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3D characterization of trans- and inter-lamellar fatigue crack in $(\alpha + \beta)$ Ti alloy

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ABSTRACT

This paper presents a three dimensional image processing strategy that has been developed to quantitatively analyze and correlate the path of a fatigue crack with the lamellar microstructure found in Ti-6246. The analysis is carried out on X-ray microtomography images acquired in situ during uniaxial fatigue testing. The crack, the primary β-grain boundaries and the α lamellae have been segmented separately and merged for the first time to allow a better characterization and understanding of their mutual interaction. This has particularly emphasized the role of translamellar crack growth at a very high propagation angle with regard to the lamellar orientation, supporting the central role of colonies favorably oriented for basal ⟨a⟩ slip to guide the crack in the fully lamellar microstructure of Ti alloy.

1. Introduction

Two-phase Titanium alloys are widely used by a range of industries including aerospace. Understanding short crack interaction with microstructure during fatigue loading is of great importance for improving lifing predictions, particularly for safety critical components. X-ray microtomography has developed into the technique of choice for mechanistic studies of crack propagation as it enables quantitative 3D in situ characterization, as reviewed in [1,2], provided 3D image processing methods are developed to extract features of interest.

The present work concentrates on Ti alloys with a fully lamellar microstructure. It aims at providing image processing tools to foster a better understanding on the role of α-lamellae and primary β-grain boundary (β-gb) on short fatigue crack propagation. Indeed, previous X-ray microtomography studies on Ti-6246 have shown that these features do block/deflect crack path. Complementary EBSD studies [3] have also confirmed the crystallographic influence of favorably oriented basal ⟨a⟩ slip and prismatic ⟨a⟩ slip on the crack path. However, none of those studies have investigated the mechanism by which a crack crosses the lamellae (i.e. inter-lamellar or trans-lamellar). In principle, this can be correlated, to some extent to crystallographic slip orientation, since it is known that the α plate growth in the β phase strictly obeys the Burgers relationship $(100)_\beta \parallel (0002)_\alpha$ and $[1\text{–}11]_\beta \parallel [11\text{–}20]_\alpha$ [4]. Moreover, the flat surface of the α plates is parallel to the (1–100) plane of the α phase and parallel to the (−112) plane of the β phase. Therefore, the determination of the orientation of the crack with regard to the lamellar orientation can be one key element to estimate the local crack mode, provided the use of adequate image processing strategy.

The proposed methodology consists in separately segmenting α-lamellae and β-gb in the 3D image of the microtomography scan prior to fatigue loading. Subsequently, the crack segmented in an image of the next loading step is merged with the microstructural features. Different image processing algorithms have been used to segment the three objects, but one algorithm stands out from the others: the authors' directional filter bank based on the CHG (Complementary of Hour Glass) structuring element [5]. Initially develop to segment α-lamellae, it has also shown its utility in the segmentation phase of β-gb [6] and partitioning of the fatigue crack. This is based on the fact that all 3 features correspond to surface objects (their skeleton is a two-dimensional, topological manifold) and present different orientations. The paper also highlights the importance of other methods (e.g. the hole closing algorithm [7]) for the segmentation process of the crack and the β-gb. Quantification of the type of cracking based on the local orientation of the crack with regard to the orientation of α-lamellae it crosses is therefore made possible.

2. Material and experimental set-up

The alloy used in this study was a powder metallurgical (PM) processed Ti-6246 (Ti–6Al–2Sn–4Zr–6Mo), which was provided by Rolls-Royce plc in an as-hipped (hot isostatic pressed) condition. The reason for using PM Ti-6246 in this work, instead of the more commonly

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used grade 5 Ti–6Al–4V (Ti-64), was the small β grain size (~100 μm) in the as received condition, which allowed control of the crack growth in the small samples necessary for the synchrotron X-ray microtomography experiment. Since the as-received material had a very fine lamellar microstructure, the material was first heat treated in argon atmosphere at 935 °C/2 h/water quenching and annealed at 875 °C/1 h/furnace cooling. The aim of this two-stage heat treatment was to generate a lamellar microstructure coarse enough to be revealed during the X-ray tomography experiment.

The experiments were conducted on the ID19 X-ray microtomography beam line using a coherent monochromatic beam set at ~40 keV. The targeted spatial resolution was 0.7 μm with a 2048 × 2048 CCD detector (FReLoN camera [8]) in order to analyze cross section with a maximum size of 1.4 mm. The detector-to-sample distance was set to 1 m so as to generate so-called phase contrast in the image [9]. This allows the distinction between components of very similar density, as in the case between the α-lamellae and the β phase in Ti alloy. The specimens had gauge and overall lengths of 6 and 28 mm respectively. A notch (2 μm wide, 100 μm long and 20 μm deep) was generated to form a small surface defect using focused ion beam milling. Two situations have been explored: 1) when the notch crosses a primary β-grain boundary (sample A) and 2) when it is located in a beta-grain (sample B). Tension–tension fatigue tests were carried out in situ on a 50 Hz portable fatigue loading machine at about 50% of the nominal yield stress of the material with an R ratio of 0.1. Each experiment has considered 1 tomography scan prior to fatigue and 2–3 tomography scans following fatigue cycles in the [24k–29k] range. However, only results after 27k cycles are presented in this paper for the two situations mentioned above. It is worth mentioning that this study concerns an experiment that has been performed prior to the more detailed work of Birosca et al. [3], which has combined X-ray microtomography in-situ fatigue test and EBSD studies. However, X-ray microtomography was mainly used in the latter study to investigate the interaction between the short fatigue crack and β-gb, because of low contrast between α and β phases that were observed. However, in the former study that is emphasized herein, good phase contrast was found, as presented in Fig. 1, which shows a comparison of tomography images between the initial stage and fatigue stage in the case of sample A. Particularly, this reveals qualitatively the interaction of the short cracks with the lamellar microstructure, which is only revealed thanks to the phase contrast.

