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Crystal plasticity, fatigue crack initiation and fatigue performance of advanced titanium alloys

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Abstract

The fatigue behaviour of a novel large grained variant of the near α titanium alloy Ti 685 is described. Load controlled low cycle fatigue fractures in plain cylindrical specimens demonstrate the highly crystallographic nature of the failure process. When compared to similar data for conventional grain size Ti 685 variants the LG685 material clearly offers reduced fatigue and static strength. An alternative flat plate specimen design was employed together with electronic speckle pattern interferometry and strain gauges to monitor the inhomogeneous strain accumulation in this large grained variant under load control conditions. Dwell fatigue tests indicated that the eventual location for crack initiation and subsequent failure could be identified as early as the first loading cycle. The precise crystallographic orientations of the surrounding microstructure were defined using electron back scattered diffraction. In contrast to previous models to describe facet formation and early fracture in this class of alloy, basal plane slip systems were not implicated. The use of EBSD to identify "effective structural units" of common orientation, which do not necessarily relate to colony size, will be demonstrated for both the large grained material and a conventional compressor disc alloy Timetal 834 in typical forged condition.

Keywords: Titanium; Plasticity; Anisotropy; Dwell fatigue

1. Introduction

The phenomenon of ambient temperature dwell sensitive fatigue in titanium alloys has now been a concern to the gas turbine industries for over three decades. However, due to the perpetual need to reduce engine weight and the economic constraints which resist the introduction of new materials, it is unlikely that titanium will be replaced for novel substitutes for some foreseeable future. Therefore, with the sustained use of the near α and α/β variants for safety critical components in the low and high pressure compressor sections of the engine, the potential effects of "cold dwell" or "dwell sensitivity" (i.e. a reduction in fatigue strength under relatively high stress regimes due to the imposition of a dwell or hold period at either peak or high mean stress) continue to compromise design.

Compressor disc components experience demanding mechanical conditions during routine operation. Since loading will be cyclic in nature, extensive fatigue databases have been generated in support of component design and lifing, employing both laboratory and test bed assessments. Since these components fall into a "high performance" category and their high operating stresses dictate a relatively small LEFM critical flaw size, a holistic approach to understanding the fatigue process is particularly appealing since the vast majority of the operating life will be spent in the initiation and early crack growth stages [1]. This is especially the case for some commonly employed titanium alloys which can possess a relatively large grain size.

In the case of large scale near α and α/β titanium components, or alternatively laboratory scale test specimens where the "grain size" is small compared to the volume of critically stressed material, the initiation sites of fatigue cracks are invariably characterised by the presence of "quasi-cleavage facets". Previous electron back scattered

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diffraction (EBSD) studies have shown that, to within the experimental scatter of the technique, these facets form on the basal plane of the hexagonal α crystallographic unit [2]. Despite the adjective "quasi-cleavage" it is evident that they are not considered to be the result of a brittle fracture mechanism, rather the gradual separation of slip damage concentrated within a persistent planar slip band [3].

At first sight, two specific features of these facetted fractures fail to conform to classical models to describe Stage I fatigue crack initiation and growth in metals. Firstly, components and laboratory specimens alike often fail from subsurface sites. Secondly, the earliest stage facets tend to lie on a plane perpendicular to the principal tensile loading direction and, therefore, are difficult to ascribe to an inclined slip deformation model. In order to explain this behaviour Evans and Bache [3] compared facet formation to the planar slip band model of Stroh [4]. The basis of this model, which essentially describes a process of stress redistribution between "weak" and "strong" grains [5], is believed to represent early crack formation in many titanium alloys under fatigue loading and has been widely adopted amongst the titanium research community [6–8].

Our recent experimental studies have been designed to investigate planar slip band deformation and stress redistribution behaviour, utilizing an abnormally large grained variant of the alloy Ti 685, processed via a proprietary heat treatment routine, to produce β grains up to 20 mm in diameter. Flat plate and cylindrical test specimens have been employed under a variety of static (cold creep), cyclic and dwell loading conditions, whilst crystal plasticity has been monitored within distinct grains employing miniature strain gauges and electronic speckle pattern interferometry (ESPI). Post test microstructural characterisation has been performed using electron back scatter diffraction (EBSD) to correlate plastic deformation and crack formation to crystal orientation and grain anisotropy.

