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Experimental study on pure titanium subjected to different combined tension and torsion deformation processes

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ABSTRACT

The results of the mechanical properties, microstructure and fracture analysis of the pure titanium deformed by combined tension and torsion simultaneously (TT1), combined torsion-tension successively (TT2) and combined tension-torsion successively (TT3) are investigated by micro-indentation (MI), optical microscope (OM), scanning electron microscope (SEM) and transmission electron microscope (TEM). The MI test indicates the improvement of micro-indentation hardness (H) for TT1 is the most obvious of all studied processes and the increment of H depends on the increase of tensile stress. But the H shows a different variation trend with different proportions of tensile stress during TT2 and TT3. OM observation shows the grain elongation degree on longitude section can be weakened with the increase of tensile stress during TT1. However, the grain morphology on longitude section is mainly controlled by the torsion deformation during TT2 and TT3. The results of SEM indicate tensile stress plays a different role in the process of fracture during TT1, TT2 and TT3. Different types of dimples with different sizes and depths are observed in TT1, TT2 and TT3. TEM observation shows that different dislocation structures gather in the surrounding of the grain-boundary trijunctions in TT1, TT2 and TT3. Finally, the effects of different dislocation movements caused by TT1, TT2 and TT3 on microstructure evolution are discussed.

1. Introduction

The excellent mechanical properties, high chemical stability, excellent corrosion resistance and biocompatibility of pure titanium enable it to be the preferred metal for aircraft and biomedical fields [1–3].

The torsion deformation in combination with other deformation modes is used to refine grains and improve the strength for it could obtain a higher plastic strain than the tension and compression deformation [4]. Several severe plastic deformation (SPD) processing techniques, such as high-pressure torsion (HPT) [5] and twist extrusion (TE) [6], combining torsion and compression deformation, torsion and extrusion deformation, produce exceptional grains refinement without introducing any significant change in the overall dimensions of the specimen. Therefore, the torsion deformation has attracted wide attention of scholars in materials science due to its enormous importance to SPD. Chengpeng Wang indicated that the gradient distribution of grain size on transverse section was attributed to the strain gradient introduced by torsion deformation for pure copper [7]. The tensile and compressive properties of AZ31 were improved but showed different growth trends after torsion deformation [8]. Sunisa Khamsuk found that the volume percentage of high angle grain boundaries increased with the grains refinement and strength increase for pure aluminum [9].

The refinement of the grains by SPD depends on the accumulated plastic strain. Ning Guo indicated the improvement of mechanical properties was mainly attributed to the proliferation of dislocations for AZ31 during torsion deformation [8]. D. A. Hughes et al. stated that plastic deformation of metal is related to the dislocation motion and subsequent trapping of dislocations and the relevant dislocation cell boundary misorientation angle distributions was studied. He also explored the correlations between deformation and the relevant microstructure or substructure experimentally, and introduced the incidental dislocation boundaries (IDBs) and geometrically necessary boundaries (GNBs) to explain the microstructural evolution [10,11]. The microstructural evolution caused by SPD were studied by Clayton et al. and Valiev et al. based on experiment and modeling; the microstructural evolution had a close relation to the dislocation distribution and rotational lattice defects from the perspective of multiscale volume averaging [12–14].

The proliferation and pile-up of dislocations may lead to produce micro-cracks or micro-voids, and the accumulated plastic strain is

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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

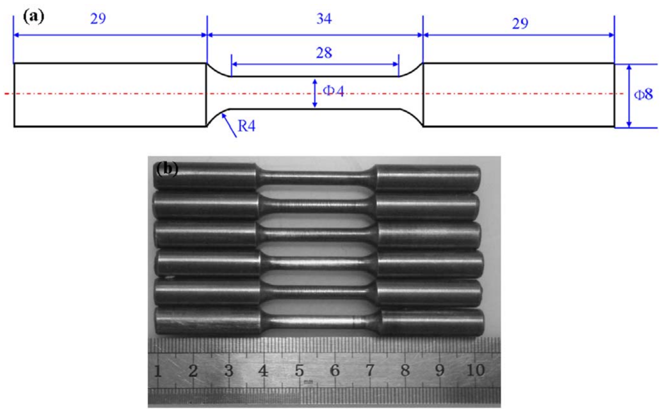

Fig. 1. (a) Detail dimensions of the specimen (Unit is mm), (b) physical figure of the specimen.

limited before fracture under the single torsion deformation. In order to obtain better refining effect and higher mechanical properties, combined deformation has been drawn extensive attention due to its accumulated higher plastic deformation. Some traditional SPD processes with many shortcomings are limited for its widely manufacturing applications [15]. For instance, there are not enough materials to be used in mechanical properties test and practical application during HPT [16]. The difficult-to-deformation materials such as magnesium alloys, which can't be processed easily using conventional ECAP [17]. Recently, a kind of simple and practical deformation process called combined tension-torsion (CTT) is used and studied by many scholars. Chengpeng Wang and Jinghui Li studied the microstructure and micro-voids evolution for pure copper during CTT [18,19]. The results indicated that the grains could be refined further compared with the single torsion deformation. Besides, the nucleation, aggregation and expansion of micro-voids were not apparent during torsion, which was different from the observation of a population of micro-voids for CTT [19]. Anna Korneva observed that the combined tension and torsion deformation resulted in the formation of gradient microstructure with the minimum grain size in the surface layer of the FeCr22Co15 [20].

