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# Titanium in the Gas Turbine Engine

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## 1. Introduction

The development of the gas turbine engine over the past 60 years has been mirrored by the success of the titanium industry, with a clear symbiant relationship existing between the two industries. Immediately apparent in the early days of the evolution of the gas turbine was the need for a material which could provide the strength required for component operation, whilst at the same time providing a low enough density to allow for successful flight applications. Whilst aluminium based alloys offer an excellent strength to weight ratio, their operation is limited to temperatures below approximately 130°C, reducing possible applications within the gas turbine to a minimum. 300 series stainless steels offer a similar strength to most conventional titanium alloys, but come with a significant density penalty of over 50% and, whilst offering reductions in cost, do not provide significant benefits in terms of operating temperatures.

Titanium however, has long been viewed as having a desirable balance of properties for applications towards the front end of the gas turbine engine (i.e. fan discs/blades, compressor discs/blades, along with other smaller components). Titanium has a density of 4.5g/cm$^3$ (which, apart from a limited number of alloys such as Ti811, does not vary significantly in alloys considered for aerospace applications) which is higher than aluminium, but lower than nickel and steel alloys. Titanium is allotropic with a HCP lattice ($\alpha$ phase) stable to 882°C, transforming to a BCC ($\beta$ phase) lattice above this temperature. Alloying elements act to stabilize either of these phases (Al, Sn for example stabilize the alpha phase, whereas Mo, V, Cr stabilize the beta phase) meaning that the transformation temperature can be altered, and subsequently the proportions of each phase existing at room temperature can be varied. The morphology of these phases may however vary, dependent on the process history, with alpha phase material being classed as primary alpha (persisting during heat treatment in the $\alpha+\beta$ phase field) or secondary alpha (structures arising from the $\beta \rightarrow \alpha$ phase transformation). This allows for the development of a range of bimodal microstructures which provide titanium alloys with inherent strength and also allows for further refinement of properties through various heat treatment and processing regimes. For example designers requiring creep strength and good elevated temperature properties may choose to opt for alloys with more alpha stabilizers (alpha or near alpha alloys), whereas metastable beta alloys, which are heavily beta stabilized offer improved forgeability. Alpha-beta alloys contain a more balanced mix of stabilizers and are widely used due their balance of properties. Ti6-4 (Ti-6Al-4V) for example has been a stalwart of the titanium industry since the 1950s due to its good weldability, relatively high strength and good fatigue properties.

The continued extensive use of titanium in the gas turbine, however, is constantly under threat, with potential new technologies showing promise at the lower temperature end of the gas turbine (fan blades) and at higher temperatures (HP compressor). Composite fan blades offer designers the opportunity for further weight reductions and, although concerns may still be raised over impact resistance, these materials offer great incentives to replace Ti6-4 as a fan blade material. Furthermore, in order to operate gas turbine engines more efficiently, it is necessary to continue to raise the temperature capability of the engine so that fuel can be burnt at temperatures closer to the stoichiometric value and also to achieve a higher compression ratio of the gas through the compressor stages. The second of these issues impacts significantly on the materials utilised within the compressor, since a higher pressure ratio will result in an increase in temperature where high temperature titanium alloys, such as Ti834 are utilized as disc materials. Ti834 was developed for high temperature applications and shows exceptional properties up to approximately 630°C. However, as operating temperatures at the disc rim increase, it clearly becomes necessary to consider viable alternatives, since Ti834 is limited by environmental degradation in the form of alpha case formation. Unfortunately however, no other titanium alloys show appropriate properties at temperatures higher than this, and designers are forced to consider other alloy systems. Nickel alloys are most commonly utilised as replacement alloys, although a significant density penalty is attached, with typical intermediate temperature alloys such as IN718 having a density of 8.19g/cm$^3$. Clearly on this basis designers will opt to utilise high temperature titanium alloys as far as possible to avoid these increases in weight. With pressure being applied to the use of titanium in the gas turbine from materials offering either lower density or a higher temperature capability, particularly in the case of $\alpha+\beta$ alloys, it is clear that it is necessary for the titanium industry to further develop the class of alloys for in service applications. However, it would be unrealistic to assume that advancements in terms of mechanical properties can be maintained through the development of new, improved alloys as has been the case in the past. Whilst alloy refinement and development may still contribute to these advances, it is clear that alternative, innovative approaches are necessary to extract further improvements in performance. The current work seeks to demonstrate three areas which may offer opportunities for advancement:-

i. The harnessing of crystallographic texture. The orientation of the HCP alpha phase lattice can result in significant anisotropy in mechanical properties. Whilst original research into titanium alloys sought to minimise this anisotropy, more recently it has been acknowledged that it should be possible to match the best properties from the textured material with the most demanding loading directions.
ii. The development of appropriate fatigue lifing methods for alloys operating in conditions where additional failure mechanisms such as creep and environmental damage interact with fatigue. Whereas the traditional view of engineers was to ensure that materials were operating at temperatures below where significant creep deformation would occur, improved lifing techniques enable accurate predictions to be made in these temperature regimes, allowing for safe operation.
iii. An improved understanding of the effect of processing on alloys which may prove extremely sensitive to issues such as residual stress. It is acknowledged that processing of components is likely to produce a less than perfect surface condition, and that the effects of surface roughness, residual stress and 'damage' to the material may cause

variations in the mechanical properties. These variations are rarely simple, with for example, the residual stress conditions being dependent on temperature and dislocation density and a lack of understanding may result in the requirement for overly conservative safety factors.

## 2. Generation of test data

The mechanical test data detailed in the following section was produced at Swansea University as part of a number of academic programmes funded either in part or fully by EPSRC, Rolls-Royce plc and TIMET UK.

## 3. Potential developments in titanium alloys

### 3.1 Crystallographic texture (Ti6-4)

The highly anisotropic nature of the HCP α phase lattice clearly gives rise to potential variations in mechanical properties of titanium alloys. This can be demonstrated by early work on the subject (Zarkades & Larson, 1970) which illustrates the variation of Young's modulus with crystal orientation, as shown by Figure 1.

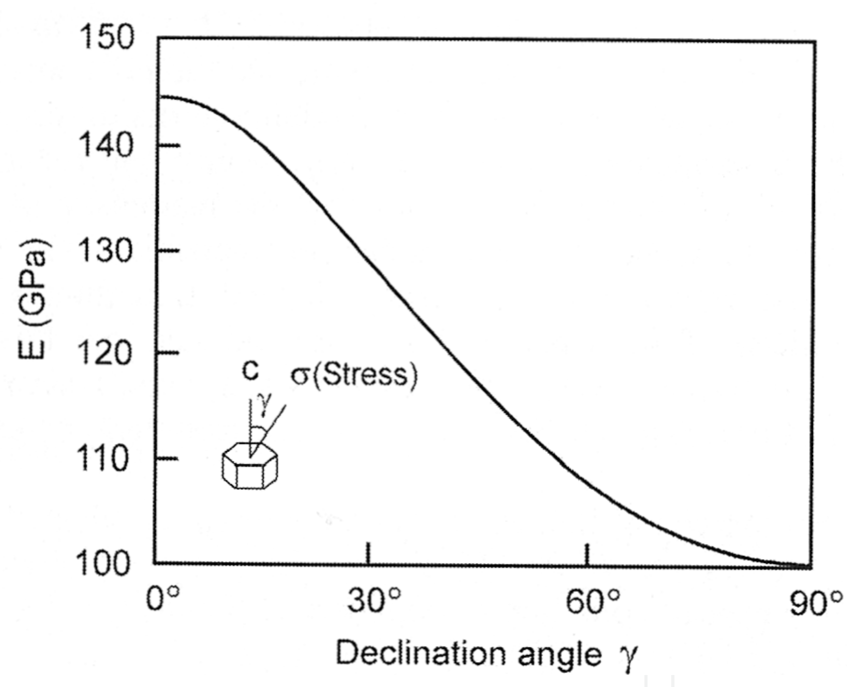


Fig. 1. The dependence of Young's modulus on increasing angle with c-axis.

It is clear that the due to the denser atomic packing along the c-axis (<0001> direction) a maximum value of the Young's modulus occurs in this direction, which shows a gradual decrease with increasing angle made with the c-axis. It is also apparent that this variation can account for differences of up to 40GPa, which significantly alters the mechanical response of the alloy. However, these changes do not only affect elastic deformation of these alloys, but also the plastic deformation, in terms of the orientation of slip planes with relatively low critical resolved shear stress (CRSS) values. As such it is necessary to understand the effects that this 'crystallographic texture' may impart to the alloy.

Clearly the anisotropy of the HCP lattice within a single grain demonstrates only the most extreme case. In terms of macroscopic properties, the averaging of these orientation effects over many thousands of grains will reduce the impact of crystallographic texture. However, as previously demonstrated (Lutjering, 1998) various forms of material processing tend to produce alignment of grain orientations, and macroscopic textures may occur which produce anisotropy in the mechanical properties of the alloy. As stated, these variations will affect not only the elastic deformation of the material, but also the plastic deformation through slip behaviour.

Fatigue accounts for approximately 80% of all in service failures and is an essential design criterion in any engineering application. LCF can be defined as failures in the region $10^3$-$10^5$ cycles, and typically involves bulk plastic deformation within the material, whereas HCF failures (>$10^5$ cycles) usually exhibit only localized plastic deformation. Both however are affected by crystallographic texture, and it is important that designers understand the potential variations of this mechanical anisotropy. Whilst research in the 1970s sought to minimise the variations to produce a more isotropic product, more recently attention has turned to texture as a means of extracting improved properties from the alloy.

