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Names and affiliations of applicants (* indicates experimentalists):
*M. Karadge, School of Materials, University of Manchester, UK.
*F. Garcia-Pastor, School of Materials, University of Manchester, UK.
*Laurent Babout, Politechnicka Lodzka, 90-924 Łódź, Poland.
*M. Preuss, School of Materials, University of Manchester, UK.
*Jean-Yves. Buffiere, GEMPPM INSA, Lyon, France.
Philip Withers, School of Materials, University of Manchester, UK.

Report:

Exploratory in-situ fatigue deformation studies of three different families of titanium based alloys were conducted on the ID-19 tomography beam line. It is demonstrated that phase contrast can be used to directly visualise and correlate the interaction between microstructure and damage mechanisms.

Titanium alloys are widely used in the aeronautical, power generation and biomedical industry because of excellent mechanical and corrosion properties combined with a relatively low density. The mechanical properties of these alloys, especially fatigue related properties are severely dependent upon changes in the microstructures. Most importantly, the short cracks under fatigue loading conditions have been known to grow at lower stress intensity factor than long cracks, and propagate faster than long cracks at a given stress intensity factor. Therefore, understanding the effects of microstructure on short crack growth behaviour of titanium alloys is critical. To date, studies investigating fatigue damage mechanisms have been restricted to surface observations of the crack and post mortem analysis, which excludes any direct observations of how the crack front interacts with the microstructure. A capability to 'noninvasively and directly see in real time' both damage evolution and microstructure in 3D will prove to be a boon for further understanding and development of new microstructures in structural alloys. Recent works by the ID-19 team hinting at capabilities of directly observing microstructure and damage development in 3D by a combination of absorption and phase contrast imaging using the ID19 micro-tomography beamline prompted us first to carry out a series of exploratory in-situ fatigue defortmation tests on the three diferent types of titanium alloys mentioned below.

The chosen alloys form different classes of titanium alloys : Ti-6246 (Ti-6Al-2Sn-4Zr-6Mo, an $\alpha+\beta$ titanium alloy), BurTi (Ti-2.5V-15Cr-2Al-0.2C, burn resistant β-titanium reinforced with titanium carbides)] and an intermetallic alloy based on $(\alpha_2+\gamma)$ TiAl reinforced with titanium borides. The experiments were conducted on the ID19 X-ray microtomography beam line operating at ~40 keV. The targeted spatial resolution was 0.7 μm with a 2048x2048 CCD detector in order to analyse cross section with a maximum size of 1.4 mm. The specimens had gauge and overall lengths of 6 and 28 mm respectively. A crack (2μm wide, 100 μm long and 20 μm deep) was initiated to form a small surface defect using focused ion beam milling. Tension-tension fatigue tests were carried out on a 50 Hz portable fatigue loading machine at about 50% of the nominal yield stress of each material with an R-ratio of 0.1.

Attempts to simultaneously observe microstructure and damage evolution were fully sucessful for Ti-6246 and partially successful for BurTi and $(\alpha_2+\gamma)$ TiAl. The observations are briefly discussed below:

<u>*Ti-6246*</u>: Prior β grain boundaries and lamellar microstructrure were clearly visible as shown in fig 1. Some important observations were made however only qualitatively and most important were: (i) Crack bifurcation at grain boundary as shown in fig 2a, (ii) Crack growth along and perpendicular to the lamellar colonies, a related complex mechanism is shown in fig 2b and (iii) Crack growth along prior β boundaries consisting of fine α platelets. Quantitative information such as crack growth rate changes however could not be identified as this experiment employed Ti-6246 specimens with coarse prior β grain sizes (>500μm) which led to uncontrolled and

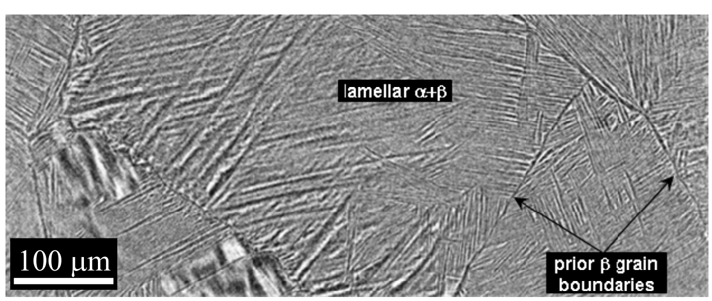

Fig. 1. Microtomograph of microstructure in Ti-6246..

catastrophic failures during the experiment. Nevertherless, aims of the experiment to directly and simultaneously visualize the microstructure and damage evolution in real time did materialize.

