Dwell-Fatigue in Near Alpha Titanium Alloys: a Multiscale, Interdisciplinary Challenge

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Abstract: A study was undertaken to examine the life dispersion of 15 specimens made of near-alpha titanium alloy (IMI 834) tested in dwell-fatigue loading conditions. Nucleation and propagation features were examined and results were discussed in relation with results obtained from experiments and simulations undertaken by the various authors of the present paper. Micromechanical mechanisms seem to play critical roles in the nucleation and propagation of cracks and the presence of strong local textures are thought to intensify and explain the dramatic scatter of dwell fatigue lifes.

1. Introduction

When tested in dwell-fatigue at room temperature, near-α titanium alloys display significant lifetime reduction (in comparison to standard continuous cycling) [1-3]. The addition of several-second dwell at the maximum load can result in over an order of magnitude fewer cycles to failure, which is very penalizing in terms of performance and design of turboengine compressor parts. Because of the magnitude of the life debit increases with decreasing temperature, the phenomenon has been called “cold-dwell” debit. Although it is recognized that both the creep and the cyclic deformation contribute to the early failure of some titanium alloys, the metallurgical features and micromechanical mechanisms favouring this cold-dwell sensitivity still need to be understood to prevent early withdraw from the field of such manufactured parts.

2. Typical fractography features

Surprisingly, the fracture surfaces under dwell-fatigue loading display some unusual features: subsurface nucleation sites and bright mesoscopic highly faceted regions, called “fish eyes,” exhibiting a significant amount of ‘quasi-cleavage’ facets (Figure 1a) [1-6]. These latter characteristics reveal the presence of strong crystallographic local textures that seems to play a significant role in the crack propagation behaviour (as only grains with specific orientations can undergo this quasi-cleavage behaviour).
It was found that these millimetre large textured regions (Figure 1b) are generated during the billet forging process and their presence and size may control the in-service performance of the alloys and consequently condition the notion of optimised manufacturing process (both cogging and close die forging) [7].

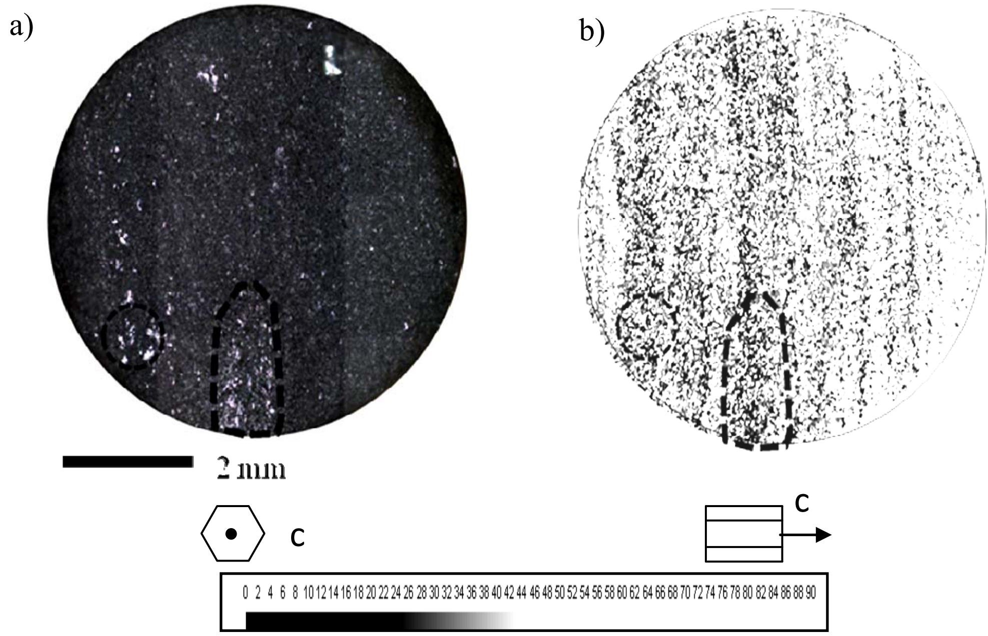


Fig. 1. (a) Optical fractography of a specimen showing a fish eye feature and (b) the EBSD map 100µm below the primary nucleation site showing the presence of macrozones (the grey intensity is related to the angle between the c axis of the crystal and the solicitation direction - SD)

2. Experimental campaign

Years of collaboration between various laboratories from France and Québec-Canada aimed to document the relative contribution of the crystallographic texture at various scales on both, the crack nucleation and crack propagation under dwell-fatigue loading conditions. This project included extensive experimental work, mainly based on the use of Electron Backscattering Diffraction (EBSD) [7-10], numerical simulations through either cellular automata [11, 12] or finite element crystal plasticity approaches [13], fatigue testing [10, 14, 15], and ultrasonic inspections [16].