Many studies (Bowen, 1977; Peters et. al., 1984; Evans et. al., 2005a) have focussed on the type of variations in monotonic, axial fatigue and torsion-fatigue that can be expected in strongly textured alloys. However, for many design applications these conditions are overly simplistic. The presence of stress raising geometric features results in a non-linear stress state in components, which requires evaluation. In the study undertaken at Swansea, consideration was given to these features, which are represented in a laboratory environment by notched specimens. The geometrical discontinuities give rise to biaxial or even triaxial stress states which have not yet been thoroughly evaluated in textured materials. Furthermore, previous work has tended to focus on fully reversed (R=-1) or zero-maximum (R=0) loading conditions. The current work sought to further understanding by considering R ratios from R=-1 to R=0.8.

The titanium alloy Ti6-4 has long been regarded as the workhorse of the titanium industry and accounts for approximately 60% of total titanium production (Boyer, 1996). It is an $\alpha+\beta$ alloy which is used in all forms, including forgings, bar, castings, foil, plate and sheet. In the current study however, only the plate form is considered. Uni-directional (UD) rolling of the alloy within the $\alpha+\beta$ temperature field usually leads to the formation of a transverse or basal/transverse texture. The current material is no exception with a bimodal microstructure with an average primary alpha grain size of 15μm (some deviation from equiaxality was shown in the form of slight elongation towards the rolling direction), and a basal/transverse texture with a x3 random intensity as shown in Figure 2, recorded over an area of 0.5 x 0.5 mm. The crystallographic texture of the material is completely described by the three orthogonal pole figures shown in Figure 2.

A number of previous studies have also focussed on the behaviour of the material under load controlled conditions. However, a number of potential applications for textured alloys more closely simulate strain controlled deformation behaviour, mainly because of the constraint of surrounding material. It is also argued that material at the notch root in tested specimens (and therefore at stress raising features in components) undergoes an essentially strain control type of deformation (Evans, 1998). It is therefore critical that the effect of texture under this mode of deformation is accurately characterised.

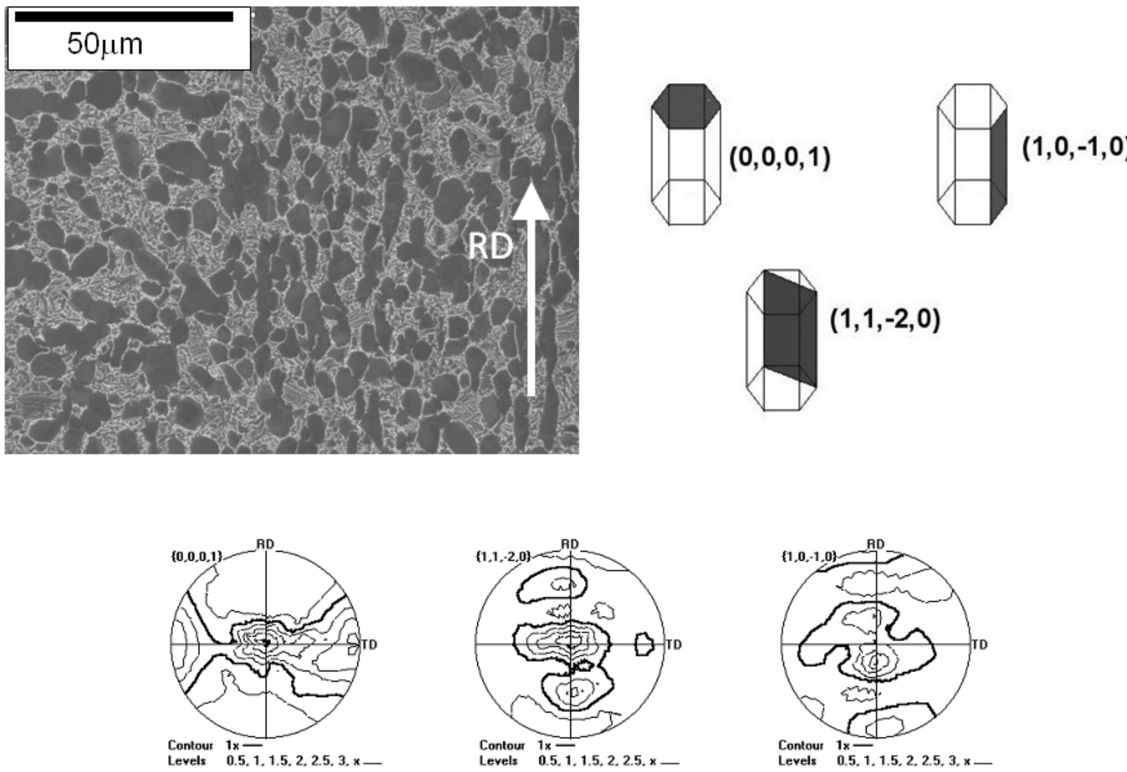


Fig. 2. Microstructure and texture of Titanium 6-4 UD plate.

### 3.1.1 Plain specimen behaviour

Figure 3 illustrates the type of effect that may be seen in textured alloys. Under strain control testing at R=0 (20°C, 1-1-1-1 second trapezoid cycle) it can be seen that specimens taken parallel to the rolling direction of the material show longer fatigue lives than counterparts taken from the transverse direction of the plate (TD), i.e. at 90° to the rolling direction. Initially this result may be considered counterintuitive; the increased density of basal planes perpendicular to the TD direction results in a higher modulus in the TD specimens, and also higher yield stress and UTS values. However, in order to understand this effect, it is necessary to consider the behaviour of the material under strain control, and the effect of the material texture.

Figure 4 illustrates the evolution of the maximum and minimum stress values achieved during a strain control test with a peak strain of 1.4%. It can be seen that there are significant differences between the RD and TD specimens, with considerably more stress relaxation in the early part of the test in the RD specimen. This is related to the availability of prismatic planes (which have a low critical resolved shear stress in titanium at room temperature) for slip in the early part of the test (see Figure 2). This leads to the TD specimen operating at a higher maximum stress. In combination with this, the TD specimen also has a higher modulus, and consequently a lower minimum stress during the test. The TD specimen therefore operates over a larger stress range for a given strain range and shows a reduced fatigue life. When considered only on a stabilised stress range basis, previous work has shown that no difference in fatigue life occurs between the RD and TD specimens in this material.

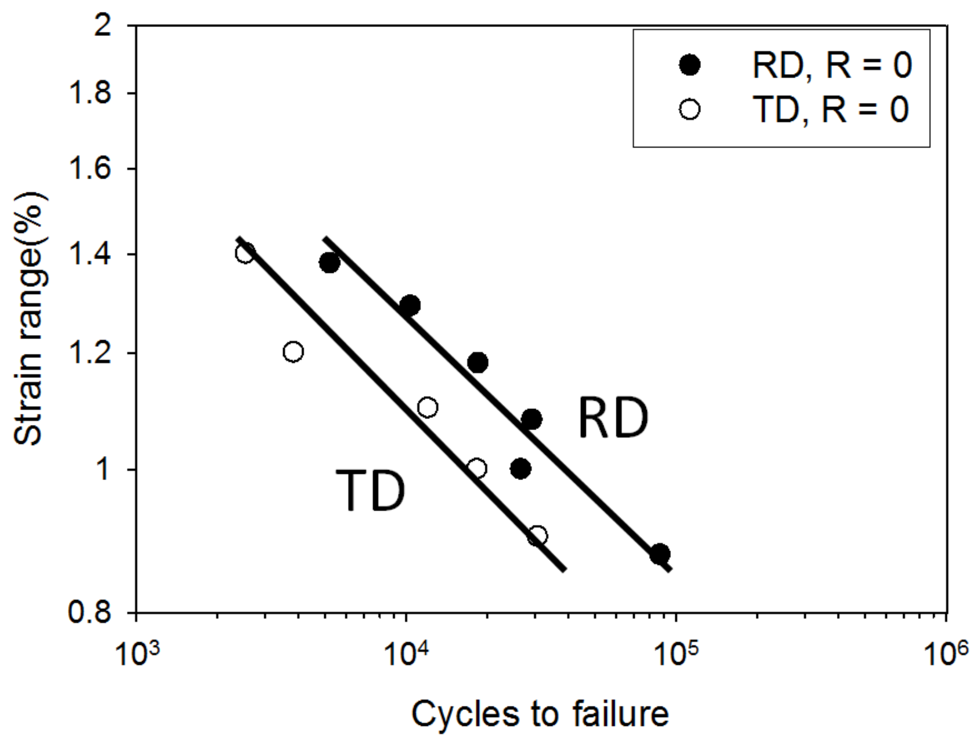


Fig. 3. The effect of orientation on the strain-life of Ti6-4.

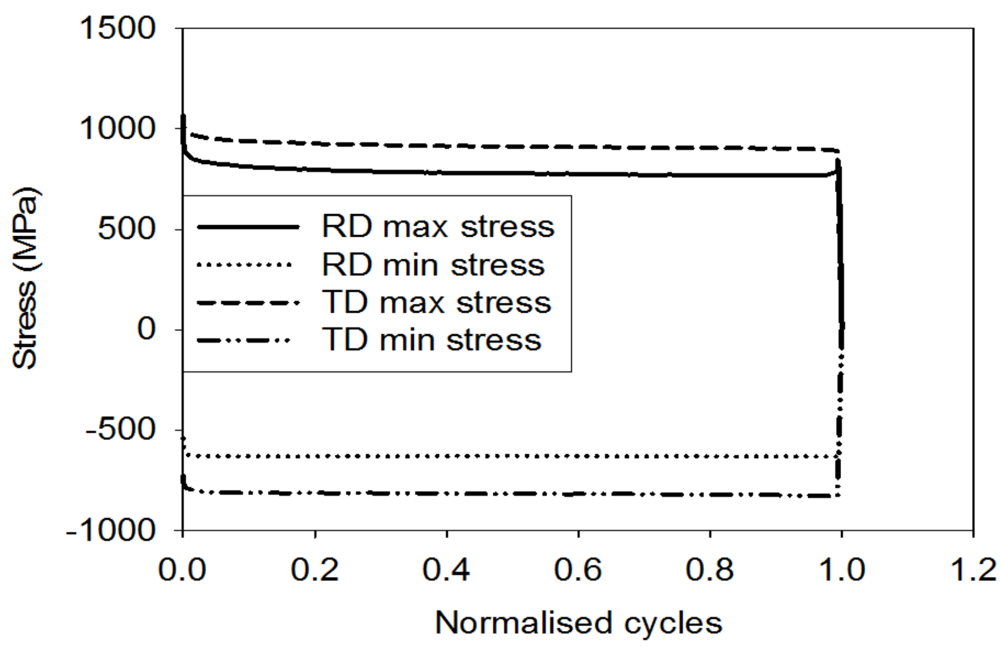


Fig. 4. The effect of orientation of the stress response of Ti6-4 under strain control loading ($\varepsilon_{max}$=1.4%, R=0).

