Materials Science & Engineering A 612 (2014) 1–6

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Simultaneously enhancing fracture toughness and strength in a hierarchical nanolamella-structured alloy

Ming Li [a,b], Defeng Guo [a], Qian Zhang [a], Tengyun Ma [a], Yindong Shi [a], Guosheng Zhang [a], Xiaohong Li [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

ARTICLE INFO

Article history:
Received 30 March 2014
Received in revised form
5 June 2014
Accepted 9 June 2014
Available online 17 June 2014

Keywords:
Nanostructured materials
Hierarchical structure
Fracture
Toughness
Mechanical characterization

ABSTRACT

In general, strength and fracture toughness are mutually exclusive in most structural materials. Here, we report a simultaneous enhancement of both the strength and fracture toughness in a hierarchical nanolamella-structured TiZrAlV that consists of lamellae with nano- and submicrometer-sized widths together with a few submicrometer- and micrometer-sized grains. The hierarchical nanolamella-structured alloy shows an excellent combination of high yield strength ($\sigma_s \sim 1438$ MPa) and fracture toughness ($K_{IC} \sim 57$ MPa m$^{1/2}$) as compared with its coarse-laminated counterpart. The high strength results from a lot of nanoscale lamellae in the alloy, and the enhanced fracture toughness can be attributed to both the coarse α lamellae and grains that have a high strain hardening capability and the complex strain paths caused by a hierarchical nanolaminated structure, which may enhance the resistance to crack growth and change the crack path during fracture processes.

1. Introduction

A key requirement for almost all structural materials is that they have both the high strength and fracture toughness [1–3]. Unfortunately, the strength and fracture toughness are mutually exclusive in most materials [1,2]. For example, nanocrystalline metals and alloys usually exhibit a high strength but a disappointingly low ductility and toughness [4–7], which limit their practical utility. Although a great progress has been made in enhancing the ductility of nanocrystalline materials [8–10], it is still a big challenge to produce a high toughness in these materials [11–13]. Recently, a hierarchical structure that consists of nanoscale grains (NGs), ultrafine grains (UFGs) and coarse grains (CGs) is successfully employed to enhance the ductility of nanostructured metals [10,14–16]. This hierarchical structure also shows a potential in solving the problem of low toughness in nanostructured metals [15]. Previous studies [1] show that some natural materials are excellent damage-tolerant (hard and tough) materials, e.g., seashells, due to a hierarchical architecture that has characteristic structural features on multiple length scales from molecular to near-macroscopic dimensions [17,18]. Moreover, a lamellar structure has a large potential in the enhancement of toughness as compared with homogeneous nanocomposites [19]. These studies imply that a complex hierarchical nanolaminated microstructure may be promising for enhancing the toughness of nanostructured metals and alloys while maintaining a high strength. Beta Ti alloys with a fully lamellar microstructure are extensively used for their good mechanical properties [20]. In the present study, using a β-metastable TiZrAlV alloy as a model system, a hierarchical nanolaminated structure has been successfully produced in the alloy by employing a thermomechanical processing approach with a large severe plastic deformation (SPD) at room temperature. The hierarchical nanolaminated alloy shows a simultaneous enhancement of the fracture toughness and yield strength, yielding an excellent combination of high yield strength and fracture toughness ($\sim$1438 MPa and 57 MPa m$^{1/2}$), as compared with its coarse-laminated counterpart.

2. Experimental details

40.2Ti–51.1Zr–4.5Al–4.2 V (wt%) alloy (named as TiZrAlV below) with a composition belonging to β Ti alloys was prepared by melting sponge Zr (Zr+Hf > 99.5 wt%), Ti (99.7 wt%), industrially pure Al (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 the β phase field, the sheets were solution treated (ST) at 850 °C for 1 h and then quenched into water to keep

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

http://dx.doi.org/10.1016/j.msea.2014.06.026
0921-5093/

a large fraction of soft β phase and make the TiZrAlV more deformable at room temperature (RT). The sheets were then suffered from an SPD by RT rolling with a thickness reduction in the range of 50–93% at a strain rate of $\dot{\varepsilon}=1.5\ s^{-1}$. To yield an SPD on the samples, an RT accumulative roll bonding (ARB) technique was employed with a reduction of ~2% per pass. To produce a hierarchical laminated structure, the SPD TiZrAlV was subjected to recrystallization annealing (675 °C for 10 min) and two-step aging treatments (625 °C for 2 h and 300 °C for 1.5 h), respectively.

Uniaxial tensile tests were performed on samples with a cross-section of $2.50 \times 0.35\ mm^2$ and a gauge length of 5.0 mm using an Instron 5848 Micro-Tester at a strain rate of $0.001\ s^{-1}$ at RT to achieve tensile properties and a stress–strain curve. The tensile direction was parallel to the rolling direction of samples. Fracture toughness was measured on samples with a diameter of 10 mm and a height of 0.35 mm by employing the small punch test (SPT) technique [21–23] at room temperature, where a borescope with video camera was used to monitor the bulged specimen surface for identifying the appearance of crack and the onset of fracture that is characterized by a length of 0.05 mm for the surface crack, as suggested in previous studies [21]. The strain energy density absorbed at the observed crack location up to the onset of visible cracking (the critical fracture criterion) was determined by simulating small punch load–displacement curves by the finite element (FE) analysis with a commercial software (Ansys), where the tensile stress–strain curve of specimens was used. The fracture toughness (K_{IC}) of specimens was then determined, by the FE analysis, from the estimation of the load level at which the fracture criterion (critical strain energy density) is expected to be met at the crack-tip of a large standard geometry fracture test specimen, e.g., a compact tension (CT) specimen. For each deformation condition, three specimens were used for both the uniaxial tensile and small punch tests, yielding an error bar for strength and fracture toughness.