For the present communication, several cylindrical specimens were machined in accordance with E606-04 ASTM standard practice for strain-controlled fatigue testing [17] from a α/β-forged IMI 834 reported to be cold-dwell sensitive. The microstructure was bimodal with about 25% of globular primary alpha α_p, 3% β phase and 72 % of acicular secondary alpha α_s phases. EBSD analysis of the grain orientations throughout the fracture surfaces showed the presence of strongly textured band-like regions called “macrozones” (an example of such local texture can be seen in Figure 1b).

15 Specimens were machined smooth in the standard round bar specimens, with a gauge diameter of 6.2 mm and a 20.5 mm gauge length. The specimens were loaded and unloaded in 0.5 s on a hydraulic machine at load ratio R = 0 in a load

control mode at 26.5 kN (824 MPa, i.e. 90 % of the yield strength). Thirty-second dwell time was imposed at the maximum load test to perform a dwell fatigue test.

3. Experimental Results

The fatigue life of the specimen can be described by a Weibull distribution with a shape parameter β equal to 1.98 and a characteristic life α of 6690 cycles (see Figure 2).

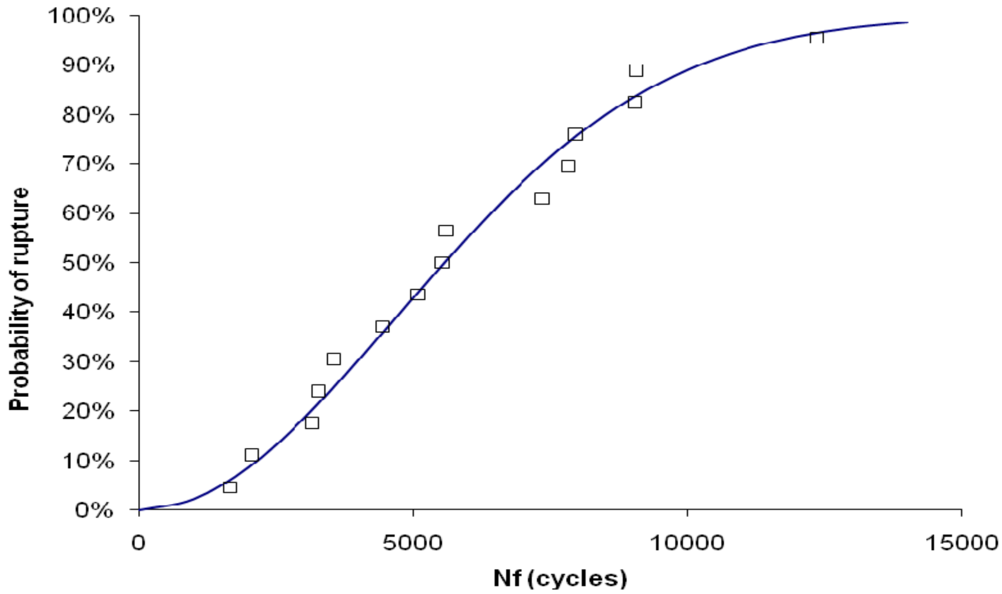


Fig. 2. Weibull distribution of fatigue life

Nucleation sites were always found to be pure cleavage facets tilted by 15° to 25° relative to the solicitation axis (Figures 3), whereas the crack propagated mainly along faceted α_p grains with their c-axis inclined 10 to 30° from the solicitation axis Figure 4). These similarly oriented grains on the propagation region, all characterised by quasi-cleavage morphologies, form the so-called “fish eye” region. It is quite clear that the size and texture sharpness of these regions is related to the propagation performance of the alloy as quasi cleavage involves rather fast propagation. Moreover, it seems also that if these regions are smaller than a threshold value, the specimen lifetime is significantly increased as nucleation is postponed. At a mesoscopic scale, the presence of strong local textures generates strong variations of elastic and creep behaviours during loading that may dictate the nucleation kinetics. Experimental results have shown it clearly [10]. Several simulation tools, including crystal-plasticity modeling [13] or cellular automata [11, 12] (figure 5a and 5b, respectively), were developed to describe the local mechanical elasto-plastic behaviour. These simulations have successfully shown that in fatigue as well as in dwell fatigue the conditions that control the nucleation are strongly related to local cumulated strain and stress fields. Tools are now used to gather the multiscale aspect of the present issue: local creep plasticity, stress transfer during loading, macrozone sizes, and nucleation/propagation in dwell fatigue.

