Dwell-Fatigue Behavior of a Near α Ti 6242 Alloy

P. Lefranc *, C. Sarrazin-Baudoux *, M. Gerland *, V. Doquet +, J. Petit*

* LMPM-ENSMA UMR 6617 CNRS, 1, Avenue Clément Ader, Téléport 2, BP 40109, F-86961 Futuroscope-Chasseneuil Cedex, France.

+ LMS, UMR CNRS 7649, Ecole Polytechnique, 91128 Palaiseau Cedex, France.

Keywords : Dwell-fatigue, fatigue, creep, titanium alloy

Abstract. For over three decades, aeroengine manufacturers are confronted to the phenomenon of room temperature dwell-effect consisting in a decrease in structure life due to the introduction of hold periods at the maximum stress of the pure cyclic loading waveform. Even if many studies have been conducted to analyze the parameters responsible of this life decrease the so called "dwell effect" remains not completely understood. The present paper focused on damage occurring during pure cyclic, dwell fatigue and creep tests on a β–forged Ti-6242 alloy. It results from SEM and TEM analysis that crack initiation occurs by coalescence of shear-induced cavities nucleated at α/β interfaces in large colonies of α laths nearly parallel to the loading axis. The density and average size of cavities were larger in dwell-fatigue and creep than in fatigue.

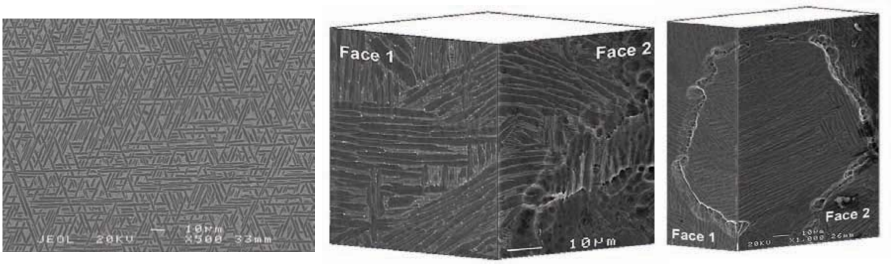
Introduction

Due to their high mechanical properties even at temperatures ranging up to 600°C, titanium alloys are used by aeroengine industries to manufacture gas turbine and compressor discs. However, since 1972, engineers are confronted to the so called dwell-effect, phenomenon consisting in a reduction at room temperature of the fatigue life due to the introduction of hold periods at the peak stress of the cyclic loading waveform. Up to now, the problem remains opened as well on the scientific as on the engineer point of view.

It is generally accepted that the dwell effect is mainly due to creep-induced strain accumulation (dwell periods have a beneficial influence in strain control, due to stress relaxation [1]) and that stress-controlled dwell-fatigue loading most often leads to internal crack initiation due to stress-level-dependent mechanisms [2]. The low-stress mechanism (transverse, near-basal quasi cleavage ahead of blocked slip bands) has been well documented, whereas the shear-induced high-stress internal crack initiation mechanism is not so well understood. One of the objectives of this study was thus to investigate the deformation and internal damage mechanisms in β-forged Ti6242 at a relatively high stress level, in the range where the dwell effect, more limited in this fully lamellar alloy than in bimodal microstructures, becomes most severe.

Material and Experimental procedure

The material used in this study is a Ti-6Al-2Sn-4Zr-2Mo (Ti-6242) alloy. The heat treatment consisted in a forging above the beta transus, inducing a purely lamellar microstructure. SEM observations exhibited a high level of microstructural heterogeneity, resulting from the thermo mechanical treatments performed after the forging. The microstructure is characterized by a mixture of either Basketweave (figure 1-a) or Windmanstätten areas (figure 1-b) in prior β grains (figure 1-c). In all cases the average width of the lamellas is around 2.5 mm and the size of β grains is about 200 μm.



(a) (b) (c)

Figure 1: (a): Basketweave microstructure, (b): Windmanstätten microstructure, (c): Equiaxed grain

The cylindrical specimens (3.4 or 8 mm) were subjected to tensile tests at various strain rates or stress-controlled cyclic loading (triangle waveform 1s-1s, R=0), dwell-fatigue loading (trapeze waveform, 1s-80s-1s, R=0) or creep loading (loading in 1s as well) for σ_{max} / σ_y ranging from 0.92 to 1.05 (where σ_y is the 0.2% yield stress of base metal) at room temperature.