### 3.1.2 Notched specimen behaviour

In considering notched specimen behaviour, it is important to acknowledge the requirement for a predictive methodology, to enable designers to extrapolate to conditions for which reliable test data does not exist. Previous work has shown that the Walker strain approach

(Walker, 1970) is an appropriate method for these types of predictions. The Walker strain relationship is an empirical method for correlating R values and involves correlating strain control data of different R ratios, allowing for the derivation of a 'master curve'. As stated earlier, the material at a notch root is assumed to experience strain control type conditions, due to restraint from material surrounding the critically stressed volume of material. Through application of Neuber's rule (Neuber, 1968), that the product of stress and strain is a constant, conditions at the notch root can be approximated allowing for the calculation of the individual Walker strain value for that specimen. Subsequently a predicted life can be inferred from the 'master curve' based on the strain control data. This approach has been found to be accurate for similar titanium alloys to Ti6-4 (Whittaker et. al., 2007), but has not previously been tested on a textured alloy.

During the course of the work, two notched specimen geometries were tested, both with cylindrical notches; the first was a V shaped cylindrical notch (VCN) which has a stress concentration factor, $K_t$, of 2.8, the second a round cylindrical notch (RCN) with a $K_t$ of 1.4. Initially apparent from Figure 5 is the fact that no orientation effect appears to exist in the RCN specimen, with both RD and TD specimens showing similar fatigue lives to the plain specimen data. However, this is not the case with the VCN specimen, as shown in Figure 6, with the RD specimens showing longer fatigue lives than the TD specimens.

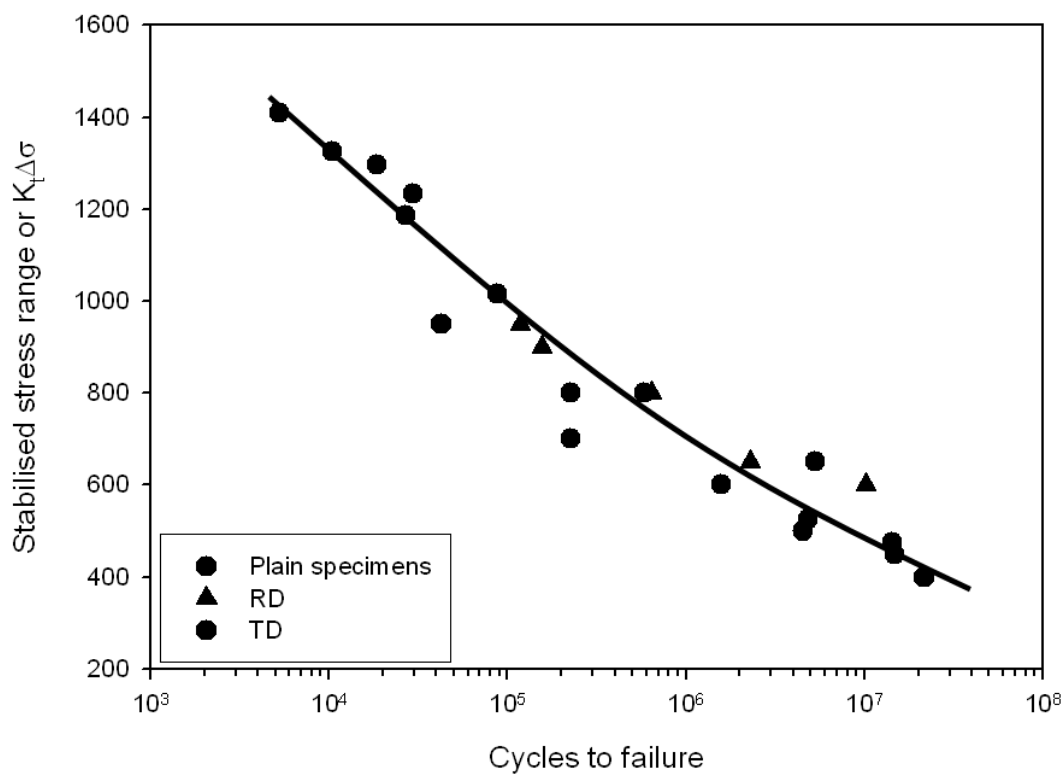


Fig. 5. Comparison of notched (RCN) and plain specimen response showing no orientation effect.

To interpret these results, it should be noted that these notched specimen tests are performed under load control; it is the geometry of the notch which imposes strain control type conditions on the material at the root of the notch. Figure 5, showing the results for the RCN specimen, is illustrative in a number of ways. Along with the fact that no orientation effect exists, it can also be seen that RD and TD specimens show similar fatigue lives. Furthermore, the notched specimen behaviour correlates well with the plain specimen response. The VCN specimens, however, do not follow either of these trends, Figure 6. Specimens in the RD orientation show longer fatigue lives than either plain or RCN specimens. This is consistent with previous experience since a lower volume of material is critically stressed in the VCN specimen. Since fatigue is essentially probabilistic in nature and relies on 'weak links' present in the material to initiate the fatigue process, a lower material volume infers a lower probability of a 'weak link' being present, and hence a longer fatigue life is statistically more likely.

The fact that the RCN specimen shows no orientation effect and correlated well with the plain specimen data when plotted on a stabilised stress basis indicates that a lack of constraint is occurring at the notch root. In this case a large volume of material is critically, or near critically stressed, similar to the plain specimens. Since the notch testing is performed under load control, the lack of constraint at the notch results in a shallow stress gradient, and hence the material at the notch root experiences conditions closer to load control than strain control. As a result these specimens behave like the plain specimens when considered on a stabilised stress basis, with no orientation effect. In the VCN specimens the stress gradient is far steeper, constraining material at the notch root, which then behave like the plain specimens, when considered on a strain range basis, and RD specimens show longer lives than TD specimens for the same reasons described in plain specimens (i.e. changes in relaxation behaviour and differences in modulus), as explained in the previous section.

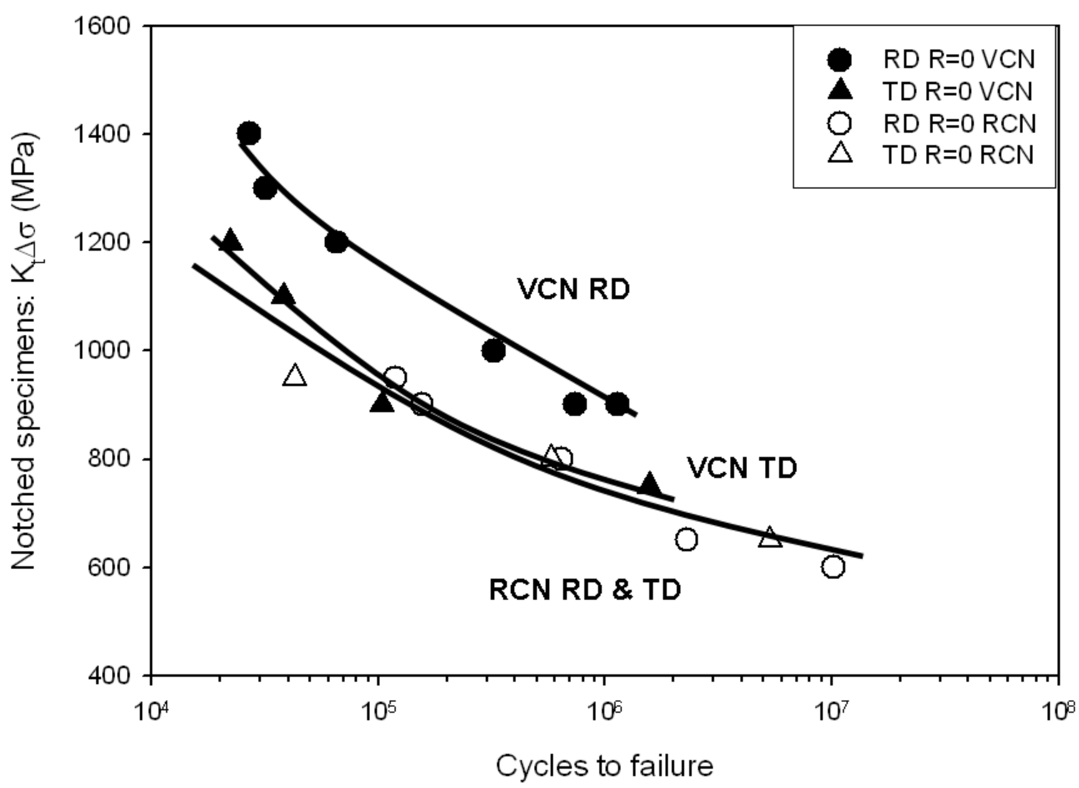


Fig. 6. Comparison of notched specimen fatigue lives showing an orientation effect in the VCN notch, whereas no such effect exists in the RCN notch.