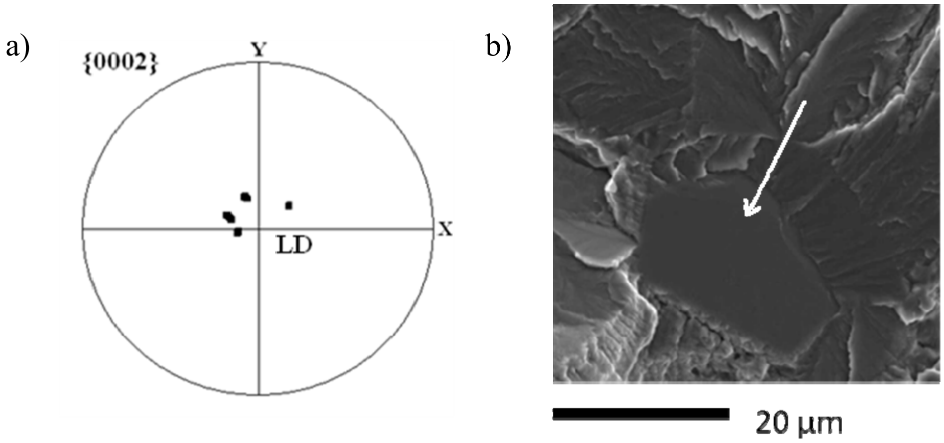


Fig. 3. Nucleation sites; a) pole figure of several nucleation sites; b) an example of a nucleation site (pure cleavage facet) – white arrow.

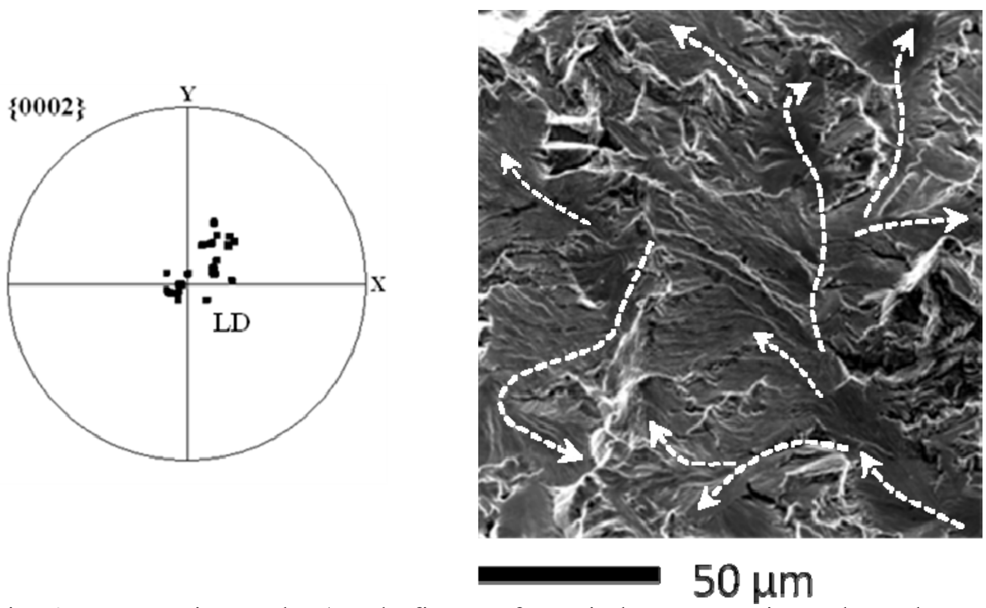
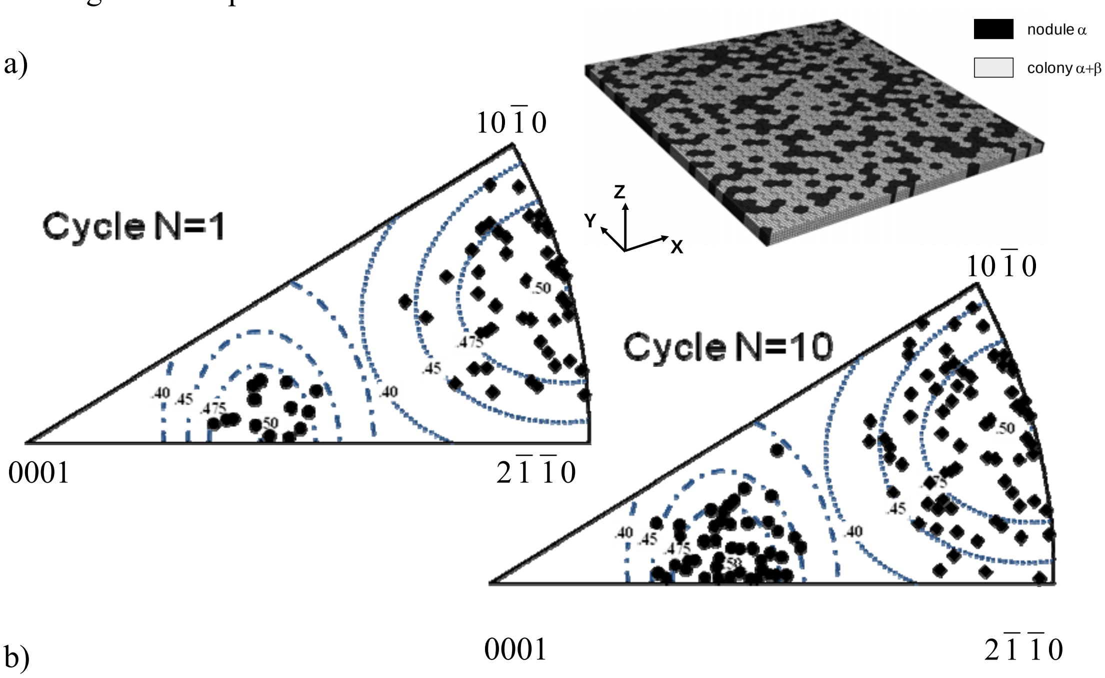


