Materials and Design 31 (2010) 3599–3604

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

# Effect of hot working on flow behavior of Ti–6Al–4V alloy in single phase and two phase regions

A. Momeni [a,*], S.M. Abbasi [b]

[a] Department of Mining and Metallurgy, AmirKabir University of Technology, Tehran, Iran
[b] KNT University of Technology, Tehran, Iran

ARTICLE INFO

*Article history:*
Received 22 September 2009
Accepted 26 January 2010
Available online 21 February 2010

*Keywords:*
Ti–6Al–4V
Hot compression
Flow stress
Characteristic strain

ABSTRACT

Hot deformation behavior of the alloy Ti–6Al–4V was investigated via conducting hot compression tests at temperatures of 800–1150 °C and at strain rates, ranging from 0.001 $s^{-1}$ to 1 $s^{-1}$, at an interval of an order of magnitude. The apparent differences of flow stress curves obtained in dual phase $\alpha + \beta$ and single phase β regions were analyzed in term of different dependence of flow stress to temperature and strain rate and different microstructural evolutions. The values of strain rate sensitivity and apparent activation energy were obtained respectively as 0.20 and 530 kJ/mol for two phase microstructure. However, for single phase β microstructure they were approximated as 0.19 and 376 kJ/mol, respectively. It was found that in two phase region the values of strains corresponding to peak point, $\varepsilon_p$, and the highest rate of flow softening, $\varepsilon^*$, are almost independent to Zenner–Hollomon parameter. In single phase region, $\varepsilon_p$ and $\varepsilon^*$ exhibited a direct relationship to $Z$ parameter and the corresponding empirical equations were proposed.


## 1. Introduction

The desired mechanical characteristics and good corrosion resistance in most of titanium alloys are concomitantly satisfied when a precise control is considered on processing route and thereby on microstructure. Particularly, the influence of resulting microstructure upon the mechanical properties and the corrosion behavior in different alloys were widely discussed by other researchers [1–4].

The Ti–6Al–4V alloy is the most applicable among titanium alloys due to its excellent mechanical properties as well as good corrosion resistance. The use of this alloy is particularly attractive in aerospace and biomaterials industry [5]. Hot deformation in different actual industrial processes such as hot forging or rolling is extensively used for manufacturing of both semi-finished and finished products of this alloy. The previous researchers have tried to investigate the microstructural and mechanical behaviors of this alloy under hot working conditions by physical and mathematical simulative techniques. Seshacharyulu et al. [6] were studied the hot deformation behavior and damage mechanisms in an extra low interstitial (ELI) grade Ti–6Al–4V. Other studies have got involved in the effect of texture or morphology of α-phase in ($\alpha + \beta$) microstructure on the hot deformation characteristics of the alloy [7–10].

Tracking microstructural evolutions and mechanical properties, many investigations have done in two phase domain to analyze the restoration mechanisms [11–15]. Irrespective of morphology of constituent phases at dual phase state, globularization of α-phase during hot deformation is the major microstructural phenomenon which is considered to be responsible for flow softening. Although, less attention have paid to the hot working of the Ti–6Al–4V alloy in single phase β region, beyond β transus, it is proposed the likely occurrence of dynamic and metadynamic recrystallizations (DRX and MDRX) in this phase [16]. Dealing with industrial hot working processes, Hu and Dean [17] probed the hot forging response of the Ti–6Al–4V alloy for production of near to net-shape products and Park et al. [18] analyzed deformation stability in hot forging using a processing map. Moreover, Kim et al. [19] analyzed the high temperature deformation mechanisms of a single phase α titanium alloy as well as an $\alpha + \beta$ two phase one by an inelastic-deformation theory. More recently, Li and Zhang [20] investigated the Ti–6Al–4V alloy in hot compression and proposed the effect of hydrogen content on hot deformation characteristics.

The aim of present research is to investigate the behavior of the Ti–6Al–4V alloy under straining via hot compression at both single β-phase and dual phase ($\alpha + \beta$) regions. Even though resembling other previous investigations, in this study mechanical analysis have assigned, the attention was particularly paid to apparent features of flow behavior and characteristic points in order to make more exact and reliable results.

* Corresponding author. Tel.: +98 9123349007.
*E-mail address:* ammomeni@aut.ac.ir (A. Momeni).

0261-3069/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.matdes.2010.01.060

## 2. Experimental procedures

The studied Ti–6Al–4V alloy with the composition of 6.66 wt.% Al, 5.13 wt.% V, 0.21 wt.% Fe, 0.03 wt.% Mo, 0.02 wt.% Mn, 0.02 wt.% Si and the balance of Ti was received as wrought strip of 12 mm thick. The β transus temperature was measured to be approximately 980 °C by thermal dilatation method. The vanadium content of the studied alloy was about 1% higher than the standard average. As vanadium is a β stabilizer element [21], the β transus was about 20 °C lower than that was measured by previous investigators [10–12].