It is well known that the material imposed on different stress-strain histories results in different microstructures, mechanical properties and micro-voids evolution [21,22]. However, scarce special attention has been paid to the comparison of different CTT techniques. Therefore, the aim of the present work is to present the results of the microstructure, mechanical properties and fracture analysis of the pure titanium deformed by different combined tension and torsion deformation processes.

2. Experiments and methods

The pure titanium Ti-GR2 (ASTM) rods are annealed at 823 K for 1 h in argon atmosphere and air cooled in order to remove residual stress. The chemical composition of pure titanium is given in Table 1.

The rods after annealing are subjected to tension and torsion deformation. The detailed dimensions of the specimen are shown in Fig. 1. The uniaxial tensile test and torsional test are conducted using the Instron 3382 (Instron Inc., USA) and XC-10 wire torsion testing machine (Kntest Inc., China) respectively. The accumulated maximum tensile strain is about 19% during uniaxial tensile test. The tensile test and torsional test are conducted at room temperature with a constant strain rate 10^{-3} s^{-1} during tension and rotate speed 30r/min during torsion. The specimen ruptured by uniaxial tensile is marked as Ti-19%t. Similarly, the specimen ruptured by pure torsion is flagged as Ti-7.6r (7.6 turns before fracture). After that, three groups of specimens are subjected to three kinds of combined tension and torsion deformation. The first group of specimens is subjected to combined tension and torsion simultaneously (TT1). During TT1, 100N, 1000N and 2000N are loaded along the axial direction in XC-10 wire torsion testing machine respectively. The stress state and deformation mode of material are changed owing the introduction of axial load during torsion. Then the specimens are twisted 7.9, 6.8 and 6.6 turns before fracture. Therefore, the three specimens after fracture are marked as Ti-(100N+7.9r), Ti-(1000N+6.8r) and Ti-(2000N+6.6r). The second group of specimens is firstly subjected to torsion deformation, and then tension deformation (TT2). As above, the five specimens after torsion-tension deformation are marked as Ti-(1r+1%t), Ti-(1r+5%t), Ti-(1r

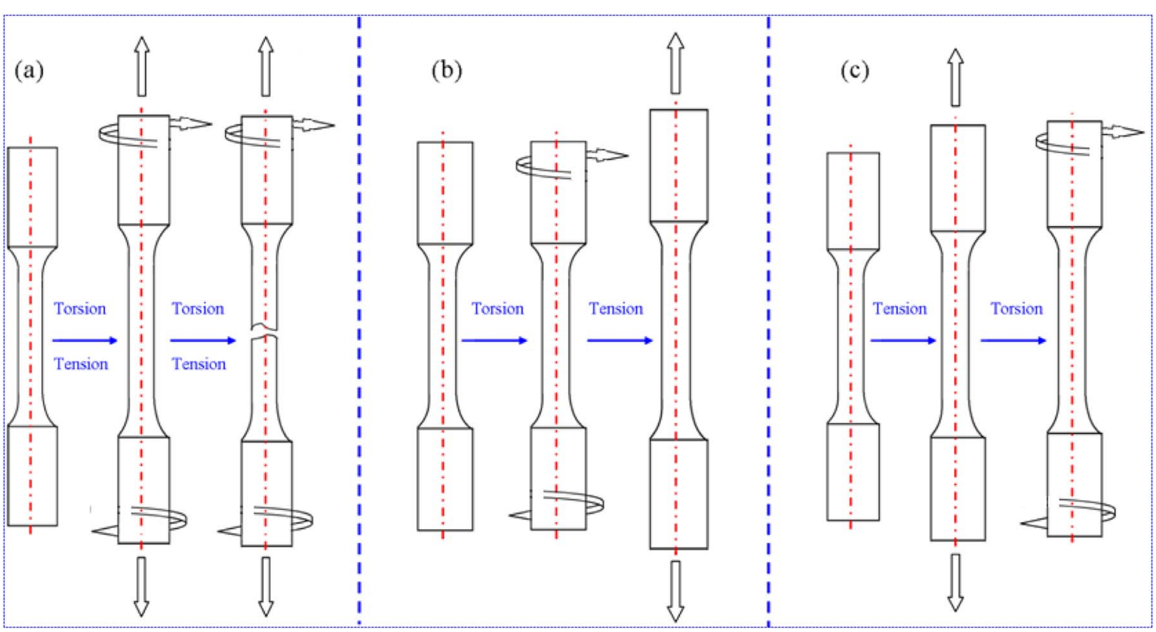

Fig. 2. The schematic diagram of different deformation processes: (a) TT1, (b) TT2, (c) TT3.