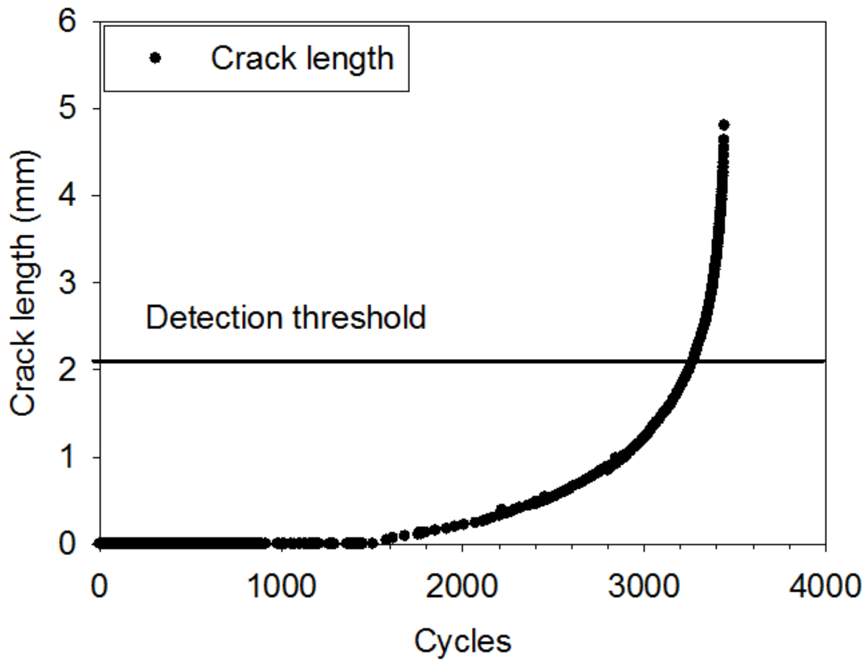


Figure 5: Detecting initiation in Double Edge Notch specimens. Using PD monitoring a crack of approximately 2mm can be detected, although the voltage trace indicates that crack initiation occurs at roughly 40-50% of the total life in this specimen

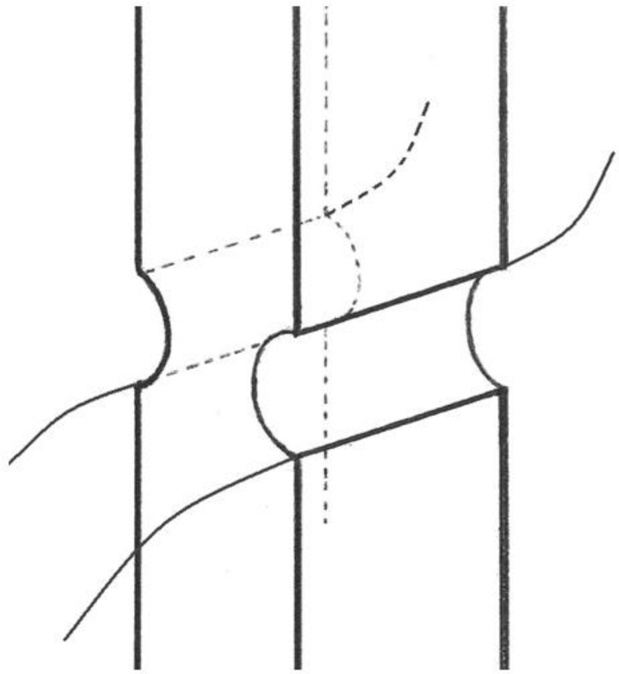


Figure 6: Attachment of platinum PD wires to allow for crack initiation monitoring.