Microstructures of the samples in rolling plane were characterized using a JEM-2010 transmission electron microscope (TEM). To obtain a statistical distribution of lamellar width, sample regions of $\sim 0.8\ mm^2$ were analyzed by the TEM technique. The fracture surface of tensile specimens was observed by employing a Hitachi S-4800 field emission scanning electron microscope (SEM).

3. Results and discussions

Fig. 1 shows small punch load–displacement curves of SPD TiZrAlV suffered from various strains after recrystallization annealing and aging treatments. Both the load and displacement increase with increasing strain from $e=0$ to 93%, indicating an enhanced fracture toughness. After the simulation of load–displacement curves by FE analysis, the local strain energy density to crack initiation in the punch tests was determined. The fracture toughness of the samples was then yielded (see Fig. 2) by determining the CT specimen load to the point where crack tip strain energy density reaches the fracture criterion using the FE analysis [21]. The undeformed TiZrAlV (i.e., $e=0\%$) shows a low tensile yield strength and fracture toughness (see Fig. 2), $\sigma_s \sim 1284$ MPa and $K_{IC}=37\ MPa\ m^{1/2}$, and these values increase to ~1438 MPa and $57\ MPa\ m^{1/2}$, respectively, with increasing strain to $e=93\%$. In most engineering structural materials, a high fracture toughness is usually accompanied by a low yield strength [1–3]. The most striking result here is that the SPD TiZrAlV shows a simultaneous enhancement in both the yield strength and fracture toughness with increasing strain (see Fig. 2).

For a comparison, Fig. 3 shows the data of yield strength and fracture toughness from both the present study on SPD TiZrAlV and the previous studies on $\alpha+\beta$ and β Ti alloys [20]. Like most structural materials [1,2], an inverted relationship between the fracture toughness and yield strength is clearly observed in the $\alpha+\beta$ and β Ti alloys (see the shade area in Fig. 3). However, a striking result is that, for the SPD TiZrAlV, fracture toughness is in proportion to yield strength (see the data marked with an ellipse), and the sample with $e=93\%$ is far away from the shade, showing an excellent combination of high yield strength and fracture toughness.

To reveal the factors governing the unusual enhancement of fracture toughness with increasing yield strength in the TiZrAlV,

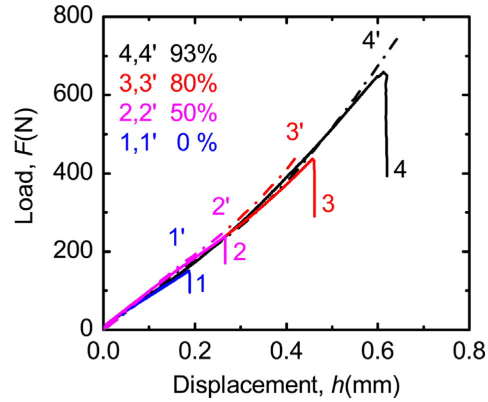

Fig. 1. Typical small punch load–displacement (SPLD) curves of SPD TiZrAlV with various strains after recrystallization annealing (675 °C for 10 min) and aging treatments (625 °C for 2 h and 300 °C for 1.5 h). The SPLD curves were simulated (the curves indicated with 1′, 2′, 3′ and 4′) by the finite element (FE) analysis based on tensile properties and stress–strain curve of the specimens.

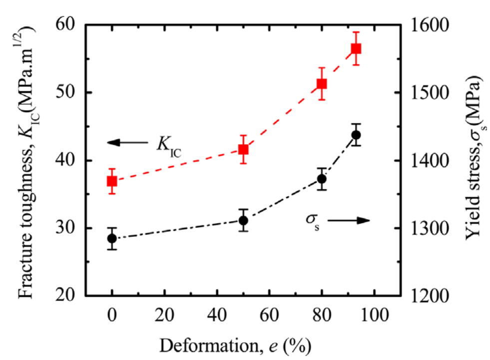

Fig. 2. Strain dependence of the fracture toughness and yield strength in SPD TiZrAlV after recrystallization annealing and aging treatments. A simultaneous enhancement of both the fracture toughness and yield strength is observed with increasing strain.

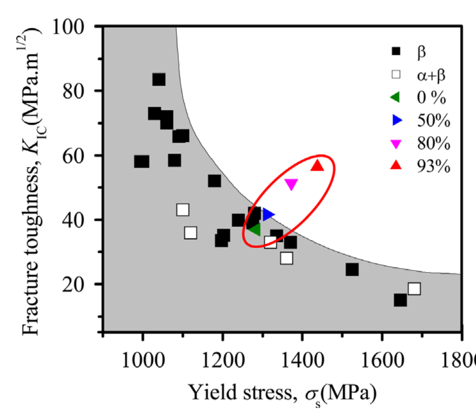

Fig. 3. Fracture toughness and yield strength of some Ti alloys. The data are from both the present study on the SPD TiZrAlV after recrystallization annealing and aging treatments and from the previous studies on $\alpha+\beta$ and β Ti alloys [20].