Dwell Fatigue, Cyclic Fatigue and Creep Behaviors

The pure cyclic and dwell fatigue lives are illustrated in Figure 2. These results exhibit a fatigue life decrease due to the introduction of dwell periods with a dwell life debit in the range 2 to 30 according to the applied stress ratio. These results are in agreement with those stated by Kassner et al.[3] who noticed on a bimodal Ti-6242 alloy a fatigue life reduction under dwell waveform by a factor of 3 to 5 at low stresses and by over one order of magnitude of cycles at elevated stresses.

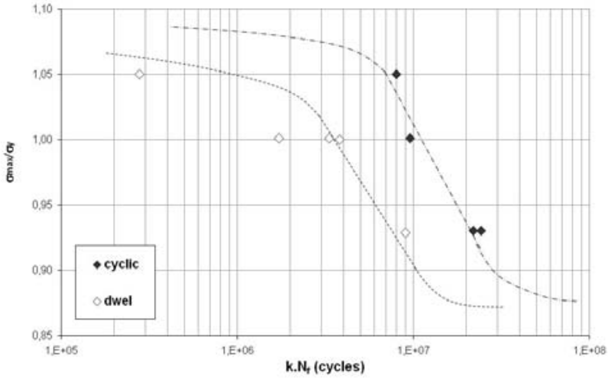


Figure 2: Dwell and cyclic fatigue lives

As illustrated in Figure 3, the introduction of dwell periods induced a significant increase in strain accumulation, whatever the applied stress.

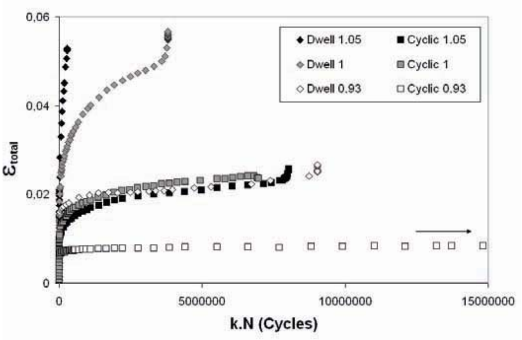


Figure 3. Evolution of the total strain for both pure cyclic and dwell fatigue loadings (indicated by the ratio σ_{max}/σ_y).

Total strain accumulation presented in figure 4 for σ_{max} / σ_y = 1.05 indicates a much faster strain accumulation in creep than in dwell-fatigue in the primary regime indicating that repeated elastic unloadings thus restrict strain accumulation at this stress level.

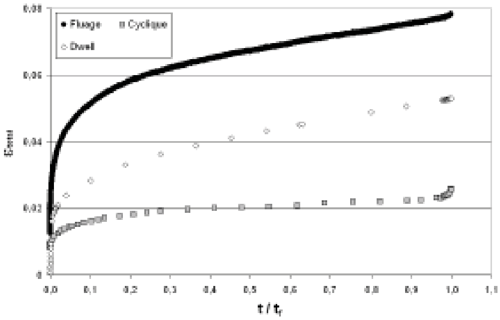
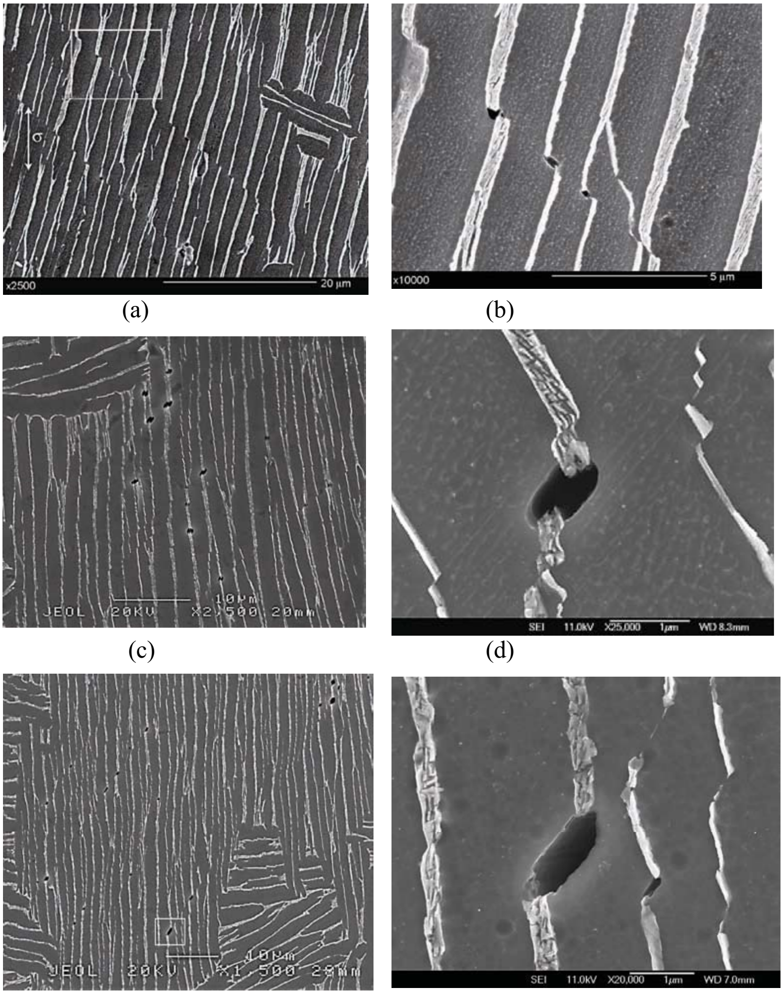


