Materials Science & Engineering A 703 (2017) 399–412

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Effect of temperature on microstructure and texture evolution during uniaxial tension of commercially pure titanium

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ARTICLE INFO

Keywords:
CP-titanium
Tension test
Deformation twinning
Microstructure
EBSD

ABSTRACT

Commercially pure (CP) titanium samples were subjected to uniaxial tension of 5, 15, 25, 35 and 45 elongation (%) at room temperature (298 K), 673 K and 873 K respectively. The texture and microstructure evolution as a function of temperature and elongation (%) were evaluated in the present study. The following observations were made: (i) twins of both $\{10\bar{1}2\}$ type tensile twins and $\{11\bar{2}2\}$ type compressive twins were significant during deformation at 298 K while at high temperatures, these twins were observed till 15 elongation (%) only; (ii) both the twins were mostly activated in the grains/orientations of high Schmid factor values, although these twins were also activated in some grains with low Schmid factor values; (iii) both grain refinement and misorientation developments as a function of elongation (%) was higher for the samples deformed at 298 K compared to those at 673 K and 873 K; (iv) The initial texture concentrated along $(11\bar{2}5)<1\bar{1}00>$ was observed to be strengthened with progressive deformation irrespective of the temperature of deformation. However, the texture intensity was higher during deformation at high temperatures.

1. Introduction

Titanium and its alloys are most widely used in structural applications such as manufacturing of aerospace components, equipments for chemical plants and automobiles, heat exchangers, medical equipments and implants etc. [1–4]. It has been well understood that the performance of these materials for different structural applications rely upon controlling the thermo-mechanical processing which create suitable texture and microstructure. The evolution of texture and microstructure in cubic materials is well documented in the literature compared to that of hexagonal materials [5–8]. This aspect, thus, needs to be further exploited.

At room temperature, both twinning and slip have been proven to be important deformation modes for hexagonal titanium [9,10]. The most favorable slip systems being the prismatic slip with a-type Burgers vectors followed by basal and pyramidal slips with a-type Burgers vectors [11,12]. These deformation modes, however, provide inadequate number of slip systems that is required for the plastic deformation of polycrystalline titanium [13]. On account of the above it is important that pyramidal $<a+c>$ slip or deformation twinning has to be activated during plastic deformation of hexagonal titanium [14]. The commonly observed slip and twin systems in pure titanium is shown in Table 1 [10,15–18]. However, at high temperature the reduction of CRSS (critical resolved shear stress) values of different slip systems reduced the activation of twin systems [19]. The activities of slip and twin systems at room temperature deformation of pure titanium are observed to be mostly in the order of prismatic slip, basal slip, tensile twin, compressive twin and 1st order pyramidal slip [11,20]. It is important to note here that 1st order pyramidal slip, i.e. $\{10\bar{1}1\}<11\bar{2}3>$, is found to be more active compared to basal slip and tensile & compressive twins as reported by some workers [21]. At high temperature deformation, the activity is observed to be highest for basal slip followed by tensile twin, compressive twin, prismatic slip and 1st order pyramidal slip in that order [22,23].

The typical cold rolling texture in cp-titanium has been observed along $\{10\bar{1}3\}<1\bar{1}00>$ which is at $\{\varphi_1 = 0°, \varphi = 30–40°, \varphi_2 = 0°\}$ [10,12,24,25]. As an exception, some workers have observed that maximum intensity was centered at $\varphi_2 = 30°$ which is along $\{11\bar{2}5\}<1\bar{1}00>$. The cold rolling texture was maintained during the hot rolling of cp-titanium up to 1073 K [26] whereas a dominant basal texture was observed when cp-titanium with nearly random texture was subjected to hot rolling at 873 K [27]. The initial basal texture perpendicular to the compression axis got inclined at 45° during uniaxial compression of cp-titanium at high temperatures (up to 973 K) [23]. Also a dominant basal texture was observed during uniaxial compression of cp-titanium at room

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http://dx.doi.org/10.1016/j.msea.2017.07.081
Received 5 March 2017; Received in revised form 23 July 2017; Accepted 25 July 2017
Available online 26 July 2017
0921-5093/

Table 1
Commonly observed slip and twin systems in pure titanium [10,15–18].

Slip Systems		Twin Systems	
Basal < a >	$\{0001\} \langle 11\bar{2}0 \rangle$	Tensile Twin	$\{10\bar{1}2\} \langle \bar{1}011 \rangle$
Prismatic < a >	$\{10\bar{1}0\} \langle 11\bar{2}0 \rangle$		$\{11\bar{2}1\} \langle 11\bar{2}6 \rangle$
Pyramidal < a >	$\{10\bar{1}1\} \langle 11\bar{2}0 \rangle$	Compressive Twin	$\{11\bar{2}2\} \langle 11\overline{23} \rangle$
1st order Pyramidal < a+c >	$\{10\bar{1}1\} \langle 11\bar{2}3 \rangle$		$\{11\bar{2}4\} \langle 11\bar{2}1 \rangle$
2nd order Pyramidal < a+c >	$\{11\bar{2}2\} \langle 11\bar{2}3 \rangle$		

temperature. Various authors have also been exploited the texture evolution through different strain-paths. The formation of {$\varphi_1 = 0-90°$, $\varphi = 0°$, $\varphi_2 = 0-60°$} fiber texture during cross rolling of cp-titanium at ambient temperature has been reported [28]. Similarly, the cross rolled samples showed near basal texture whereas split basal texture was observed in samples rolled through unidirectional rolling and reverse rolling [29].

