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Microstructural evolution and grain refinement mechanism of pure tungsten under explosive loading condition

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ABSTRACT

The microstructural evolution and grain refinement mechanism of pure tungsten prepared by chemical vapor deposition under explosive loading condition were systematically investigated. Results show that dynamic recrystallization is the main deformation mechanism of pure tungsten under explosive loading condition, and new refined tungsten grains were observed in the deformed tungsten. However, the grain refinement mechanism of tungsten is obviously different from that of subgrain rotational dynamic recrystallization (RDR) mechanism and progressive subgrain misorientation recrystallization (PriSM) mechanism. Under the explosive loading condition, the tungsten grains are severely elongated into fibrous grains. Because the deformation time is ultra-short, dislocation slips are conducted through single slip system within the elongated tungsten grain, resulting in the formation of high density dislocation walls consisting of parallel dislocation lines. With continuous deformation, the high density dislocation walls are transformed into subgrain boundaries, which further evolve into refined boundaries. Then the fibrous tungsten grains are fragmented into equiaxed grains. No deformation twins were observed in the deformed pure tungsten.

Introduction

Explosive loading technique uses the shock wave generated by high explosion to introduce large strain in materials within an ultra short time, and the strain rate under explosive condition can exceed 10^5 s^{-1}. Under explosive loading, the stress and temperature within materials increase rapidly, and materials are approximately considered as fluids [1]. After explosive loading deformation, the grains of metal materials are remarkably refined. The mechanical behaviors of materials under explosive loading are distinctive from those under low strain rate loading, and the corresponding deformation mechanism and grain refinement mechanism are also varied significantly [2–8].

Over the past decades, tungsten has drawn much attention in the field of structure materials [9–15]. Tungsten has high density (19.3 g/cm^3), high strength and high melting temperature (3410 °C). Tungsten also has the advantages of high hardness, good wear resistance and great resistance to high temperature. As tungsten has outstanding comprehensive properties, it has been widely used in the field of aerospace, mechanical fabrication and electronics. With the development of armament science and improvement of metallurgy manufacturing technology, tungsten also exhibits good potentiality in the fields of warhead materials, such as shaped charge liner materials.

Many researches have been focused on the mechanical behaviors and deformation mechanism of tungsten under high strain rate (10^3 s^{-1}–10^4 s^{-1}) and quasi-static strain rate (10^{-3} s^{-1}–10^{-1} s^{-1}) loading conditions. Dummer showed that the weak grain boundaries and stress concentration led to the damage of polycrystalline tungsten [12]. Subhash et al. found that twin and grain boundary crack interaction induced failure in <011> chemical vapor deposition (CVD) tungsten [13]. Wei Q found that the strain rate sensitivity of ultra-fine grained W was much lower than that of conventional W. The dislocation mediated plastic deformation mechanism of body-centered cubic metals can explain well this phenomenon [14]. Pappu et al. studied several oriented single crystal tungsten rods after ballistic penetration and the deformation twins were identified to be in the {211} planes [15]. However, little studies were focused on the deformation mechanism of tungsten under explosive loading which create an ultra-high strain rate condition.

The microstructural evolution of single-phase materials which are subjected to high/ultra-high strain rate condition has been systematically studied, such as Cu, Fe, Mo and other metals [16–20], and the corresponding deformation mechanisms were also revealed, respectively, including dislocation and twinning [21–25]. In a recent study, a grain refinement mechanism of multiple laser shock processing impacts on ANSI 304 stainless steel was proposed, and the mechanical twin intersections were considered to lead to grain subdivision during the ultra-high strain rate deformation process [26]. While under ultra-high strain rate condition induced by the same multiple laser shock,

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the deformation mechanism of LY2 Al alloy involved more with dislocation multiplication and transformation [27]. L.E. Murr compared the microstructures of Cu and Ta in the shaped-charge regime. It was found that the grains in the jet fragments of Cu after explosive loading are much finer than those of Ta, and dynamic recrystallization (DRX) plays a dominant role in the jet elongation and microstructure evolution of both materials [28]. Guo W investigated the DRX of tungsten which underwent explosive loading, and the results showed that the microstructures of tungsten after deformation were refined, indicating that the DRX process occurred during deformation [29]. However, the microstructural evolution process was not observed, thus the specific grain refinement mechanism of tungsten under explosive loading condition was still in suspense. Thus, the study of microstructure evolution in tungsten under explosive loading will promote a further understanding of body-centered cubic materials subjected to ultra-high strain rate. Meanwhile, it will reveal more new features of dislocations in the grain refinement process. In addition, the study of deformation mechanism of tungsten under explosive loading will also have beneficial influences on the wide application of tungsten in the field of armament, such as warhead materials.

In the present study, explosive loading was performed on tungsten and the deformed tungsten was elaborately retrieved and investigated. The microstructural evolution of tungsten during the deformation process was systematically analyzed, and the deformation mechanism and the grain refinement mechanism of tungsten were revealed.