Figure 4. Strain accumulation for σ_{max} / σ_y = 1.05 vs time normalized by the time to fracture tf for the three loading modes.

Multiple crack initiation either superficial or internal (even in fatigue) was generally observed. A comparison of Young's modulus evolution during fatigue and dwell-fatigue tests at the same stress level [4] suggests earlier and more intensive damage when dwell periods are applied, which is consistent with the much higher density of microcracks observed at an early stage on the dwell-fatigue specimens gage length during interrupted tests.

Damage analyses from SEM and TEM observations

Post fracture SEM observations on samples tested to failure at σ_{max} / σ_y = 1.05 in the three loading conditions revealed the presence of micro cavities, with an oblate shape, at the intersections between localized slip bands and the β phase (Fig 6). This type of damage was localized within lamellas colonies rather close to the fracture surface. The shearing of the β phase and the formation of cavities were observed for the three types of loading e.g. fatigue, dwell-fatigue and creep.



(a) (b)

(c) (d)

(e) (f)

Figure 6. Internal damage by cavities along shear bands, (a) and (b) after fatigue, (c) and (d) after dwell-fatigue, (e) and (f) after creep.

Shear bands and cavities were observed in colonies of very different sizes, from 10µm to over 100µm. However, the shearing activity is more intense in large colonies, and no transmission of shearing was observed from a colony to another one. The same type of damage mechanism is present following the three loading conditions. This result suggests an intrinsic mechanism resulting from a high local strain level. EBSD (Electron Back Scattering Diffraction) observations performed in colonies of lamellas showed that in most cases, pyramidal glide was primarily responsible for the cavitation of the β phase, whatever the loading mode [5].

Here and there, the coalescence of aligned cavities, as for example, after dwell-fatigue (Fig 7a), illustrates the process initiation of a microcrack. In this figure, the length of the shift of the broken β phase segments required for the coalescence of neighbouring cavities, is of the order of half of the thickness of the α lamella. The quantitative damage as estimated from the cavity size and density is more intense after dwell-fatigue and creep than after fatigue.

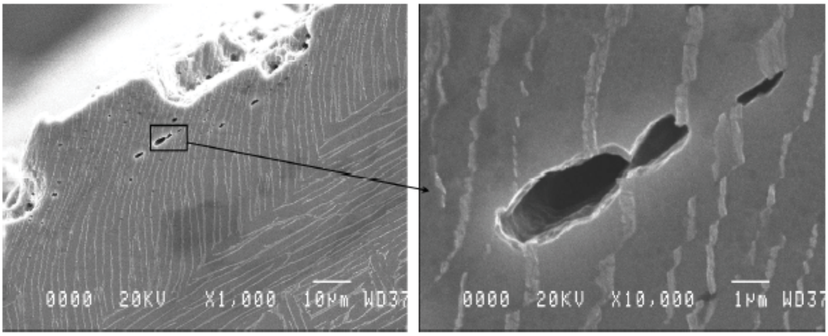


Figure 7. Coalescence of aligned cavities after dwell-fatigue

Two tests at $\sigma_{max} / \sigma_y = 1$, were stopped before failure, one in dwell-fatigue, at mid-life and the second, in creep, after a few hundreds thousand of hours. After dwell-fatigue, SEM observations exhibited the presence of shear bands and cavities, near the free surface as well as in the bulk. The cavities were always localized inside colonies of lamellas slightly misoriented with respect to the loading axis. In this sample, cavities were observed for an accumulated macroscopic strain of 4.4% corresponding to a plastic strain of 3.35%.

