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Mechanistic basis of temperature-dependent dwell fatigue in titanium alloys

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ABSTRACT

The temperature-dependent dwell sensitivity of Ti-6242 and Ti-6246 alloys has been assessed over a temperature range from −50 °C to 390 °C using discrete dislocation plasticity which incorporates both thermal activation of dislocation escape from obstacles and slip transfer across grain boundaries. The worst-case load shedding in Ti-6242 alloy is found to be at or close to 120 °C under dwell fatigue loading, which diminishes and vanishes at temperatures lower than −50 °C or higher than 230 °C. Load shedding behaviour is predicted to occur in alloy Ti-6246 also but over a range of higher temperatures which are outside those relevant to in-service conditions. The key controlling dislocation mechanism with respect to load shedding in titanium alloys, and its temperature sensitivity, is shown to be the time constant associated with the thermal activation of dislocation escape from obstacles, with respect to the stress dwell time. The mechanistic basis of load shedding and dwell sensitivity in dwell fatigue loading is presented and discussed in the context of experimental observations.

1. Introduction

The study of dwell sensitivity in titanium alloys can be traced back to the early 1970s when cold dwell fatigue was first detected in Rolls-Royce RB211 engines on Lockheed Tristar aircraft (Bache, 2003). The dwell fatigue loading cycle can be represented for a single duty cycle of a gas turbine engine (Bache, 2003) as shown in Fig. 1. Despite the long (cruise) stress dwell shown, the most damaging part of the loading history is thought to be quite early in the cycle close to peak load achievement. Under the low-cycle dwell fatigue tests, where each loading cycle consists of a stress hold period at the maximum stress, near-α titanium alloys have been reported to display significant lifetime reduction in comparison to low-cycle fatigue tests. Dunne et al. (2007a) and Zheng et al. (2016a) have demonstrated that stress-controlled dwell fatigue loading causes higher damage compare to loading with a strain hold. The lifetime reduction has been called 'cold dwell debit' because its magnitude is maximized at low temperatures, e.g. $\sim 0.4T_m$ where T_m is the absolute melting point. The formation of facet micro-cracking on basal slip planes of hexagonal close-packed crystals (HCP) is argued to cause the early nucleation of defects hence leading to a short lifetime under dwell fatigue loading (Bache, 2003; Evans and Bache, 1994; Lütjering and Williams, 2003; Sinha et al., 2006). The nucleation of faceting has been reported to be highly related to the strong anisotropy

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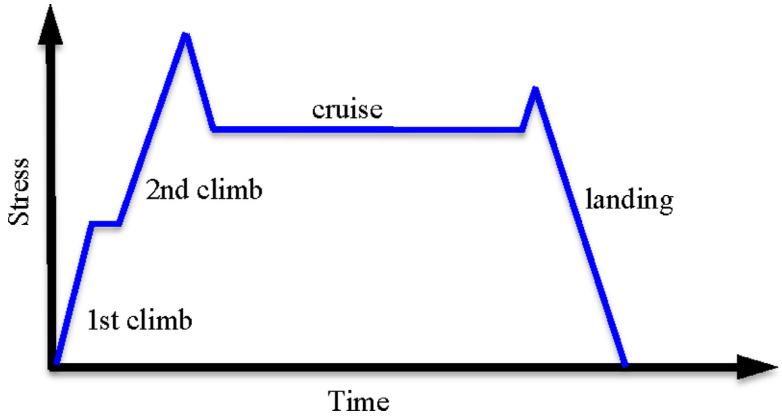

Fig. 1. Schematic diagram of a single duty cycle for a gas turbine engine (Bache, 2003).

of the HCP structure and always associated with a particular crystallographic orientation combination: a soft grain (well-orientated for slip) sits adjacent to a hard grain (c-axis parallel to the loading), sometimes known as a *rogue* grain combination (Anahid et al., 2011; Dunne, 2014; Dunne and Rugg, 2008; Dunne et al., 2007b; Kirane et al., 2009; Sinha et al., 2006).

