

An investigation into the warm deformation behavior of Ti–6Al–1.5Cr–2.5Mo–0.5Fe–0.3Si alloy



E. Ghasemi^a, A. Zarei-Hanzaki^{a,*}, S. Moemeni^a, M. Ghambari^b, M. Rezaee^a

^a The Complex Laboratory of Hot Deformation and Thermomechanical Processing of High Performance Engineering Materials, School of Metallurgy and Materials Engineering, College of Engineering, University of Tehran, Tehran, Iran

^b School of Metallurgy and Materials Engineering, College of Engineering, University of Tehran, Tehran, Iran

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ABSTRACT

The microstructural evolution and the flow behavior of Ti–6Al–1.5Cr–2.5Mo–0.5Fe–0.3Si alloy were investigated in this research. The flow behavior of the alloy at temperatures in the range of 100–600 °C was studied using warm compression testing under the strain rate of 0.001–0.1 s^{−1}. The results indicate that the formability of the alloy is significantly increased at temperatures higher than 400 °C due to the activation of pyramidal slip systems. Moreover, optical observations confirm the occurrence of flow localization and adiabatic shear banding within the microstructure due to the adiabatic heating phenomenon at lower temperatures. The adiabatic heating is also led the experimental material to exhibit a negative strain rate sensitivity behavior. The tensile deformation behavior of this alloy was also studied at temperatures in the range of 100–400 °C through warm tension testing. The results show that the alpha phase grains are elongated along the tensile direction at lower temperatures but would be globularized at higher temperatures.

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1. Introduction

It is well-known that titanium alloys hold a wide range of applications in various industries. Among their different types, the $\alpha + \beta$ (two phase) alloys are extensively used in aerospace, compressor disks and blades of gas turbines owing to their high toughness and strength as well as good resistance to corrosion at high service temperatures [1]. To this end, their corresponding plasticity behavior at such service conditions has always been an important issue for materials engineers. Therefore, many researches have been conducted to study the deformation behavior of titanium alloys at high temperatures up to date [2–4].

Various mechanisms are activated during deformation of titanium alloys at high temperatures. Among them, phase transformation from $\alpha + \beta$ microstructure to single β phase [5], adiabatic shear banding [6–8], activation of new slip or twinning systems [9], fragmentation and globularization of α phase [10,11] and restoration mechanisms such as dynamic recovery (DRV) and/or dynamic recrystallization (DRX) are the most common ones [12,13]. The occurrence of dynamic recrystallization during hot deformation in the β phase region has been reported for $\alpha + \beta$ Ti–6Al–4V [14], $\alpha + \beta$ Ti–6246 [15], near- α IMI834 [16,17],

$\alpha + \beta$ Ti–6Al–7Nb [18] and near- α Ti–1100 [19]. Jackson et al. [20] illustrated that the dominant restoration mechanism of Ti–10V–2Fe–3Al changes from DRX to DRV by increasing the temperature. During the hot working in the $\alpha + \beta$ region however, the globularization of α lamellae has been detected in several investigations [10,11,21,22]. Seshacharyulu et al. [23] studied the hot deformation behavior of Ti–6Al–4V in both the dual phase ($\alpha + \beta$) and single phase (β) regions. Their results showed that at temperatures between 850 and 950 °C under strain rates ranging from 0.001 to 0.1 s^{−1}, globularization of the lamellar structure was occurred. At temperatures lower than 850 °C under strain rates below 0.1 s^{−1}, cracking at the prior β grain boundaries might take place under mixed mode conditions. For strain rates higher than 1 s^{−1} and temperatures lower than 950 °C, the material exhibits a wide range of flow instabilities. Recent investigations have reported the occurrence of DRX during hot working of titanium alloys within the dual phase region too [24–26].

Ti–6Al–1.5Cr–2.5Mo–0.5Fe–0.3Si is one of the most common $\alpha + \beta$ alloys in gas turbine blade industries (known as BT3-1). However, little attention has been paid regarding the medium-to-high temperature deformation behavior of this alloy. Specially, most of the performed studies aimed to investigate the deformation behavior of BT3-1 at temperatures higher than 800 °C where the primary processing of the alloy is conducted [27,28]. Unfortunately, the BT3-1 behavior at temperatures below 600 °C, which is considered as servicing temperatures, has not been

* Corresponding author.

E-mail address: zareih@ut.ac.ir (A. Zarei-Hanzaki).

discussed so far. It should be noted that the behavior of titanium alloys at temperatures higher than 800 °C totally differs from the medium (warm) temperatures regime (below 600 °C) in many aspects; for example alpha beta phase transformation would no more occur and deformation conditions are more severe. Therefore, the previous studies, which concentrate on the hot deformation conditions, are less helpful for the warm temperature regime.

In the present work, the microstructural evolution and the flow behavior of BT3-1 alloy at warm deformation region are investigated. For this purpose, the stress–strain curves, microstructural observations and fracture surface investigations obtained from tension and compression tests are employed to investigate the deformation behavior of the experimental alloy at servicing conditions (i.e. at temperatures in the range of 100–600 °C under quasi static strain rates).

