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Evolution of lattice strain in Ti–6Al–4V during tensile loading at room temperature

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Abstract

The evolution of intergranular lattice strains in a textured, forged bar (Bar) sample of the $\alpha-\beta$ titanium alloy Ti–6Al–4V has been characterised using *in situ* X-ray diffraction. A two-phase elastic–plastic self-consistent (EPSC) model has been developed to rationalise the results. Of the orientations analysed, it is found that the $\{200\}$ β orientation is the most compliant and that load partitions to this orientation during plasticity. The results from the bar material have then been used to predict the response of unidirectionally rolled plate (UD) Ti–6Al–4V. It is predicted that the residual lattice strains in the $\{10\bar{1}0\}$ and $\{11\bar{2}0\}$ orientations will be significantly higher in the UD material.

Keywords: Titanium alloys; X-ray diffraction; Lattice strains; Micromechanical modelling

1. Introduction

Ti–6Al–4V is the most commonly used titanium alloy, accounting for roughly 50% of total worldwide titanium production [1]. It is of particular importance to the aerospace industry where its high strength-to-weight ratio and resistance to fatigue and corrosion make it an ideal material for the manufacture of fan and turbine blades in jet engines. It is used in a variety of microstructural conditions, depending on the properties desired. The typical, bimodal microstructure of Ti–6Al–4V consists of equiaxed α grains and transformed β grains containing lath-like α structures, produced by deformation in the $\alpha+\beta$ region with subsequent recrystallisation and ageing.

During the lifetime of such components, subjection to considerable cyclic stresses is common, and in order to fully explain observed phenomena such as fatigue life behaviour and component failure, one must consider the role played by intergranular and interphase microstresses. X-ray diffraction is a particularly useful, non-destructive method of analyzing microstress. *In situ* diffraction experiments during tensile loading of a material can be used in conjunction with micromechanical models such as elastic–plastic self-consistent (EPSC) models to rationalize observed phenomena.

The present self-consistent model is a two-phase extension of the model originally created by Turner and Tomé [2]. Their model has been used extensively in the study of load partitioning in grains of different orientations in various materials such as zirconium [3–6], nickel [7] and the α-titanium alloy, IMI-834 [8]. A single-phase EPSC model was also used by Clausen et al. in their study of three randomly textured face-centred cubic (fcc) materials, *i.e.* copper, aluminium and steel [9,10], but this model utilised a different hardening law to the present model and that of Turner and Tomé. A two-phase EPSC model was also used to model the accumulation of microstrains in the nickel superalloy Waspaloy [11]; this model used a grain-within-

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a-grain framework to account for the interaction of the two phases, in contrast to the model presented here. The present model has also been used by Raghunathan et al. in their study of Ti–10V–2Fe–3Al during room temperature tensile loading [12]. Since EPSC models are texture specific, they can be used to investigate the role played by texture in determining macroscopic and microscopic behaviour.

In past decades, many studies have been carried out into the effects of texture on the fatigue and other properties of Ti–6Al–4V [13–16]. In general it has been observed that a degradation in fatigue life is seen when loading occurs along the *c*-axis of the α-phase. More specifically, $R = 0$ unnotched low-cycle fatigue tests under load control show that the life of the sample is dependent upon the loading direction relative to the orientation of the $\{0001\}$ basal planes [17–19] (where R is the minimum/maximum stress, or stress ratio). Loading perpendicular to the *c*-axis leads to better fatigue life than loading parallel to the *c*-axis. This has been attributed to the greater number of available slip systems when loading perpendicular to the *c*-axis and hence to greater plastic strain accumulation during cyclic straining.

The present paper details *in situ* X-ray diffraction measurements performed on a sample of forged bar (bar) Ti–6Al–4V during tensile loading, their use in the calibration of a two-phase EPSC model, and the subsequent use of this model to predict the lattice strain response of unidirectionally rolled (UD) Ti–6Al–4V.

2. Experimental description

Forged bar and UD Ti–6Al–4V material was supplied by Rolls-Royce, Derby, UK. A backscattered image of the microstructures of each product form is shown in Fig. 1. Preparation of the samples for these images involved electropolishing in a solution of 15 ml perchloric acid (HCl_4), 147.5 ml methanol (CH_3OH) and 175 ml butan-1-ol (C_4H_9OH) at −50 °C with an imposed voltage of 12 V and a polishing time of 5 min. The bar microstructure exhibits elongated α grains that stretch along the forging axis. These grains are ~70 μm in length and ~5 μm wide, and are surrounded by β-phase material along their grain boundaries. The UD microstructure shows more equiaxed α grains, generally slightly larger than 10 μm, with small amounts of intergranular β-phase material.

