Materials Science & Engineering A 619 (2014) 107–111

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

The reciprocal relationship of orientation dependence of the dislocation boundaries in body-centered cubic metals and face-centered cubic metals

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ARTICLE INFO

Article history:
Received 26 August 2014
Received in revised form
17 September 2014
Accepted 18 September 2014
Available online 6 October 2014

Keywords:
Reciprocal relationship
Body-centered cubic
Mo
Dislocation boundaries

ABSTRACT

The orientation dependence of deformation microstructure has been investigated in uniaxial deformed body-centered cubic molybdenum by electron backscatter diffraction and transmission electron microscopy. It has been found that the dislocation boundaries in both tensile and compressed molybdenum, similar to that in face-centered cubic metals, can be classified into three types: dislocation cells (Type 2), and extended planar boundaries parallel to (Type 1) or not parallel to (Type 3) a {110} trace. Furthermore, it shows a reciprocal relationship between body-centered cubic metals and face-centered cubic metals on the orientation dependence of the deformation microstructure. Type 3 grains have stress axes direction which is near the [110] corner in the unit triangle for BCC metals, whereas Type 3 grains have stress axes direction which is near the [111] corner for FCC metals. The analysis of Schmid factors shows that the dislocation structure depends on the slip systems.

1. Introduction

For pure metals in our daily life, such as Al, Cu, Ni, γ-Fe, α-Fe, Mo, Ta, W, etc., the most common crystal structures are body-centered cubic (BCC) crystal structure and face-centered cubic (FCC) crystal structure. Both have been studied a lot on their characteristics. It has shown that a reciprocal relationship between BCC crystal structure and FCC crystal structure exists in many fields. Firstly, the reciprocal lattice of BCC crystal structure is FCC crystal structure, and vice versa. Secondly, the slip system of FCC metals, which is usually {111}⟨110⟩, has a reciprocal relationship with that of BCC metals ({110}⟨111⟩). Lastly, the texture of uniaxial deformed FCC metals has a reciprocal relationship with that of BCC metals. For example, in uniaxial compressed condition, the texture of FCC metals is ⟨110⟩ fiber texture (⟨110⟩∥compression direction (CD)) and that of BCC crystal structure is ⟨100⟩ + ⟨111⟩ fiber texture (⟨100⟩∥CD and ⟨111⟩∥CD). In uniaxial tensile condition, the texture of FCC crystal structure is ⟨100⟩ + ⟨111⟩ fiber texture (⟨100⟩∥tensile direction (TD) and ⟨111⟩∥TD) and that of BCC crystal structure is ⟨110⟩ fiber texture (⟨110⟩∥TD). Therefore, it is interesting to see whether the relationship between grain orientation and deformation microstructure in BCC metals is reciprocal with that of FCC metals.

Many studies have been done on their plastic deformation behaviors. After plastic deformation, many dislocations and dislocation boundaries are formed. It has been concluded that in micro-scale, the dislocation boundaries can be mainly divided into two kinds: extended planar dislocation boundaries (EPBs) and cell boundaries. These long and straight EPBs have also been characterized as geometrically necessary boundaries (GNBs), and cell boundaries are sometimes called incidental-dislocation boundaries (IDBs) [1–5]. An important question concerning the long and straight EPBs is what planes they lie on. So far, there are two main points about the formation mechanism of the planes [6]. The first point is that the planes are crystallographically determined, which are predominantly related to the orientation of the grain in which they form. The second point is that the planes are macroscopically determined, which are mainly related to the sample deformation geometry. The long and straight EPBs obviously attribute to mechanical anisotropy of materials. Thus, the study of EPBs has implications for the development of models of mechanical anisotropy [7–9]. It is very important to determine the relationship between the deformation microstructure and orientation, which is very helpful in the study on deformation mechanisms, mechanical properties, and texture formation of materials. Up to now, much

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http://dx.doi.org/10.1016/j.msea.2014.09.073
0921-5093/

work on this has been done in FCC metals, especially in Al and its alloys [10–13]. Their results show that the dislocation boundaries in tensile or compressed aluminum can be classified into three types: dislocation cells (Type 2), and extended planar boundaries parallel to (Type 1) or not parallel to (Type 3) a {111} trace. However, there is little work on the orientation dependence of dislocation structure in BCC metals. In this study, the refractory metal molybdenum (Mo) is chosen to study the deformation behaviors of BCC metals, since the deformation mechanism of Mo is dislocation glide and no phase transformation during plastic deformation.

2. Experimental

The commercial molybdenum bars with a diameter of ⌀18 mm were draw-forged and upset-forged to 40% at 1573–1373 K. In addition, after every pass of about 10%, the bars annealed at 1573 K for 5 min. EBSD images were taken by FEI-Sirion 200 field emission scanning electron microscope (SEM). The transmission electron microscope (TEM) observation was conducted on a Tecnai G2 20 transmission electron microscope. The specimens were jet polished in a mixing solution of H_2SO_4 and CH_3OH with a ratio of 1:3 at 273 K. The TEM specimens were the first taken TEM images and they were marked. We can make sure the relationship between the orientations and the microstructure in TEM. The same area was then conducted on SEM to get EBSD maps. We can get the EBSD maps of the same orientations as those in TEM.

