



The influence of load holds on the fatigue behaviour of drawn Ti-6Al-4V wires



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ABSTRACT

Dwell sensitivity in titanium alloys is generally attributed to the phenomenon of load shedding, which is a time dependent redistribution of stress from weak grains, with their c-axis perpendicular to the loading direction, to strong grains, with their c-axis approximately parallel to the loading direction. This leads to the formation of internal quasi-cleavage facets on the basal planes of strong grains. In this paper, the effect of load holds on the fatigue behaviour of drawn Ti-6Al-4V wires is investigated, because these wires do not contain strong α grains. It has been found that this leads to a different dwell fatigue behaviour compared to what has been described in literature. In the case of drawn wires, introducing load holds promoted crack initiation at the surface, through the formation of a facet on a prismatic plane of a surface grain that was oriented for very easy prismatic slip. This was confirmed by sectioning facets, using focused ion beam milling, and electron backscatter diffraction measurements. Because of the specific crystallographic texture of drawn wires, the phenomenon of load shedding is less pronounced, and there is no formation of internal facets. The amount of cycles to failure was reduced by two to three orders of magnitude compared to fatigue tests without load holds. The time to failure remained similar, and was even higher for some dwell fatigue tests. There was a significant amount of strain accumulation during dwell fatigue tests. The maximum strain increased more rapidly in tests with 30 s load holds compared to tests with 120 s load holds, due to creep recovery during the periods in between load holds. During these periods, the strain decreased, even though a small tensile load was still applied.

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1. Introduction

Several titanium alloys, including Ti-6Al-4V, show dwell sensitivity, which means that the fatigue life reduces if load holds are introduced [1–4]. In contrast with fatigue tests, which are generally performed using sinusoidal loading, dwell fatigue loading consists of a trapezoidal waveform with a certain dwell or hold time at the maximum load. This type of loading is highly relevant for aerospace applications, specifically for components such as fan discs in turbine engines [1]. The reduction in fatigue life because of load holds can be several orders of magnitude [5], and is reported to become more drastic at longer dwell times [3,6] and at higher stress levels [3,4]. This phenomenon is sometimes also called cold dwell [1,4,7] or cold creep [3,6] because it can be regarded as an interaction between fatigue and creep [5] and because it can occur at room temperature [4]. Cold creep at stresses below the macroscopic yield stress leads to strain accumulation, which is believed to be an important factor in dwell sensitivity [1,3]. The fracture

surfaces of samples after dwell fatigue testing generally show that cracks initiate internally, which is characteristic of creep [5], and that the initiation region contains so-called quasi-cleavage facets [1,3–9]. These facets are primary α grains which have fractured in a transcrystalline and planar manner. The formation of internal facets in Ti-6Al-4V during dwell fatigue is believed to be the result of differences in crystallographic orientation between primary α grains, which leads to load shedding. Load shedding involves a time dependent redistribution of stress from weak grains, with their c-axis perpendicular to the loading direction, to strong grains, with their c-axis approximately parallel to the loading direction. This occurs because weak grains can deform plastically during loading, which lowers the stress and can lead to a compressive stress after unloading. Strong grains do not deform plastically, but instead are subjected to an increasing stress over time because surrounding weak grains are deforming more easily and are shedding their load onto the strong grains [10,11]. This process continues until a critical stress for facet formation in the strong grain is reached [5]. A possible facet formation mechanism has been suggested by Bache [1] and involves the formation of a dislocation pile up in a weak grain at the boundary with a neighbouring strong

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grain. This induces a shear stress in the strong grain, which can lead to the formation of a basal slip band in this grain, approximately perpendicular to the loading direction. Due to the high tensile stress on this slip band, a facet can nucleate. The occurrence of internal crack initiation due to facet formation also bears a resemblance to what is observed in very high cycle fatigue experiments [6,12].

Because the differences in crystallographic orientation between neighbouring grains are believed to lead to the formation of facets and thus the reduction in fatigue life, the crystallographic texture of the material should have a large influence on dwell sensitivity. The crystallographic texture is determined primarily by thermo-mechanical treatment steps during the production process. Bearing this in mind, it appears that most research on dwell fatigue has been performed using forged titanium alloys, which contain strong grains that are oriented with their c-axis parallel to the loading direction. To the author's knowledge, no data have been reported for dwell fatigue tests on drawn Ti-6Al-4V wires, which do not contain strong grains. Therefore, the purpose of this paper is to investigate the effect of load holds on the fatigue behaviour of drawn Ti-6Al-4V wires, which will lead to new insights regarding dwell fatigue phenomena. Fatigue tests with and without load holds will be compared in terms of fatigue life, crack initiation behaviour and strain accumulation.

2. Experimental details

2.1. Material

The Ti-6Al-4V (ASTM B863, grade 5) wire used in this study has a diameter of 1 mm, and was supplied in a coil. Table 1 shows the composition as determined by the manufacturer.

