International Journal of Plasticity xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

Dislocation interactions and crack nucleation in a fatigued near-alpha titanium alloy

S. Joseph, T.C. Lindley, D. Dye*

Department of Materials, Royal School of Mines, Imperial College, Prince Consort Road, South Kensington, London SW7 2BP, UK

ARTICLE INFO

Keywords:
Titanium alloys
Dislocations
TEM
Fatigue

ABSTRACT

Dislocation interactions at the crack nucleation site were investigated in near-alpha titanium alloy Ti-6242Si subjected to low cycle fatigue. Cyclic plastic strain in the alloy resulted in dislocation pile-ups in the primary alpha grains, nucleated at the boundaries between the primary alpha and the two-phase regions. These two phase regions provided a barrier to slip transfer between primary alpha grains. We suggest that crack nucleation occurred near the basal plane of primary alpha grains by the subsurface double-ended pile-up mechanism first conceived by Tanaka and Mura. Superjogs on the basal $\langle a \rangle$ dislocations were observed near the crack nucleation location. The two phase regions showed direct transmission of a_3 dislocations between secondary alpha plates, transmitted through the beta ligaments as $a[010]$, which then decompose into $(a/2)\langle 111 \rangle$ dislocation networks in the beta. The beta ligaments themselves do not appear to form an especially impenetrable barrier to slip, in agreement with the micropillar and crystal plasticity investigations of Zhang et al.

1. Introduction

Near-alpha titanium alloys such as Ti-6242Si are used in elevated temperature service in aero-engines, e.g. in the compressor, especially in the 400–550°C range. A wide range of temperature, stress and loading frequency combinations are experienced across the flight cycle; for example during take-off, stresses in the disc bore can be high before the thermal field has equilibrated, and so room temperature fatigue behaviour can be an important consideration. Titanium alloys are generally notch sensitive and so crack initiation from the microstructure is often of greater concern than in other alloy systems where lifing can mostly be considered in terms of crack growth.

Extensive research on fatigue crack initiation mechanisms have been performed, including metallographic observations of crack initiation (Kim and Laird, 1978; Luquiau et al., 1997; Chan et al., 1981; Wagner and Lutjering, 1987; Boyer and Hall, 1993; Dunne et al., 2007; Tan et al., 2015), intrusions and extrusions on the sample surface (Bao-Tong and Laird, 1989; Basinski and Basinski, 1992; Ahmed et al., 2001; Polák and Man, 2016) and observations of dislocations structures by TEM (Basinski and Basinski, 1992; Polák and Man, 2016; Basinski et al., 1969; Essmann and Mughrabi, 1979; Laird et al., 1986; Beranger et al., 1993; Pedersen and Winter 1995). Based on these findings, theoretical models of fatigue crack nucleation (Polák and Man, 2016; Mott, 1958; Essmann et al., 1981; Tanaka and Mura, 1981; Sangid et al., 2011) have been proposed to explain the mechanism of fatigue crack nucleation. Essmann et al. (1981) proposed the first such model to explain the intrusions and extrusions formed. Tanaka and Mura (1981) then modeled the formation of an embryonic crack from the dislocation pile-ups accumulated during cyclic loading.

Ti-6242Si develops a wide variety of microstructures depending upon the thermo-mechanical history, with microstructure having

* Corresponding author.
E-mail address: david.dye@imperial.ac.uk (D. Dye).

https://doi.org/10.1016/j.ijplas.2018.06.009
Received 17 April 2018; Received in revised form 7 June 2018; Accepted 16 June 2018

a significant effect on fatigue behaviour (Singh et al., 2002, 2007; Xiao and Umakoshi, 2002; Li et al., 2007; Huang et al., 2011; Wu et al., 2013). It is also evident that the stress evolution in dual phase titanium alloys is mainly governed by the primary alpha phase, α_p (Luquiau et al., 1997; Chan et al., 1981), because the α_p is usually softer than the beta phase, β.

However, the two-phase regions having thin secondary alpha (α_s) plates in retained β also play a role. The two-phase region was found to be a barrier for slip transmission between primary alpha grains during low cycle fatigue (Joseph et al., 2018). The slip transmission within this two-phase region is mainly dependent on the orientation relation between the α_s and β plates. In general, it follows the Burgers orientation relation (Bhattacharyya et al., 2003), however, other crystallographic variants are also possible (Tong et al., 2017). Slip transmission has been reported between α and β plates (Savage et al., 2004; Zhang et al., 2016) and it was more likely to be observed when the β plates are favourably oriented for slip (Seal et al., 2012).

