Local strain rate sensitivity of α+β phases within dual-phase Ti alloys

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Abstract. Using in-situ micropillar compression, the local strain rate sensitivity in Ti6242 and Ti6246 has been investigated to strengthen our understanding on the rate- and slip system-sensitive deformation of dual-phase Ti alloys. Electron backscatter diffraction (EBSD) was used to find target grains anticipating basal and prismatic slip activities under compression test. Micropillars with similar α orientation and incomparable β morphology were made by a focused ion beam (FIB). Strain rate sensitivity (SRS) was determined based on the constant strain rate method (CSRM). The marked difference of SRS is found in the α+β of both alloys such that in Ti6242 the SRS in the basal slip is considerably higher than that in the prism whilst both slips in Ti6246 show somewhat similar SRS, inferring that either local chemical effects or the β morphology could affect rate-sensitive deformation behaviour.

1 Introduction

Dwell fatigue has been a vital issue for several decades in aeroengine industry as it significantly reduces the lifetime of titanium-based components [1-4]. It has been known that some dual-phase Ti alloys, for example Ti6242 and IMI685, are known as dwell sensitive, while others like Ti6246 are not [5-6], where this is potentially associated with the rate-sensitive deformation behaviour. As the alloys have complex microstructures and phase interactions, it was rather limited to figure out the fundamental deformation mechanisms using conventional testing methods. Through multiple small-scale experimental works [6-9], it turned out that (i) in Ti6242 the strain rate sensitivity (SRS) of the prismatic slip is remarkably higher than that of basal slip, (ii) similar SRS is found in Ti6246 irrespective of grain orientation (i.e., hard and soft grains), while a grain orientation dependence is found in Ti6242, and (iii) β phase significantly affects the modulation of the local stress states, SRS, and load-shedding phenomenon, where in particular its morphology and volume fraction alter the interactions with neighbouring α grains and consequently the α-β slip transfer mechanisms and strain localisation. To strengthen our understanding on the rate- and slip system-sensitive deformation of dual-phase Ti alloy, micropillar compression tests were carried out in-situ in this work to examine the local strain rate sensitivity of Ti6242 and Ti6246. Micropillars with similar α orientation and incomparable β morphology were compressed with variable strain rates, and the rate sensitivity was determined and further discussed with microstructural observation.

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2 Materials & Methods

Dual-phase titanium alloys, Ti6242 (Ti-6Al-2Sn-4Zr-2Mo, in wt%) and Ti6246 (Ti-6Al-2Sn-4Zr-6Mo, in wt%), were supplied as a forged bar of 20 mm diameter. The sectioned samples were heat-treated for 8 hours at β transus temperature plus 50°C, that is 1040°C for Ti6242 and 990°C for Ti6246, cooled by 1 °C/min, and metallographically prepared with SiC paper, ~50 nm OP-S, and Kroll’s reagent (see the details in [6-7]).

The microstructure and the crystallographic orientation of the samples were characterised by electron backscatter diffraction (EBSD) measurement using a scanning electron microscope (SEM, Carl Zeiss Auriga) equipped with Bruker Esprit v.1.9 software. A series of maps with variable magnifications were captured to find the target grains, identify both α and β phase crystallographic orientations, and confirm the Burgers orientation relationship (BOR) [10]. Micropillars having both phases were carefully made on the grains using a focused ion beam (FIB, FEI Helios Nanolab 600) with a Ga+ ion beam of 30kV.

The micropillars were then compressed using a flat punch tip (10 mm diameter) up to a strain of ~10% with multiple strain rates of the order of 10^{-2} to 10^{-4} s^{-1} and hold for 2 min (i.e., load-hold experiment) using a nanoindentation platform (Alemnis) set in a SEM. The in-situ video was recorded during the mechanical testing using the secondary electron detector (an accelerating voltage of 5kV). The deformed micropillars was further analysed using high resolution SEM and the load-displacement data were used to plot the engineering stress-strain curves (see the details in [8]).

3 Results and Discussion

Fig. 1. displays the EBSD maps of Ti6242 and Ti6246 where the inserted unit cell structures indicate α crystal orientations with the related Euler angles (φ₁, φ₂) within ‘B’ and ‘P’ regions. Note that the respective $a_1$ basal and $a_2$ prismatic slip activities were anticipated based on the calculation of Schmid factor (see Table 1) and BOR analysis using pole figures of α- and β-Ti [6]. Note that controlling β structure was highly challenging so that orientations and morphologies between the two alloys and hence those with micropillars were somewhat different.

![Fig. 1. EBSD maps of Ti6242 (left) and Ti6246 (right): the inserted unit cell structures show α phase within ‘B’ and ‘P’ regions, having the primary slip system of $a_1$ basal and $a_2$ prismatic, respectively.](image)

Table 1. Schmid factors of HCP α phase in regions of ‘B’ and ‘P’


| Slip System | Ti6242-B | Ti6246-B | Ti6242-P | Ti6246-P |
|-------------|----------|----------|----------|----------|
| **a Basal** |          |          |          |          |
| (0001)[2 110] | **0.46** | **0.43** | 0.02     | 0.02     |
| (0001)[1 210] | 0.36     | 0.35     | 0.05     | 0.03     |
| (0001)[1 120] | 0.10     | 0.09     | 0.07     | 0.05     |
| **a Prism**  |          |          |          |          |
| (0110)[2 110] | 0.11     | 0.09     | 0.31     | 0.33     |
| (1010)[1 210] | 0.19     | 0.15     | **0.49** | **0.49** |
| (1100)[1 120] | 0.08     | 0.06     | 0.19     | 0.15     |

Fig. 2. shows the representative SEM images of a square-shape micropillar made in ‘B’ and ‘P’ regions of Ti6242 and Ti6246. On the microstructure the α (darker) and β (brighter) phases can be distinguished, and hence the α+β structure and phase boundaries within the micropillar can be identified.