3. Results and discussion

Fig. 1a shows a typical large-scale orientation map of the tensile deformed pure Mo. It can be clearly seen that grains mainly belong to ⟨110⟩ and ⟨100⟩ fiber texture, few grains belong to ⟨111⟩ orientation. Fig. 1b shows a typical large-scale orientation map of compressed Mo. It can be clearly seen that the microstructure is very different from that of the tensile Mo. Many grains with ⟨100⟩ and ⟨111⟩ orientations are formed and few grains belong to ⟨110⟩ orientation. It means that a different texture is formed in the tensile and compressed Mo [14,15]. The main texture is in conformity with the texture of uniaxial deformed BCC metals.

Meanwhile, it can be clearly seen that different microstructures are formed in different orientations. Some grains formed microbands or EPBs and some did not. We have investigated enough grains with different orientations to characterize their microstructure and dislocation boundaries in both tensile and compressed Mo. In order to investigate the alignment of the EPBs on a large scale, the EBSD technique was carried out on FEI-Sirion 200 field emission scanning electron microscope equipped with TSL OIM Analysis 5 software. Meanwhile, the detailed dislocation boundaries in the same orientations were also investigated by TEM. Some typical EBSD orientation maps and TEM images of 40% compressed Mo sample in the LD–TD section are shown in Fig. 2. For grains with normal direction fairly close to ⟨100⟩ direction, equiaxed cells and short cell boundaries are formed (Fig. 2a). Fig. 2b shows deformation microstructure in grains with normal direction close to ⟨301⟩. It can be found that a set of parallel EPBs are formed and the EPBs are all aligned approximately with the {110} slip planes. This kind of microstructure is called a 'type 1 structure' in Refs. [16,17]. This kind of EPBs is also developed in grains with normal direction close to ⟨111⟩, as shown in Fig. 2d. However, the morphology and the mean space between EPBs in ⟨301⟩ grains and ⟨111⟩ grains are different. It means that the deformation mechanisms of the different grains are different. At least, different amount of slip systems and different slip systems are activated. For grains with normal direction close to ⟨110⟩ direction, as shown in Fig. 2c, it can be found that a set of parallel EPBs is also formed. However, these boundaries are not aligned with {110} slip planes. This type of microstructure is called a 'type 3 structure' in Refs. [16,17].Similarly, some typical EBSD orientation maps and TEM images of 40% tensile Mo sample in the LD–TD section are shown in Fig. 3. It can be found that almost the same deformation microstructure is formed in grains with normal direction fairly close to the exact ⟨100⟩ in compressed Mo, which is equiaxed cells and cell boundaries (Fig. 3a). In order to compare the deformation microstructure in tensile and compressed Mo in a similar orientation, Fig. 3b and c shows deformation microstructure in grains with normal direction close to ⟨301⟩. Compared with Fig. 2b, it can be found that a similar deformation microstructure is formed in compressed Mo. A set of parallel EPBs which are all aligned approximately with the {110} slip planes is formed. It means that in a similar orientation, the deformation mechanism is similar in both tensile and compressed conditions. The deformation microstructure in grains with normal direction close to ⟨111⟩ is shown in Fig. 3d, where a set of parallel EPBs aligned approximately with the {110} slip planes is also developed. Fig. 3c shows the deformation microstructure in grains with the normal direction close to ⟨011⟩. As shown in Fig. 2d, similar results can be seen. That is to say, a set of

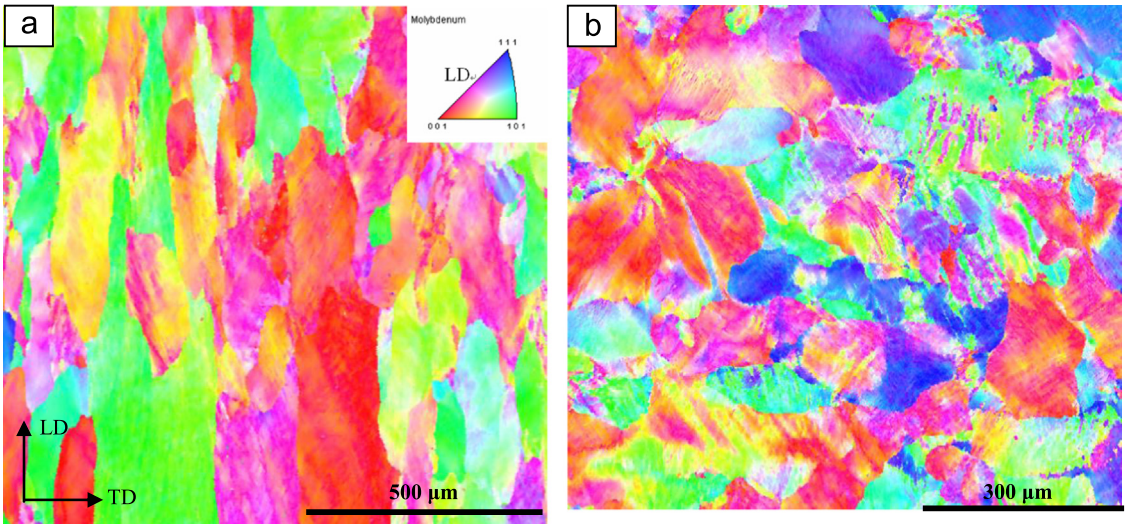

Fig. 1. EBSD microstructure of molybdenum deformed by tension (a) and compression (b) to strain of 40% in LD–TD section; the step size: 2 μm.