Materials Letters 133 (2014) 236–239

Contents lists available at ScienceDirect

Materials Letters

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

α′ martensite Ti–10Nb–2Mo–4Sn alloy with ultralow elastic modulus and High strength

Shun Guo [a,b,*], Qingkun Meng [b], Xiaonong Cheng [a], Xinqing Zhao [b,**]

[a] Institute for Advanced Materials, Jiangsu University, Zhenjiang 212013, China
[b] School of Materials Science and Engineering, Beihang University, Beijing 100191, China

ARTICLE INFO

Article history:
Received 7 May 2014
Accepted 5 July 2014
Available online 15 July 2014

Keywords:
Metals and alloys
Biomaterials
α′ martensite
Low elastic modulus

ABSTRACT

By alloying and thermo-mechanical treatment, a novel α′ martensite Ti–10Nb–2Mo–4Sn (wt%) alloy with ultralow elastic modulus and high strength was prepared. Coarse α′ martensite plates with internal twins are formed in the solution treated alloy. Upon a severe cold rolling deformation, the alloy exhibits fine microstructure consisting of nano-sized α′ and dislocation tangles, resulting in a remarkable increase in strength. Meanwhile, the cold rolled alloy exhibits an ultralow elastic modulus of 41 GPa, which is lower than that of most biomedical β-type Ti alloys containing a considerable amount of expensive Nb and Ta. Therefore, the α′ martensite Ti–10Nb–2Mo–4Sn alloy has a high potential not only for biomedical applications, but also for industrial applications, due to its low elastic modulus, high strength and low cost.

1. Introduction

Commercially pure Ti (C.P. Ti) and Ti–6Al–4V alloy have been widely used for implant materials owing to their light weight, high corrosion resistance, excellent biocompatibility and good mechanical properties [1–3]. However, the elastic modulus of C.P. Ti (~103 GPa) and Ti–6Al–4V (~110 GPa) is much higher than that of human bone (~30 GPa), giving rise to so-called "stress shielding effect" [1,4,5]. Additionally, the release of V and Al ions has been found to cause toxic reactions [1]. Therefore, in the past decades, a great deal of efforts have been devoted to develop non-cytotoxic metastable β-type Ti alloys with lower elastic modulus, e.g. Ti–Ta [6], Ti–Nb–Ta–Zr [7], Ti–Nb–Mo–Sn [8], etc.

It has been shown that metastable phases such as α′, α″, ω and β phases can be formed during quenching from the high-temperature β field, depending on the content of β-stabilizers (e.g. Nb, Ta, etc.) [9,10]. In order to obtain single β phase, a considerable amount of β-stabilizers have to be added into Ti alloys [7,10,11]. However, adding a large number of Nb and Ta can lead to a significant increase in the cost of alloys. In addition to high cost, the low yield strength of β phase has been pointed out for a long time [1,4,12]. Up to date, a feasible method to strengthen β-type Ti alloys is to introduce stable α or isothermal ω phase by the aging treatment [13]. However, the α phase and especially the ω phase possess a much higher modulus than the β phase [9,13]. In this case, there is no choice but to sacrifice the elastic modulus, so as to achieve a compromise of high strength and low modulus. Obviously, this will exacerbate the "stress shielding" problem caused by the mismatch in elastic modulus between the implant and human bone.

Recent experimental results have revealed that α′ martensite, which is formed in Ti alloys with low amounts of β-stabilizers, can exhibit elastic modulus close to β-phase Ti alloys [14,15]. For example, α′ martensite Ti–20Ta alloy has an elastic modulus of 82 GPa near to β-phase Ti–70Ta alloy (71 GPa) [14]. This implies that α′ martensite Ti alloys has a potential for biomedical applications due to its low modulus. However, it has also been point out that α′ martensite exhibits low yield strength, close to that of β-phase Ti–Ta alloys [14]. Therefore, it is quite necessary to find out an approach to strength α′ martensite alloy, while retaining its low Young's modulus for biomedical applications.

In this study, an attempt was made to prepare a low-cost α′ martensite Ti–Nb–Mo–Sn alloy with high strength and low modulus. In addition, the relation between microstructural evolution and mechanical properties was discussed.