In considering the ability of the Walker strain method to accurately predict fatigue lives, only RD specimens are currently considered, although similar calculations can be made for TD specimens (Evans & Whittaker, 2006). Although the Walker strain method is a relatively simplistic method, and does not compensate for notch type, it is a useful approach that has previously been shown to give excellent results in titanium alloys (Whittaker et. al., 2007). Figure 7 shows the type of predictions which can be made using this approach, over a wide range of R ratios. In order to consider a total life prediction methodology it should be recognised that this type of approach predicts only fatigue crack initiation in notched specimens. In strain control specimens, when a crack initiates, it will propagate quickly to failure. This is not the case in a notched specimen where the crack will grow more slowly through material away from the notch root. Previous crack monitoring work has shown that assuming a propagation phase of 50% of the total life allows for reasonable predictions (Whittaker et. al, 2010a).

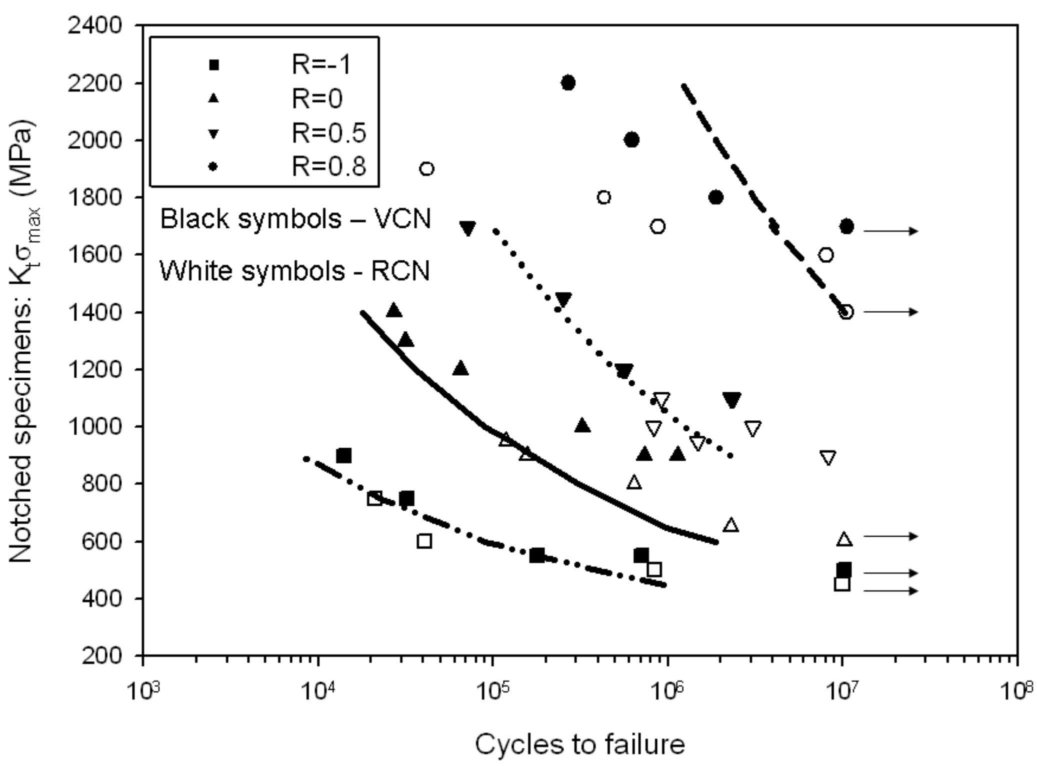


Fig. 7. Predictions of notched fatigue lives in RCN and VCN notches by the Walker strain method.

Based on these assumptions it is clear that excellent predictions are made for R ratios of -1, 0 and 0.5. However, significant over predictions are made at an R=0.8, particularly for the RCN specimens. The reason for this lies in the introduction of additional failure mechanisms. Strain accumulation at low temperatures has been widely reported in near α and α+β titanium alloys and is loosely termed 'cold dwell'. Particularly at high mean stresses, these failures are characterised by the formation of quasi-cleavage facets which form due to stress redistribution from so called 'soft' (suitably orientated for slip) grains onto 'hard' grains (unsuitably orientated for slip), as shown by the Evans-Bache model in Figure 8(a) (Bache & Evans, 1996). Clear evidence of these facets was found in both RCN and VCN R=0.8 specimens, although an increased density was found in the RCN specimens. The result of this is the reduction in fatigue lives (when compared with the Walker predictions) seen in Figure 7. The effect is more pronounced in the RCN specimens because of the larger amount of material being critically or near-critically stressed.

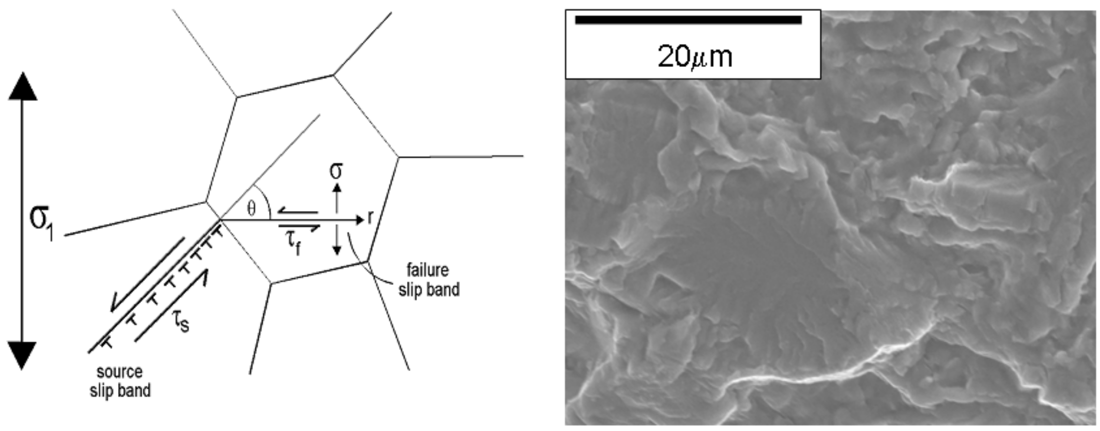


Fig. 8. The Evans-Bache model for facet generation in titanium alloys, with an example facet from an RCN, R=0.8 notched specimen.

Whilst it is clear that it is possible to accurately life notched specimens in a textured alloy, it is also evident that there are limitations. In the current work predictions have been made based on strain control data from the same orientation. Without this it is impossible to make accurate predictions. It is also apparent that for Ti6-4 there is a limited range of R ratios over which predictions can be made, with additional failure mechanisms playing a role.

### 3.2 High temperature lifing (Ti6246)

As temperatures rise in the gas turbine engine designers turn to titanium alloys with a higher temperature capability than Ti6-4, for which operation is limited to less than approximately 350ºC. Ti6246 (Ti-6Al-2Sn-4Zr-6Mo) is such an alloy with good low cycle fatigue properties and improved creep resistance over Ti6-4, Figure 9. It is immediately apparent that the microstructure of Ti6246 differs significantly to Ti6-4, showing a fine Widmanstatten microstructure that would be typical of a material processed above the beta transus. The fine nature of the microstructure infers the high strength of the material and also offers good resistance to crack propagation.

Widely used as a compressor disc alloy, Ti6246 has traditionally been employed at temperatures where creep effects would not be considered significant. However, it is not necessary for the alloy to be limited in this way provided appropriate lifing techniques are employed. The following work describes the construction of a total life prediction capability for fatigue at high temperatures in the alloy. Again, the focus of the work is on notched specimens, due to the importance of the stress raising features within the gas turbine engine. Figure 10 demonstrates the importance of considering additional failure mechanisms to fatigue by considering crack propagation rates at 550ºC in Ti6246. The vacuum 1Hz sinewave data (square symbols) represent solely the influence of fatigue on the crack propagation rate whereas the circular symbols indicate that as a dwell period is added to the waveform, by employing a trapezoidal 1-1-1-1 waveform, a significant increase is seen in the crack propagation rate. This is further increased by adding a 2 minute dwell period at peak

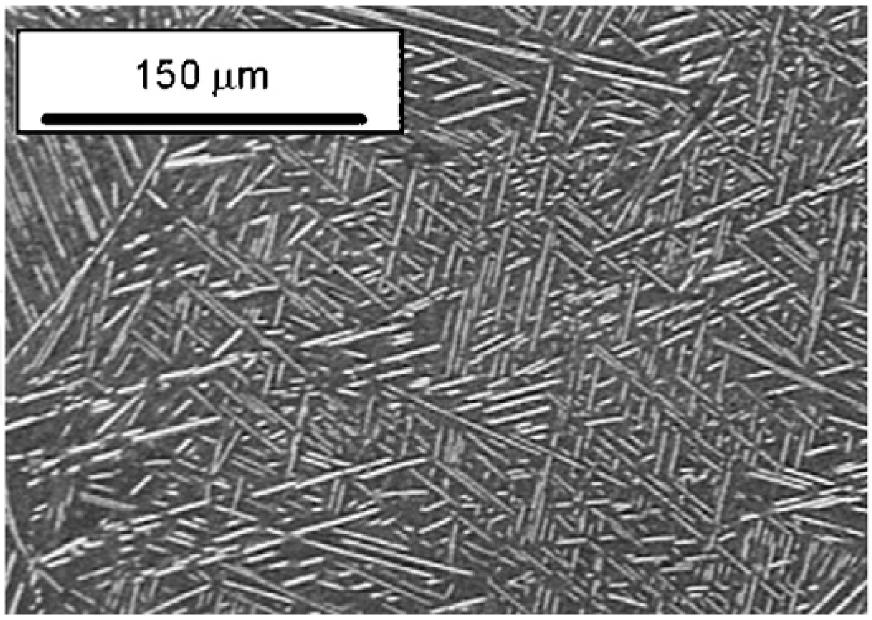


Fig. 9. Micrograph of Ti6246, showing a fine Widmanstatten type microstructure.