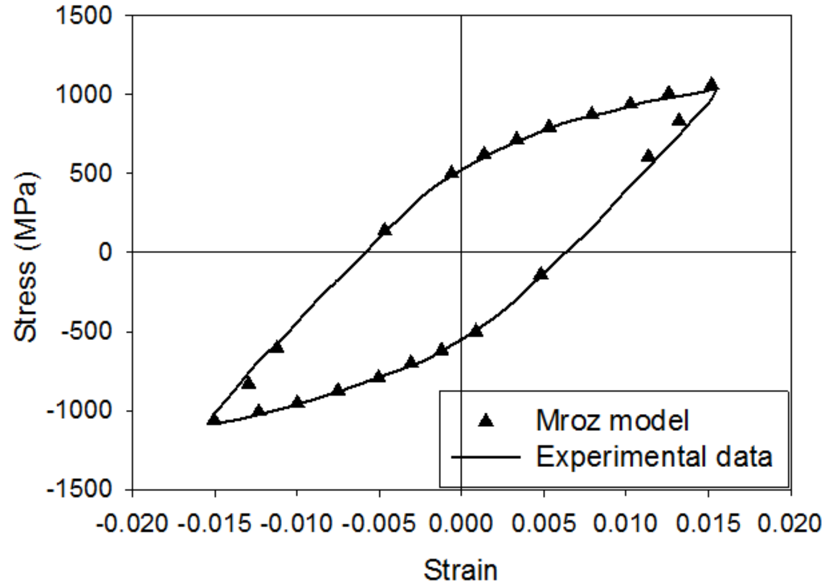


Figure 7: ABAQUS modelling of a stress-strain loop (20°C). The model is based on the Mroz multilayer plasticity model and is able to accurately replicate experimental hysteresis loops.

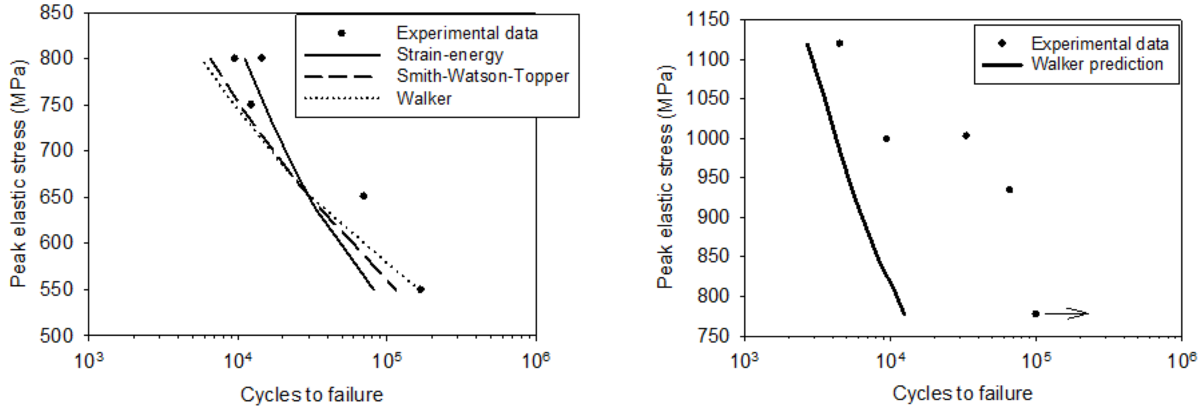


Figure 8: ABAQUS predictions at (a) 20°C (b) 500°C

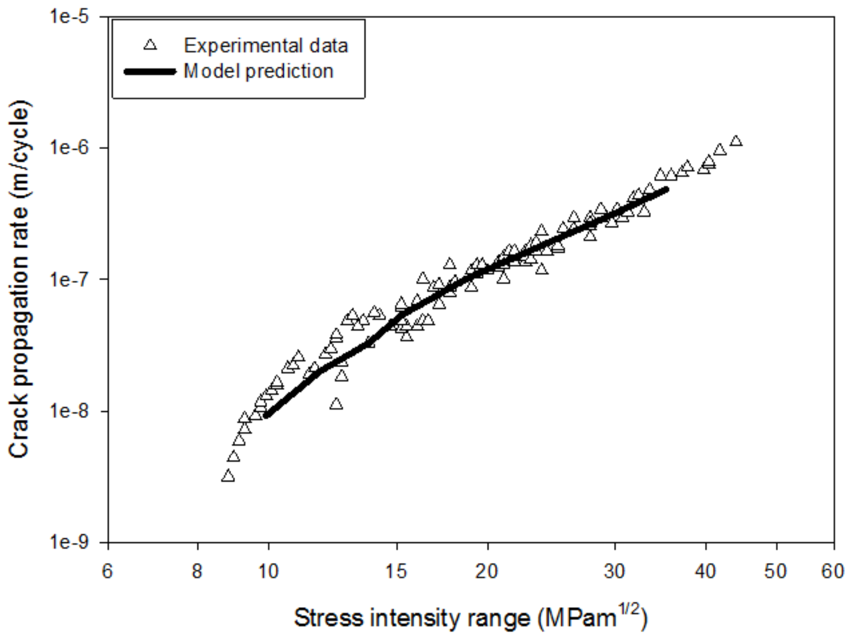


Figure 9: Prediction of fatigue crack growth rate in Ti6246 at 20°C, R=0.1. It can be seen that an excellent prediction of this stage II crack growth is achieved