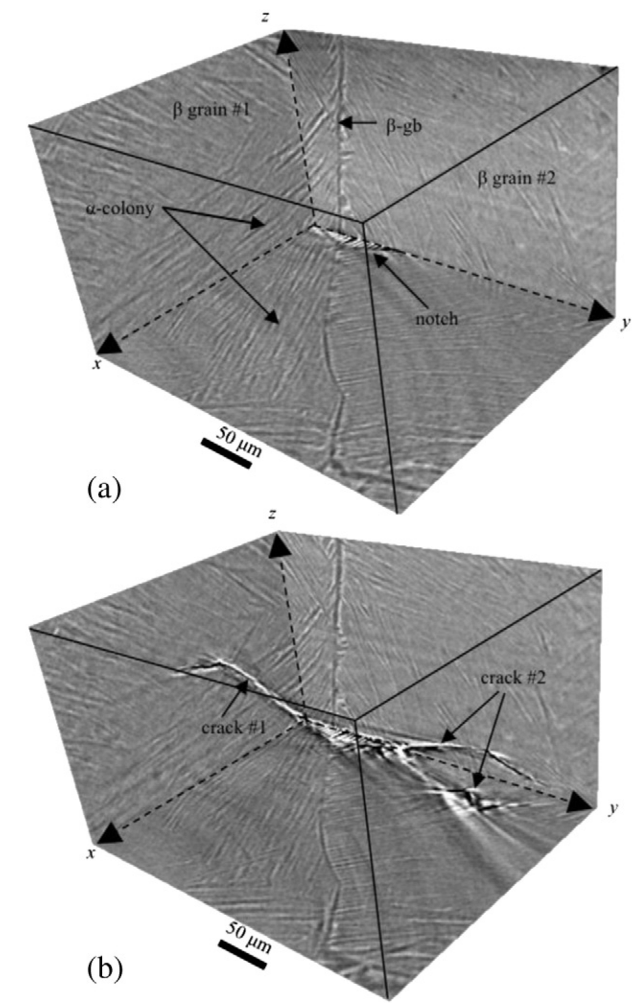

Fig. 1. 3D view of titanium sample A (a) prior to fatigue loading (initial stage) and (b) after 27k cycles. In the present case, one can see how 2 cracks have propagated from the notch, which crosses a β-gb.

3. Image processing methodology

As mentioned in the introduction, this study concentrates on the evaluation of the interaction of a fatigue crack with microstructural features of (α + β) lamellar titanium alloy, i.e. α-lamellae and β gb. This particularly aims at studying the local orientation of the crack propagation with regard to the local orientation of α plates. Therefore, not only the segmentation of the different features is of importance, but also a methodology to estimate the geometrical orientation is necessary for further analysis. In that context, the following sub-sections summarize the different methods that have been published elsewhere to classify the lamellae based on their orientation and to segment the β gb. It also explains how the crack has been segmented and superimposed in the initial tomography volume (i.e. prior to fatigue loading), in order to allow the study of its interaction with the microstructure.

3.1. Classification of α-lamellae

One important aspect of image processing and analysis is the development of methods to extract features based on texture analysis or geometrical characteristics such as shape, size or directionality of objects of interest. In the latter case, one standard approach is the image filtering in the spatial or frequency domain using special directional kernels, which can detect contour or surface singularities. This is the case of several recent approaches [10–12], which have been inspired by the well-known wavelet transform, even though they have mainly been designed for image denoising and compression purposes. Moreover, their range of application in the 3D case is relatively limited. To date, only one method, which extracts colony boundaries based on 3D gradient changes and constrained watershed, has been designed to segment Widmanstätten microstructure [13,14]. Recently, the CHG (Complementary part of Hour Glass) filter has been firstly designed to respond to directional changes in 3D images [5], mainly containing surface objects such as α plates. However, one will see later that its range of applications goes beyond the segmentation and classification of α lamellae.

The filter, which is presented in Fig. 2a, has been designed to possess cylindrical symmetry and wedge-shape support properties so as to retrieve directionality of surface features. The filter is defined by the radius r of the central disc supported by the normal **n** (a.k.a. the filter direction) and the wedge half-angle θ. In order to have a filter that accepts fluctuations for planes with their normal vector in the vicinity of the vector defining the main direction of the filter, a planar symmetric univariate kernel, which has a similar construction than the Epanechnikov kernel is used. This is illustrated in Fig. 2b. Finally, a set of directions has to be selected so as to classify the surface directions. The proposed bank of directions, which is based on the vertices, edges and faces of the Cartesian cubic grid, is shown in Fig. 2c. It uses the family of normal directions <100>, <110> and <111> (following the crystallographic plane and direction notations) and regroups 13 independent directions, which are further called the principal directions of the 3D directional filter bank.