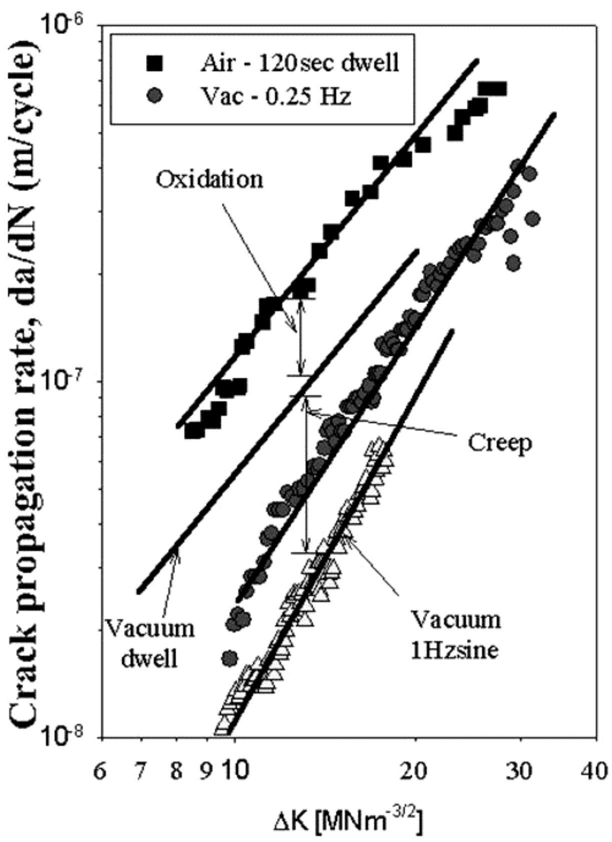


Fig. 10. Fatigue, creep and environmental effects in crack growth in Ti6246 (Evans et. al., 2005b).

load (1-1-120-1 waveform) as indicated. This increase in crack propagation rate is due to the effect of creep, with evidence seen of creep voids ahead of the crack tip. However it is also clear that at this temperature, creep and fatigue are not the only damage mechanisms in operation. For tests conducted in air, rather than under high vacuum ($10^{-6}$ mbar) conditions, a significant further increase in propagation rate is seen when the same 1-1-120-1 second trapezoid waveform is applied. This effect is environmental damage and as indicated by the graph, also requires consideration, since the increases in crack growth can be similar to, or even surpass those due to creep.

Whilst these results give an indication of the roles of fatigue, creep and environmental damage, it is clear that in order to build a total life prediction capability, their effects on fatigue crack initiation must be considered.

### 3.2.1 Fatigue modelling

As described previously the Walker strain method (Walker, 1970) has been shown to be a useful approach to the prediction of notched specimen behaviour, particularly in terms of predictions over a wide range of R ratios. However, the previous analysis was performed only at room temperature and it is necessary to investigate whether the Walker strain approach still offers accurate results at higher temperatures. In this work the notch considered is a double edged notch (DEN) with a $K_t$ = 1.9.

Figure 11 illustrates predictions made using the Walker strain approach at 20ºC and 450ºC, with notch root conditions again approximated by use of Neuber's rule (Neuber, 1968). As described previously, these predictions do not account for the crack propagation phase of a notch test and assuming a propagation phase of approximately 50% of the total life has previously been shown to be a reasonable assumption (Whittaker, 2010a). Whilst predictions under R=-1 loading conditions are excellent, it can be seen that predictions for R=0 tests at 20ºC and 450ºC tend to be non-conservative when the propagation phase is added. This is obviously undesirable for designers of critical parts.

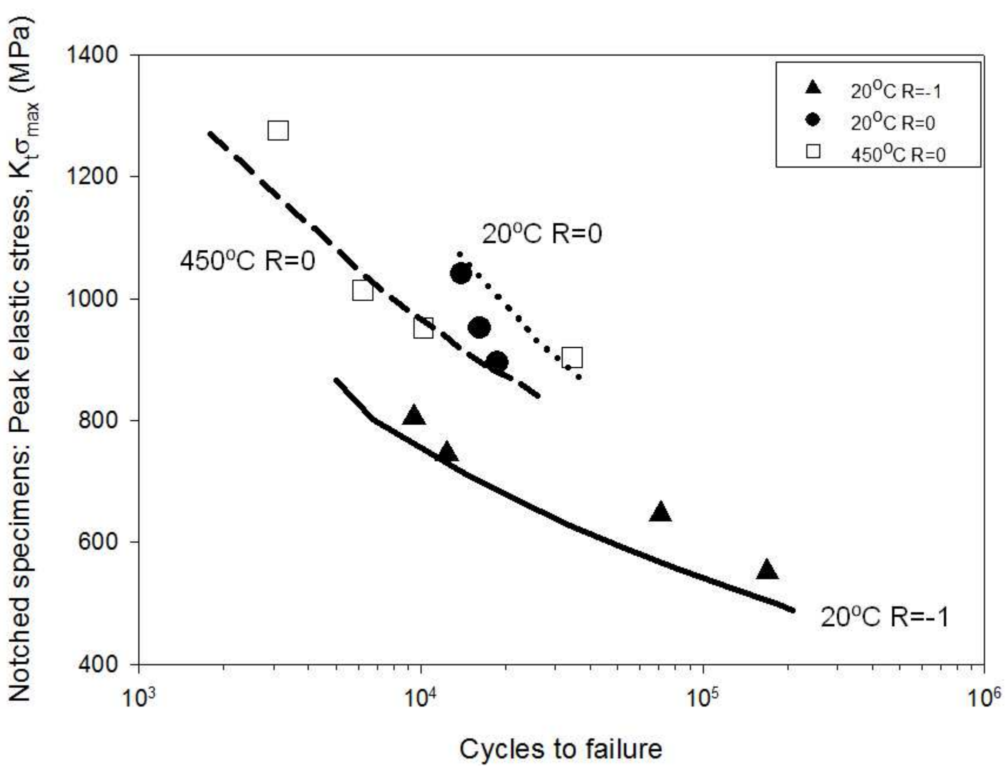


Fig. 11. Predictions of notched specimen behaviour at 20ºC and 450ºC using the Walker strain method.

The predictions made for R=-1 notch tests have improved accuracy over the R=0 tests simply for the reason that it is easier to predict the stress/strain state at the notch root for these tests. The highest load which was employed in fatigue testing of the R=-1 tests resulted in a peak elastic stress of 800MPa, which would be below yield for Ti6246 at room temperature, at a typical strain rate of 0.5%/sec. As such the stress/strain conditions at the notch root are simply 800MPa and 0.0067 (from strain = stress/modulus). However, in the R=0 tests, significant plasticity is induced at the notch root. Whilst in Ti6-4 this plasticity could be accurately approximated by Neuber's rule, clearly more accurate description is required in the current case.

### 3.2.2 Development of FEA model in ABAQUS

In order to achieve greater accuracy a model was developed in the modelling suite ABAQUS based upon open hysteresis loops generated under fully reversed strain control loading of Ti6246, over a range of temperatures. The loops were generated under laboratory air conditions so that fatigue/environment and subsequently fatigue/creep/environment interactions could be studied. The model was based around the Mroz multilayer kinematic hardening model (Mroz, 1969) which compared well with experimental observations that stress redistribution within the material allowed for the stabilization of the peak/minimum stress during the initial cycles of a strain control test. A typical stress-strain loop generated by the model is shown in Figure 12. It can be seen that the loop generated in ABAQUS accurately describes the test data generated for a strain control test with a peak strain of 1.5%.

Modelling of the double-edged notch 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, with element size reduced near to the notch to improve accuracy. Calculations of the fatigue life were then based on the stabilised conditions of stress and strain at the node adjacent to the notch root.

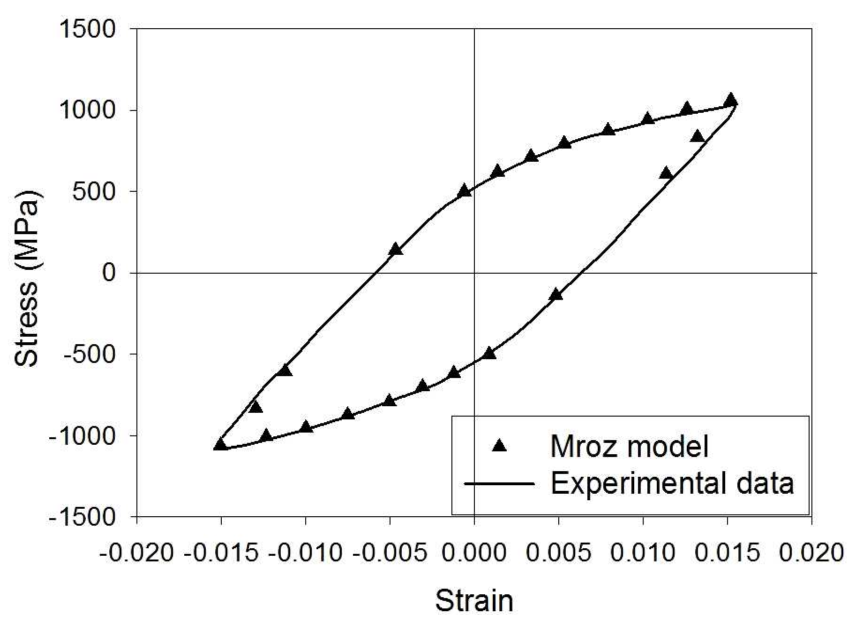


Fig. 12. ABAQUS modelling of a stress-strain loop at 20$^0$C in Ti6246 (Whittaker et. al., 2010a).

