Time Dependent Fatigue Fractures of Titanium Alloys

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Abstract

Premature failure of titanium based engineering components in the 1970s brought to attention the phenomenon of dwell effects at low temperatures in these alloys, loosely termed 'cold creep', which are currently still a major concern for designers. These failures were characterised by the formation of quasi-cleavage facets thought to be a result of extended dwell periods. However, the particular conditions under which these facets form is still not fully understood, leading to the necessity of above average safety factors in material lifing that could be reduced through increased understanding.
The current paper seeks to address the issue through exploring the results of a series of targeted tests in the titanium alloys Ti6-4, Ti685 and Ti834. The presence, extent and effect on mechanical properties of these features are investigated with conclusions made about the loading conditions under which formation occurs. The resultant effect on both creep and fatigue life is also studied through a series of comparisons.

1. Introduction

The widespread use of titanium in the aerospace industry has been a success story of the twentieth century. The combination of a high strength to weight ratio, good fatigue properties at low to mid temperatures along with good fracture toughness have ensured that titanium alloys are the desired choice of design engineers for applications in the cooler compressor stages of the gas turbine engine.
In the 1970s, however, extended periods at peak operating loads and low temperatures highlighted the potential for a dwell sensitivity in these alloys. The resultant premature fatigue failures were characterised by the formation of quasi-cleavage facets, which promote early crack development. Loosely termed 'cold creep', due to the time dependent nature of their development, these features have been widely researched in the past 30 years. Models have been proposed to account for the mechanisms [1] which have more recently been extended by Hasija et al [2] and Dunne [3] to describe cold dwell in polycrystalline Ti-6Al. The current paper seeks to analyse the alloys that display significant sensitivity to this effect, along with the loading conditions which make the alloys most susceptible.

2. Experimental methods

The work described in this paper has been undertaken at Swansea University at over the past 20 years. Testing has been performed on Mayes and ESH servo hydraulic test machines with load ranges of 100kN and 50kN respectively. Strain control testing has been widely used to characterise the fatigue performance and deformation characteristics of a wide range of titanium alloys, with tests performed to BS7270 [4] and hysteresis loop evolution recorded using in house data logging software.

3. Results

Although the mechanisms of facet formation are reasonably well understood, the specific macroscopic loading conditions under which they form is not fully appreciated. The number, type and orientation of facets formed show a dependence on temperature, stress and dwell time. Indeed Sinha et al [5] have shown that orientation of facets in Ti6242 is dependent on loading type, with the angle the facet makes with the loading direction decreasing in the order cyclic fatigue, dwell fatigue, static loading. Through analysis of facet formation in a number of titanium alloys, it is believed that a better understanding of dwell sensitivity and of the loading conditions promoting facet formation should be possible.

The formation of these facets is consistent with a variation on the Stroh pile up model, proposed by Evans and Bache [6], Figure 1. At room temperature relatively small amounts of thermal energy are available and dislocation pile ups can occur easily. These pile ups facilitate the formation of quasi cleavage facets in titanium alloys including the near alpha alloy Ti834. The facets, which generally have a near basal plane orientation develop due to the gradual separation of intense slip bands under the action of a tensile stress normal to the slip plane. The presence of strong and weak regions within the microstructure promotes this mechanism through stress redistribution. Grains that have a basal plane orientation nearly perpendicular to the loading direction act as a ‘strong’ grain, i.e. slip is difficult. However, if adjacent grains have easily available slip systems, they can generate dislocation pile ups at the boundary. The pile up provides the required induced shear (τ_f) and tensile (σ) stress on the unfavourably orientated basal plane with τ_s the resolved shear stress in the ‘weak’ grain. The applied stress (σ_1) provides the overall driving force.

