Phase dependent restoration mechanisms of TC8 titanium alloy during hot compression in the two phase region

K Wang\textsuperscript{1,2}, B F Luan\textsuperscript{1}, M Q Li\textsuperscript{2} and Q Liu\textsuperscript{1}

\textsuperscript{1} College of Materials Science and Engineering, Chongqing University, Chongqing 400045, China
\textsuperscript{2} School of Materials Science and Engineering, Northwestern Polytechnical University, Xi’an 710072, China

E-mail: study_ke@cqu.edu.cn

Abstract. The TC8 titanium alloy was isothermally compressed at 1133 K and 1213 K in the (\(\alpha+\beta\)) two phase region. The microstructural evolution and restoration mechanism in the \(\alpha\) and \(\beta\) phases were characterized by optical microscopy and transmission electron microscopy. The results show a significant effect of phase content on the microstructural evolution and restoration mechanism. The grain refinement occurs in the \(\alpha\) phase at both temperatures, but in the \(\beta\) phase only at the higher temperature of 1213 K. This difference in microstructural evolution is attributed to the different temperature dependence of restoration mechanisms in the two phases. A significant increase in the volume fraction of \(\beta\) phase makes the restoration mechanism in the \(\beta\) phase change from dynamic recovery (DRV) to dynamic recrystallization (DRX), which subsequently induces the \(\beta\) grain refinement.

1. Introduction

The \(\alpha/\beta\) titanium alloys have been widely used in the aeronautical industries due to their high strength, low density, good toughness and good high-temperature properties [1, 2]. Optimizing mechanical properties of titanium alloys can be achieved by controlling the microstructure obtained via complex thermomechanical processing routes [3, 4]. However, the deformation process of \(\alpha/\beta\) titanium alloys is difficult to control due to the sensitive microstructural evolution to small fluctuations in both temperature and strain rate [5, 6]. Therefore, a better understanding of the effect of processing parameters on the microstructural evolution and restoration mechanism is essential for process optimization and microstructure control of \(\alpha/\beta\) titanium alloy.

Significant efforts have been made to investigate the microstructural evolution and restoration mechanism of titanium alloys. Some investigators [7, 8] pointed out that dynamic recovery (DRV) dominated if the apparent activation energy for deformation was close to the activation energy for self-diffusion. Hua et al. [9] pointed out that dynamic recrystallization (DRX) was more noticeable at a temperature of 1173 K. Some investigators [10, 11] also found that the restoration mechanism of \(\alpha\) and \(\beta\) phase depended on the temperature. Chen et al. [10] investigated hot deformation microstructures of an \(\alpha/\beta\) titanium alloy with an equiaxed structure, and found that the \(\beta\) phase bore the main deformation and presented DRX at a high temperature near the \(\beta\) transus, while the \(\alpha\) phase bore the main deformation and presented DRX, and the \(\beta\) phase deformed to match the deformation of \(\alpha\) phase at a low temperature. He et al. [11] studied the deformation mechanism and microstructural evolution...
during hot deformation of Ti-6Al-2Zr-1Mo-1V alloy, and found that the high angle grain boundaries were mainly formed via dislocation accumulation, subboundary sliding and subgrain rotation at the temperatures ranging from 973 K to 1073 K, while DRX was the dominant mechanism at a high temperature of 1123 K. It is therefore can be concluded that the restoration mechanism depends on the phase content of α and β phase, which needs further investigations.

In this work, an α/β titanium alloy (TC8) is isothermally compressed in the two phase region where the phase content varies with the temperature. Based on the microstructure examination using an optical microscope (OM) and a transmission electron microscope (TEM), the dynamic restoration mechanisms of the α and β phases are studied.

2. Experimental
The TC8 titanium alloy used in this study was received in the form of rod with a diameter of 25 mm and had the chemical composition (wt.%) of 6.5 Al, 3.3 Mo, 0.3 Si, 0.06 Fe, 0.01 C, 0.002 H, 0.075 O, 0.005 N, and a balance of Ti. The microstructure of the as-received TC8 titanium alloy is shown in figure 1. The β transus temperature was measured to be 1273 K [12]. Cylindrical specimens that were 8.0 mm in diameter and 12.0 mm in height were machined from the TC8 titanium alloy rod. The specimens were isothermally compressed on a Gleeble 3500 thermal simulator at temperatures of 1133 K and 1213 K, a strain rate of 30 s\(^{-1}\), and a height reduction of 60%. Before compression, the specimens were heated to the pre-defined temperature and held for 3 min to establish a uniform temperature. After compression, the specimens were cooled in air to room temperature.

To observe the microstructural evolution, the compressed specimens were sectioned along the compression axis and prepared for microstructure examination by standard metallographic techniques. For the OM examination, the sectioned specimen was prepared following standard grinding/polishing procedures and etched in a solution of 5% HF, 15% HNO\(_3\), and 80% H\(_2\)O. For the TEM examination, the sectioned specimen was mechanically ground to 60~80 μm followed by twin-jet electropolishing. An OLYMPUS GX71 OM and a Tecnai F30 G\(^3\) TEM were used to examine the microstructure.

