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Deformation nanotwins in coarse-grained aluminum alloy at ambient temperature and low strain rate

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ABSTRACT

In order to reveal the possible occurrence of deformation twins in coarse-grained aluminum/aluminum alloy at normal experimental conditions, a 5A02-O aluminum alloy with coarse grains was compressed quasi-statically to various plastic strains at ambient temperature, followed by high-resolution transmission electron analysis. The results revealed some long streaks produced by the thin plate-like structure with 2 atomic planes thick in the specimen undergoing a large strain, while under a relatively small plastic strain, the striped characteristics disappeared. The fast Fourier transform and theoretical analysis have shown that these long streaks are nanotwins, derived from the overlapping of stacking fault ribbons formed by Shockley partial dislocation on adjacent slip planes, which are triggered by the large plastic strain.

1. Introduction

Deformation twin merits attention because of its intrinsic importance as a mode of plastic deformation in metallic materials [1]. The deformation twins have long been identified in hexagonal close-packed (*h.c.p.*), body-centered cubic (*b.c.c.*) and lower symmetry metals/alloys [2–4], but in recent years they have also been found in many face-centered cubic (*f.c.c.*) crystal structure metals/alloys [5–7], even in these aluminum/aluminum alloys with high stacking fault energy (SFE) [8–12]. For example, Gray III [12] first observed the deformation twins in polycrystalline aluminum–magnesium alloy under extreme experimental conditions of liquid nitrogen temperature, high strain rate and huge pressure. Yamakov et al. [13,14] predicted the occurrence of deformation twinning in pure aluminum with a sufficiently small grain size through molecular dynamics (MD) simulation. Subsequently, Chen et al. [8] experimentally confirmed the deformation twinning in a nanocrystalline (*nc*) aluminum film produced by physical vapor deposition, in consistence with these *nc* aluminum powders ball milled in liquid nitrogen [7,10,11]. Recently, Han et al. [9] observed the deformation twins in aluminum single crystal that was specially designed with the necessary crystallographic orientation, in order to obtain the maximum shear stress that was regarded as one of the critical factors to the nucleation of deformation twins [15].

However, whether deformation twins can occur in coarse-grained aluminum polycrystal or aluminum alloy (with high SFE) at normal experimental conditions, and what the underlying physical origin is for this deformation twinning, are questions that still remain unanswered because no further research has been carried out yet. In the present work, a 5A02-O aluminum alloy [16] with coarse grains was selected and plastically deformed under quasi-static compression at ambient temperature. The deformation nanotwins derived from the overlapping of stacking fault ribbons formed by Shockley partial dislocations are observed, and the physical mechanism is discussed in detail.

2. Experimental procedures

The 5A02-O aluminum alloy used in this work was provided by the Southwest Aluminum Company (China) as ⌀7.0 mm rod in a recrystallized condition, and the nominal chemical composition (wt%) of the alloy is shown in Table 1 [16]. The grain size distribution of the un-deformed 5A02-O aluminum alloy was probed by electron backscatter diffraction (EBSD) that is conducted using a field emission scanning microscope (FSEM, FEI Sirion 200) equipped with an EBSD detector. The samples for EBSD investigation were electrolytically polished in a 5:1 alcohol–perchloric acid solution using 316 stainless steel as cathode at 20 V for 60 s at room temperature.

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Table 1
Nominal chemical composition of 5A02 aluminum alloy (in wt%).

Si	Fe	Cu	Mn	Mg	Ti	Al
0.40	0.4	0.1	0.15–0.40	2.0–2.8	0.15	Balance

The compression specimens with diameters of 5 mm and normal aspect ratio of 1.0 were cut from the corresponding cylindrical rods using a diamond blade under water cooling condition. Two ends of the specimens were polished carefully to ensure that they are parallel to each other and are perpendicular to the longitudinal axis of the sample. Uniaxial compression tests were conducted at room temperature with a constant strain rate of $1 \times 10^{-3}\ s^{-1}$. Various plastic strains with a maximum value of 0.85 were introduced to facilitate the observation of microstructure evolutions, which were characterized by using a transmission electron microscope (TEM, FEI 200 kV Tecnai G20) and high-resolution transmission electron (HRTEM, FEI 300 kV Tecnai G30). TEM thin foils were first ground mechanically to about 50 μm thickness, followed by a twin-jet polishing method in a solution of 30% nitric acid and 70% methanol at a voltage of 20 V and at a temperature of -20 °C.

3. Results

Fig. 1(a) illustrates the morphology of grains in the un-deformed 5A02-O aluminum alloy obtained via electron back-scatter diffraction. It can be seen clearly that the grains are uniform, near-equiaxed with diameters in the micrometer (μm) range. Fig. 1(b) describes quantitatively the grain size distribution of the as-received/un-deformed 5A02-O aluminum alloy, which reveals an average size of about 13.3 μm, indicating a coarse-grained structure [17].