![SEM images of micropillars](image)

Fig. 2. SEM images of micropillars fabricated within Ti6242 and Ti6246 by focused ion beam: both micropillars have similar α (darker) orientation with different β (brighter) orientation/morphology.

Fig. 3. displays the engineering stress and strain curves obtained from micropillar contacting α+β phases tested with variable strain rates within both ‘B’ (a and b) and ‘P’ (c and d) regions. Most of the curves show some microplasticity (probably due to, e.g., misalignment between the top surface of the micropillar and the flat punch) in the elastic regime, where considerable hardening and less hardening/softening are found in the basal and the prismatic slip of both alloys, respectively. This may indicate that more complicated interactions of dislocation motion occurred in basal slip with neighbouring β structure (although the implication of α/β phase boundaries is still not clear).

![Stress-strain curves](image)
In each rate, stresses at three strains in the plastic regime were further collected to evaluate the SRS exponent ($m$ value), which is known as the constant strain rate method (CSRM) [11], using the following equations:

$$m = \frac{d\ln\sigma}{d\ln\dot{\varepsilon}}$$  

where $\sigma$ is the flow stress and $\dot{\varepsilon}$ the strain rate. In Fig. 4, the strain rate sensitivity exponents of both alloys are compared with regard to the active slip system (i.e., basal and prismatic slip) and the phase structure (i.e., $\alpha$ and $\alpha+\beta$), where the SRS of $\alpha$ phase in Ti6242 was acquired from the previous work [8]. The marked difference can be found in the $\alpha+\beta$ of both alloys such that in Ti6242 the SRS in the prismatic slip is significantly lower than that in the basal slip while both slips in Ti6246 show somewhat similar SRS.

Interestingly, previous indentation work tested on hard and soft grains of the same alloys [6] also reveals rather similar SRS trend although the active slip system under indentation test is challenging to determine without applying appropriate simulation technique (e.g.,
crystal plasticity modelling [12]). Furthermore, in Ti6242 the SRS trend of α and α+β is reversed. Note that the β volume fraction of Ti6242 and Ti6246 is ~10% and ~45%, respectively, resulting in different size of β-ligaments. These results imply that either local chemical effects or the β morphology could affect rate sensitive deformation behaviour.

The resultant SRS variations were further investigated using the SEM still images taken in the micropillars tested with the marked strain rates as shown in Fig. 5. Note that the yellow-dash lines superimposed on the images to reveal the β phases. In (a), the primary slip band (blue line) shown in higher rate was not observed in slower rate, and the slip initiated in α phase interacted with the β-ligaments (much severer in slower rate), resulting in the occurrence of wavy slip band and the slip transition (green line). In (c), similar primary slip band (blue lines) was found in both rates, but in slower rate further phase interaction occurred leading to activate another prism slip system (probably α1 slip based on the Schmid Factor calculation shown in Table 1). These results indicate that in Ti6242 the slip activities are highly affected by the applied strain rate and the β morphology. On the other hand, in (b) and (d), similar slip bands were formed in both rates despite the incomparable β morphologies. It can be thought that significant rate- and slip system-sensitive deformation mechanisms shown in Ti6242 and Ti6246 (but in a different way) are considerably associated with the α orientation and the β morphology, which are linked to complicated dislocation interactions caused by dislocation plasticity, slip transfer, and slip localisation.

Fig. 5. SEM still images taken at the beginning of 2 min holding stage in region ‘B’ of (a) Ti6242 and (b) Ti6246, and region ‘P’ of (c) Ti6242 and (d) Ti6246: β phases within micropillars are highlighted in yellow-dash lines, and some distinguished slip bands are indicated by the solid lines in different colours.

Correlating the m values to the associated local deformation of dual-phase Ti alloys is still an open question due to its complexity. However, it can be argued that the resultant data are crucial to develop suitable hypotheses towards a detailed understanding on how local microstructure having both α and β phases controls dwell fatigue and failure of in-service components. The experimental approach shown in this work effectively used to examine
mechanistic understanding in local deformation mechanisms, as well as opens further studies of new alloy design.

4 Conclusion

In this work, we have examined the local strain rate sensitivity of Ti6242 and Ti6246 so as to strengthen our understanding of rate- and slip system-sensitive deformation in dual-phase Ti alloys, using in-situ micropillar compression tests. EBSD and FIB were effectively used to select the comparative grains between the alloys, and fabricate the square-shape micropillars with similar α orientation and incomparable β morphology due to the difference of β volume fraction (~10% in Ti6242 and ~45% in Ti6246), resulting in different size of β-ligaments. The marked difference of SRS is found in the α+β of both alloys such that in Ti6242 the SRS in the basal slip is considerably higher than that in the prism whilst both slips in Ti6246 show somewhat similar SRS. This infers that either local chemical effects or the β morphology could affect rate sensitive deformation behaviour and could be vital to understand in detail about how local microstructure having both α and β phases controls dwell fatigue and failure of in-service components.

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