### 3.2.3 Creep and environmental damage

Figure 13 shows the predictions made by the model under 20$^0$C R=-1 loading conditions, and also 500$^0$C R=0 loading conditions. It can be seen that the low temperature predictions of initiation life are again extremely accurate. At 500$^0$C the predictions are slightly conservative, but clearly more acceptable than those previously demonstrated without the use of FEA. Previous work (Whittaker et. al., 2010a) has in fact shown that in this material, using DEN specimens, fatigue lives at 500$^0$C are actually longer than at 450$^0$C. This is due to the effect of creep within the vicinity of the notch root. At 450$^0$C creep has a limited effect, whereas at 500$^0$C it becomes more prevalent, and acts to decrease the stresses around the notch root, creating a shallower stress gradient and hence an improved fatigue life. Further increases in temperature to 550$^0$C however, lead to a reduction in fatigue life as creep and environmental effects become more damaging.

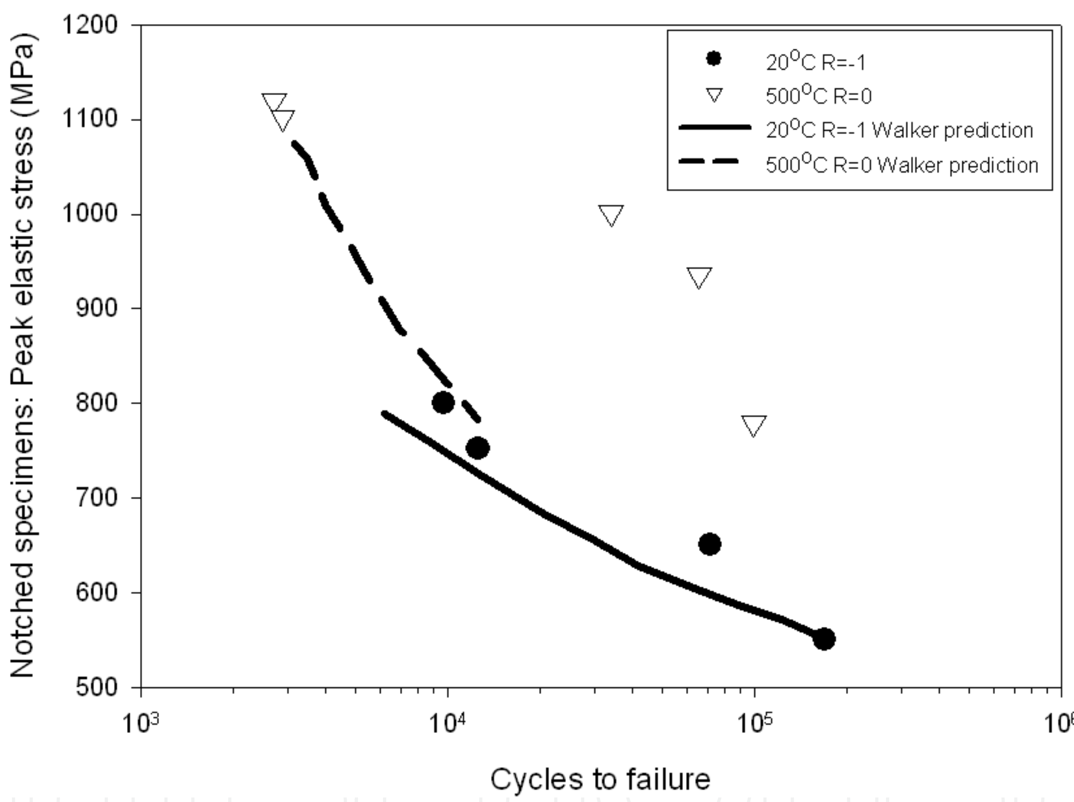


Fig. 13. Predictions of notched fatigue life made by ABAQUS model at 20$^0$C and 500$^0$C.

Further evidence of the significance of environment is demonstrated in Figure 14. Previous authors have described the development of a marked transition in the fatigue life curve of Ti6246 when tested under strain control (Mailly, 1999). Similar effects have been observed in the current work, where for lives greater than approximately $10^4$ cycles the fatigue lives of the material may be highly variable as the curve becomes very flat. At this point the material is protected by an oxide layer which forms during the test, preventing further oxidation. However, as material strain increases as the applied stress is raised, the oxide layer cracks and allows further ingress of oxygen, causing damage to the material and resulting in a more typical fatigue curve. The effect is not observed at 20ºC, but interestingly has been seen in strain control tests at temperature as low as 80ºC.

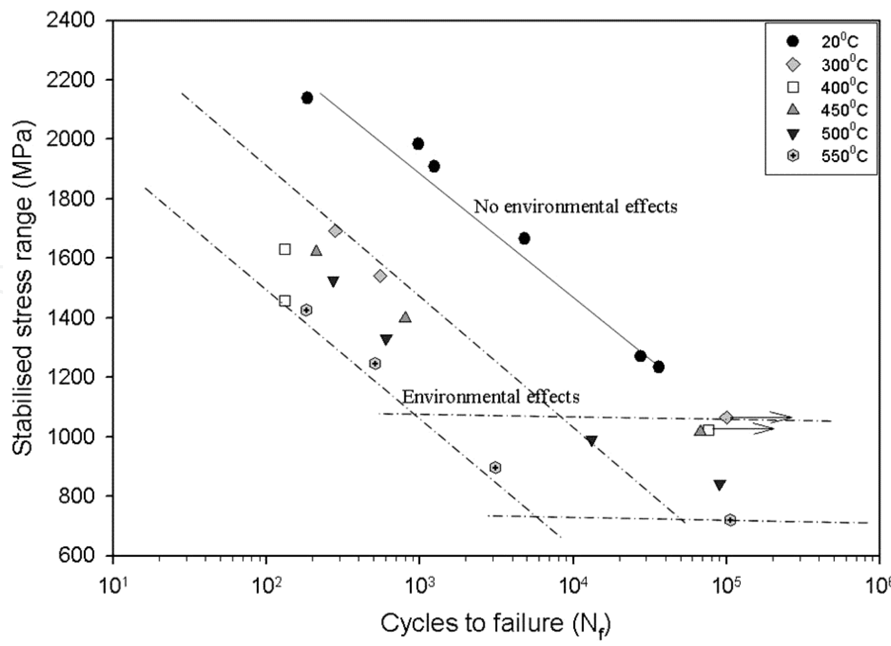


Fig. 14. Influence of environment on the fatigue lives of notched specimens in Ti6246 (Whittaker et. al., 2010a).

### 3.2.4 Combining fatigue, creep and environmental damage

Clearly the interactions of fatigue, creep and environment within the material are complex and offer a challenge to designers who wish to make accurate life predictions. However, some limited success has been achieved by the development of a fatigue-creep-environment model for crack growth. To construct the model it was necessary to combine fatigue crack predictions based on laboratory air conditions with damage due to creep effects, in the form

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

where the first term on the right hand side represents fatigue damage and the second term represents creep damage.

To calculate the creep damage, a suitable creep model was required. Previous experience had shown that the theta projection method offered acceptable results of creep behaviour in Ti6246, so an ABAQUS subroutine for the relationship was compiled which included creep rupture based on a Kachanov type failure process. In order to predict fatigue crack growth at high temperatures fatigue and creep damage were then calculated separately and combined at each time increment to give the total growth rate. Figure 15 indicates the results of this approach for growth rates at 500°C, R=0.1. It is clear that a prediction based purely on fatigue significantly underestimates the growth rate, but when the combined fatigue-creep-environment prediction is made, predictions are accurate. The effect of further creep damage is represented by the growth rates under a waveform with a two minute dwell at peak stress, although currently predictions have not been made for this data.

Whilst it is acknowledged that there is still much work to be completed in developing a total life prediction methodology for fatigue performance at high temperatures, the results of the work are encouraging. It has been demonstrated that interactions between fatigue, creep and environment are complex and produce many non-linear effects which are difficult to model. However, some success has been achieved in the production of a fatigue crack growth model at high temperatures and the belief is that similar models could be produced to describe crack initiation lives based on suitable deformation data for the alloy. Clearly, to accurately build the model, all three damage mechanisms should be considered independently before coupling in a model which considers their effects. However, in order to achieve this, a greater proportion of vacuum data will be required, particularly under strain control conditions, which will be experimentally challenging.

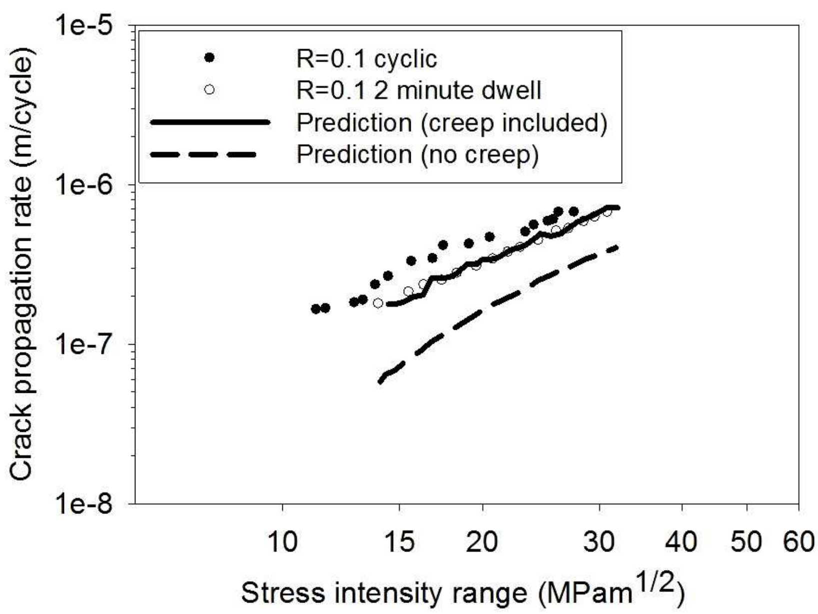


Fig. 15. Predictions of crack growth behaviour of Ti6246 at 500°C, R=0.1 (Whittaker et. al., 2010a).