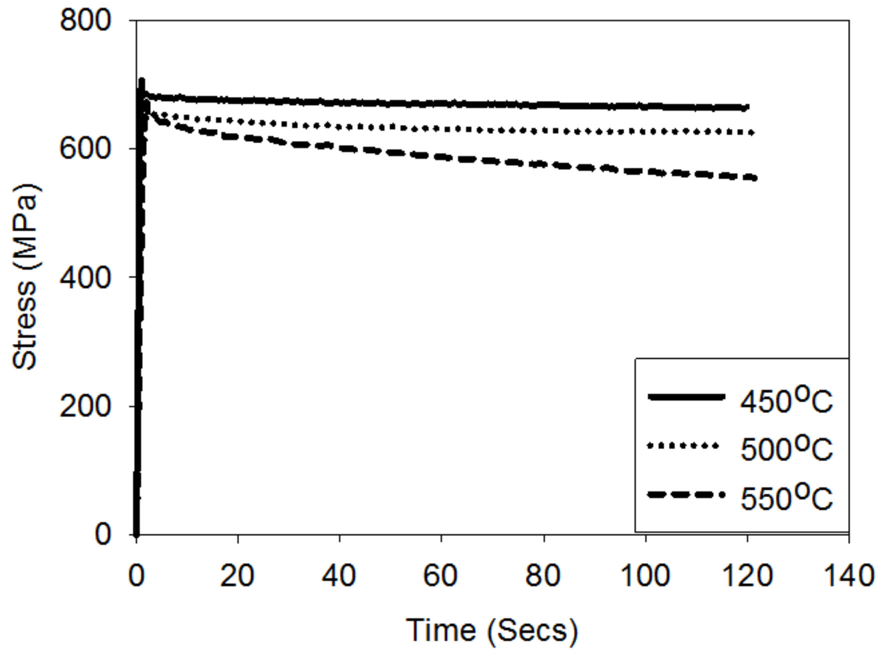


Figure 10: Stress response of Ti6246 at 450, 500 and 550°C. The graph shows the evolution of stress in the first ½ cycle of a 1-120-1-1 dwell cycle. The influence of creep at increasing temperature can be seen by the continuous decrease in stress at 550°C

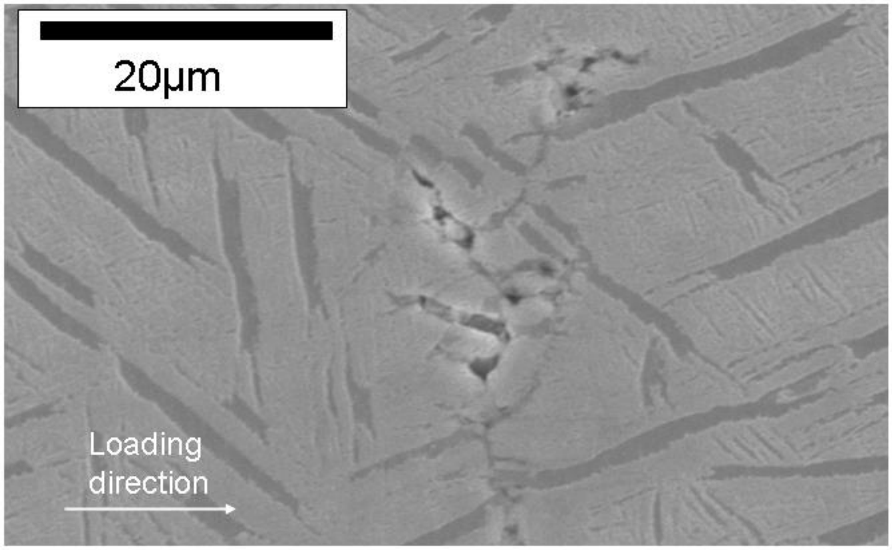


Figure 11: Evidence of creep damage in Ti6246 ahead of the fatigue crack (strain control specimen, longitudinally polished, 550°C $\Delta\varepsilon$=2%, R=0.5, N_f=511)

