DWELL FATIGUE OF TI 6246 AT NEAR AMBIENT TEMPERATURES

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ABSTRACT

The effect of a two minute hold at peak load on cyclic lives and crack growth rates in the titanium alloy Ti6246 is explored. The effect on the cyclic lives of plain specimens is small and not influenced by temperatures in the range of 20° to 150°C. This contrasts with the titanium alloy IMI834 where dwell periods can significantly reduce fatigue lives. The notched fatigue performance of Ti6246 has also been evaluated and shown to be insensitive to dwell. This insensitivity is then confirmed for crack growth rates which are also unaffected by R values in the range -0.5 to 0.5. The implication of the findings for titanium alloys in general is discussed.

KEYWORDS

Dwell, initiation, crack growth, near beta titanium alloy, notch, temperature.

INTRODUCTION

The detrimental effects of dwell periods during cyclic loading of titanium alloys were first appreciated some 20 years ago following the in-service failures of fan discs in the RB211 engine (Jeal, 1982). During the ensuing period, a considerable amount of research on dwell sensitivity has been carried out. Factors implicated include microstructural condition, time dependent strain accumulation and hydrogen content.

The near β titanium alloy Ti6246 (Ti-6Al-2Sn-4Zr-6Mo) is currently being evaluated for advanced gas turbine disc applications. The continual drive for higher efficiencies generates a need for greater rotational speeds and hence materials with enhanced tensile strength and fatigue capability. The Ti6246 alloy has the potential of meeting this requirement and of providing a significant weight reduction relative to current alloys such as Ti-6Al-4V (IMI318) and IMI834 for applications up to 500°C.

The dwell sensitivity observed for some titanium alloys has resulted in the imposition of larger safety factors than are usually necessary for component lifing thereby limiting the performance benefit. It is important now to establish if Ti6246 is also limited by the cold dwell phenomenon. To this end a detailed evaluation has been carried out on basic fatigue characterisation, notch fatigue respose and crack growth behaviour. The implications of the findings for our general appreciation of dwell sensitivity are discussed.

EXPERIMENTAL TECHNIQUE

The Ti6246 alloy was supplied by Rolls-Royce in the form of specimens that had been machined from an intermediate compressor disc. The disc was beta forged and heat treated to give the microstructure illustrated in Fig. 1. This particular source ensured that the properties evaluated were representative of service operating conditions. This is particularly important as previous work on IMI834 has revealed that material from discs can exhibit a more marked dwell sensitivity than that from barstock (Bache et al, 1996a). All specimens in the present programme were from the disc rim and had a tangential orientation.

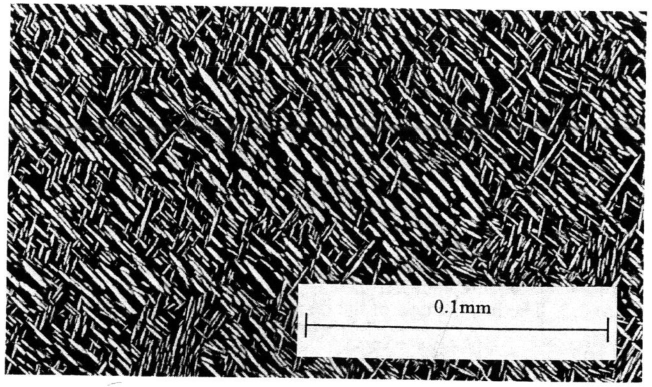

Fig. 1. Microstructure of Ti6246

Testing was carried out on servo-hydraulic and servo-mechanical fatigue machines under constant load amplitude waveforms. Plain specimens with a diameter of 5 mm and a gauge length of 12 mm were used to construct baseline S-N curves for the three temperatures, 20°, 80° and 150°C. Lives to failure were also obtained from a double edge notched (DEN) specimen which typified conditions at component stress concentration features. This test piece has a 10x10 mm cross section at the notch root and a root radius of 3mm which gives a stress concentration factor, K_t, of 1.9. Three loading waveforms were employed: a 15 cycles per minute (CPM) trapezoidal; a 0.5 Hz triangular; and a two minute dwell at peak load achieved with linear ramps equivalent to the 15CPM and 0.5 Hz cycles.