### 3.3 Application of prestrain (Ti834)

Ti834 is a near α titanium alloy which was developed with a carefully controlled microstructure to enable exceptional mechanical properties at temperatures up to approximately 630°C. Combined with the high strength to weight ratio of the alloy, this excellent elevated temperature behaviour makes the alloy a popular choice for applications such as compressor discs and blades.

Clearly it is critical that the alloy is utilised under well understood conditions where any effect of the processing history can be accounted for. This may be a complex issue with different forging/machining/peening parameters influencing the surface condition of the material. During processing of components it is highly likely that surface roughness variations may occur, along with the possibility of further 'damage' to the material. Combined with the effect of residual stresses brought about by the peening process (commonly used to extend fatigue life), it is clear that significant variation may occur in the material mechanical properties. It is therefore necessary to understand these effects through a detailed investigation. In the current work, this was undertaken through a programme of mechanical testing aimed at detailing these variations in a range of prestrained Ti834 specimens.

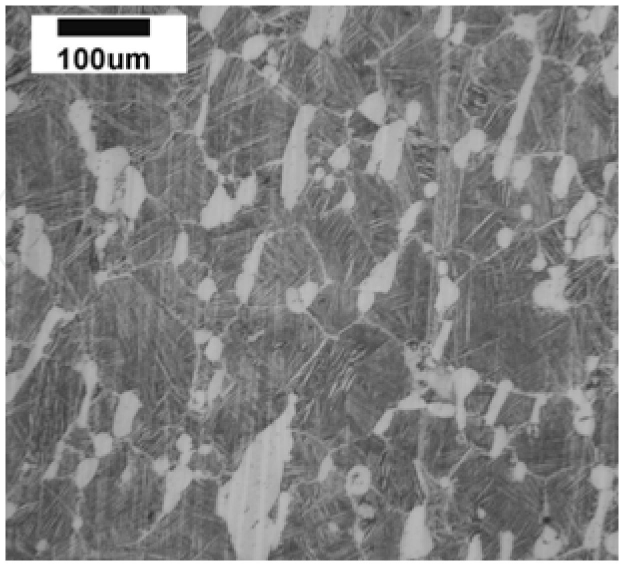


Fig. 16. Micrograph of Ti834, indicating a bimodal microstructure with primary alpha grains ranging in size from 20-200μm.

Figure 16 shows the microstructure of Ti834 tested, with a bimodal microstructure clearly evident encompassing primary α grains of 20-200μm in diameter. Total tensile prestrains of 2% and 8% (resulting in 1.25% and 7.25% plastic prestrains respectively) were applied to individual batches of specimens along with a compressive prestrain of 2%, denoted as -2% (plastic prestrain of -1.25%). These four different conditions, -2%, 0% (as received), 2% and 8% could then be compared under different loading conditions such as fully reversed strain control fatigue (20°C), stress relaxation at 1% strain (20°C) and creep (20°C and 600°C).

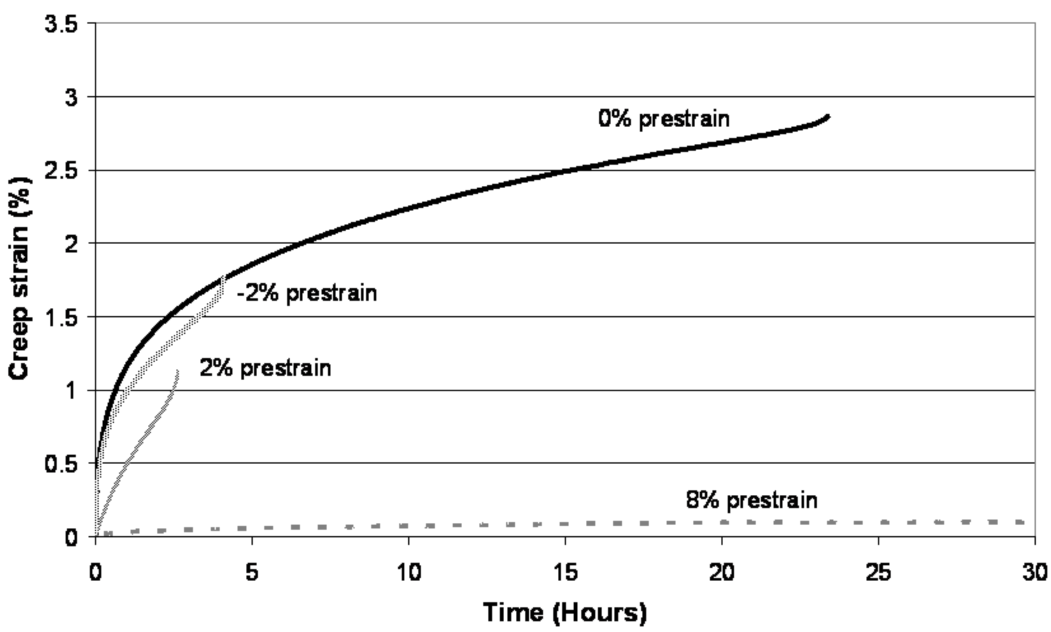


Fig. 17. Effect of prestrain on the creep rate of Ti834 at 20°C (Whittaker et. al. 2010b)

Fully reversed strain control loading at a peak strain of 1% was shown not to result in the formation of quasi-cleavage facets and as such was used as a control mechanism to produce eventual failure in test samples. In this way specimens could be separated and fracture surfaces investigated with the confidence that any facets generated would have been generated by the previous loading conditions and not the strain control fatigue.
Creep rates at room temperature (tested at 950MPa) were shown to be significantly affected by the application of prestrain, Figure 17. It can be seen that for 2% and -2% tests the primary creep is greatly reduced, although the creep strain rate increases and the strain at failure and creep life are markedly reduced. These effects offer only a limited improvement window for the material, in which creep strain is reduced over first few hours. However, the specimen which had undergone 8% prestrain showed a dramatic reduction in creep rate, eventually being removed from test after 250 hours, in which little creep was seen.

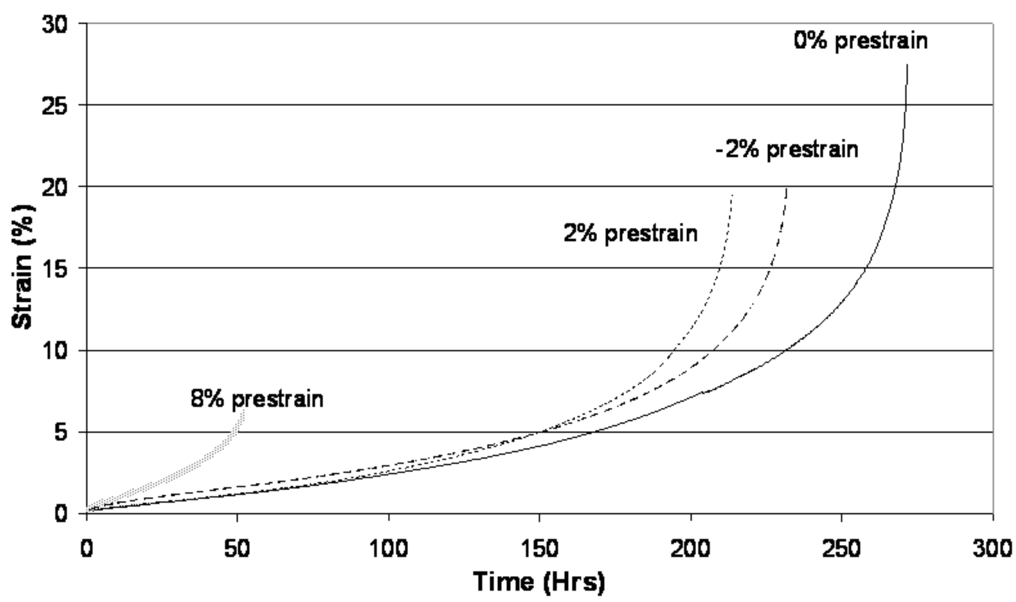


Fig. 18. Effect of prestrain on the creep rate of Ti834 at 600°C (Whittaker et. al., 2010b).

Clearly for designers interested in reduced creep rates at room temperature, this effect is attractive. Figure 18 illustrates though that these advantages will be temperature dependent. At 600°C the 8% prestrain specimen now shows a faster creep rate, shorter lives and reduced strain at failure. The reason for both of these effects will be related to the dislocation structure following prestrain. During the prestrain process, dislocations are generated as the yield stress is exceeded, which occurs at approximately 0.75% strain. It is clear that as the specimen continues to extend towards 8% strain, the dislocations will continue to multiply and as a result a high dislocation density occurs in the material. At room temperature, under creep conditions, dislocation mobility in the structure is significantly reduced, and the creep rate remains very low. However, at 600°C the increased thermal energy means that processes such as climb and cross slip become more prevalent, increasing dislocation mobility. This results in an increased creep rate when compared with the as received (0% prestrain) material.
Based on these results, it is clear that the effects of prestrain on the creep performance of the alloy vary significantly with temperature, and as such, dislocation mobility. At low

temperatures increased prestrain restricts further creep damage because of the high dislocation densities and apparent difficulty in processes such as climb and cross slip. Conversely, these processes occur more readily at 600°C and increases in prestrain lead to an acceleration in creep damage.