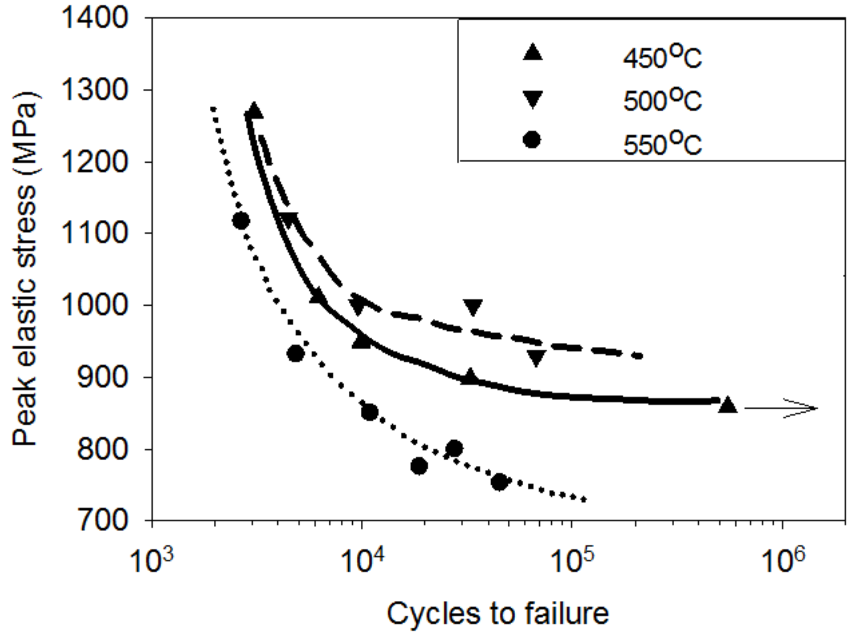


Figure 12: Fatigue lives of DEN specimens at 450, 500 and 550°C for R=0. A non linear response is seen with increasing temperature as a longer fatigue life is seen at 500°C than at 450°C

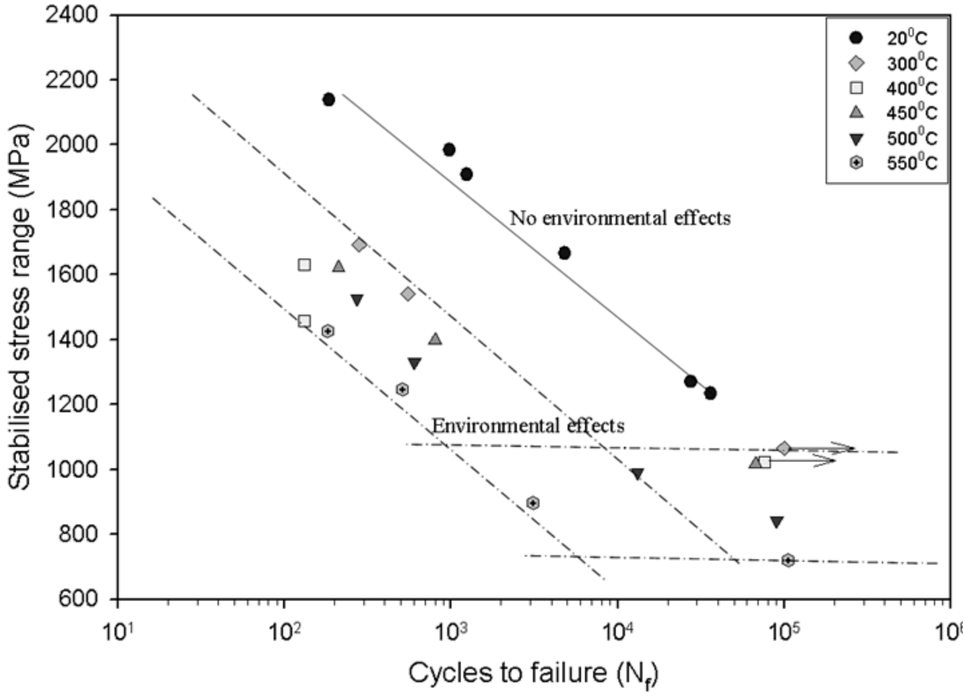
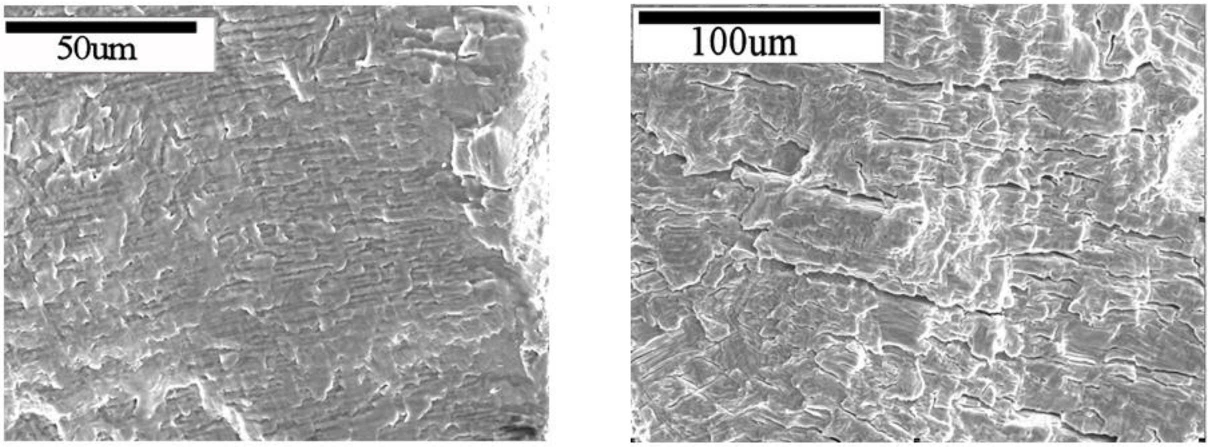


