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A hierarchical nanolamella-structured alloy with excellent combinations of tensile properties

Ming Li [a,b], Defeng Guo [a], Tengyun Ma [a], Yindong Shi [a], Guosheng Zhang [a], Xiangyi Zhang [a,*]

[a] State Key Laboratory of Metastable Materials Science and Technology, Yanshan University, 066004 Qinhuangdao, PR China
[b] College of Mechanical Engineering, Yanshan University, 066004 Qinhuangdao, PR China

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ABSTRACT

Dual phase ($\alpha+\beta$)-Ti alloys with a fully fine laminated microstructure usually exhibit a high strength but a limited ductility. In the present study, a hierarchical nanolaminated microstructure consisting of lamellae with nano- and submicrometer-sized widths has been produced in a TiZrAlV alloy by employing severe plastic deformation (SPD) combined with subsequent thermal annealing. The hierarchical nanolamella-structured Ti alloy exhibits excellent combinations of tensile properties, e.g., an ultimate tensile strength $\sigma_{UTS}=1600$ MPa and an elongation to failure $\varepsilon_f=6.5\%$. The high strength can be attributed to the formation of a lot of nanoscale α lamellae in the alloy, and the enhanced ductility results mainly from both the coarse α lamellae that have a high strain hardening capability and the complex strain paths caused by a hierarchical nanolaminated structure.

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1. Introduction

Dual phase ($\alpha+\beta$) Ti alloys with a fully lamellar microstructure are extensively used for their good mechanical properties, e.g. high specific strength and fracture toughness [1–3]. Mechanical properties of $\alpha+\beta$ Ti alloys are closely related with their microstructure, and several key features of these phases individually and in combination determine the mechanical properties of the two-phase mixtures [3]. A small size of α lamella and α colony, which can be usually achieved by tuning alloy composition or increasing cooling rate from recrystallization processes, is expected to result in high strength and good ductility due to a reduction in effective slip length and a large resistance to microcrack nucleation and propagation [1,3]. Although a great progress has been made in enhancing the mechanical properties of $\alpha+\beta$ Ti alloys, the alloys with a fully fine α lamellar structure usually exhibit a high strength but a limited ductility [1–3]. It is still a challenge to produce a lamella-structured $\alpha+\beta$ Ti alloy with high strength combined with good ductility. In general, conventional lamellar structures in Ti alloys are composed of single-modal or single-scale lamellae. Previous studies show that a bi-lamellar structured Ti alloy composed of coarse and fine lamellae with a large difference in size exhibits a high tensile strength with a good ductility, as compared with the single-modal lamellar structured Ti alloys [1,3]. More recently, a multi-modal structure, i.e., hierarchical structure, is successfully used to enhance the ductility of nanostructured metals and alloys [4–9]. These studies imply that a complex hierarchical laminated structure that consists of α lamellae with different sizes, e.g., in width with nanometer, submicrometer or micrometer scales, may be promising for yielding a good combination of mechanical properties in $\alpha+\beta$ Ti alloys with a fully lamellar microstructure.

Previous studies demonstrate that severe plastic deformation (SPD) at room temperature (RT), i.e., cold deformation, or at low temperature is an effective technique to introduce high-density dislocations in materials [5–7], as compared with hot-deformation approaches (e.g., deformation in β phase field of Ti alloys), which may permit a high recrystallization nucleation rate of α lamellae and thus produce a hierarchical laminated structure in an $\alpha+\beta$ Ti alloy. In the present study, a severe plastic deformation with an accumulated strain $e=2.2$ at RT has been employed, instead of thermomechanical processing in β phase field, to tailor the lamellar microstructure of an $\alpha+\beta$ TiZrAlV alloy, which has potential applications in aerospace and nuclear industry [10]. A hierarchical laminated structure consisting of nano- and submicrometer-sized lamellae has been successfully produced in the alloy, yielding an excellent combination of high tensile strength and good ductility.