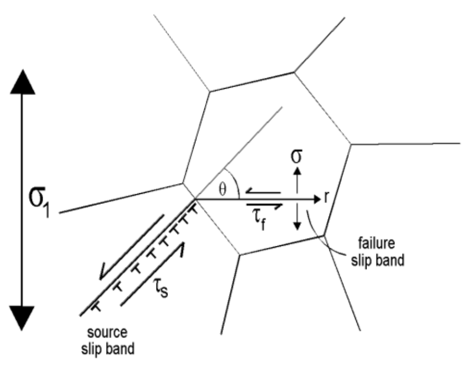

Figure 1: Mechanism of facet formation in titanium alloys

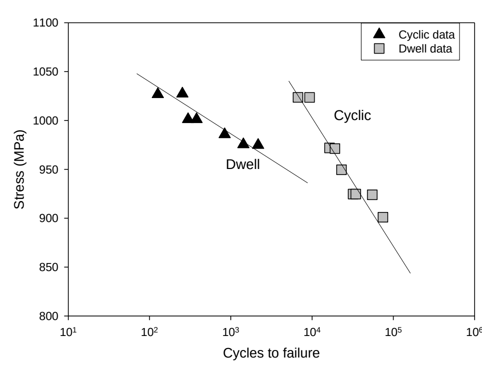

Figure 2: Cyclic and dwell data in Ti685

3.1 Ti685 (Ti-6Al-5Zr-0.5Mo-0.2Si)

Ti685 is widely acknowledged as being the first of the titanium alloys shown to have a dwell fatigue sensitivity. This arose from the premature failure of two fan discs in 1972. The alloy itself is widely utilised in two microstructural conditions; the desired basketweave microstructure produced by rapid cooling from above the beta transus, and a rogue aligned morphology, obtained by slow cooling through the transus. The latter is representative of the type of structure that can occur in thick sections.

Previous work has shown that the contribution of these microstructures to facet formation and to a reduction in life under dwell conditions is complex. Facet formation occurs in both but is more extensive in aligned material. In the basketweave material the facets have a more elongated morphology. A sensitivity to dwell, however, is limited in the aligned material which, incidentally, is considerably weaker in fatigue response and monotonic behaviour to the basketweave form. The greatest dwell sensitivity occurs in the basketweave microstructure provided it contains some regions of alignment. Pure basketweave microstructures display a very weak sensitivity to dwell. It appears that dwell sensitivity is probably associated with two microstructural factors. Firstly, in a uniform microstructure, grain to grain orientation differences are important allowing the 'weak' grains to offload stress on to the 'strong' grain. Secondly, where the microstructure is non-uniform, i.e. basketweave with some aligned regions, there are sensitive zones with a fatigue performance that falls considerably short of that for the principal (i.e. basketweave) microstructural forms. Either process can cause an apparent dwell effect but when acting together the overall impact is extremely detrimental to performance.

