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Quantification of strain localisation in a bimodal two-phase titanium alloy

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ABSTRACT

High Resolution Digital Image Correlation in combination with orientation imaging microscopy has been applied to compare quantitatively strain localisation in Ti-6Al-4V alloy with a bimodal microstructure subjected to two different ageing treatments, i.e. above and below the α_2 solvus temperature. Interestingly, the most pronounced strain heterogeneity was observed in the secondary-α regions for the sample heat-treated to promote α_2 formation. The high local strain was associated with intense slip bands within single long secondary-α laths with low levels of neighbouring strain, which is likely to have a significant impact on the low-cycle fatigue performance.

Titanium alloys are widely used in the aerospace industry due to their high strength to weight ratio, good elevated temperature properties and good fatigue performance during service [1,2]. The most widely used alloys are two-phase (α + β) alloys, such as Ti-6Al-4V, which can be thermomechanically processed to produce a range of different microstructures which offer different property balances and can be tailored to specific applications [3]. A bimodal microstructure, consisting of primary-α (α_p) grains and secondary-α (α_s) lamellae imbedded in a β matrix, is typically used for structural components where a good combination between strength, toughness and fatigue crack growth resistance is sought [4].

Since a bimodal microstructure is obtained by solution heat-treating the material in the two-phase region, aluminium partitions to α_p that is already present during the solution heat treatment resulting in lower aluminium content in α_s which only forms during cooling [3]. In principle, this reduces the level of solute strengthening in α_s, however, the lamellar morphology of α_s is known to improve toughness and fatigue crack growth resistance by both minimizing slip length and slip localisation, and increasing crack tortuosity [3]. The comparatively rapid quenching, required to produce the bimodal microstructure, creates residual stresses, which need to be relieved by annealing at intermediate temperatures. Depending on the annealing temperature, this can lead to the precipitation of very fine and coherent Ti_3Al (α_2) precipitates. Although α_2 precipitation strengthens the alloy it also increases slip planarity and strain localisation [5–11], which in turn decreases fatigue resistance and fracture toughness. However, because slip planarity and strain localisation have traditionally been difficult to quantify, the effect of α_2 precipitation, particularly in the case of a complex microstructure such as a bimodal microstructure, is not fully understood. Recently, it has been demonstrated that High Resolution Digital Image Correlation (HRDIC) can be used to quantify such differences in strain localisation due to ordering [11]. In this case, equiaxed Ti-6Al-4V was investigated with and without α_2 precipitates demonstrating that α_2 precipitation almost doubled strain localisation [11].

Since in a bimodal microstructure the aluminium concentration is somewhat concentrated in α_p, one might expect that ageing this microstructure to promote α_2 formation results in a greater increase in strain localisation in this constituent compared to the α in an equiaxed microstructure aged in the same way. In α_s, slip is primarily controlled by the width of α_s lamella and the size and orientation of the β ligaments [3]. Since these morphological parameters do not necessarily change during annealing/ageing and the Al content in α_s should be comparatively low, the effect of the final heat treatment on strain localisation is expected to be more pronounced in α_p than α_s.

In the present work, HRDIC was used to quantify strain localisation in the two α constituents in a bimodal microstructure of Ti-6Al-4V. This analysis was carried out for the two different final heat treatments that either minimise or promote α_2 precipitation.

The material investigated in this study was provided by Rolls-Royce and had been forged and annealed but not rolled. To provide samples with similar microstructures both sets of samples with dimensions of $70 \times 20 \times 20\ mm^3$ were initially solution heat treated in the α + β phase regime followed by water quenching to generate a bimodal microstructure. Subsequently, one set of samples were annealed above the α_2 solvus temperature (700 °C) for 2 h followed by water

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quenching, which minimises α_2 precipitation, while the other set of samples were annealed at 500 °C for 24 h followed by furnace cooling at 1 °C/min which promotes the formation of α_2 precipitates. Flat tensile specimens with dimensions of 26 mm gauge length; 3 mm gauge width and 1 mm thickness were prepared for tensile loading combined with imaging to undertake HRDIC by polishing to #4000 grit paper followed by polishing for 1 h with colloidal silica. Macro hardness measurements were also performed using a Cooke, Troughthon and Simms macrohardness tester with a 20 kg load and a Vickers pyramid.

Transmission Electron Microscopy (TEM) experiments were performed using a FEI® Tecnai® G2 20 TEM equipped with DITABIS® high-resolution imaging plates. Specimens were sectioned from the alloy and mechanically thinned to <200 μm before discs of 3 mm diameter were extracted and thinned to approximately 120 μm. These discs were then electrolytically thinned in a solution of perchloric acid (50 ml/l) and ethanol (950 ml/l), using a Julabo FP50 twin-jet electropolisher at −21 °C and 40 V.