2. Experimental details

45Ti–47Zr–5Al–3V (wt%) (named as TiZrAlV below) with a composition belonging to an $\alpha+\beta$ alloy was prepared by melting sponge Zr (Zr+Hf > 99.5 wt%), Ti (99.7 wt%), industrially pure Al

* Corresponding author. Tel./fax: +86 335 8074724.
E-mail address: xyzh66@ysu.edu.cn (X. Zhang).

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(99.5 wt%) and V (99.9 wt%) using a ZHT-001 type vacuum consumable electro-arc furnace. After heat forging and rolling at 850 °C in β phase field (β transition temperature $T_\beta \sim 789$ °C), the sheets were solution treated (ST) at 850 °C for 1 h and then quenched into water. The aim of water quenching is to keep a large fraction of soft β phase to make the TiZrAlV more deformable at RT. The sheets were sectioned into a size of $70 \times 8 \times 3$ mm^3 and then rolled from 3.2 to 0.32 mm in thickness at a strain rate of $\dot{\varepsilon} = 2.2$ s^{-1} at RT, yielding an accumulated strain of $e = 2.2$. To produce a hierarchical laminated structure, the SPD TiZrAlV was annealed at 850 °C for 1 h with a cooling rate of 100–120 °C/min. For a comparison study, a bi-lamellar alloy was also produced by annealing the SPD TiZrAlV at 900 °C for 1 h.

Uniaxial tensile tests were performed on samples with a cross-section of 2.50×0.30 mm^2 and a gauge length of 5.0 mm using an Instron 5848 Micro-Tester at a strain rate of 1×10^{-3} s^{-1} at RT. The tensile direction was parallel to the rolling direction of samples. Three samples for each condition were measured, yielding an error bar for the measurement of mechanical properties.

Microstructures of samples in rolling plane were characterized using a JEM-2010 transmission electron microscope (TEM) and a Hitachi S-4800 filed emission scanning electron microscope (SEM). TEM specimens were prepared via the twin-jet electrochemical polishing in a solution containing 10% perchloric acid and 90% acetic acid at a voltage of 13 V and a temperature of ~30 °C. To obtain a statistical distribution of lamellar width, sample regions of ~0.8 mm^2 have been analyzed by SEM and TEM techniques. X-ray diffraction (XRD) patterns were recorded from the rolled surface using a Rigaku D/max-2500 X-ray diffractometer with Cu K_α radiation.

3. Results and discussions

The TiZrAlV after ST and water quenching exhibits a low ultimate tensile strength of $\sigma_{UTS} = 1032$ MPa and a large elongation to failure of $\varepsilon_f = 13.8\%$ (curve A in Fig. 1). After SPD at RT, the σ_{UTS} increases to ~1529 MPa, while ε_f decreases to ~3.3% (curve B in Fig. 1), which can be attributed to an accumulation of high-density dislocations and microstructure refinement (e.g., the formation of small dislocation cells and subgrains) in the alloy [11]. After 850 °C annealing, the SPD TiZrAlV shows an obvious increase in tensile ductility ($\varepsilon_f = 6.5\%$) combined with an unexpected enhancement in strength ($\sigma_{UTS} = 1600$ MPa) (see curve C in Fig. 1), in contrast to conventional thermal annealing of SPD metals where a reduced strength is usually observed [6,12]. However, with further increasing annealing temperature to 900 °C (curve D in Fig. 1), the SPD TiZrAlV shows a considerable reduction in strength ($\sigma_{UTS} = 1498$ MPa) and only a little increase in tensile ductility ($\varepsilon_f = 6.8\%$) as compared with the alloy annealed at 850 °C.

Fig. 2 shows a comparison of the tensile properties of TiZrAlV with the data from previous studies on $\alpha+\beta$ Ti alloys [1,10,13–17]. An inverted relation between the strength and ductility is clearly observed in the alloys (see the shade area in Fig. 2). The most striking result is that the data C from the SPD TiZrAlV after 850 °C annealing (named as Ti-850 below) is far away from the shade, indicating an excellent combination of high tensile strength and good ductility. To check the reproducibility, two additional samples with same SPD and thermal annealing processes were measured, yielding the error bars for the data C.