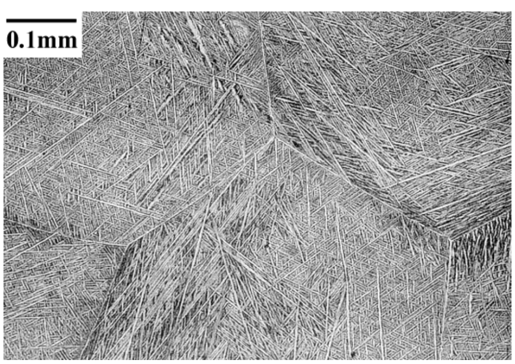

Figure 3: Ti685 basketweave microstructure

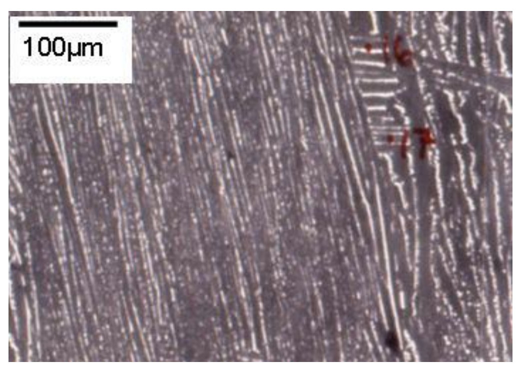

Figure 4: Ti685 aligned microstructure

Interestingly, torsion testing of either aligned or basketweave forms of Ti685 does not produce a significant dwell sensitivity [8]. Figure 5 shows a comparison of cyclic and dwell tests at room temperature, R=0, under both tension and torsion loading conditions, for the aligned microstructure. The limited dwell effect produced by the tension loading can be seen. However, it is clear that a similar effect does not occur under torsional loading. Whilst there is good correlation between the tension and torsion results through use of the von Mises criterion, the application of a 2 minute dwell at peak torsional load does not result in a reduction in fatigue life. Even so, facets were still found on the fracture surface of the torsion specimens. It is logical to conclude that a reduction in fatigue life requires the application of both a tensile and shear stress. Under tensile loading conditions this occurs naturally. However, torsion is a pure shear loading condition so that there is no tensile component on the shear plane.

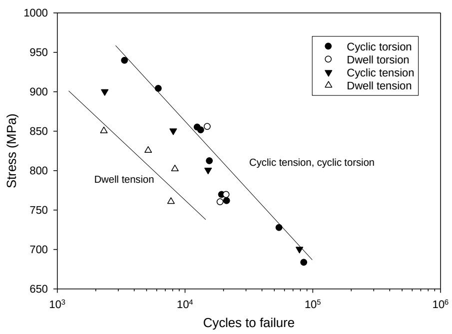

Figure 5: Cyclic and dwell comparison in Ti685 at 20°C, R=0

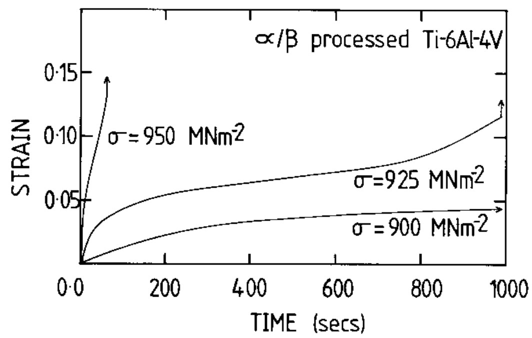

Figure 6: Cold creep rates in Ti6-4, 20°C

3.2 Ti6-4 (Ti-6Al-4V)

Ti6-4 is the most widely used titanium alloy with aerospace, industrial and medical applications. It is available in a number of microstructural conditions which can be tailored to specific applications, but is most often found as a bimodal structure containing equiaxed alpha grains of diameter approximately 10-30μm. Figure 6 shows an example of how the effect of cold creep at ambient temperatures. The creep tests performed at 950, 925 and 900MPa show appreciable strain accumulation. Microstructural condition, however, has a considerable effect, with furnace cooled variants showing facet dominated failures at lives longer than 10^4 cycles, particularly in the case of β processed forms, Figure 7.

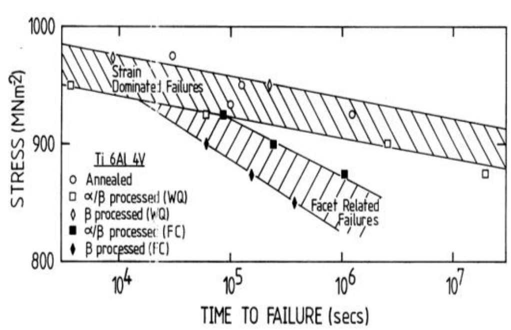

Figure 7: Facet failures in Ti6-4 under load control, R=0 conditions (20°C)

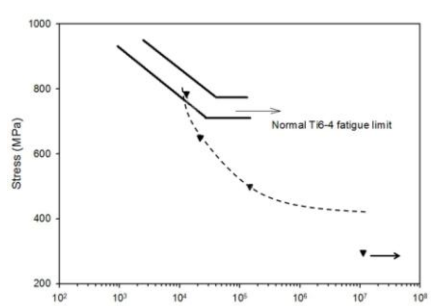

Figure 8: Effects of Stress relaxation in Ti6-4 (20°C)