In lamellar microstructures fatigue cracks initiate either within slip bands in α lamellae or along prior beta grain boundaries (Wagner and Lutjering, 1987; Boyer and Hall, 1993). In bimodal microstructures, cracking can initiate either on the interface between the lamellar microstructure and the α_p or within the α_p itself; initiation also depends on the fraction and size of the α_p. In near-α alloys, such as Ti6242, with more than 50% α_p, crack nucleation is expected to occur in the α_p due to extensive grain boundary dislocation pile-up (Tan et al., 2015). Further, a recent in-situ micro-fatigue study in Ti6246 identified that crack nucleation sites are associated with microtextured regions favourably oriented for basal or prism slip (Szczepanski et al., 2013).

Despite this extensive research, very few observations have been made of the dislocation structures associated with naturally initiated fatigue crack initiation sites, as opposed to those associated with cyclic plasticity from gauge sections, or SEM studies of the orientations and coarse microstructural features associated with cracking. However, it has recently become possible, with focused ion beam milling, to perform such site-specific studies.

In this paper, we perform such studies with the aim of elucidating the dislocation mechanisms near a fatigue crack origin, in order that more fatigue-resistant microstructures and alloys might be developed in future. The dislocation mechanisms associated with fatigue crack nucleation and the role of the two-phase regions are discussed in detail.

2. Experimental description

The Ti-6Al-2Sn-4Zr-2Mo-0.1Si (wt.%) alloy investigated in this work was melted from elemental stock and then processed by rolling in both the β and $\alpha + \beta$ domains, recrystallized in the $\alpha + \beta$ domain at 950°C for 5 h and air-cooled. The alloy was then aged at 593°C for 8 h and air cooled to promote nanometre-scale Ti_3Al precipitation. This processing route resulted in bimodal microstructure with 50% volume fraction of α_p in the transformed β. The initial microstructure of the alloy can be found in our previous work (Joseph et al., 2018). Very thin secondary alpha α_s platelets of 50–100 nm thickness were observed in the retained β.

Low cycle fatigue (LCF) tests were carried out on cylindrical plain fatigue samples with a 2.9 mm diameter and 15 mm long gauge length using a Mayes servohydraulic machine with an Instron 8800 controller. A trapezoidal waveform with a ramp up/down time of 1 s, a 1 s hold at maximum stress of 95% of yield stress (831 MPa), 1 s hold at minimum stress and an R ratio of 0.05 was used. One sample failed after 23,914 cycles.

A Zeiss Auriga field emission gun scanning electron microscope (FEG-SEM) in secondary electron imaging mode was used for fractography. Dislocation analysis was conducted using a JEOL JEM-2100F TEM/STEM with an accelerating voltage of 200 kV. TEM samples were prepared using the focused ion beam (FIB) lift-out technique in a dual beam FEI Helios NanoLab 600 using a 30 kV Ga ion beam. Foils were extracted near the crack origin from the fracture surface. To protect the area of interest, a gas injection system was used to deposit a Pt-containing protective layer. Samples were made electron transparent by thinning down to a thickness of 150 nm.

To obtain the orientation relation between α_s and β ligaments in a two phase region of the foil, Transmission Kikuchi Diffraction (TKD) was carried out. TKD data was collected on the same Auriga SEM used for fractography, at an accelerating voltage of 30 kV and at a working distance of 2 mm. The stage was tilted to 30° to make the sample in the TKD holder normal to the electron beam. Detailed description of the orientation relations found by TKD can be found in Tong et al. (2017).

3. Results

The fracture surface was investigated and smooth, near-planar crack initiating facets were found very slightly below the sample surface, Fig. 1(a). The spatial and crystallographic orientation of these facets obtained by quantitative tilt fractography and EBSD are reported in Joseph et al. (2018). TEM foils were extracted from the two regions identified, at the crack nucleation site and, for comparison purposes, a region 50 μm away in the fatigue crack growth region. The foils are shown in Fig. 1(b-c) and the α_p and two phase regions, $\alpha_s + \beta$ marked. Each grain in the foils was tilted to at least three different beam directions B and three different g vectors under each beam condition to analyze the dislocations. The dislocations observed in the foils are discussed in the following sections.

3.1. Dislocation activities at the crack origin

Foil 1 contained three different two phase regions and two α_p regions, Fig. 1(b). The dislocation activities in the two-phase $\alpha_s + \beta(1)$ region under a two-beam condition with $B \approx [11\bar{2}3]$ and $g = [0\bar{1}11]$ are shown in Fig. 2. The $g.\,b$ invisibility analysis shows that these are $\langle a \rangle$ type dislocations with Burgers vector $(a/3)[\bar{1}\bar{1}20]$ and $(a/3)[\bar{1}2\bar{1}0]$ in the α_s plates. They are found to be of screw character, gliding on the $(\bar{1}100)$ and $(\bar{1}010)$ prism planes, respectively. Further, they are gliding on their respective planes without