Fig. 4. Propagation path; a) pole figure of quasi cleavage regions along the propagation path; b) example of propagation path (note river marks).

4. Macroscopic load transfer and micromechanics

Numerical simulations allowed investigating further the undergoing micromechanics taking place during fatigue or dwell fatigue cycling. A crystal plasticity finite element calculations on a 2D aggregate of 900 grains in a Ti64 was developed [13]. Experiments reported that the plastic slip activity concerns mainly single slip in basal and prismatic systems and is mainly developed during the first cycles [10]. This has been modeled by a local softening law of the threshold stress of the activated slip system. The progressive occurrence and relative percentages of activated slip systems were well displayed in the simulation and have shown good agreement with experimental results. On the other hand, cellular automata were developed to monitor how the elastic and plastic (creep) environment of a grain may influence their local stresses during dynamic loading (in fatigue and in dwell fatigue) [11, 12]. Results have shown that complex interactions between elastic stress transfer (like in composite materials) and local plasticity due to local creep may generate large local normal stress susceptible to reach cleavage thresholds and nucleate a crack. Both finite elements and cellular automata modelling approaches are complementary and are now developed to take into account the influence of local texture heterogeneities on fatigue life dispersion.

a)



b)

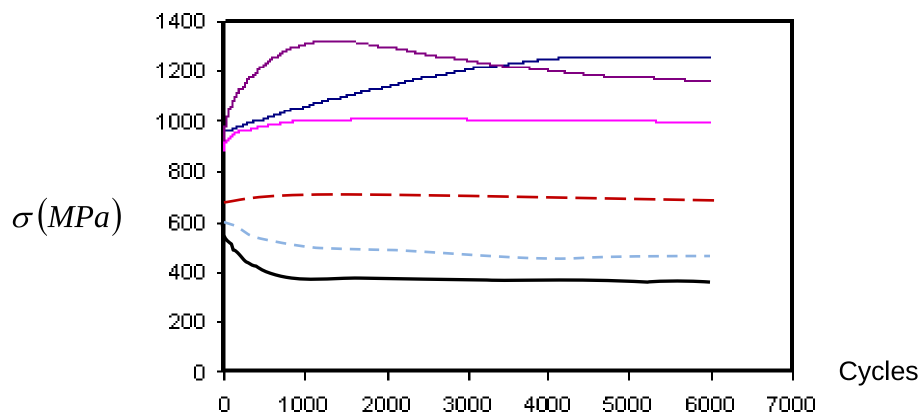


Fig. 5. Micromechanics in fatigue (a) and dwell fatigue (b) investigated by: a) crystal plasticity and inverse pole figures displaying which slip system has been activated after 1 and 10 cycles; and b) cellular automata showing how the local stress may vary according to their orientations, environments and the number of cycles.

5. References

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