Crack growth behaviour was assessed for both uniform and notch stress fields in order to provide base line data and to simulate the more complex in-service conditions. The majority of the crack propagation tests were conducted at room temperature and a load ratio, R=0.1. Cyclic behaviour was evaluated for the 0.5 Hz triangular wave. The two minute dwell cycle allowed the effect of a hold at peak load to be assessed. A corner crack (CC) test piece with a 10x10 mm square section provided representative data for a uniform stress field. A fine starter slit was used to initiate the crack and ensured accurate measurement of the subsequent growth by a pulsed direct current potential drop (DCPD) system. Growth of cracks at notches was measured in a similar manner through a fine starter slit at one corner of the root. Additional cyclic tests

were carried out on CC specimens with R values of 0.5 and -0.5. Crack growth rates were calculated using a 3 point secant method and related to the range of applied stress intensity, ΔK.

RESULTS

Cyclic and dwell lives for plain specimens at 80°C are illustrated in Fig. 2. The dotted and solid lines represent linear regressions for the cyclic and dwell data respectively. The arrow indicates that the cyclic test at 870 MPa remained unbroken. It is evident that the dwell lives fall short of those for 15CPM but that the difference is small being typically a factor of 1.5 to 2.2. The regression lines converge towards the low stress region, suggesting that any dwell effect may be even smaller or non existent at low stresses. The tail off in the cyclic curve at 870 MPa suggests that this stress is close to the endurance limit. This is a high proportion of the yield stress of the material (approximately 92% of the 0.2% proof stress).

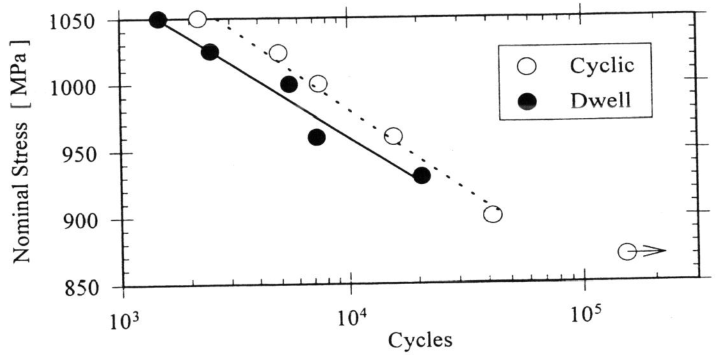

Fig.2. Comparison of cyclic and dwell response at 80°C.

To assess the role of temperature in dwell sensitivity, comparisons were made between 20°C, 80°C and 150°C at two normalised stress values of σ/σ_{uts} (with σ_{uts} the ultimate tensile strength at the relevant temperature). Normalised values of 0.86 and 0.90 were selected for the comparison. The equivalent stresses were 960/1000 MPa at 80°C, 1012/1045 MPa at 20°C and 900/930 MPa at 150°C. Figure 3 illustrates the lives for cyclic and dwell loading on a normalised stress basis for the three temperatures. It can be seen that the additional data reinforces the view that there is little difference between cyclic and dwell loading. The three lines superimposed on the data are linear regressions for the combined cyclic and dwell data at the three respective temperatures.

At 20°C a number of repeat tests were carried out for a stress of 1012 MPa and a frequency of 0.5 Hz. These results have been amalgamated in Fig. 4 together with cyclic and dwell data for the three temperatures. The variation in test data is approximately 2.3. The figure includes regression fits and $\pm 3\sigma$ intervals for the full data set. These emphasise that the effect of a two minute dwell at peak load is small for Ti6246. The ratio of $+3\sigma/-3\sigma$ lives is approximately 8.

Fatigue lives due to cyclic (0.5 Hz) and dwell loading of DEN test pieces at 20°C are presented in Fig. 5 in terms of nominal applied stress. The dotted and solid lines are the linear regressions for the cyclic and dwell data respectively and indicate that their lives to failure are

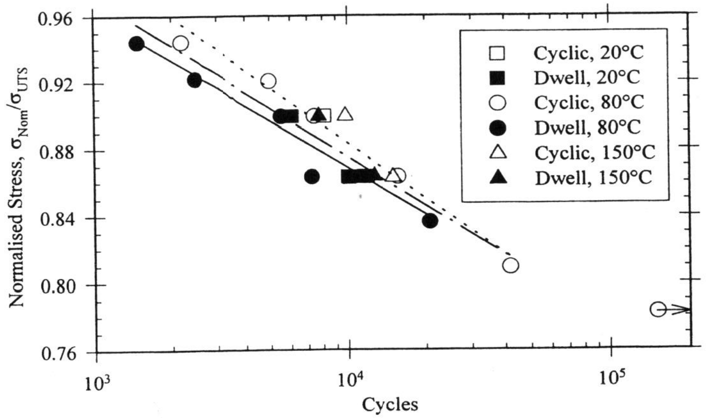

Fig. 3. Comparison of cyclic and dwell response at 20°C, 80°C and 150°C.