Cylindrical compression samples of 15 mm height and 10 mm diameter were prepared with the axis along the rolling direction of the as-received plate according to the ASTM E209 standard. Dimensions of the specimens were chosen in a manner to minimize the buckling phenomena, and also to ensure appropriate rigidity in the testing system. Concentric grooves of 0.5 mm depth were made on the both surfaces contacting the anvils to keep lubricant material and help to reduce friction. A 1 mm 45° chamfer was machined on the specimens edges to avoid fold-over of the material during the early stages of hot deformation. A small hole of 0.8 mm diameter and 5 mm depth was drilled at mid height of the specimens for embedding a thermocouple used for the measurement of real temperature of the specimens. Graphite powder was used to reduce the friction and therefore minimizing the sample barreling. The temperature of the specimens was monitored using a chromel–alumel thermocouple. An INSTRON 8502 testing machine equipped with a fully digital and computerized control furnace was employed to perform hot compression tests under constant strain rates, ranging from $10^{-3}$ $s^{-1}$ to 1 $s^{-1}$ at an interval of an order of magnitude and at temperatures of 800 °C, 850 °C, 900 °C, 950 °C, 1000 °C, 1025 °C, 1050 °C and 1075 °C.

## 3. Results and discussion

Typical flow stress curves obtained at low and high temperatures, i.e. in two phase α + β and single phase β regions, are shown in Fig. 1. It is well known and also clearly seen here that flow stress level actually increases with strain rate and descends with temperature [9,12].

The apparent discrepancies between the flow curves obtained at temperatures below and above β transus, i.e. in two phase and in single phase regions respectively, reflect the different microstructural evolutions and restoration processes which are dominant during individual regime. In the two phase region of α + β, the flow stress increases rapidly and reaches a sharp summit followed by a steep downfall up to a plateau. This behavior is more obvious at higher strain rates. Otherwise, in the single phase β region, the rate of work hardening is almost lower than that in the two phase region and the flow curve degrades more gently leaving a blunt peak. In addition, more oscillatory appearance of flow curve at higher temperatures can be likely attributed to the occurrence of dynamic recrystallization in β [6,8,9,15].

Fig. 2 demonstrates the typical microstructures of hot deformed specimens at different temperatures. Fig. 2a and b exhibits the effect of deformation temperature in two phase regime on resulting microstructure. The globularized morphology of α in a matrix of transformed β is the characteristic feature of both micrographs. However, it is apparent that the progress of globularization process diminishes with decrease in temperature. The lower volume fraction of α at higher temperatures which is the result of α to β transformation degrades the softening effect of globularization and leads to more sluggish subsidence of flow stress. In single phase β regime, Fig. 2c and d shows dynamically recrystallized β grains surrounded by irregular boundaries. At higher deformation tem-

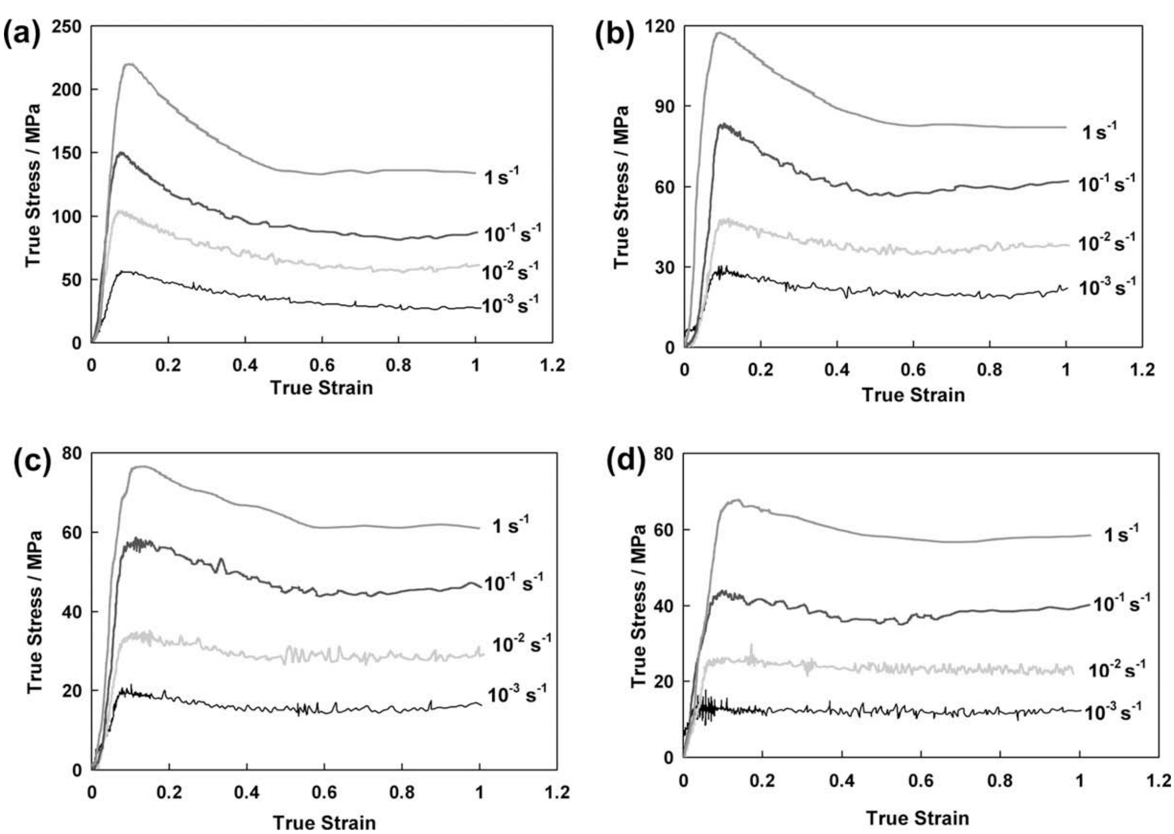


**Fig. 1.** True stress–true strain curves obtained from hot compression tests at different strain rates and temperatures of (a) 900 °C, (b) 950 °C, (c) 1000 °C and (d) 1050 °C.