After creep, the same kind of damage was also observed and the coalescence of cavities leading to a microcrack, several tens of micrometers long, was observed (Fig 8).

If the presence of cavities and intense shearing in the failed samples, near the fracture surface, could have been due to the stress concentration produced by the development of the main crack, the fact that it has also been observed in the unfailed specimens proves that this damage is not a consequence of crack initiation but rather a consequence of a high localized accumulated strain and a potential cause for crack initiation.

A well documented MET analysis is performed in [6]. Thin foils observed after a fatigue test exhibit dense pileups with slip activity either in the basal plane (Burger's vector $\mathbf{b_b}$ = 1/3 <11-20>) or in a pyramidal plane (Burger's vector $\mathbf{b_p}$ = 1/3 <11-23>) as shown in figure 9.

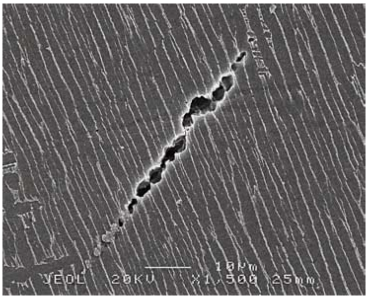


Figure 8. Coalescence of cavities in the unfailed creep loading sample at $\sigma_{max} / \sigma_y = 1$

Even though prismatic slip was locally observed, it was quite scares compared to the profuse basal and pyramidal slip. In this sample, one micro cavity was observed in the β phase, associated with localized and intense slip activity. The presence of numerous bent contours fringes did not allow us to unambiguously identify the nature of the dislocation bands.

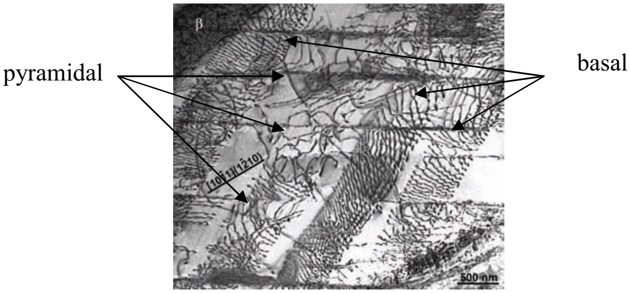


Figure 9. Dislocations structures observed on base metal after fatigue: dense pileups (basal mode) and horizontal traces (pyramidal mode).

As after fatigue, observations performed in the foils of samples tested in creep exhibit cavities, often with a “z-like” shape, associated with localised and intense slip activity, mostly in a pyramidal mode and sometimes in the basal mode. However, dislocations distributions are locally more homogeneous than in fatigue, as it can be seen in figure 10, after 7000 hours creep at $\sigma_{max} / \sigma_y = 1$.

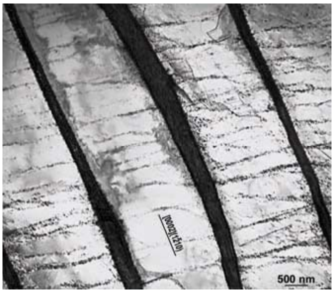


Figure 10. Dislocations structures after creep during 7 000 hours at $\sigma_{max} / \sigma_y = 1$.

Intense shearing was observed in the thin foils of samples tested in dwell-fatigue. Furthermore, the figure 11 shows a clear shearing of β phase as indicated by the arrows. A possible explanation for the localized deformation has been related to the Short Range Order which appears to be high in the dwell fatigue sample [6]. Whereas after fatigue only one cavity was observed, after dwell-fatigue, they are numerous, and always associated with dense and localized dislocation activity. An example is shown in figure 12 where four α-lamellas are visible, separated by β phase laths with different orientations. Intense dislocations bands are visible, even if partially masked by fringes, as well as two elongated cavities through two β phase laths.