2. Experimental method

The material used in this research is a BT3-1 titanium alloy with the chemical composition listed in Table 1. The β transus temperature of the alloy is 965–970 °C [29]. The initial microstructure of the as-hot rolled material is shown in Fig. 1. As is seen, the initial alloy possesses a typical dual phase microstructure, which consists of a combination of primary equiaxed alpha grains, lamellar alpha phase and matrix transformed beta phase.

In order to study the warm deformation behavior of BT3-1 alloy, the warm compression and warm tension testing methods were utilized. The related specimens were machined from the as-received material according to ASTM E-209 and ASTM E-21 standards (Fig. 2a and b). The warm compression tests were carried out at temperatures in the range of 100–600 °C under the strain rates of 0.001, 0.01 and 0.1 s^{−1}. The warm tension tests were performed at temperatures in the range of 100–400 °C under the initial strain rate of 0.001 s^{−1}. All specimens were homogenized for 5 min at testing temperature before deformation. Right after straining, the specimens were quenched in water to preserve the hot-deformed structures for further microstructural investigations.

In order to study the microstructural evolution, the specimens were sectioned along the longitudinal direction. The cut surfaces were prepared for optical microstructure examination using standard grinding and polishing techniques and were etched using Kroll's reagent (5% HF; 15% HNO₃; 80% distilled H₂O). The optical observations were accomplished using ML-7000 Microscope. CLEMEX image analysis software as a quantitative metallurgy tool was employed to analyze the microstructural features such as phase fraction, morphology of phases and fraction of globularized area. The fracture surfaces of tensile specimens were investigated using Environmental-Scanning Electron Microscope (E-SEM), Model Cam Scan MV 2300.

3. Results and discussion

3.1. Hot compression flow behavior

The variations of compressive true stress – true (logarithmic)

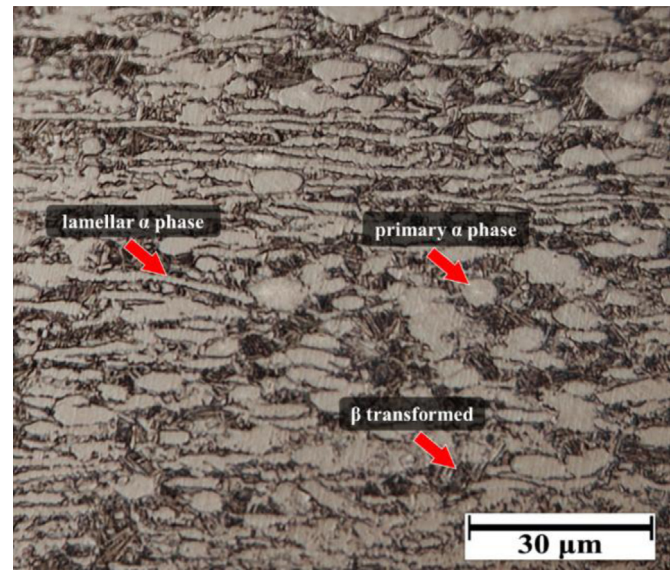


Fig. 1. Initial microstructure of the as-received BT3-1 material.

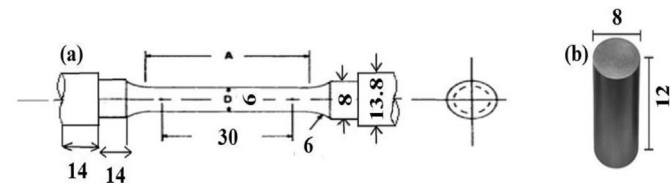


Fig. 2. Schematic presentation of (a) hot tension and (b) hot compression test specimens.

strain of BT3-1 alloy at different temperatures ranging from 100 to 600 °C are depicted in Fig. 3a–c. It is observed that the curves exhibit the strain hardening behavior at examined temperatures of 100–400 °C (Region I) for all strain rates. In this temperature regime, the failure of specimens has started earlier at logarithmic strain of about ~0.35 and led to the complete fracture at logarithmic strain of ~0.4.

At higher temperatures (between 500 and 600 °C), the flow behavior is completely changed, i.e. the stress increases up to a peak followed by a softening (Region II). Moreover, these specimens were easily deformed up to logarithmic strains of 0.7 without failure. This variation in the flow behavior of the alloy can be due to the activation of a new deformation mechanism, which will be discussed in detail using microstructural images in the subsequent sections.

3.2. Hot compression microstructures

The optical microstructures of the experimental alloy, obtained from the hot compression tests at temperatures of 200 °C and 600 °C are depicted in Fig. 4. Present phases are specified and marked with colored arrows in Fig. 4 (red arrow: primary alpha phase, yellow arrow: lamellar alpha phase and green arrow: β transformed). The microstructures of 200 °C and 600 °C were selected as a representative for Region I (100–400 °C) and Region II (500–600 °C) behaviors, respectively.

Table 1
Chemical composition of BT3-1 experimental alloy.

Element	Al	Mo	Cr	Fe	Si	Sn	Zr	Nb	V	C	Ti
%wt	6.3	2.8	1.3	0.4	0.16	0.01	< 0.005	0.002	0.008	< 0.005	Balanced

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