It is clear from the work reported that the formation of facets is requires time dependent strain accumulation. Previous work [9] has shown that monotonic loading of Ti6-4 specimens did not produce facets. However, when a period of stress relaxation is introduced, before subsequent reloading, significant facets are found. This is important since it shows that cyclic deformation is not a necessary condition for facet formation. This is further emphasised by the introduction of a period of stress relaxation at a strain of 2% before cyclic fatigue loading, Figure 8. Premature formation of facets occurs and subsequently the fatigue response of the material is significantly reduced, as these facets provide sites for the development of fatigue cracks.

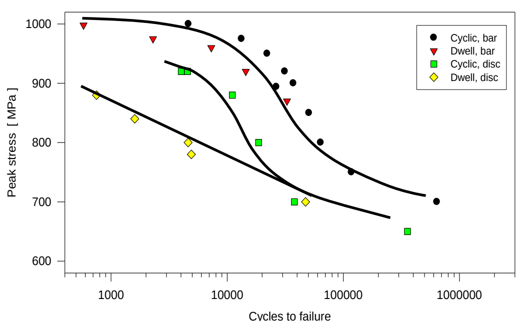

Figure 9: Dwell fatigue in Ti834, R=0, 20°C

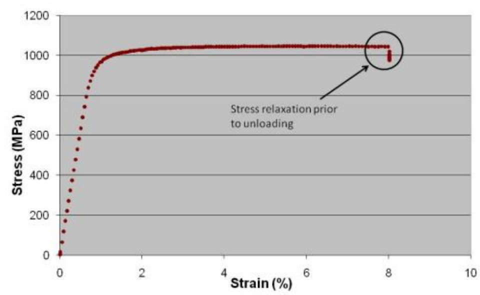

Figure 10: Relaxation in prestrain loading (20°C)

3.3 Ti834 (Ti-5.8Al-4Sn-3.5Zr-0.7Nb0.5Mo-0.35Si-0.06C)

Ti834 has long been recognised as an alloy that is particularly sensitive to dwell effects, Figure 9. A programme of testing designed to investigate the formation of quasi-cleavage facets in the titanium alloy Ti834 at 20°C was undertaken [10, 11] and included the prestrain of specimens to either 2% tensile, 8% tensile or 2% compressive prestrain (-2%). Subsequent testing on each of these batches of specimens, along with as received material (0% prestrain) included stress relaxation, where the applied strain was held at 1% while the load was monitored, creep tests at room temperature and 600ºC (at 950MPa and 400MPa respectively) and fully reversed strain control tests (at a peak strain of 1%).

Initial results from the testing programme sought to isolate conditions under which facet formation occurred. By analysis of the fracture surface of a 0% prestrain specimen, cycled under fully reversed strain control conditions, it became clear that this type of loading did not cause extensive facet formation. Fully reversed strain control loading could therefore be used to ‘open up’ test specimens subjected to other loading regimes in order to determine if they caused facet formation. Clearly any facets observed would not be the result of the strain control cycle. On this basis clear evidence was found of isolated individual facets within the as received specimen, subjected to stress relaxation conditions. This indicates that facets form readily during the relaxation process.

Of particular interest was the effect of prestrain. Low amounts of applied prestrain (2%) were found not to significantly affect the mechanical properties of the material. Large amounts of prestrain, however, caused a significant reduction in creep rate, and also a reduced fatigue life. Through analysis of the fracture surfaces, it was found that isolated individual facets had formed, prior to failure. Since fully reversed strain control loading at 1% peak strain had been discounted as a facet forming process, it was inferred that these facets formed during the prestrain process. Previous work [9], however, has shown that this type of monotonic loading is unlikely to have produced these facets. As described earlier, in the work on Ti6-4, it was shown that facets were not found during monotonic loading, unless a period of stress relaxation was introduced.

