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Ductile-to-brittle fracture of CP titanium with torsion deformation

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ABSTRACT

In this paper, the mechanical properties and fracture mechanisms of coarse-grained (CG) commercial-purity Ti subjected to both tensile and torsion deformations are investigated. During tensile deformation, CG Ti exhibits general excellent extendibility and ductile fracture. However, CG Ti presents absolutely brittle fracture during torsion deformation, despite its high torsion deformability. This is attributed to the specific fracture mechanism in torsion that the microcracks nucleate at the surface layer and propagate from the surface to the interior of torsion sample, which is contrast to the typical microcrack nucleation and propagation behaviors of ductile metals in tension. This study has an important significance for the design and application of metals carrying torsional load.

1. Introduction

Mechanical properties and fracture mode are important factors influencing the utility of metallic structural materials. In general, metals fracture in a ductile or brittle manner depending on both their mechanical properties and the conditions of bearing load (e.g., temperature or strain rate) [1–3]. As is well-known, the fracture process includes the nucleation and propagation of microcracks. The microcrack nucleation is associated with the plastic deformation and stress concentration. The microcrack will nucleate if the large stress concentration equivalent to a large shear displacement can not be relieved by localized cross-slip [4]. The microcrack propagation is dependent on the sample geometry and deformation mode [5–7]. In notched round tensile bars, the microcrack propagation path is usually flat or zigzagged [5], while the fracture path is usually slanted in plane strain bars [6]. In practical engineering applications, structural components can carry different load mode, including tension, compression and torsion etc. However, the reports on the mechanical behavior and fracture mechanism of metals subjected to torsion deformation are rare, although this is of significance for the design and application of metals carrying torsional load, such as drills, gear shafts and transmission shafts. In the present study, the mechanical behavior and fracture mechanism of CP titanium in torsion are studied and an extraordinary brittle fracture occurs for the CG Ti in torsion, despite its high torsion deformability, which is fundamentally contrast to the ductile fracture in tension, and the corresponding mechanism is discussed in comparison with that in tension.

2. Material and methods

In the present study, CP Ti bars were supplied with a composition of (wt.%) 0.02C, 0.009 N, 0.005H, 0.007O, 0.15 Fe, bal. Ti. The Ti bars were machined into a dog-bone-shaped geometry with a gauge dimension of φ 10 mm × 70 mm. The dog-bone-shaped specimens were vacuum-annealed at 700 °C for 2 h to obtain a homogeneous CG microstructure with an average grain size of ~35 μm (not shown here).

The microstructure of the annealed CP Ti was characterized using OM and XRD. The specimens for OM measurement were prepared by grinding, polishing and etching. The grain size was determined by approximating the equivalent sphere diameters of grains by directly measuring their areas from the OM images [8]. The fracture surfaces of CP Ti after tensile and torsion deformations were investigated by employing SEM.

In order to study the isolated effect of the loading mode (i.e., torsion) on the fracture behavior of Ti, both tensile and torsion tests were conducted at RT and with a quasi-static strain rate. Uniaxial tensile tests were conducted under a constant strain rate of $5 \times 10^{-4}\ s^{-1}$. The strain was measured with a contacting extensometer with 50 mm gauge. The torsion tests were carried out at a constant rate of 0.1 rpm, which resulted

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in a maximum equivalent strain rate of $1 \times 10^{-3}\,s^{-1}$ at the sample surface. For both tests, at least three samples of each condition were used for good reproducibility. The deviations in the ultimate torque, total torsional angle, tensile strength and elongation to failure were less than 15 N·m, 50°, 20 MPa and 3%, respectively.

3. Results and discussions

Fig. 1(a) presents the torque-torsional angle curve of CG Ti. During torsion, the Ti sample experiences two stages of elastic and plastic deformation, which is analogous to those in tensile deformation (see Fig. 1(b)). After torsion elastic limit of about 60 N·m, the torque increases persistently with torsional angle up to abrupt fracture without localized deformation, which is fundamentally different from that in tensile deformation (see Fig. 1(b)). The catastrophic fracture of CG Ti in torsion can be brittle fracture, despite its superior torsional deformability.