The material was heat treated in vacuum ($<1 \times 10^{-3}$ Pa) at 920 °C for 10 h followed by furnace cooling. The wires were then straightened by applying a deformation of 1% plastic strain. Next, the wires were subjected to a stress relief treatment in vacuum ($<1 \times 10^{-3}$ Pa) at 600 °C for 1 h followed by furnace cooling. The resultant microstructure contains equiaxed primary α (hcp) grains with partially transformed β (bcc) at the grain boundaries, as can be seen in the backscattered electron image of the polished cross-section of the wire (Fig. 1). The average primary α grain size is approximately 5 μm . From tensile tests, the 0.2% yield stress was found to be 836 ± 15 MPa, using a strain rate of $2 \times 10^{-4} \text{ s}^{-1}$.

The crystallographic texture of the α phase, measured by electron backscatter diffraction (EBSD) on the polished wire cross-section, is illustrated by $\{10\bar{1}0\}$ and $\{0001\}$ pole figures in Fig. 2. It can be seen that there is a high tendency for grains to be oriented with the normal direction of the prismatic $\{10\bar{1}0\}$ planes parallel to the wire axis, as well as a tendency for grains to be oriented with the normal direction of the $\{10\bar{1}0\}$ planes rotated approximately 60° from the wire axis. The $\{0001\}$ pole figure shows that there are virtually no grains oriented with their c-axis parallel to the wire axis.

2.2. Experimental procedure

Prior to fatigue testing, all wires are electrochemically polished for 10 min in an electrolyte containing 55 vol% CH_3COOH , 30 vol%

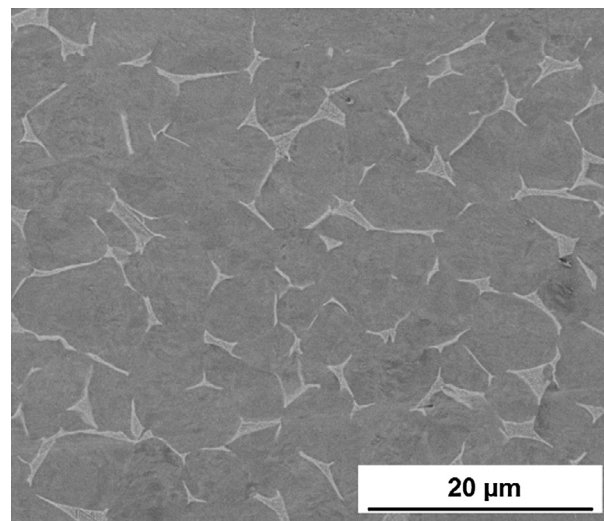


Fig. 1. Backscattered electron image of the cross-section of the Ti-6Al-4V wire.

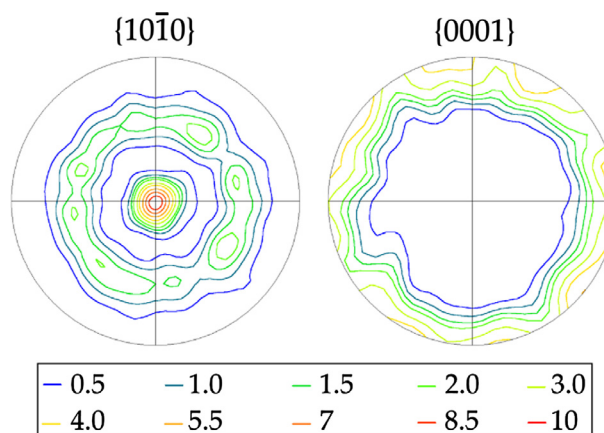


Fig. 2. $\{10\bar{1}0\}$ and $\{0001\}$ pole figures of the α phase, obtained from EBSD measurements on wire cross-section (wire axis is perpendicular to the paper).

H_2SO_4 and 15 vol% HF (48% purity) using a current density of 1.2 mA/mm^2 . Further details of this process are described by Pyka et al. [13]. The wires are then glued with two grooved plates on each side, using Araldite Rapid epoxy adhesive. The grooved plates are also made of Ti-6Al-4V and have a length of 20 mm, width of 15 mm and a thickness of 1 mm. The V-shaped groove has a width of 1 mm and a depth of 0.5 mm. Samples that fail inside the clamping plates are discarded. The gauge length, which is approximately 50 mm, is coated with Sicomet 85 cyanoacrylate glue to protect the wire surface from damage during storage and fatigue testing. Fatigue and dwell fatigue testing is performed using an Instron ElectroPuls E3000. A FEI Nova NanoSEM 450 is used to obtain scanning electron microscope (SEM) images of the microstructures and fracture surfaces and for EBSD measurements. Focused ion beam (FIB) milling is performed with a FEI Nova 600 NanoLab microscope using a 30 kV voltage and a current of 9 nA. EBSD data are cleaned using a neighbour confidence index correlation of 0.1, with TSL OIM Analysis 7 software.

Table 1
Chemical composition of the wire, as determined by the manufacturer (wt%).

Al	V	Fe	C	N	H	O	Others	Ti
6.1	4.1	≤ 0.10	≤ 0.01	≤ 0.01	≤ 0.01	≤ 0.009	≤ 0.2	Bal

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