To reveal the factors governing the excellent combinations of tensile properties in the Ti-850 sample, in-depth SEM and TEM observations have been performed on the sample. The SEM studies show a hierarchical lamellar structure, in which coarse and fine lamellae with different scales coexist in the sample (see Fig. 3(a)). TEM studies further show that these lamellae can be at least classified into three levels indicated with numbers 1, 2 and 3, correspondingly, according to their width (see Fig. 3(b)). A statistical analysis of TEM images shows that there are three kinds of lamellae with a mean width of ~50, 136 and 229 nm in the sample (Fig. 3(c)), correspondingly. This clearly demonstrates a hierarchical nanolaminated structure in the sample. Comparing with the conventional lamellar microstructure of $\alpha+\beta$ Ti alloys with an α lamellar width larger than 0.5 μm [1], the Ti-850 sample shows an extremely small mean width of α lamellae, contributing to a high strength since phase boundary plays an important role in hindering dislocation's motion [1]. The nano-scale lamellae are believed to contribute more to strength than the coarse ones by providing high-density phase boundaries [1–3].

To understand the good tensile ductility achieved in the hierarchical nanolamella-structured TiZrAlV, the TEM observations on the fractured sample have been performed. It can be seen that a lot of dislocations are left in the coarse lamellae (indicated with arrows in Fig. 3(d)), indicating these coarse alpha lamellae can accumulate relatively large plastic strains at ambient temperatures and thus accommodate strains preferentially [3,6]. Moreover, the nano-scale lamellae (e.g., indicated with number 3 in Fig. 3 (b)) precipitated from retained β phase will make the β phase

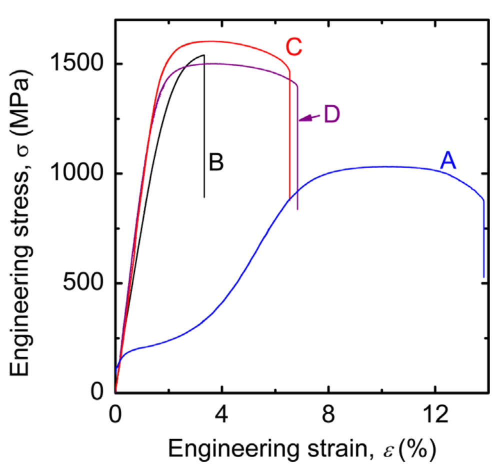

Fig. 1. Engineering stress–strain curves of TiZrAlV after solution treatment (ST) and water quenching (curve A), severe plastic deformation (SPD) (curve B), and the SPD TiZrAlV after 850 (curve C) and 900 °C (curve D) annealing for 1 h.

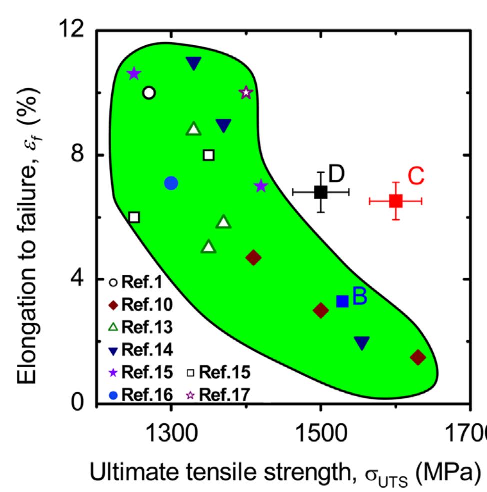

Fig. 2. Representative tensile properties of dual phase ($\alpha+\beta$) Ti alloys. The mechanical properties of SPD TiZrAlV before (B) and after 850 °C (C) and 900 °C (D) annealing are given. The data from other $\alpha+\beta$ Ti alloys, i.e., Ti–6Al–2Sn–4Zr–6Mo [1], Ti–45Zr–5Al–3V [10,13], Ti–10V–2Fe–3Al [14], VT25U (Ti–Al–Zr–Mo–Sn–W–Si, ★) [15], VT3-1 (Ti–Al–Mo–Cr–Fe–Si, □) [15] and Ti–6Al–4V [16,17] are presented for a comparison.

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