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Mechanical properties and deformation mechanisms of Ti-3Al-5Mo-4.5 V alloy with varied β phase stability

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ABSTRACT

Evolution of deformation mechanisms and mechanical properties of Ti-3Al-5Mo-4.5 V alloy with different β phase stability have been systematically investigated. β phase stability alteration is achieved through quenching temperature variation from dual α + β field (700 °C) to single β field (880 °C). Tensile tests at ambient temperature show that apparent yield strength of the alloy experiences an abrupt decrease followed by a significant increase from 700 °C to 880 °C. Work hardening behavior is characterized by transition from the initial two-regime feature to the three-stage outlook. Concurrently, the maximum working hardening rate drops from 14000 MPa to 3000 MPa, which is concurrent with the shrinking volume fraction of primary α phase. Detailed discussion about the relationship between deformation mechanisms and β phase stability has been outlined.

1. Introduction

Titanium alloys have drawn significant research interests in recent years owing to their excellent properties, such as high specific strength, low density and good corrosion resistance [1–3]. It is generally believed that mechanical properties of the titanium alloys are largely dictated by deformation mechanisms during service [4–6].

Deformation behaviors of titanium alloys can be divided into different mechanisms, namely, dislocation slipping, deformation twining and deformation induced martensite. These deformation modes may operate in single or concurrent ways [7,8]. The occurrences of different deformation mechanisms depend on the ability of matrix to transform into martensite or to trigger slip and twining. It is worth nothing that mechanical properties of titanium alloys usually gain significant improvement derived from transformation induced plasticity (TRIP) and twinning induced plasticity (TWIP) effects [7,9,10].

Conventionally, TRIP and TWIP effects exist in metastable β titanium alloys. The deformation mode of the metastable β phase evolves from dislocation glide to mechanical twinning then to stress or strain induced martensite (SIM) when its chemical stability decreases [11–14]. Although such effects have been extensively investigated in metastable β titanium alloys, few studies have been carried out on dual-phase α + β titanium alloys. Grosdidier et al. [4,15] revealed that the deformation mechanisms changed from SIM to slip with increasing volume fraction of primary α in β-CEZ alloy. The presence of primary α reduce the size of β domain and increase the concentration of β stabilizing elements, inducing the metastable β phase to be difficult to transform into martensite. It must be pointed out that the β phase stability, β domain size, the element distribution, and primary α will play important roles in the formation of SIM [16–18]. In Ti-10V-2Fe-3Al alloy, Li et al. [16] found that the deformation mode of the β phase varies from {112} <111> twinning to SIM with the decrease of β phase stability. Besides, Ahmed et al. [5,19] reported both {332} <113> and {112} <111> β twinning co-exist in Ti-10V-3Fe-3Al alloy, which is a modified version of the Ti-10V-2Fe-3Al alloy.

Ti-3Al-5Mo-4.5 V alloy has been widely used in the field of structural engineering. However, most of the available reports are concentrated on its microstructure features [20], systematic studies concerning mechanical properties and deformation mechanisms are still lacking. In this work, to the authors' best knowledge, the relationship between mechanical behaviors and deformation mechanisms of Ti-3Al-5Mo-4.5 V alloy with various β phase stability has been presented for the first time. Apparent yield strengths and working hardening behaviors have been investigated. Detailed

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Table 1
Chemical compositions of Ti-3Al-5Mo-4.5 V alloy (wt.%).

Al	Mo	V	Fe	O	N	H	Ti
2.92	5.00	4.47	0.034	0.090	0.007	0.005	Bal.

discussion about the relationship between deformation mechanisms and β phase stability has been outlined, which could provide theoretical basis for the design of α + β titanium alloys.

2. Experimental

The ingot of Ti-3Al-5Mo-4.5 V alloy was processed by self-consumable arc-melting furnace under argon atmosphere. The chemical analysis is shown in Table 1. The β transus temperature of this alloy is approximately 860 ± 5 °C. The obtained ingot was forged at the α + β phase field into plate with equiaxed microstructure. Bulk samples (60 mm × 40 mm × 20 mm) were cut from the plate, followed by solution treated at 700 °C, 750 °C, 800 °C and 880 °C for 120 min and then water quenched, respectively. The samples were coined as ST700, ST750, ST800 and ST880.

Tensile specimens with gauge diameter of 10 mm and gauge length of 60 mm were employed. Tensile tests were conducted on a Zwick Z150 machine using a 15 mm gauge length extensometer at a nominal strain rate of 2.5×10^{-4} s^{-1} at ambient temperature. After tensile test, the samples were cut parallel to the tensile axis from the plastic regime of the tensile specimens, then mechanically ground, polished, and etched in the solution (100 ml H_2O, 3 ml nitric acid and 2 ml hydrofluoric acid) for 50–60 s. The quantitative element analysis was carried out by the electron probe micro analysis (EPMA) with a spatial resolution of 1 μm performed on an EOL JXA-8530F system at 15 kV. SEM images were collected on a Zeiss MERLIN Compact at 20 kV. Thin foils for TEM observation were prepared by the twin jet electrolytic polishing method in an electrolyte of 5% perchloric acid, 35% butyl alcohol and 60% methanol (vol.%) at −25 °C and 12 V. TEM examinations were conducted on Tecnai G2 F20 microscope operating at 200 kV.