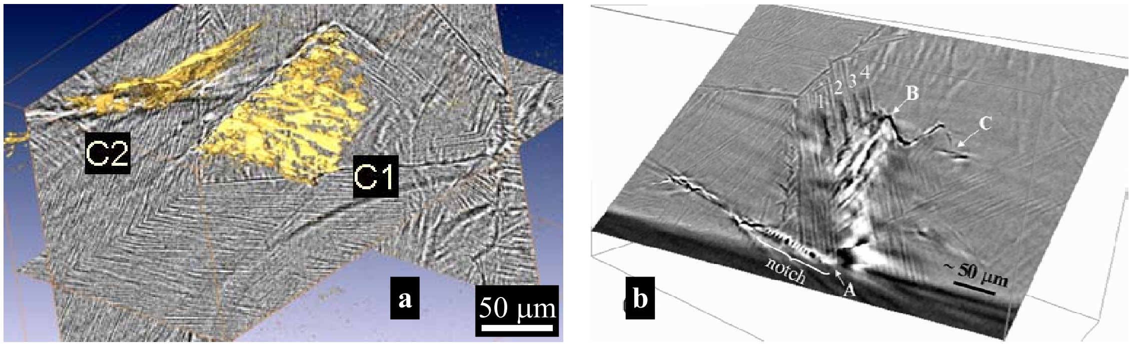

Fig. 2. (a) A bifurcated crack forming components C1 and C2 growing in grains two different grains with different lamellar orientations and (b) a complex crack growth pattern, the crack has propagated in steps from point A to B and then sinusoidally between points B and C, also observed are apparent crack branches propagating between lamellae (points 1 to 4 in b).

BurTi: Elongated titanium carbide precipitates were visible, however grain boundaries were not visible as the alloy matrix is a single phase alloy in itself. A mechanism of void nucleation at grain boundary tripple points leading to failure was observed as shown in fig 3.

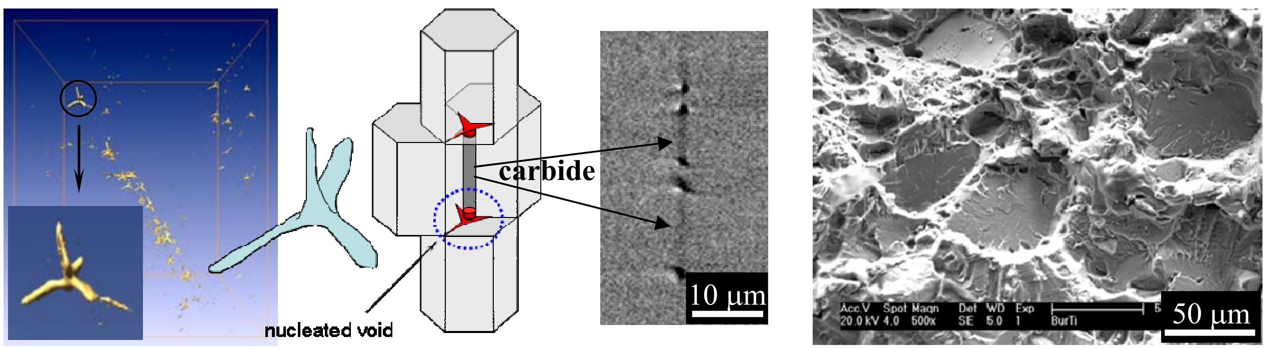

Fig. 3. (a) Decohesion induced void nucleation at grain boundary tripple points in BurTi and (b) eventual failure apparently due to large scale separation at grain boundaries.

Fully lamellar $(\alpha_2+\gamma)$ TiAl: Lamellar structure was barely visible, however, ribbon shaped titanium borides were clearly visible. It is our belief that through optimization of tomography parameters such as beam energy and specimen-acquisition camera distance would eventually allow us to observe the lamellar structure in these alloys. Acoustic measurements during tensile testing of lamellar TiAl have indicated that pre-yield cracking ocurring at low stresses could be responsible for poor fatigue properties. Therefore, inspite of an inability to observe the lamellar features under the tomography conditions used above, experiments were carried out to check for any microcracking (detectable due to absorption contrast). However, no evidence was found until the specimens failed catastrophically. SEM (scanning electron microscopy) observations (fig. 4) have shown that microcracking might be ocurring at a very fine scale at the twin intersections across different lamellae. It was concluded that microcracking at low stress levels may not be visible due to extremely small size of the cracks putting a limitation on possible observations with the current level of obtainable tomographic resolution.

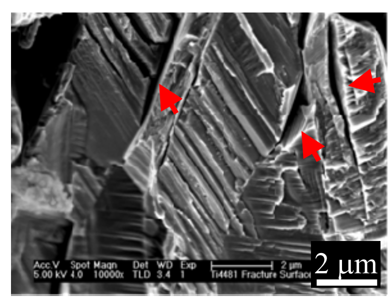

Fig. 4. Micro-cracks in $(\alpha_2+\gamma)$ TiAl.

We have successfully demonstrated that simultaneous microstructure and damage evolution in titanium alloys can be observed in situ in 3D using the ID19 beamline. We expect that this capability will shed new light on defect nucleation and crack propagation mechanisms and their dependence on microstructures and loading conditions. Two research publications are currently under preparation based on this work. With further detailed experiments, it is expected that a combination of the 3D microstructure information with in-situ fatigue testing will for the very first time allow us to directly illucidate the acute but complex dependence of fatigue crack growths on different microstructural features through studies on varying microstructures in various titanium alloys.

We hope to carry out further detailed and quantitative investigations using the above technique to assess the role of microstructural features such as grain boundaries, colony orientations, α/β and former β/β boundaries and reinforcing precipitates on the crack tip propagation. Combining this technique with other characterization techniques such as EBSD (electron back scattered diffraction) to determine grain, colony orientations will provide the most complete information on crack growth mechanisms in titanium alloys.