It can now be concluded that the evolution of microstructure and texture during plastic deformation of cp-titanium at ambient/high temperatures have been investigated by various researchers [8,10,12,14,17–31]. However, the evolution of microstructure and texture during uniaxial tension of cp-titanium at elevated temperatures is hardly discussed in the existing literatures. With this background, in the present study the microstructure and texture evolution during uniaxial tension of cp-titanium at different temperatures has been investigated and reported in details.

2. Experimental details

2.1. Material and sample preparation

Annealed cp-titanium (Grade-2) sheet of 1 mm thickness was used as the starting material for the present study. The material had an equiaxed grain structure of ~ 75 µm average grain size. The chemical composition (in wt%) of the sheet is shown in Table 2. Tensile specimens (dimension shown in Fig. 1) were prepared along the rolling direction of the sheet by using wire EDM (Electrical Discharge Machining). Uniaxial tensile tests were carried out at temperature of 298 K, 673 K and 873 K respectively. Subsequently, different specimens were subjected to uniaxial tension of 5, 15, 25, 35 and 45 elongation (%) at temperature of 298 K, 673 K and 873 K respectively. Samples of 4 mm × 10 mm were made from the specimens after uniaxial tension for microstructural and textural characterizations. These samples were prepared from the regions adjacent to the neck regions of the specimen after uniaxial tension. The samples were metallographic polished followed by electro-polished before microstructural and textural characterizations. Metallographic polishing was carried out in a Struers Labopol using different grit of SiC grinding papers, while electro-polishing was carried out in a Struers Lectopol-5 using an electrolyte of methanol and perchloric acid (80:20) at a temperature of − 20 °C at 25 V for 20 s.

2.2. Tensile testing

Tensile testing was carried out in an instron 5567 screw driven UTM (universal testing machine) at temperature of 298 K, 673 K and 873 K respectively. The strain rate of $1 \times 10^{-3} s^{-1}$ was maintained during different uniaxial tension. Three tests were performed under each condition and the average values of tensile results are being reported (Fig. 2).

Table 2
Chemical composition (in wt%) of cp-titanium used in the present study.

Ti	Fe	C	N	H	O
0.823	0.034	0.004	0.004	0.0004	0.134

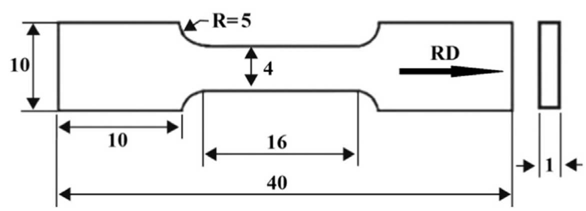

Fig. 1. The schematic of used tensile specimens (all dimensions are in mm).

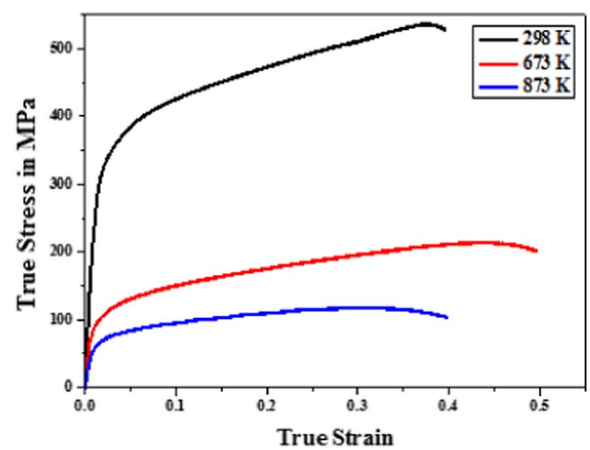

Fig. 2. True stress-strain plot of cp-titanium at different temperatures.

2.3. X-Ray Diffraction (XRD)

A Bruker D8 Advance XRD system with Co-Kα radiation (λ = 1.7909 Å) source of 2 mm beam diameter was used to measure the bulk texture of the samples. A Lynxeye detector is attached to record the data. Four poles, (0002), $(10\bar{1}1)$, $(10\bar{1}2)$ and $(10\bar{1}3)$, were measured and subsequently the orientation distribution functions (ODFs) were calculated using the commercial software package Labotex V 3.0.

2.4. Electron Backscattered Diffraction (EBSD)

A FEI Quanta-3D-FEG scanning electron microscope was used for the EBSD measurement of the samples. Using a step size of 0.5 mm, an approximately 1 mm × 1 mm area from two different locations of the samples was scanned through EBSD. Both beam and video conditions were kept identical between the scans. A TSL-OIM Version 6.2 EBSD package was used for the analysis of the EBSD scans. In EBSD analysis, grains were identified based of 15° misorientation criterion i.e. continuous presence of more than 15° boundary demarcated as grains. Grain size was measured with the TSL software as the circle-equivalent diameter based on area in each scan divided by the number of grains. Similarly, misorientation in a grain was represented by grain average misorientation (GAM) which is defined as the average misorientation between each neighboring points in a grain. Twin boundaries were