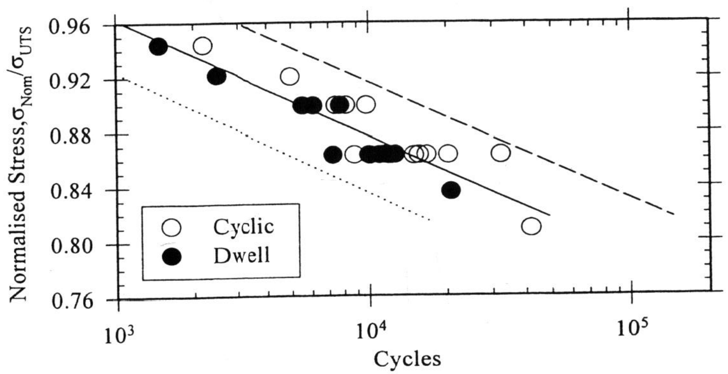

Fig. 4. Variability in cyclic and dwell data.

indistinguishable. Five repeat tests at 750 MPa allowed inherent scatter of the notch fatigue tests to be assessed. The measured lives were 15320, 16280, 19600, 22720 and 23900 cycles respectively. 'Life to first crack' design methods would apply a factor of 3.05 to the mean of these data to arrive at a '-3σ' safe life of 6338 (CAA, 1990).

The effect of R value on fatigue crack growth rates in CC specimens is illustrated in Fig. 6. It is evident that a high R (R=0.5), has minimal effect on crack growth rates when compared with data at R=0.1. A negative R (R=-0.5), on the other hand, leads to a reduction in growth rates in comparison to R=0.1 if ΔK is expressed as $\Delta K=K_{max}-K_{min}$. However, when only the tensile component is used for the negative R data then the two sets superimpose. Dwell crack growth rates were found to be indistinguishable from the cyclic data in Fig. 6. The low dwell sensitivity is confirmed by the crack growth rates for 0.5 Hz triangular wave and dwell loading of the DEN in Fig. 7.

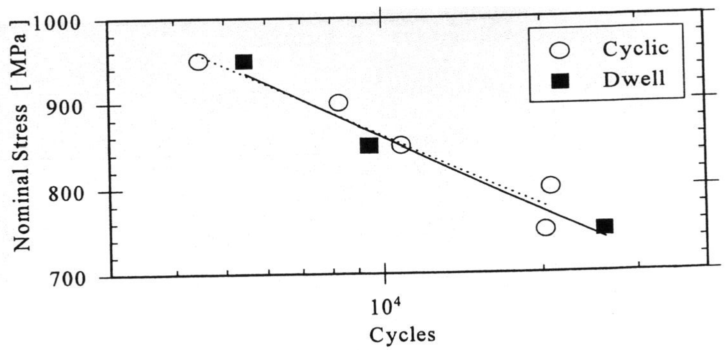

Fig. 5. Cyclic and dwell lives for DEN specimens.

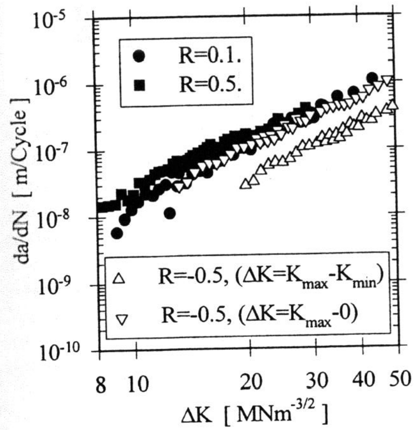

Fig. 6. Effect of R value on fatigue crack growth response.

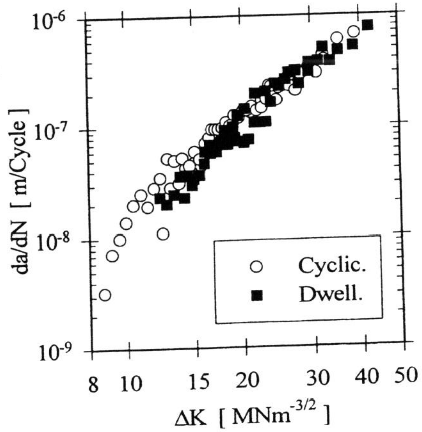

Fig. 7. Cyclic and dwell growth rates for DEN specimens.