The near-room temperature creep behaviour of near-α Ti alloys is argued to be responsible for their dwell sensitivities. Hasija et al. (2003) examined the creep of Ti-6Al alloy and found that it led to the redistribution of stress from the soft grain to the adjacent hard grain, termed load shedding, under dwell fatigue loading, and argued that this contributed to local crack initiation. Stroh (1954) established an analytical model to calculate the stress developed by a dislocation pileup along a line of slip in an elastic medium, from which a crack nucleation criterion was derived. This model was recently developed further to include alternative loading stress states and validated using discrete dislocation plasticity (DDP) modelling to understand the dwell fatigue behaviour of Ti-6Al alloy (Zheng et al., 2016a). Recent experimental evidence (Qiu et al., 2014) has shown that the Ti-6Al-2Sn-4Zr-2Mo (Ti-6242) alloy is dwell sensitive while Ti-6Al-2Sn-4Zr-6Mo (Ti-6246) is not at 20 °C. Consistent crystal plasticity and DDP models used by Zheng et al. (2016b) found that the energy barrier for thermally activated dislocation escape from obstacles in alloy Ti-6246 is higher than that for Ti-6242 and demonstrated that the remarkably different stress dwell behaviours between the two alloys result from the differing time constants associated with the thermal activation process with respect to the dwell loading time. The dwell debit in aero-engine disc components is known empirically to be worst between temperatures of 90 °C and 120 °C (Zhang et al., 2015) for a number of commercially-useful Ti alloys, but not for others. Alloy Ti-6246, for example, is considered to show a low dwell debit at 20 °C, but its dwell response at other temperatures has not been investigated.

Zhang et al. (2015) utilised crystal plasticity finite element modelling (CPFE) to address the temperature sensitivity of cold dwell fatigue in Ti-6Al alloys. Their results revealed that the maximum load shedding in these α-titanium alloys occurs at 120 °C and diminishes to zero at 230 °C, for which the mechanistic basis was a changing rate sensitivity with temperature combined with the progressive decrease in slip strengths, noting that the rate of change of strength with temperature for $\langle a \rangle$-type slip differs from that of $\langle c+a \rangle$ slip. Ozturk et al. (2016) investigated the temperature sensitivity of alloy Ti-6242 also using CPFE and showed that the dwell effect in this alloy also diminishes with increasing temperature, but interestingly as a result only of the slip strength changes with temperature, therefore suggesting a subtly different mechanistic explanation to Zhang et al. (2015). The differences potentially originate from the veracity of the single crystal slip strength data utilised since these materials show strong strain rate sensitive behaviour (even at 20 °C), but reported slip strengths are often not presented together with the strain rates at which the tests were carried out.

Dwell and no-dwell 10^4 cycle endurance fatigue tests carried out by Arthurs & Walker (reported by Zhang et al., 2015) on alloy Ti-829 found that the difference between the applied stresses respectively to give the same number of cycles to failure initially increased with temperature from 20 °C but peaked at a temperature of 120 °C and subsequently decreased and vanished at about 230 °C. Zhang et al. (2015) showed that the predicted magnitude of the stress redistribution from soft to hard grain resulting from the dwell mirrored closely this temperature sensitivity. Spence et al. (2012) showed that the dwell debit in Ti-6246 is negligible and not influenced by temperature in the range of 20 °C–150 °C. Whittaker et al. (2010, 2013) revealed that Ti-6246 alloy displays a modest lifetime reduction between 450 °C and 550 °C under dwell loading in vacuum and the fatigue life is further reduced if the tests are carried out in air, but the mechanistic basis at these elevated temperatures, outside of those for which cold dwell is normally anticipated, remains unclear. Alloy Ti-6246 morphologies in service are often complex, comprising alpha-beta lath basket weave structures which may, in their own right, influence load shedding (Zhang and Dunne, 2017). These complex morphologies are not addressed in this paper, but are the subject of future investigation. In aero-engine applications, the early take-off stage is key in the context of dwell because of the interactions of high stress and transient temperature, which is initially low but quite quickly increases to a level higher than that critical for dwell. The transient, together with the critical dwell temperature and applied stress,