2. Experimental

A α′ martensite Ti alloy with nominal composition of Ti–10Nb–2Mo–4Sn (wt%, hereafter denoted as Ti-1024) was prepared by

* Corresponding author at: Institute for Advanced Materials, Jiangsu University, Zhenjiang 212013, China. Tel.: +86 511 88783268; fax: +86 511 88797783.
** Corresponding author. Tel.: +86 10 82338559; fax: +86 10 82338200.
E-mail addresses: shunguo@ujs.edu.cn (S. Guo), xinqing@buaa.edu.cn (X. Zhao).

http://dx.doi.org/10.1016/j.matlet.2014.07.044
0167-577X/

arc-melted using high purity Ti, Nb, Mo and Sn. The arc-melted Ti-1024 button was homogenized at 1273 K for 4 h in vacuum and then forged at 1173 K. After forging, the ingot was solution treated at 1173 K for 1 h in an evacuated quartz tube, followed by quenching into water (~298 K). The specimens which were cut from the solution treated ingot will be hereafter called solution treated specimens. The solution treated ingot was cold rolled to about 1 mm in thickness at a reduction of 85%. The resultant specimens will be subsequently referred to as cold rolled specimens.

Phase constitutions were characterized by X-ray diffraction (XRD) using Cu Kα irradiation. Microstructure observations were carried out on an optical microscope (OM) and a JEM 2100F transmission electron microscope (TEM). Uniaxial tensile tests in the rolling direction were conducted on an Instron-8801 testing system. To improve the accuracy of testing, a strain extensometer was used to record the value of strain.

3. Results and discussion

Fig. 1 shows the XRD patterns of solution treated (a) and cold rolled (b) Ti-1024 specimens. It can be observed that the solution treated specimen consists only of α' martensite. Similarly, single α' martensite can also be detected in the cold rolled specimen, indicating that the severe cold rolling does not change the phase constituent. Nevertheless, the α' martensite peaks of cold rolled specimen become broader compared with those of solution treated specimen. This peak broadening appears to suggest that some subtle changes occur upon the severe cold rolling deformation.

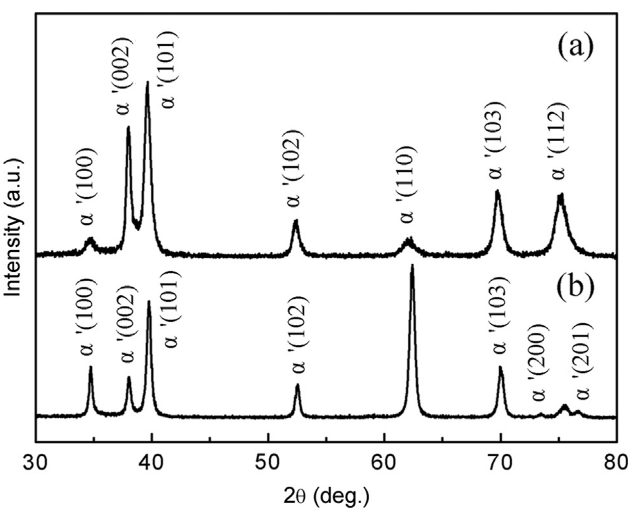

Fig. 1. XRD patterns of solution-treated (a) and cold-rolled (b) Ti-1024 specimens.

Fig. 2 represents (a) an optical image of solution treated Ti-1024 specimen, (b) a corresponding TEM image of internal twins in α' martensite and (c) the $[01\bar{1}\bar{1}]_{\alpha'}$ zone axis selected area diffraction (SAD) pattern taken from the twin interface. It can be seen from Fig. 2(a) that acicular α' martensite plates are distributed in large equiaxed grains with an average grain size of about 140 μm. TEM observations in Fig. 2(b) and (c) evidently indicate the presence of $\{10\bar{1}1\}$ type internal twin in acicular α' martensite. Referring to the formation mechanism of $\{10\bar{1}1\}$ type twin in α' martensite, Williams et al. reported that the $\{10\bar{1}1\}$ type twin is derived from transformation shear [16], whereas Menon et al. found that the internal $\{10\bar{1}1\}$ twin is closely involved in martensitic transformation [17]. As shown in Fig. 2(b), these $\{10\bar{1}1\}$ twins exhibit nearly identical space and thickness, and the ratio of the twinned to untwinned area is about 1:3, which is in consistent with the theoretical prediction on the α' martensitic transformation. Therefore, it is concluded that $\{10\bar{1}1\}$ twins formed in Ti-1024 alloy are attributed to the martensitic transformation from β to α'.