Figure 10 shows the prestrain loading of a Ti834 specimen to 8% total strain. Following loading to peak strain, specimens were returned under load control to zero load. It is clear however that although this process was completed rapidly (< 3secs after peak applied strain had been reached) there is significant stress relaxation (~60MPa within 0.5 secs). It is more likely that this is responsible for the formation of these individual facets. A typical example is shown in Figure 11.

It is also useful to analyse the fracture surfaces of specimens tested under cold creep (20°C) conditions at 950MPa. It is clear that with a constant high stress applied to the specimen, significant plastic strain is accumulated and leads to the formation of large areas of facetting, Figure 12.

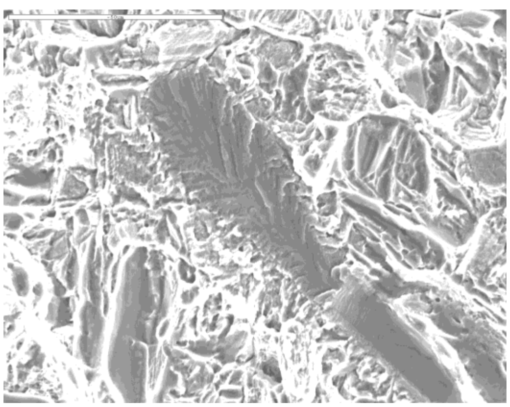

Figure 11: Facet in stress relaxation specimen

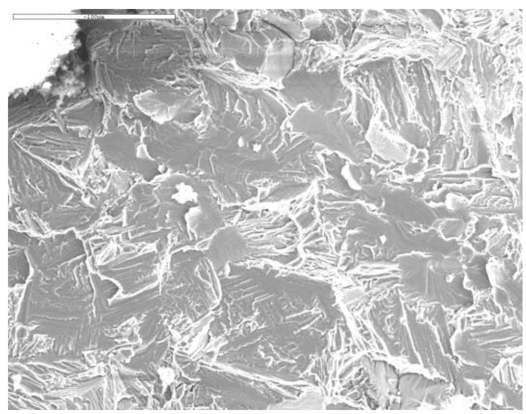

Figure 12: Fracture surface of creep specimen

4. Discussion

It has been clearly shown that facet formation and a sensitivity to dwell periods at low temperatures are an integral feature of the α/β and near α titanium alloys. Plastic strain accumulation is associated with a build up of dislocations at grain boundaries. This process is accentuated by the offloading of stress from a suitably orientated ‘soft’ grain onto an adjacent ‘hard’ grain, where slip is more difficult. Previous work has shown [3, 5] that the ‘hard grain is usually orientated with the c-axis of the HCP lattice parallel to the primary loading direction. However, recent work [12] has shown that in the absence of suitably orientated basal planes, cleavage can occur on prismatic planes.

In each of the materials considered, microstructure has a strong influence on facet formation, although there is no necessity for a specific type of microstructure. Basketweave, aligned, bimodal and equiaxed microstructures have all been shown to form facets and exhibit a dwell deficit. The requirement is only for grains to be suitably orientated for dislocation pile ups to occur at grain boundaries. It is also clear that despite facet formation occurring under torsion loading, a dwell effect is not evident. Under these conditions of pure shear, the lack of a tensile stress means that the transition from facet to initiated crack does not readily occur.

The recent work on Ti834 has been useful in defining the types of loading under which facet formation is most likely to occur. It is clear that the time dependent strain accumulation associated with creep testing or stress relaxation is critical and is probably associated with the build up of dislocations at grain boundaries. Under cyclic stresses and monotonic loading these conditions do not appear to occur so readily on a microscopic scale. This is emphasised by the previous work in Ti6-4 which has demonstrated that a period of stress relaxation is required during monotonic loading in order to generate facets. It is also evident that it is the period of relaxation at the end of prestrain loading in Ti834 which generates facets, and not the monotonic loading as initially thought.