For 2D strain analysis using HRDIC, a speckle pattern was applied to the surface of each sample using the gold remodelling technique detailed further in [12]. Subsequently, the specimens were deformed (ex-situ) incrementally in tension to approximately 1% and 5% applied strain (room temperature) at a strain rate of 0.1 mm/min using a Kammrath-Weiss 5 kN Tension-Compression microtester. The load was recorded from the 5 kN load cell while the displacement was measured using a Linear Variable Differential Transformer (LVDT). Displacement was subsequently transformed to strain by considering the initial gauge length. The strains quoted here are for the unloaded conditions. After each deformation stage, the sample was removed from the microtester and mounted in the SEM where images were acquired using backscattered electron imaging mode at 20 kV. Images were taken at field widths of 29.6 μm, with a resolution of 2048 × 1768 pixels^2 and a 30 μs dwell time. The total area was composed of an array of 4 × 4 images, covering an area of 100 × 70 μm^2. HRDIC was performed using La Vision's DaVis imaging software. No drift correction was applied to the images as a low scan rate and small working distance were used, which minimises the spatial drift [12–14]. The average error associated with this drift was estimated by comparing pairs of images taken before deformation, and found to be ~0.3% for an interrogation window size of 116 × 116 nm^2. This window size was chosen, as previous work [11] gave a low systematic error while maintaining a high spatial resolution.

Fig. 1 shows backscattered electron images of the two microstructures and the corresponding maximum shear strain maps at 1% and 5% macroscopic strain, which will be discussed in more detail below. The two microstructures, Fig. 1a and b, indicate a bimodal microstructure containing α_p grains and α_s lamellae in a β matrix with both having similar α_p grain sizes and volume fractions. However, there is a difference in the α_s morphology between the two conditions with slightly coarser α_s lamellae, Fig. 1a, after the high temperature anneal compared

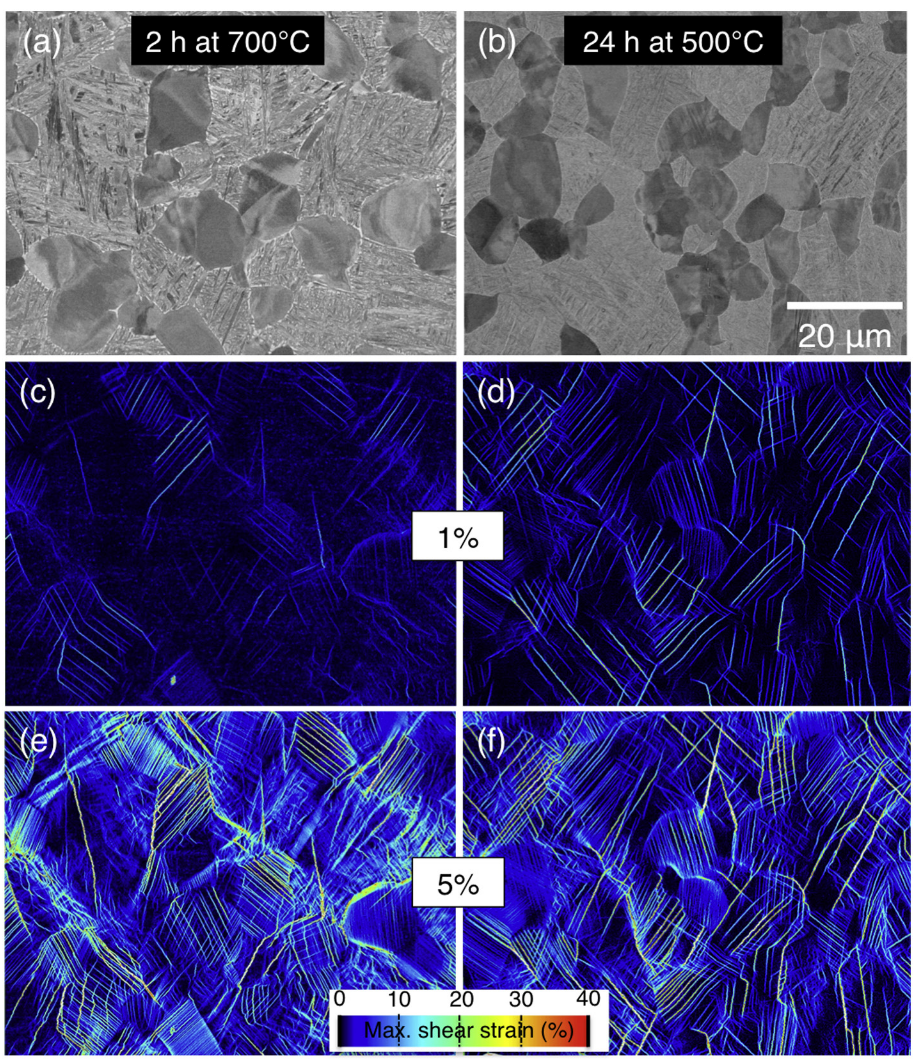

Fig. 1. (a), (b) Backscattered Electron Images of the microstructure and corresponding HRDIC maps of maximum shear strain at (c), (d) 1% and (e), (f) 5% plastic strain. The left-hand column shows 700 °C for 2 h and right-hand column shows 500 °C for 24 h.