The fracture surfaces contained a number of characteristic features which were common to both cyclic and dwell fractures. There is some evidence of featureless quasi-cleavage facets but these are mostly restricted to small crack lengths and are found at near surface locations. They are particularly evident for the more highly stressed LCF tests. The most dominant features are relatively flat regions which display evidence of underlying microstructural features, Fig. 8. Individual platelets are evident in relief on the fracture surface together with secondary cracking which appears to be along the α/β interfaces.

DISCUSSION

The data obtained on plain and notch specimens confirms that the objective behind the processing route for Ti6246 has been achieved in that there is no evidence to date of a low temperature dwell response. It is interesting to assess how this improvement has arisen. It is

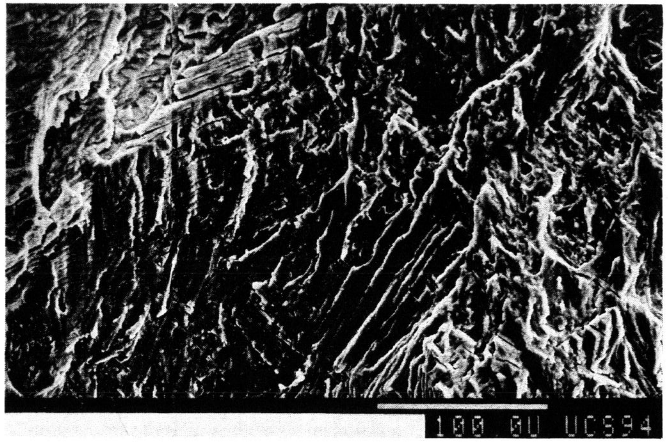

Fig. 8. Fractographic features.

well established (Evans and Bache, 1994) that dwell sensitivity requires a number of contributary factors to operate in conjunction. In the first place, there must be a redistribution of stress between weak and strong sites within the microstructure. Weak sites are related to crystallographic orientations in which the basal plane in the hexagonal lattice is favourably placed for slip. Strong regions occur where slip on the basal plane is difficult such as when the plane lies perpendicular to the applied stress. The redistribution process is apparent as time dependent strain accumulation sometimes referred as 'cold creep'. The second requirement is that there is a suitably orientated basal plane for separation to occur. This involves several issues including critical combinations of tensile and shear components on the basal plane, an alpha region that is sufficiently large for the fracture process to make a significant impact and possibly some influence from either an internal or external environment.

The Ti6246 alloy has a near beta composition. It has been worked above the beta transus but heat treated just below to give only small regions of alpha in a very fine acicular matrix. Within the large prior beta grain structure there will be statistical distributions of size and slip plane

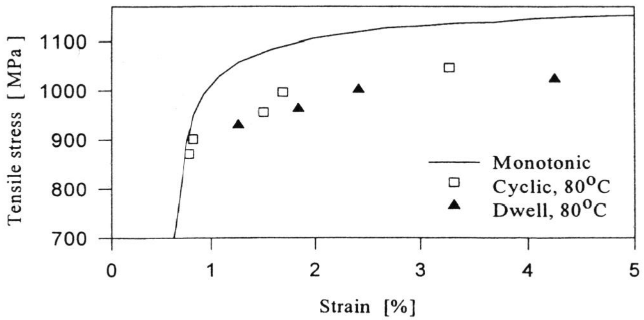

Fig. 9. Monotonic and cyclic stress-strain response of Ti6246.