![Figure 1. Microstructures of the as-received TC8 titanium alloy: (a) transverse section, (b) longitudinal section.](image)

3. Results and Discussion
3.1 Microstructural evolution
To compare the difference in the microstructure between the compressed and uncompressed TC8 titanium alloy, two specimens were only heated to 1133 K and 1213 K and held for 3 min followed by air cooling. Figure 2 shows that the volume fraction of α phase decreases significantly from 58% to 30% as temperature increases from 1133 K to 1213 K, and the volume fraction of β phase attains 70% and becomes a dominant phase at 1213 K. Figure 3 shows the microstructure of the isothermally compressed TC8 titanium alloy at temperatures of 1133 K and 1213 K, a strain rate of 30 s\(^{-1}\) and a
height reduction of 60%. It can be seen from figures 2 and 3 that, after the isothermal compression, only the α phase appears with grain refinement at 1133 K, which agrees well with some previous investigations [13, 14], but both α and β phase show grain refinement at 1213 K. This contrast in microstructural evolution between the two temperatures is closely related to the different restoration mechanisms, which will be discussed in the next section.

Figure 2. OM micrographs of the uncompressed TC8 titanium alloy heated for 3 minutes at (a) 1133 K, (b) 1213 K.

Figure 3. OM micrographs of the TC8 titanium alloy isothermally compressed at (a) 1133 K, (b) 1213 K.

3.2 Restoration mechanism

The restoration mechanism of the α phase could be analysed based on TEM observations in the isothermally compressed TC8 titanium alloy. As shown in figure 4, the temperature has a significant effect on the microstructural evolution. At a low temperature of 1133 K (figure 4(a)), the α phase forms a DRX grain, which is bounded by distinct grain boundary with a high angle and contains few intragranular dislocations, and subgrains, which are bounded by the fuzzy subboundaries with a low angle and contain many intragranular dislocations. While at a high temperature of 1213 K, many subboundaries with long and fuzzy morphology (figure 4(b)) and subgrains (figure 4(c)) are formed in the α phase. This phenomenon indicates that both the DRX and DRV occur in the α phase and induce the occurrence of DRX grains and subgrains at a low temperature of 1133 K, while the DRV acts as a dominant restoration mechanism and induces the occurrence of subboundaries and subgrains at a high temperature of 1213 K. Therefore, the grain refinement of the α phase at the two temperatures can be interpreted by a β phase wedging model [15, 16], i.e. the wedging of the β phase into the α phase along
the subboundary or DRX grain boundary in the $\alpha$ phase would break the elongated $\alpha$ grain to get refinement eventually.

![Typical TEM micrographs of the $\alpha$ phase in the TC8 titanium alloy isothermally compressed at (a) 1133 K, (b) and (c) 1213 K.](image)

It is worth noting that the information on crystal defects, such as dislocations and subboundaries, cannot be acquired well in the $\beta$ phase, due to the quick precipitation of secondary $\alpha$ phase in the $\beta$ matrix phase, inducing a difficulty to reveal the restoration mechanism of the $\beta$ phase. However, as shown in figure 5, this work finds that a lot of dislocations are generated in the $\beta$ grain and arranged along the $\alpha$-$\beta$ phase interface, and the $\alpha$ grain with surrounded dislocations appears cleanly with few intragranular dislocations at a high temperature of 1213 K. The generation of dislocations means that the $\beta$ phase bears large plastic deformation in the isothermal compression, and then provides sufficient stored energy for the DRX of $\beta$ phase, which could explain the grain refinement of the $\beta$ phase well, as shown in figure 3(b). However, the little morphology change of the $\beta$ phase indicates a dominant restoration mechanism of DRV in the $\beta$ phase at a low temperature of 1133 K.

Therefore, it can be concluded that the volume fraction of the $\beta$ phase plays a key role in the dynamic restoration mechanisms of the $\alpha$ and $\beta$ phases in the isothermal compression of TC8 titanium
Li et al. [16] have pointed out that, the deformation would mainly concentrate on the β phase due to the following two reasons: (i) the β phase with a bcc structure has more slip systems than the α phase with a hcp structure; (ii) the β presents a dominant phase in the titanium alloy. In this work, the high temperature (1213 K) makes the β phase become the dominant phase to bear the main plastic deformation, which subsequently induces sufficient stored energy for the DRX of the β phase, and while less stored energy makes DRV dominant in α phase. However, at a low temperature of 1133 K, a low volume fraction of β phase makes the β phase mainly play an accommodation role in the deformation of the α phase [10], and then the DRV dominates in the β phase due to the less stored energy, while both DRX and DRV occur in α phase due to the sufficient stored energy. This is the main reason for the contrast in grain morphology and restoration mechanism between the two temperatures in this work.

![Figure 5. Typical TEM micrograph of the β phase in the TC8 titanium alloy isothermally compressed at 1213 K.](image)

4. Conclusions

Based on the OM and TEM examinations, this work has investigated the restoration mechanisms of the α and β phases of the TC8 titanium alloy isothermally compressed in the two phase region, and the following conclusions can be reached:

(1) Only the α phase shows a grain refinement at 1133 K, but both α and β phases show grain refinement at 1213 K.

(2) Both the DRX and DRV occur in the α phase and induces the occurrence of DRX grains and subgrains at 1133 K, while the DRV acts as a dominant restoration mechanism and induces the occurrence of subboundaries and subgrains at 1213 K.

(3) A high volume fraction of β phase makes the β phase bear the main deformation, inducing sufficient stored energy for the DRX of the β phase to occur.

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