3. Results

3.1. Mechanical properties

Fig. 1 presents the stress-strain curves coupled with work hardening rate plots at various heat treatment conditions. ST700 (Fig. 1(a)) shows high yield strength and almost no work hardening in the plastic deformation regime. On the contrary, double yielding phenomenon is clearly observed and the strain-stress curves show a stress plateau in ST750 (Fig. 1(b)) and ST800 (Fig. 1(c)), which may be attributed to SIM [4,5,18]. Similarly, a weak double yielding effect is also visible in ST880.

Corresponding work hardening behaviors for ST700, ST750, ST800 and ST880 are also shown in Fig. 1. The hardening behavior exhibited by ST700 (Fig. 1(a)) demonstrates only two stages (region I and II) of work hardening profile comparing with the three stages (region I, II and III) seen in ST750, ST800 and ST880. The stage in which work hardening rate increases is not observed in ST700. Instead, a slow plateauing decrease is observed directly after region I. Work hardening behaviors exhibited by ST750 (Fig. 1(b)) and ST800 (Fig. 1(c)) initiate with a decrease of work hardening rate in region I; subsequently, work hardening rate increases from the elastic limit to a certain level in region II. The second work-hardening rate stage extends to maximum value, after which the third stage begins. Region III continues with a decrease in the work-hardening rate until the ultimate tensile strength (UTS) is reached. The hardening behavior exhibited by ST880 (Fig. 1(d)) demonstrates three distinct work hardening regions similar with the hardening behaviors of ST750 and ST800. It is interesting to note the remarkable difference in maximum work hardening rates under various quenching temperatures. As demonstrated in Fig. 1, the maximum work hardening rate decreases from 14000 MPa (ST750) to 3000 MPa (ST880).

Tensile properties under various quenching temperatures, including yield strength (YS), UTS, as well as elongation at UTS, are listed in Table 2. It can be seen that quenching temperature has a significant impact on YS. With the increase of quenching temperature from 700 °C to 880 °C, the apparent YS decreases from 673 MPa to 343 MPa and then increases to 607 MPa. However, the increase of quenching temperature leads to an improvement of UTS (from 773 MPa to 910 MPa) and elongation at UTS (from 6.8% to 14.8%).

3.2. Mechanism of plastic deformation

Microstructures of the alloy before deformation have been presented in a separate study [21]. The results showed that the alloy consists of primary α phase and metastable β phase in ST700 and ST750. With the increase of quenching temperature, the acicular athermal α” martensite is visible in metastable β phase of ST800. Whereas, only orthogonally oriented lath α” martensite is found in ST880. The SEM images shown in Fig. 2 present microstructures of ST700, ST750 and ST800 after ambient tensile test. ST700 (Fig. 2(a)) exhibits thin and river-like lines which can be closely related to slip traces. In ST750, parallel thin lines (Fig. 2(b)) and intersecting laths are observed in β matrix (Fig. 2(c)). These nanoscale laths as shown in Fig. 2(c) are similar to SIM which has been reported previously [5,22]. Furthermore, the thick and parallel laths (Fig. 2(d)), identified as deformation twins [13], are also visible in ST750. For ST800, in addition to the morphology of athermal α” martensite, certain parts of the β matrix are full of thick laths with a width hundreds of nanometers (Fig. 2(e)).

The detailed deformation modes are investigated by TEM. For ST700, only dislocations and entanglements are observed (Fig. 3(a)), indicating that only slip is activated. This is in good consistence with the low work hardening rate during plastic deformation region (Fig. 1(a)). For ST750, The bright field (BF) image and corresponding dark field (DF) image of the SIM laths are shown in Fig. 3(b) and (c). The selected area electron diffraction (SAED) pattern along the [1-1-1]$_\beta$ zone axis in (Fig. 3(d)) shows the reflections with characteristics of orthorhombic structure in addition to the spots of β matrix. SAED pattern (Fig. 3(h)) along the [110] β^T‖[110] β^M zone axis indicates the presence of {332} <113> β twins. In addition to the spots belonging to the β matrix and β twins, another type of SIM is visible, which satisfies the following relationship: [−110]$_\beta$‖[−12-3]$_{\alpha''}$. Fig. 3(f) and (g) show the corresponding DF images of {332} <113> twins and SIM α”. Fig. 4(a) shows a BF image of β deformation twinning in ST750. The diffraction pattern (Fig. 4(c)) taken along the [110]$_\beta$ zone axis also indicates the presence of {112} <111> β twins structure. For ST800 (Fig. 5), only SIM α”$_1$ is observed and the associated spots of α”$_1$ martensite are clearly visible (Fig. 5(d)). The orientation relationship between β phase and α”$_1$ phase is [1-1-1]$_\beta$‖[001]$_\alpha$”$_1$ which has been observed in ST750. In addition, the diffraction spots of martensite α”$_2$ are discernible in the β matrix, and can be identified as athermal martensite α”$_2$ which has been found in ST800 before deformation in our previous study [21].

4. Discussion

4.1. Apparent yield strength

YS plays a crucial role in the materials used in structural engineering applications. In this study, a noticeable influence of

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