Experimental

The tungsten in this study was fabricated by CVD. Tungsten hexafluoride was deoxidized by hydrogen to produce tungsten continuously on a conical copper matrix. After deposition, the copper matrix was dissolved by nitric acid, and the tungsten hollow cone was processed by precision machining. Fig. 1 shows the microstructure of pure tungsten before explosive loading experiment. It can be found that the original tungsten grains are typical columnar structures and the microstructure is homogeneous, with the average length of tungsten grains being 150 μm and the average diameter being 30 μm. Along the growth direction of tungsten grains, there is a preferred orientation of <100> direction, as is shown in Fig. 2(a).

The tungsten hollow cone was subjected to an explosive loading in order to obtain ultra-high strain rate. When the explosive is detonated, the in-wall of the hollow cone forms the jet and the out-wall forms the slug. The schematic diagram of the deformation process of the tungsten hollow cone is shown by Fig. 2(a)–(c), and Fig. 2(d) shows the actual slug of tungsten hollow cone after deformation. The plastic strain in slug is calculated to reach 5–7.5 by finite element modeling, thus the strain rate reaches $3.3 \times 10^5\ s^{-1}$–$5 \times 10^5\ s^{-1}$, which belongs to the range of ultra-high strain rate. After explosive loading experiments, the slug was retrieved and cleaned, and then it was cut along a longitudinal direction by electrical discharge machining (EDM). The sectioned surfaces were polished to a mirror finish, and then the surfaces were

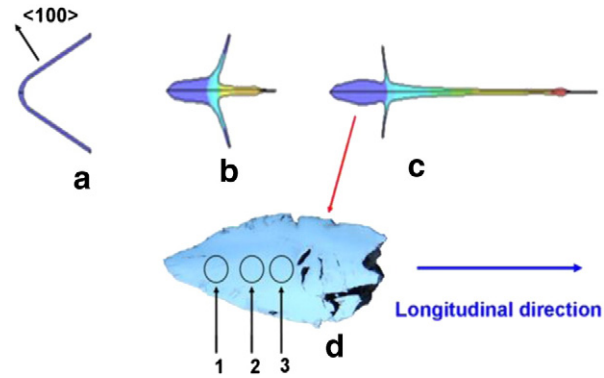

Fig. 2. Schematic diagram of the deformation process of the tungsten hollow cone: (a) original tungsten hollow cone; (b) the formation of the jet and slug; (c) the elongation of the jet and slug; and (d) the actual tungsten slug retrieved after explosive loading experiments.

etched. Optical microscopy (OM) and electron backscattered diffraction (EBSD) were employed to observe the microstructure and texture of deformed tungsten. Transmission electron microscope (TEM) samples with a shape of 2 mm × 2 mm × 0.5 mm were cut off from the tungsten after explosive loading. These samples were first polished to a thickness of 20–30 μm by hand, and then followed by ion-milling for electron transparency. TEM was employed to reveal the microstructure features within the grains of deformed tungsten.

Results and discussion

Fig. 3 shows the morphologies of the cross-section parallel to longitudinal direction in deformed tungsten obtained by optical microscopy. Fig. 3(a)–(c) corresponds to area 1–3 marked in Fig. 2(d), respectively. During the deformation process, the strain rate and stress in the center of the slug are higher than those in the edge of the slug, which results to gradient strains in the deformed tungsten. Fibrous tungsten grains are observed in area 1, and the average width of the fibrous tungsten grains is 15 μm, as is shown in Fig. 3(a). In area 2, the average width of observed fibrous tungsten grains decreases to 10 μm, and there is a fragmentation tendency of the fibrous tungsten grains, as Fig. 3(b) shows. While in area 3, equiaxed tungsten grains with an average size of 10 μm are observed, and the tungsten grains are remarkably refined, as Fig. 3(b) shows.

EBSD is used to analyze the grain orientation and the misorientation angle between adjacent tungsten grains after explosive loading deformation. Fig. 4 shows the EBSD results of deformed tungsten in area 2 (parallel to longitudinal direction) in Fig. 2. As is shown in Fig. 4(a), tungsten grains are severely elongated into fibrous structures, which are consistent with the observed results of optical micrographs. Fig. 4(b) shows the inverse pole figure of this area, and it can be clearly seen that there is an obvious preferred grain orientation in

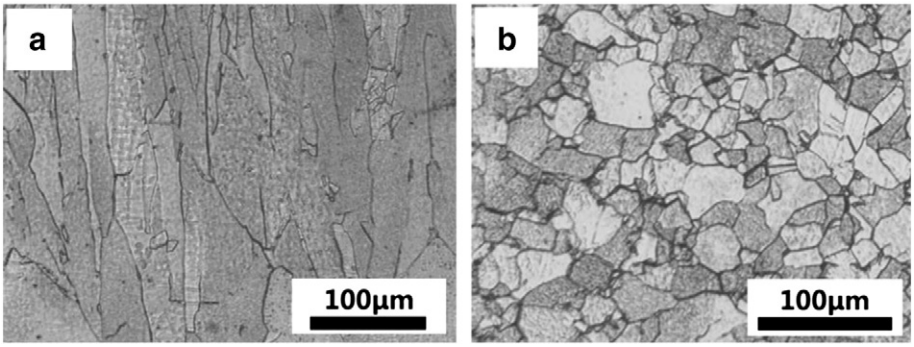

Fig. 1. Microstructure of pure tungsten before explosive loading experiment: (a) parallel to the direction of growth; and (b) perpendicular to the direction of growth.