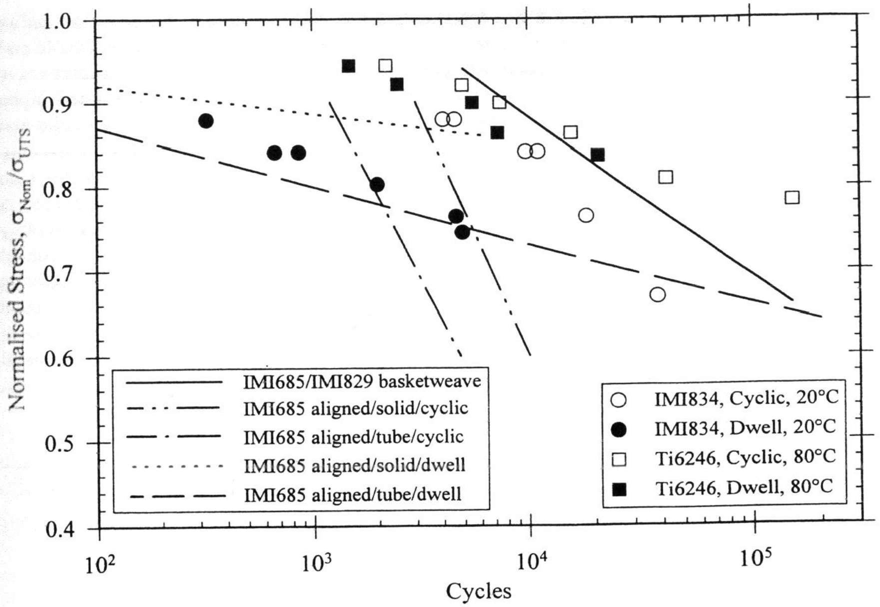

Fig. 10. Comparison of cyclic/dwell response of Ti6246 and IMI834

orientation. Thus stress redistribution will occur and this is apparent as strain-time accumulation. Figure 9 is derived from such data and is the half life strain level plotted against the original applied stress. It clearly shows relaxation to a cyclic stress-strain curve. Interestingly, the observed reduction in stress is of a similar magnitude to that found in IMI834. On this basis, the different dwell fatigue response of the two alloys, as depicted by the tensile strength normalised data in Fig. 10, is not due to the stress redistribution process but is a consequence of the differences in microstructure. In particular, the near alpha IMI834 contains about 15% primary alpha in a relatively coarse (c.f. Ti6246) transformed matrix. The alpha is about 20 μm in diameter and is directly associated with facetting on basal planes (Bache et al, 1995). However, it is argued that this alone is not sufficient for a dwell sensitive response. The IMI834 material referred to in Fig. 10 was taken from a large disc forging. In contrast, barstock IMI834 has a similar microstructure but does not display the same level of dwell sensitivity (Bache et al, 1996). The explanation is related to the processing procedure. Working above the beta transus produces a large beta grain size (0.5 mm). On heat treatment below the transus, primary alpha develops in each of these grains and the remaining beta phase (~ 85%) largely transforms to acicular or plate-like alpha through a Widmanstatten reaction. If the transformed alpha colonies are of similar orientation to the primary alpha then a large region with a common basal plane is available for crack initiation and facet development. The different response of the two sources of IMI834 is related to the greater level of work for barstock which would reduce the prior beta grain size and could also alter the orientation relationship for primary and transformed regions.

It is interesting that in Fig. 10, the line representing the cyclic fatigue response of the earlier near alpha alloys, IMI685 and IMI829, lies very close to the normalised curves for Ti6246 and IMI834. These alloys have a large prior beta grain structure (0.5 mm) containing a basketweave transformation product. A slow cool, however, produces a much coarser aligned alpha morphology. Figure 10 includes normalised cyclic and dwell curves obtained from solid and tubular testpieces for this aligned product (Evans and Bache, 1994). The much weaker response is clear, however, the interesting fact is that the basketweave versions of these two alloys do display dwell sensitivity with the reduced lives virtually coincident with the aligned trend in Fig. 10. It has been argued that this is due to the redistribution process seeking out favourably orientated 'aligned' regions in a generally basketweave matrix. In this respect, it is pertinent that the normalised dwell data for IMI834 fall within the aligned bands for IMI685 suggesting that a similar weak link hypothesis applies with the 'rogue' regions being similarly orientated regions of primary alpha and transformation product. On this basis, the present Ti6246 is dwell insensitive because the microstructure generated breaks up large areas with a common basal plane orientation. Clearly, the important step now is to establish that such regions might not inadvertingly develop during the prescribed processing operations.

Finally, it is interesting to note that although small facets develop, the primary mode of crack growth involves the fracture of alpha/beta interfaces. This results in a 'meandering' crack path and lower growth rates than IMI834. A Paris exponent of 2.7 perhaps suggests a 'process zone' mechanism of crack development.

CONCLUSIONS

The principal conclusion is that compared with near alpha alloys, such as IMI834, 829 and 685, the near beta Ti6246 is dwell fatigue insensitive at near ambient temperatures. The insensitivity is attributed to the microstructure which consists of small regions of primary alpha in a very fine and almost martensitic transformation product. As a consequence, large regions with a common basal plane orientation do not develop. Such regions in conjunction with stress redistribution due to the inhomogeneous character of the crystallography are associated with the formation of quasi-cleavage facets. It is important to establish that similar 'weak' links might not inadvertently develop during the prescribed processing procedures.

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