Upon a severe cold rolling deformation, the coarse α' martensite plates vanish, as shown in the bright-field image of cold rolled specimen in Fig. 3(a). Instead, the cold rolled specimen exhibits fine microstructure consisting of fine α' grains and dislocation tangles. In the corresponding SAD pattern shown in Fig. 3(b), continuous diffraction rings arising from α' martensite can be observed, suggesting that the severe cold rolling lead to significant grain refinement. Therefore, the peak broadening of α' martensite (Fig. 1) in the cold rolled specimen is mainly attributed to grain refinement. Fig. 3(c) shows a dark-field image recorded using the diffraction spot from the α' labeled by a circle in the SAD pattern. It is clear that after the cold rolling, the coarse α' martensite plates are crushed and replaced by fine grains with an average grain size of about 100 nm. An experimental study on commercial pure titanium by Gil et al. revealed that the presence of α' martensitic plates could lead to a decrease in the fatigue response [18]. The role of α' phase on the fatigue response of the Ti-1024 alloy needs to be addressed in detail and will be the subject of future research. Here, it is expected that the fine α' martensite can be beneficial for strengthening the Ti-1024 alloy.

The tensile stress–strain curves of solution treated and cold rolled Ti-1024 specimens are shown in Fig. 4(a). The solution treated specimen exhibits an ultralow elastic modulus of 41 GPa, but a low yield strength of 374 MPa. However, upon the cold rolling deformation, the Ti-1024 alloy is remarkably strengthened and the yield strength of the alloy is raised to ~768 MPa. Combining the TEM observations shown in Fig. 3, it is reasonable

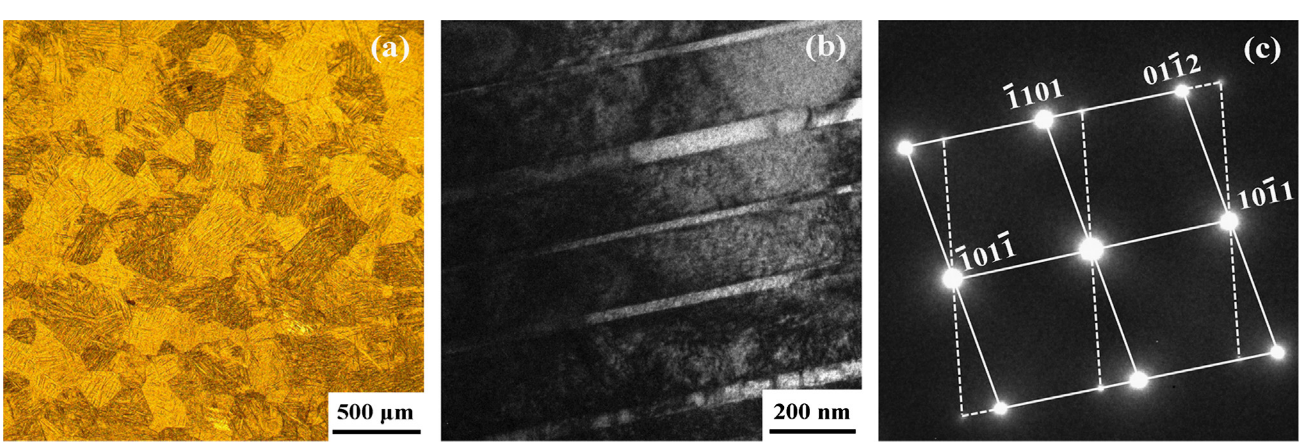

Fig. 2. An optical micrograph (a), a TEM bright-field image (b) and the corresponding $[01\bar{1}\bar{1}]_{\alpha'}$ zone axis SAD pattern of solution treated Ti-1024 alloy.