In the present paper, the identification of "effective structural units", regions of common orientation which may not necessarily relate to optical grain size but which fundamentally control early fatigue damage, will also be illustrated for both the large grained Ti 685 material and a conventional near α compressor disc alloy, Timetal 834, which has been reported as a dwell sensitive alloy in a previous publication [9].

2. Experimental methods

The majority of the current research relates to a novel, large grained form of the near α titanium alloy Ti 685 (Ti–6Al–5Zr–0.5Mo–0.25Si). A proprietary vacuum heat treatment routine was applied to plates of nominal dimensions 180 × 180 × 25 mm to induce an apparent grain size of approximately 20 mm diameter, clearly visible to the naked eye, Fig. 1. Metallographic inspection confirmed a coarse, interlocking, aligned α lath structure within the individual grains, Fig. 2. This material has been designated LG685.

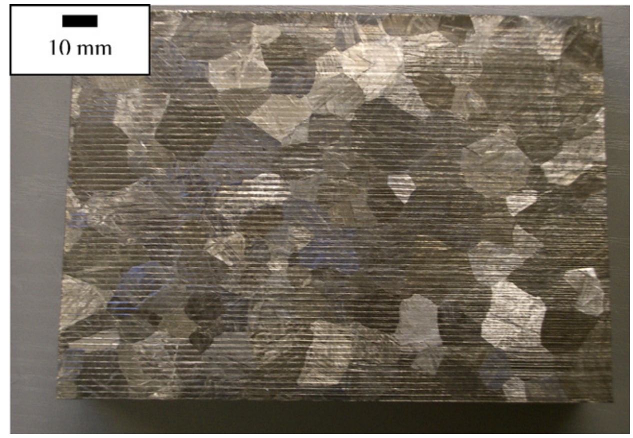

Fig. 1. Large grained variant of Ti 685 (designated LG685).

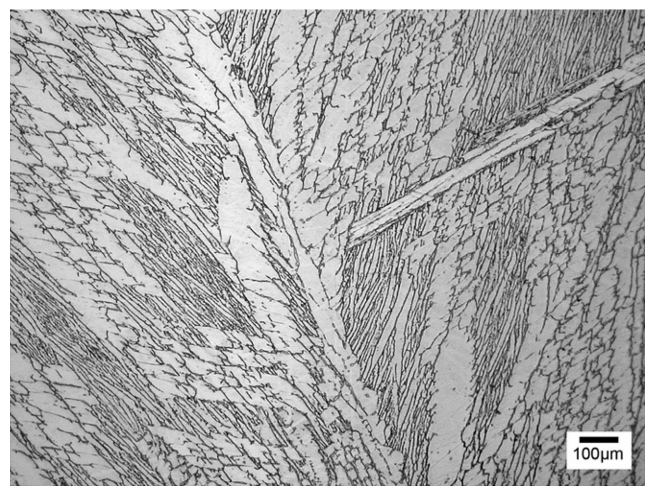

Fig. 2. Coarse, aligned α lath microstructure of LG685 variant.

Two forms of mechanical test specimen were machined from the heat treated stock materials. The first was a standard plain cylindrical geometry, normally employed for either load or strain controlled low cycle fatigue assessments of conventional grain size alloys. The dimensions of the critically stressed gauge section were a diameter of 6 mm and parallel length of 12 mm. It should be emphasized that these specimens were extracted from random locations within the plates. As a consequence of the relatively large grain size, the gauge section of these specimens could feasibly sample just a single grain. This could not be established prior to testing since the gauge section was prepared with a longitudinally polished finish. These specimens were employed for constant amplitude load controlled LCF testing to establish baseline fatigue strength, dwell fatigue strength and generate freely initiated fractures for inspection. "Cyclic" fatigue loading was applied at room temperature, utilising a 15 cycle per minute trapezoidal waveform at $R = 0.1$, with peak stresses selected to induce fatigue failures in less than 10^5 cycles. The "dwell" fatigue tests employed identical 1 s loading and unloading linear ramps with a 2 min hold imposed at