Figure 13: The influence of environment at temperatures ranging from 20°C to 550°C. It can be seen that for increased temperatures similar effects are seen to those reported previously[12] where oxide layer cracking above a critical strain range results in a 'knee' in the fatigue curve.



(a) (b)

Figure 14: Fracture surface of Ti6246 notched specimens at (a) 20°C, $K_t\sigma_{max}$=1350MPa, R=0, N_f=16736, (b) 500°C, $K_t\sigma_{max}$=1000MPa, R=0, N_f=33283. At 20°C a flat fracture surface is observed with numerous striations indicating fatigue to be the dominant failure mechanism. At 500°C interface cracking between α and β product indicates an additional failure mechanism, most likely environmental damage.

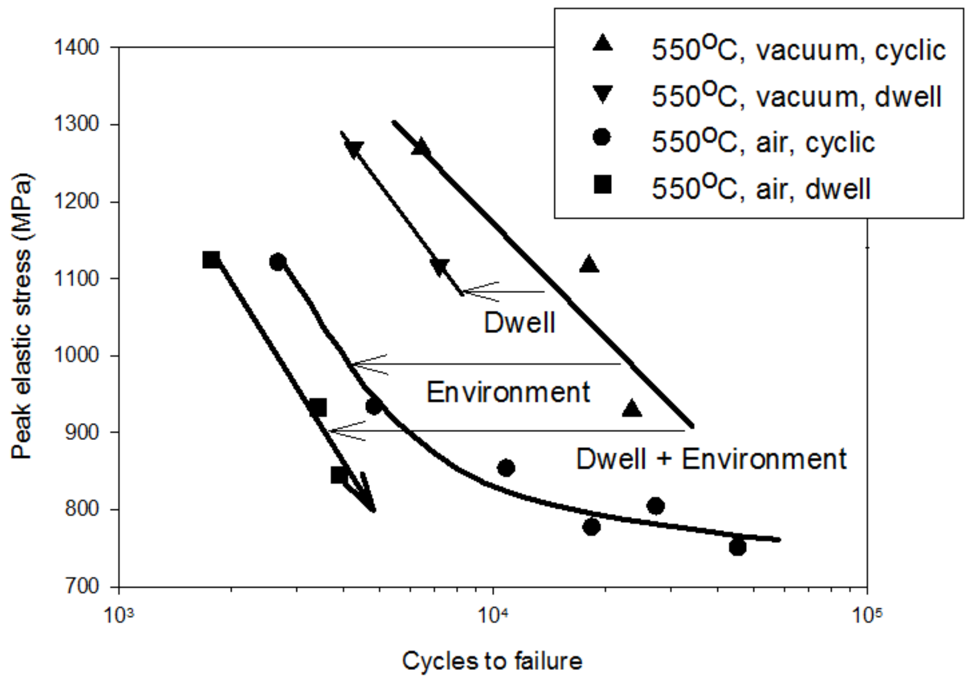


Figure 15: Fatigue lives of DEN specimens

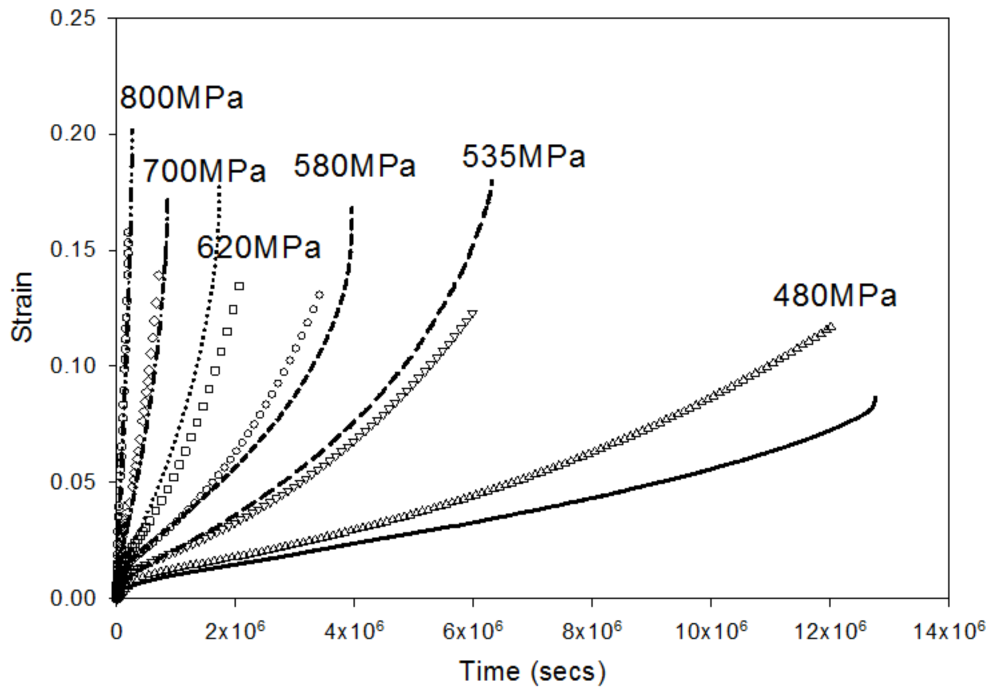


Figure 16: Modelling of creep curves in Ti6246 at 500°C using the theta projection method. Within the bounds of test to test scatter, excellent results are found. Test data is shown by lines whereas predictions are shown by symbols.

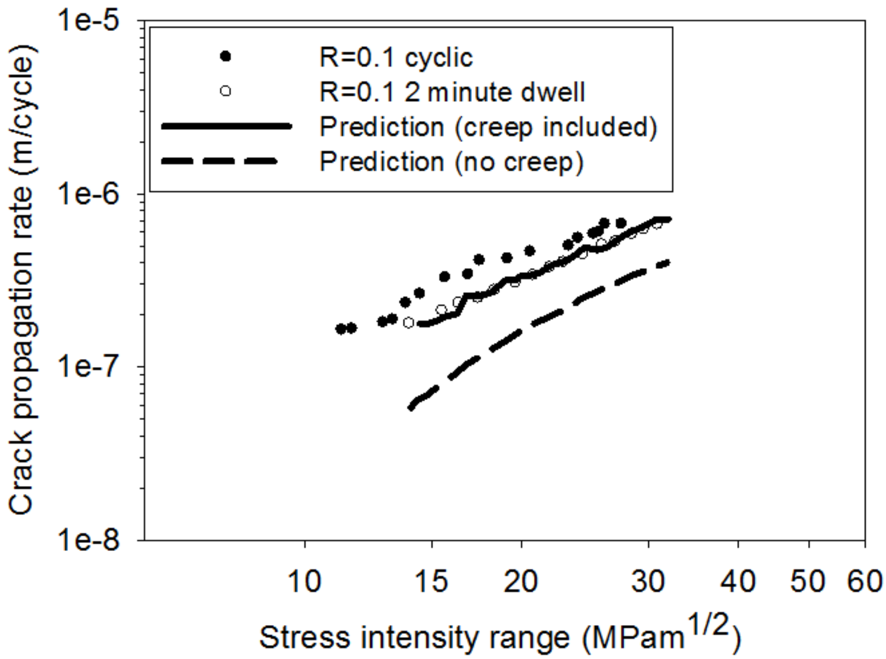


Figure 17: Predictions of crack propagation rates at 500°C using a pure fatigue model underestimate the propagation rate. The formation of a loosely-coupled fatigue-creep model however allows for accurate predictions.