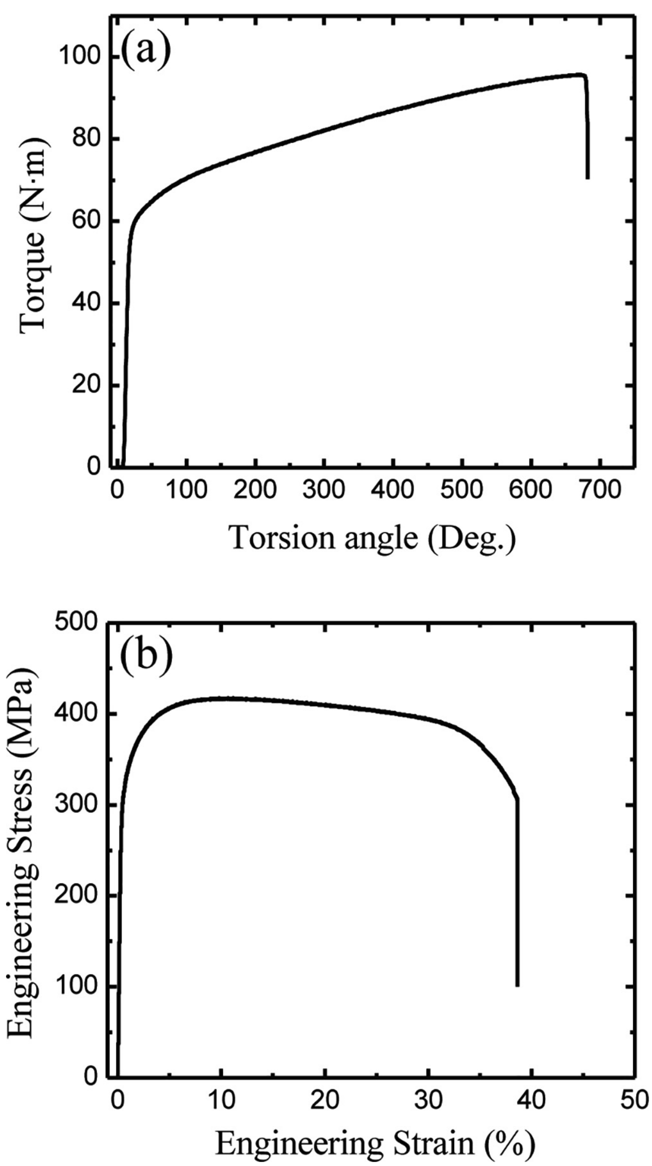

Fig. 1. (a) Torque-torsional angle curve and (b) tensile engineering stress-strain curve of Ti.

Fig. 1(b) shows the tensile engineering stress-strain curve of CG Ti, which presents a low strength and superior ductility. The yield strength ($\sigma_{0.2}$) and ultimate tensile strength (σ_b) are 314 MPa and 416 MPa, respectively, and the uniform elongation and elongation to failure are 11.9% and 38.7%, respectively, which is comparable to the tensile properties of CG Ti in other studies [9]. The large elongation of 26.8% after necking hints that the fracture mode of the CG Ti can be ductile.

Fig. 2 gives the SEM images of tensile fracture surface of CG Ti. As shown in Fig. 2(a), rough fracture surface composed of three distinct regions (indicated by b, c and d, respectively) can be observed forming a well-known cup-and-cone facture, which is a typical ductile fracture mode [1,5]. This fracture characteristic can correspond to the microcrack initiation in the central region and propagation to the final unstable fracture in the peripheral region. The observation of the b region at a higher magnification shows deep dimples (see Fig. 2(b)), indicating that the microcrack initiation take the form of microvoid coalescence, a ductile fracture. The crack propagation region (see Fig. 2(c)) also consists of dimples with more shallow depth than those in crack initiation region (see Fig. 2(b)). The peripheral region, i.e., shear lip, exhibits cleavage fracture (see Fig. 2(d)).

Fig. 3 shows the SEM images of torsion fracture surface of CG Ti. The torsion fracture surface (see Fig. 3(a)) looks smoother compared with the tensile fracture surface (see Fig. 2(a)) and the fracture characteristics are almost identical for different regions. Therefore, CG Ti can present a catastrophic brittle facture mode in torsion deformation. Based on the observations of at a higher magnification (see Fig. 3(b)), cleavage fracture features the peripheral region of the torsional fracture surface, and steps and "rivers" (indicated by dotted arrows) can be definitely identified, which is attributed to the change of the directions of cleavage facets when they cross grain boundaries [1]. The crack propagation direction can be determined to be the direction of the "rivers" flows. It can be drawn that the microcracks nucleate at the sample surface layer and propagate from the peripheral region to the central region in torsion, which is distinct from the microcracks nucleation and propagation behaviors in tension (see Fig. 2(a)). The roughness increases from the surface to the core and fracture characteristic transforms from cleavage to dimples (see Fig. 3(c) and (d)). However, the dimples in the core region (see Fig. 3(d)) were much finer and more shallow than those in the crack initiation region in tensile deformation (see Fig. 2(b)).

Above experimental results reveal that the mechanical performance, especial fracture behavior of CG Ti are extremely sensitive to the load mode. As mentioned above, the fracture process is composed of the nucleation and propagation of microcracks. Therefore, it is reasonable to infer that the nucleation and propagation of microcracks are closely related to the load mode. For torsion deformation, the strain and strain rate continuously increase from the interior to the peripheral region [10]. Hence, stress concentration firstly forms at the peripheral region. However, the torsional deformation has little influence on the shape and size of the specimens [10]. This hints that the stress concentration cannot be relieved by localized cross-slip due to uniaxial stress state in torsion. When the normal stress reaches the levels