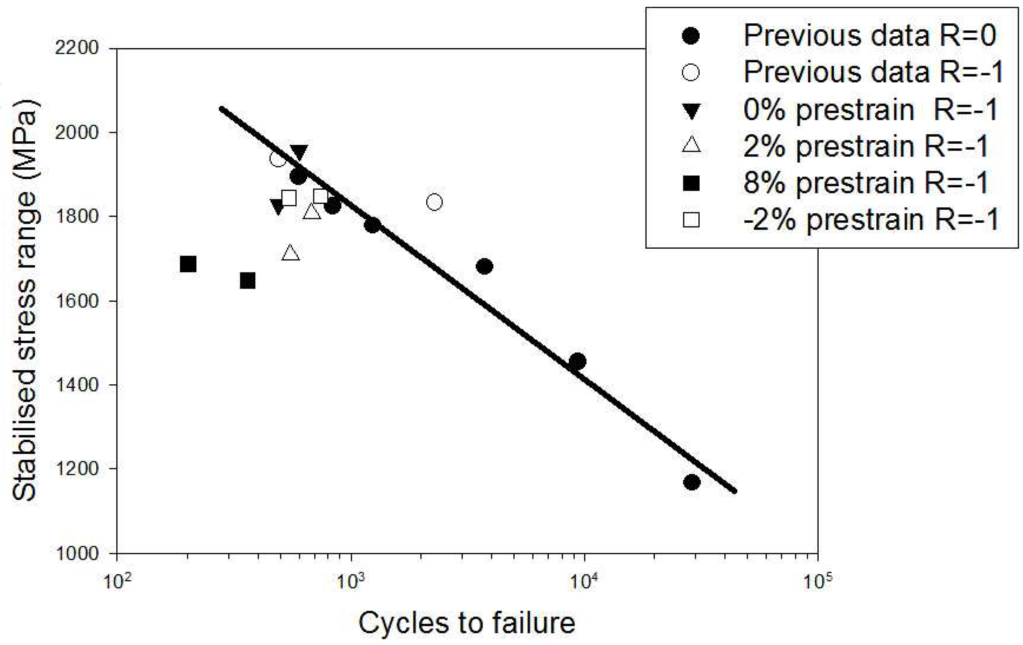


Fig. 19. Effect of prestrain on the fatigue properties of Ti834 at 20°C (Whittaker & Evans, 2009).

However, stress states in the gas turbine are rarely static and as such further consideration must be given to the effect on fatigue performance of the material, Figure 19. In the current work it was found that a small period of stress relaxation (<2 seconds) occurred at the end of the prestrain process before the specimen was unloaded. Previous work (Evans, 1998) has demonstrated that near α and α+β titanium alloys tend to form facets under stress relaxation, and fractographic analysis of failed specimens showed that this was indeed the case here. These facets offer initiation sites for fatigue cracks, which along with the increased dislocation density contributes to the 8% prestrain specimens showing significantly shorter fatigue lives.

## 4. Discussion

It is clear that whilst the rate of development of new titanium alloys has slowed in recent years, there are further areas which may be explored in order to achieve further improvements in mechanical properties. The research described here has shown that there is definite potential through the harnessing of texture, improved high temperature lifing techniques or improved understanding of processing effects.

Of these, perhaps improvements in high temperature lifing offer designers the greatest reward. Since the development of the gas turbine engine, increased efficiency has acted as the driver which has led to operation at higher and higher temperatures. Enabling components to operate at higher temperatures whilst retaining low density/low cost materials in their manufacture is obviously desirable and operation at temperatures where creep and environmental damage operate need not be ruled out. Indeed, provided a robust methodology is developed, it need not only apply to titanium alloys, and could be utilised throughout the engine.

It is useful, however, that the method is developed using Ti6246. The alloy is well understood and offers relatively few surprises to design engineers, particularly in its lack of susceptibility to cold dwell. The creep behaviour of the alloy is well detailed and suitably described by techniques such as the theta projection method. It also shows relatively good environmental resistance to approximately 500°C, giving a desirable combination of properties.

The research described here has shown that accurate predictions can be made for the fatigue behaviour of the alloy at high temperature, in the form of a model that described fatigue crack growth. It is recognised that this is only an initial step in the process of developing a total life prediction capability, but it is at least encouraging. Further work would seek to produce strain control deformation behaviour under vacuum conditions in order to isolate the effects of environment, which has been shown to be at least as significant as creep. It is also recognised that the model requires further refinement in order to describe the effects of the type that cause notch lives to be extended as the temperature is raised from 450°C to 500°C. To allow for this the creep deformation should be integrated more closely to fatigue damage in each cycle to describe the stress state of the notched specimen. There is no doubt that these requirements are challenging, but as described, the benefits are clear.

Textured alloys have been trialled for some applications previously, but the current research has demonstrated that it may be possible to widen the field of opportunity. By showing that textured alloys provide a predictable, consistent response, even in the presence of stress raising features, confidence can be gained towards applications in more complex components. Furthermore the work demonstrates that in this alloy, techniques such as the Walker strain approach are able to deal with a wide range of R ratios, although limitations do exist at high R ratios when cold dwell failure mechanisms become apparent. However, it is recognised that this may not be the case across all titanium alloys or process conditions.

The work in fact indicates how cold dwell still acts as a limiting factor in a number of titanium based applications. Essentially it can be seen that a threshold stress exists above which prediction becomes difficult and an extremely shallow S-N curve develops. Recent research at Swansea has shown that in attempting to model this type of behaviour, it is often more appropriate to base predictions on the creep behaviour of the alloy at room temperature, rather than its fatigue response, although further work is still required to characterise behaviour in this area. Such predictions, based on time at a high stress, rather than cyclic fluctuations, have been shown to capture the shape of the curve more accurately and to give reasonable estimates of life.

Indeed, one of the goals of the gas turbine industry is the increased understanding of cold dwell in order to further raise safe operating stresses. However, whilst a good understanding of the mechanisms of facet formation exists (Sinha et. al, 2009, Bache et. al., 1996) further work on the sensitivity of particular alloys would be useful. The three alloys considered here accurately demonstrate the range of effects seen in near $\alpha/\alpha+\beta$ titanium alloys. Ti834 has always shown a high sensitivity to cold dwell, particularly in disc form (Bache et. al., 1997) and as such has required designers to carefully consider operating conditions in components where it is utilised. Ti6246 on the other hand, has shown almost no sensitivity to cold dwell (Bache et al, 2007). Whilst this lack of sensitivity is possibly related to the fine Widmanstatten microstructure of the alloy, the mechanisms are still not fully understood. Ti6-4 sits between these two more extreme cases, showing cold dwell sensitivity which is often affected by microstructural form. However, since it is an alloy that tends to be used for more low temperature applications than Ti6246 or Ti834, it is clear that a good understanding of the effects is critical for safe utilisation of the alloy.

## 5. Conclusions

Whilst titanium alloys are under pressure to improve from either lighter, more complex materials (such as composite fan blades) or materials with higher temperature capability (polycrystalline nickel alloys in the HP compressor) it is clear that there are areas of development which have not yet been fully explored, which may offer significant opportunities for titanium alloys. In particular:-

a. The harnessing of crystallographic texture is capable of providing improved properties, providing the most effective orientations are aligned with direction of loading. It has been shown that despite this anisotropy, predictions of fatigue life can still be made accurately provided the input data for approaches such as the Walker strain method is from the same orientation and of a high enough quality.
b. High temperature lifing allows for extending the operational envelopes of alloys and is an area which requires further research. It has been shown that predictive models can be accurate provided all damage mechanisms (i.e. fatigue, creep and environment) are considered. Whilst the work here is only a start, it is clear that there is scope for further model development/refinement which may result in the safe operation of alloys such as Ti6246 at temperatures in excess of those currently used in service.
c. Improved understanding of the effect of processing conditions, and the resultant surface finish/damage and residual stress effects in alloys such as Ti834 can lead to increased minimum properties and hence a reduction in safety factors. It has been demonstrated that these effects, represented by prestrained specimens, can significantly alter mechanical properties, and show significant variation with temperature. Whereas room temperature creep rates may be reduced, the creep rates at 600°C are increased and would need to be accurately accounted for in deformation modelling of components Furthermore, fatigue properties at room temperature are reduced, as a result of the formation of quasi-cleavage facets under stress relaxation. This is the type of critical result which designers must account for when lifing such components.

## 6. Acknowledgements

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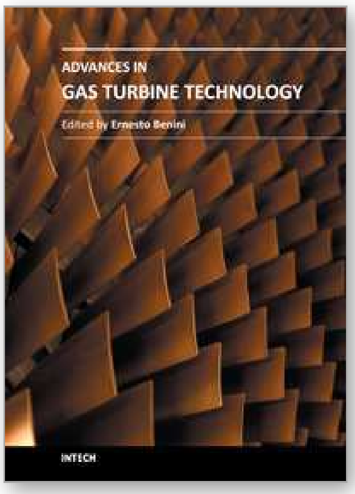


**Advances in Gas Turbine Technology**

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Gas turbine engines will still represent a key technology in the next 20-year energy scenarios, either in stand-alone applications or in combination with other power generation equipment. This book intends in fact to provide an updated picture as well as a perspective vision of some of the major improvements that characterize the gas turbine technology in different applications, from marine and aircraft propulsion to industrial and stationary power generation. Therefore, the target audience for it involves design, analyst, materials and maintenance engineers. Also manufacturers, researchers and scientists will benefit from the timely and accurate information provided in this volume. The book is organized into five main sections including 21 chapters overall: (I) Aero and Marine Gas Turbines, (II) Gas Turbine Systems, (III) Heat Transfer, (IV) Combustion and (V) Materials and Fabrication.



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