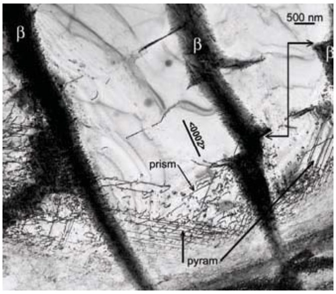


Figure 11. Dislocations structures and shearing of the β phase (double arrow) in base metal after dwell-fatigue.

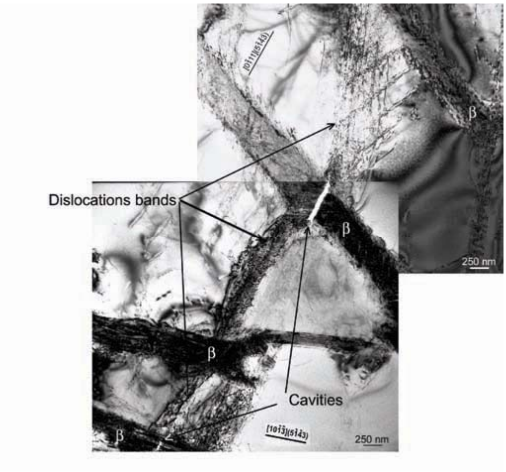


Figure 12. Cavities in the β phase associated with localised and intense dislocations activity after dwell-fatigue

They are obviously linked together as for all observed cavities in the different thin foils. Moreover, most of the cavities associated with dislocations activity have the shape of a "z". Cavities have also been seen by Savage et al. [7] at α–β interfaces in Ti-6242Si, after a tensile test. This was associated with prismatic glide, contrary to our observations where prismatic glide is rather rare and not intense. When basal slip was activated, these authors found that glide remained localised inside the α–lamellas. Figure 13 shows four α-lamellas with dislocations pileups running across them as well as across the β phase, leaving small steps at almost each crossing with the β phase. In several places, dislocations are distinguishable inside the β phase. It seems to be the onset of an intense shearing process, and the glide mode is still pyramidal.

One can see, in a given lamella or in adjacent lamellas, apparently similar dislocation pileups having dissimilar consequence in terms of damage. Some pileups generate steps at the interface, while some others do not, even so very close and in the same configuration, as in figure 13. Besides the number of dislocations leaving elementary steps at the interface, and thus visible shearing or not, an explanation for the apparent absence of shearing can be the local constitution of the β phase, especially the local size and orientation distribution of the secondary α phase, which is very inhomogeneous. This inhomogeneity can locally favor or hinder dislocation glide across the interface.

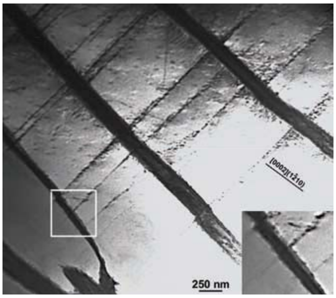


Figure 13. Shearing of the β phase after creep in an unfailed sample. In medallion, an enlargement of the white square where steps are visible at the dislocations crossings.

Conclusions

The main following conclusions can be drawn:

- The introduction at room temperature of dwell periods at each applied stress peak of pure cyclic loading induces a decrease in fatigue life. This dwell life debit is accompanied by a significant increase in strain accumulation.
- SEM and TEM analyses conducted on longitudinal sections exhibit an internal damage consisting in small cavities which nucleate along shearing bands at the α/β interface. This damage is much intense under both dwell fatigue and creep loadings than under cyclic fatigue.
- ESBD and TEM investigations show that a predominant pyramidal slip is controlling the cavities nucleation and growth.
- Cracking results from coalescence of cavities.

References

[1] M.R. Winstone and M. J. Weaver: in : Proceedings of International Conference of Titanium, Berlin (1984), p. 2275.

[2] M. R. Bache : Int. Journ. Fatigue **25** (2003) pp 1079.

[3] M. E. Kassner, Y. Kosaka and J.A. Hall : Met. and Mat. Trans. **30A**, (1999) pp 2383.

[4] P.Lefranc, V. Doquet , M.Gerland, C. Sarrazin-Baudoux, In press in Acta Materialia (2008)

[5] P. Lefranc, PhD Thesis, Univ. de Poitiers (2008).

[6] M. Gerland , P. Lefranc ,V. Doquet and C. Sarrazin-Baudoux , in press in Mat. Sc. And Engng. (2008)

[7] M. Doner, H. Conrad , Met. Trans. 4, (1973) pp2809.