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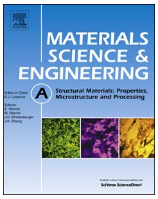

Experimental study on pure titanium during the positive-torsion and positive-negative-torsion

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ABSTRACT

The results of the mechanical properties, microstructure and fracture analysis of the pure titanium deformed by positive-torsion (PT) and positive-negative-torsion (PNT) are investigated by uniaxial tensile (UT) test, micro-indentation (MI) test, optical microscope (OM), transmission electron microscope (TEM) and scanning electron microscope (SEM). The UT test indicates that the strength increases obviously with the increase of torsion radian during PT. However, the strength firstly increases quickly, and then tends to steady with the increase of deformation during PNT. The similar phenomena are also shown through MI hardness analysis. The results from geometrically necessary dislocations (GNDs) and statistically stored dislocations (SSDs) indicate that the dislocation density varies differently with the increase of deformation during PT and PNT. OM observation shows the grains are elongated and large numbers of deformation twins are observed during PT while the equiaxial grains are always presented during PNT. The variations of dislocation density during PT and PNT are verified by TEM. Besides, quantities of subgrains (SGs) are observed owing to the accumulated larger plastic strain during PNT while large numbers of deformation twins intersect with each other during PT. The fracture analysis indicates that large numbers of micro-voids distribute non-uniformly on fracture surface of sample twisted by PNT. However, the characteristics of ductile and brittle fracture are observed on fracture surface of sample twisted by PT.

1. Introduction

The pure titanium has a wide application due to its good mechanical properties, high chemical stability, excellent corrosion resistance and biocompatibility [1,2]. Especially the pure titanium has been paid attention to orthopedic applications owing to its good biocompatibility.

The torsion deformation is combined with other deformation modes to refine grains and improve the mechanical properties for the pure shear could obtain a higher plastic strain than the tension and compression [3]. For instance, high pressure torsion (HPT) [4] combines torsion with compression deformation, and twist extrusion (TE) [5] combines torsion with extrusion deformation. The grains can only be elongated along the direction of the tensile stress during tension deformation while the rotation tensor can be introduced to maximize the simple shear deformation during torsion deformation [6]. The severe plastic deformation (SPD) has been drawn extensive attention due to its enormous advantages in improving the comprehensive properties of materials [7–9]. Therefore, the evolution of microstructure and mechanical properties during torsion are studied by many scholars. Chengpeng Wang and Hyoung Seop Kim indicated that the grains of pure Cu were refined and that the hardness was improved with the increase of deformation during torsion based on experiment and simulation [10–12]. Besides, the microstructure and hardness of deformed pure Cu distributed non-uniformly on transverse section [10]. Ning Guo found that the tensile and compressive strengths of AZ31 were improved during torsion [13]. Sunisa Khamsuk indicated that the strength of pure Al was improved; the grains were refined and the high angle grain boundaries increased with the increase of equivalent strain during torsion [14]. In addition, the pure Cu after combined tension and torsion deformation was also studied by Jinghui Li and Chengpeng Wang [6,15]. It can be inferred that a higher plastic strain can be obtained under the combined deformation mode than single deformation mode. Qudong Wang studied that the microstructure of AZ series magnesium alloys could be refined uniformly during the cyclic extrusion compression. The results indicated that the microstructure was more homogeneous under the cyclic deformation mode [16].

Many scholars studied that the hardening of material was mainly attributed to the proliferation of dislocations for pure Cu

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Table 1
Chemical composition of pure titanium.

Elements	Fe	C	N	H	O	Ti
Weights%	0.12	0.02	0.03	0.01	0.20	99.62

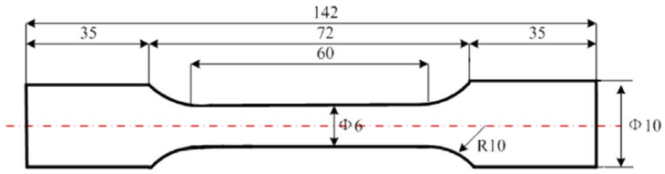

Fig. 1. Detail dimensions of the sample (Unit mm).

and AZ31 during torsion deformation [10,13]. The grains were elongated, laminar substructures or shear bands were formed, then the dislocations were activated, accumulated and rearranged. Finally, the equiaxed cells and networks appeared, and subgrain boundary formed. The dislocation can be divided into statistically stored dislocations (SSDs) and geometrically necessary dislocations (GNDs) based on the strain gradient plasticity theory [17–19]. The SSDs and GNDs can be calculated by the micro-indentation test according to the Taylor dislocation model [20,21]. N. A Fleck indicated that the macroscopic strengthening of material was related to GNDs [22]. Researches found that GNDs provided the lattice continuity when the curvature was presented, and SSDs evolved from random interactions of dislocations [23]. The dislocation density can be obtained according to the TEM measurement or simulation under the certain dislocation theory.