It is also useful to consider the difference in the extent of the facet formation in Ti834. Extensive regions of facetting were evident on the fracture surfaces of specimens creep tested at room temperature. These facets also encompassed transformed regions. In the stress relaxation tests only individual isolated facets were found, and these were associated with primary alpha phase grains. To illustrate the reason for this, it is useful to consider the accumulation of plastic strain during a stress relaxation test

$$\varepsilon = \varepsilon_{el} + \varepsilon_{pl}$$

$$\varepsilon = \left(\varepsilon_{el} - \frac{\Delta\sigma}{E} \right) + \varepsilon_{pl} + \Delta\varepsilon_{p}$$

And clearly for a fixed total strain the plastic strain is exchanged for elastic strain according to the relationship

$$\Delta\varepsilon_{p} = \frac{\Delta\sigma}{E}$$

Typical values of $\Delta\sigma$ are 100-150MPa giving

$$\Delta\varepsilon_{p} = 0.00083 - 0.00125 = 0.083\% - 0.125\%$$

If we compare these levels of plasticity to the creep curves for room temperature, Figure 13 it is clear that this level of plasticity is significantly lower than that achieved in creep tests, approximately 4%.

It is useful to take these assumptions a step further. Figure 14 illustrates the room temperature creep curve in Ti834. A numerical description of the curve has been achieved by summing a logarithmic strain relationship with a linear damage criterion, $\varepsilon_t = \alpha_1 \log(\alpha_2 t+1) + \alpha_3 t$. The second term defines linear damage and represents the formation of facets within the material. Linear damage implies a constant rate of damage accumulation. A constant damage rate is associated with an exponential failure criterion. Such a criterion can be derived from a 'weak link' theoretical model. In the present case, the weak link can be associated with critical regions within the microstructure. Perhaps the most interesting observation is that the numerical description requires that facet formation begins at the beginning of the creep test, and continue through to final failure.

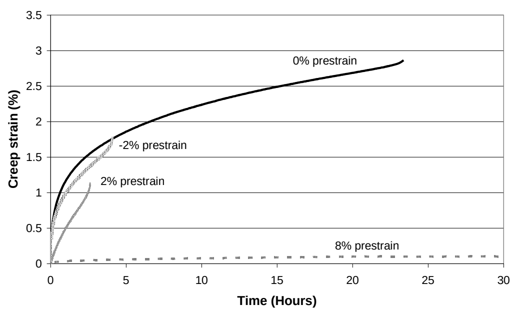

Figure 13: Extent of plasticity in stress relaxation specimen

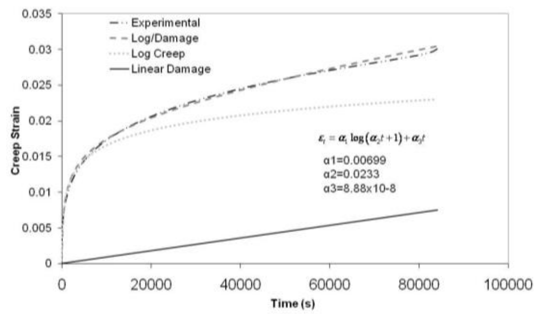

Figure 14: Modelling of cold creep in Ti834

5. Conclusions

- Low temperature dwell in titanium alloys has been invoked as the cause of in service failures lives that are significantly lower than the conventional safe life fatigue design methods would indicate.
- Dwell fatigue failures are characterised by quasi-cleavage facets which form due to dislocation build up at boundaries. These facets are the result of time dependent strain accumulation and were seen extensively in high stress creep tests at ambient temperature.
- Microstructure has a strong influence on facet formation, by varying slip path length for dislocations.
- Facets form under torsional loading, but a significant dwell effect is not seen, when compared with tensile loading. A tensile stress on the slip plane is necessary for dwell sensitivity.
- The extent of facet formation is related to the amount of plastic strain accumulated. Creep tests at room temperature result in extensive facetted areas, particularly in Ti834.

6. Acknowledgements

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7. References

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