The effect of plastic deformation on the micro-orientation of grain boundaries in an aluminum alloy can be visualized by using EBSD analysis, and the reconstructed boundary maps are shown in Fig. 2, in which different colored lines define various misorientation angles (θ), here red line (θ=2–5°), blue line (θ=5–15°) and green line ($\theta > 15°$) represent small, low and high angle grain boundaries, respectively. Therefore, from the morphology of the colored lines one can distinguish the distributions of micro-orientation of grain boundaries. Such as in the original specimen without deformation (see Fig. 2a), there is a small number of subgrains (see the red line) with a fraction of 15.1%, whereas the fraction of red line increases up to 62.7% after mechanical deformations, indicating that the plastic deformation induced the occurrence of a large number of subgrains.

To characterize the microstructure evolution of 5A02-O aluminum alloy after quasi-static compression, TEM analysis was carried out. Fig. 3 displays the TEM morphologies of the deformed aluminum alloy with a plastic strain of 0.85. The bright-field TEM image as shown in Fig. 3(a) exhibits dislocation cell structures accompanied by some tangled elongated dislocations, indicating that the dislocation glide is the main deformation mechanism in the aluminum alloy with *f.c.c.* crystal structure [18,19]. It is worth noting that in the tangled region with high dislocation density (see the square region in Fig. 3a), the HRTEM analysis revealed some nanoscale streaks with regular shape, as labeled by the black arrow in Fig. 3(b). These streaks mainly align along one direction, but few stripes distribute along two directions with an intersecting angle of approximately 69.40°, which is very close to the dihedral angle of two {111} planes [9].

In order to further analyze the microstructure of nanoscale streaks that were observed in Fig. 3, the magnified HRTEM image of one typical streak was obtained, as described in Fig. 4(a). According to the observations in previous literatures [8,9], the

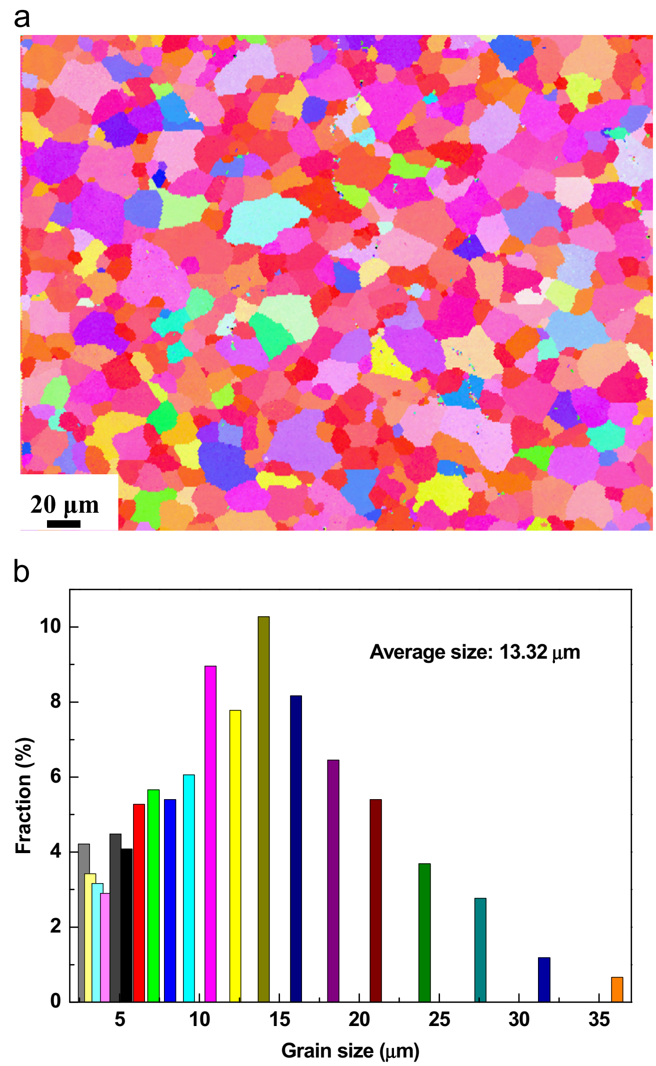

Fig. 1. (a) EBSD image of the as-prepared coarse-grained 5A02-O aluminum alloy and (b) the grain size distribution of the aluminum alloy.

atomic scale lattice image in Fig. 4(a) is that of nanotwins or stacking faults. To further probe the possible microstructure defects, part of the selected region in HRTEM image (see the square region in Fig. 4a) was analyzed by fast Fourier transform (FFT), and the streaking in FFT pattern reflects the planar defect diffraction characteristic, in which diffraction spots degenerate along the direction of the defect plane [20], showing stacking faults or very thin nanotwins on the {111} plane [21,22], as depicted in Fig. 4(b). The corresponding inverse Fourier-filtered transform (IFFT) was further obtained and is illustrated in Fig. 4(c), which reveals clearly the deformation nanotwin with 2 atomic planes thick, as depicted by the white line.

4. Discussion

The above HRTEM observations provide direct experimental evidence confirming the plastic deformation nanotwins in coarse-grained aluminum alloy at ambient temperature and low strain rate, which was previously considered as impossible due to the high stacking fault energy of aluminum/aluminum alloy. Though several conventional mechanisms such as the pole mechanism, prismatic glide mechanism and faulted dipole mechanism have been introduced to illustrate the deformation twinning in coarse-