The proliferation and pile-up of dislocations may lead to the micro-crack or micro-voids to be formed, and then the accumulated plastic strain is limited before fracture under the single torsion deformation. Jinghui Li indicated that the micro-voids proliferated and grew up with the increase of torsion deformation. The volume percentage of the micro-voids reduced, and micro-voids tended to aggregate when a critical torsion strain was reached during the combined tension and torsion deformation. However, the nucleation, extension and aggregation of micro-voids were not obvious during the torsion [6]. It can be inferred the micro-voids are liable to form, grow up and expand under the complex deformation mode. During PT, the formation and expansion of micro-voids may move along the constant direction under the single stress mode, which has an obvious difference in contrasting to PNT. During PT, the accumulated plastic strain is smaller than that of PNT. However, scarce attention has been paid to the comparison of PT and PNT. On the basis of above researches, the aim of the present work is to present the results of the microstructure, mechanical properties and fracture analysis of pure titanium deformed by PT and PNT.

2. Experiments and methods

The pure titanium Ti-GR2 (ASTM) rods are annealed at 823 K for 1 h in argon atmosphere and cooled in air for removing residual stress. The chemical composition of pure titanium is given in Table 1. The rods after annealing are subjected to torsion deformation. Fig. 1 shows the detailed dimensions about the sample. Two groups of torsion experiments are conducted using the XC-10 wire torsion testing machine with the torsion speed 30 r/min. The first group of rods is subjected to PT, and the samples are twisted until fracture. The maximum torsion radian is 19.91, and the samples after twisted 6.28, 9.42, 12.56, 15.70, 18.84 rad are marked as PT-6.28, PT-9.42, PT-12.56, PT-15.70 and PT-18.84. The second group of rods is subjected to PNT, and the samples are twisted back and forth by a radian of 1.57. The maximum cycle times are 105. The samples after twisted 20, 40, 60, 80 and 100 times are marked as PNT-1.57-20, PNT-1.57-40, PNT-1.57-60, PNT-1.57-80 and PNT-1.57-100. The schematic diagram of processes of PT and PNT are shown in Fig. 2.

The mechanical properties of deformed samples are obtained based on uniaxial tensile test. The uniaxial tensile tests are conducted at room temperature with a constant strain rate of $10^{-3}\,s^{-1}$ using Instron 3382 (Instron Inc., USA). Besides, the mechanical properties of deformed rods can be characterized by MI test using the method of Oliver and Pharr [24,25]. It is well known that the micro-indentation elastic modulus E and hardness H

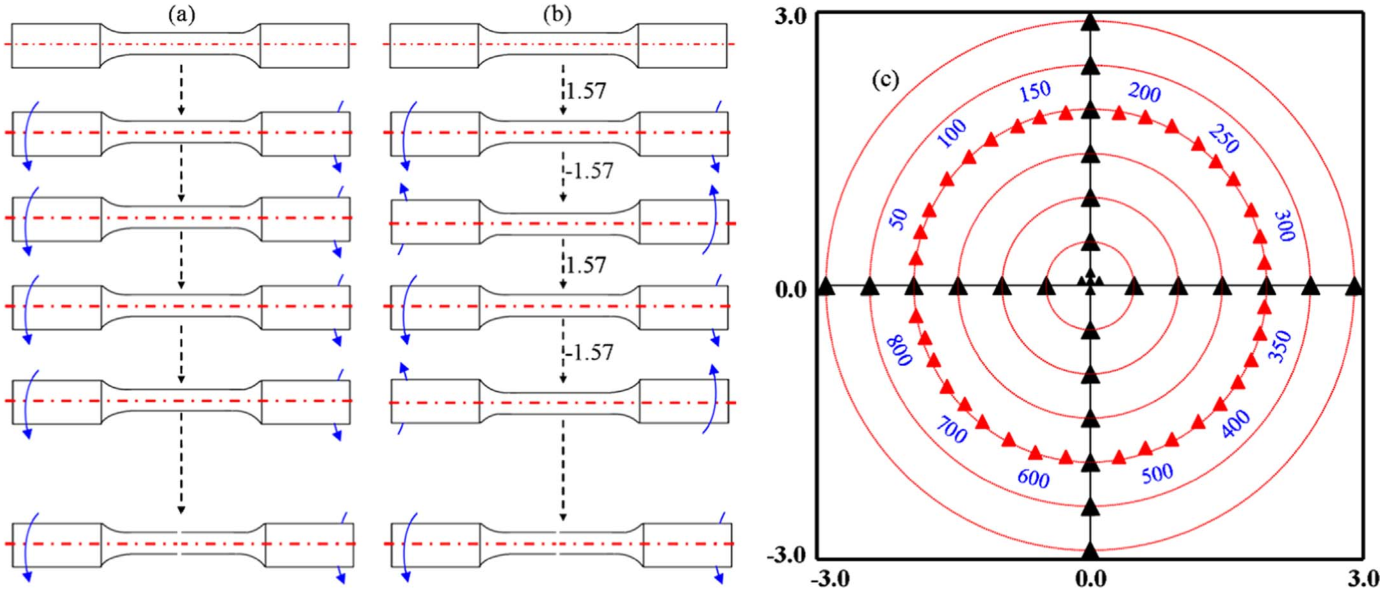

Fig. 2. The schematic diagram of processes of (a) PT, (b) PNT; (c) the positions of the micro-indentation on transverse section. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.).