Pole figures were obtained for the α-phase of the different product forms by laboratory X-ray diffraction (Fig. 2). The effects of defocussing and absorption in the sample mean that only 80° of the pole figure can be directly measured; the missing data was reconstructed using a WIMV (Williams–Imhof–Matthies–Vinel) analysis [20]. The subsequently rotated and symmetrised complete pole figures were then used to generate a sample orientation distribution function using the software tool popLA. From this, a set of 1000 grain orientations each weighted by a volume fraction was generated and used to model the texture of the α-phase of the material for the two product forms. The β-phase was modelled using a set of 1000 grains possessing a random texture.

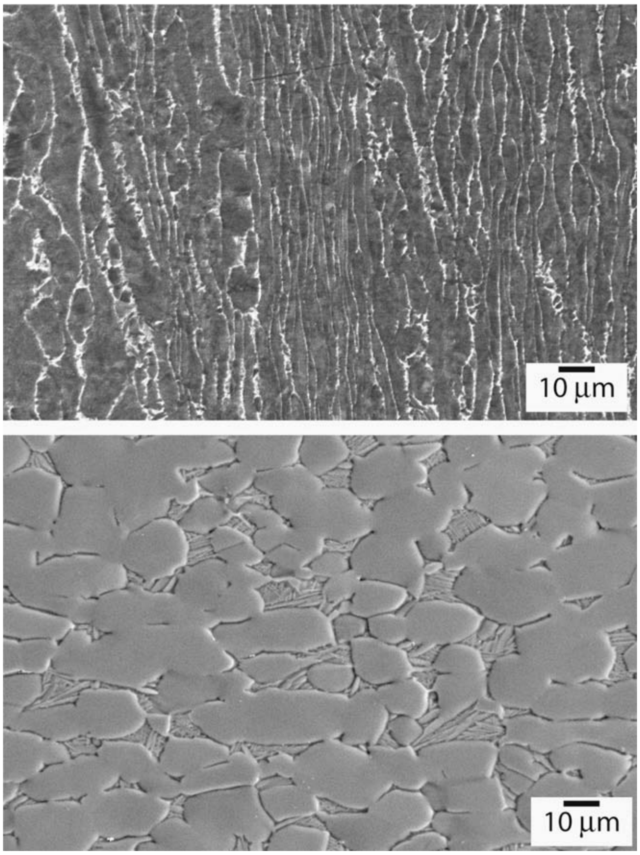

Fig. 1. Backscatter electron images of the microstructures of the forged bar (top) and UD plate (bottom) of Ti–6Al–4V.

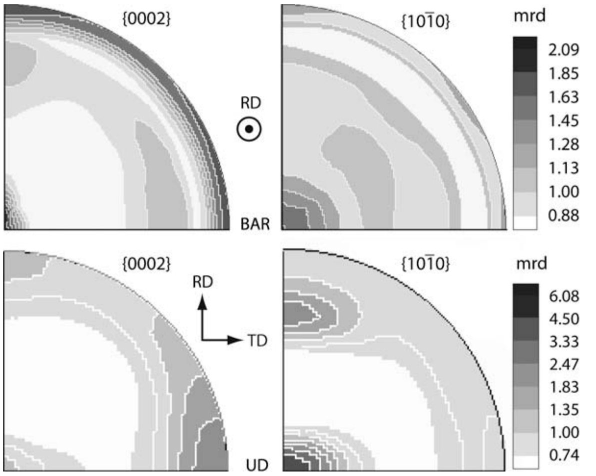

Fig. 2. Texture pole figures produced by X-ray diffraction for the $\{0002\}$ and $\{10\bar{1}0\}$ α poles for the bar (top) and UD (bottom) product forms. The tensile samples were tested along the long axis of the bar (RD) and the rolling direction of the UD plate (RD). TD denotes the long transverse direction of the plate.

The samples used in the X-ray diffraction experiment are necessarily small in order to allow sufficient penetration of X-rays; thus, they do not allow for an extensometer to be