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Plastic deformation mechanisms in face-centered cubic materials with low stacking fault energy

Y.Z. Cao*, X.S. Zhao, W.D. Tu, Y.D. Yan, F.L. Yu

Center for Precision Engineering, Harbin Institute of Technology, Harbin 150001, PR China

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ABSTRACT

The microstructural evolution process of face-centered cubic Cu-30 wt%Zn, which has very low stacking fault (SF) energy of only 14 mJ/m^2, processed by high-pressure torsion, was investigated using transmission electron microscopy. Results reveal that deformation SFs/twin boundaries and cell blocks play the key role in the grain refinement process from ultrafine grains to nano grains. Equiaxed coarse grains with grain sizes of several microns were refined to ultrafine grains through the formation of high density of SFs, twins and cell blocks. With the accumulation of high density of dislocations at SF/twin boundaries, the emission of secondary SFs/twins further refined grains and transformed ultrafine grains into equiaxed grains with grain size of several tens nanometers. The observed grain refinement mechanism is significantly different from those of materials with medium to high SF energies in which full dislocation activities play a key role for grain refinement.

1. Introduction

Nanocrystalline metals and alloys produced by severe plastic deformation (SPD) have been extensively investigated over the past two decades. Several different SPD processing techniques were developed, such as equal channel angular pressing [1–3], accumulated roll bonding [4], surface mechanical attrition treatment (SMAT) [5], high pressure torsion (HPT) [1,6–10]. HPT is a recently developed technique that can induce grain refinement into the nanometer regime. This technique has been successfully applied to various materials including metals such as Al and Al alloy [11–14], Ni [10,11,15–18], Cu and Cu-Zn alloy [10,13,19–25], Fe and Fe alloys [26,27], Mg [28] and Ti [29]. HPT shows an alternative approach to effectively upgrade the global properties of engineering materials without introducing impurity and changing chemical composition of materials. Meanwhile, HPT is simple and low-cost equipment, and provides a unique opportunity to investigate the plastic deformation induced grain refinement process.

As for grain refinement mechanisms, Hansen and coworkers [30–37] have systematically studied the microstructural evolution in rolled face-centered cubic (FCC) metals with medium to high stacking fault (SF) energies, such as Cu, Ni and Al. In their studies, it was observed that during deformation subdivision may occur over several length scales. On a microscopic scale, cell blocks are formed by long, continuous dislocation boundaries that have been called geometrically necessary boundaries (GNBs), which accommodate the lattice misorientation between neighbouring cell blocks. Within the cell blocks defined by the GNBs, individual dislocation cells are delineated by incidental dislocation boundaries (IDBs) [33,34]. With increasing strain other features are also seen, including regions of localized glide (regions of finer scale cell blocks) [35,36] and micro-shear bands [37]. At high strains a well defined lamellar dislocation boundary structure is developed, comprised of GNBs cross-linked by the IDBs forming finer areas. Meanwhile, some cell block boundaries become large angle grain boundaries (GBs), and smaller grains form inside the initial coarse grains. The work from Hansen and co-workers gracefully described the grain refinement mechanisms for medium to high SF energies metals under low strain rate. However, for SMAT deformation mode with high strain rate (an estimated value of strain rate is about 10^3–10^4 s^{-1} in the surface of the SMAT samples), recent investigation on Cu [38] by means of transmission electron microscopy (TEM) revealed different grain refinement mechanism, which is first the formations of high density, nanometer thick twins dividing the original coarse grains into twin/matrix lamellar; then development of dislocation walls that further subdivide the lamellar into equiaxed nano-sized blocks; last evolution of these preferentially oriented blocks into randomly oriented nanosized grains.

Above these results revealed some grain refinement mechanisms under low strain. However, for ultra-high strain, for example HPT, less investigations have been conducted to date to study the grain refinement mechanisms, although there has been lots of

* Corresponding author.
E-mail address: cflying@hit.edu.cn (Y.Z. Cao).

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works by HPT, only based on the relation of mechanical properties with grain sizes by microhardness measurements and tensile experiments. Especially for low SF energy metals, no systematic investigation of the effects of SF/twin boundaries (TBs) on grain refinement mechanism under HPT is reported. The present investigation objective is to address grain refinement mechanisms by conducting a series of careful experiments on Cu-30 wt% Zn alloy (low SF energy is 14 mJ/m^2) subjected to HPT processing, and by observing the variation of microstructural characteristics in the deformed disks everywhere using TEM and high resolution TEM. In comparison with cold rolling and SMAT, the advantage in HPT is to provide different grain size distribution under similar deformation conditions due to a gradient variation of the shear deformation from the center of circle to radius edge according to von Misés strain formula [7]:

$$\varepsilon = \frac{2\pi NR}{\sqrt{3}\,h} \tag{1}$$

Where N is the number of HPT turns, R is the distance from the center of the disk and h is the thickness of the disk. This implies that shear strain in the center of the disk is zero. However, in practice, the presence of a high external applied pressure by HPT will lead to some extent strain in the center of disk [39]. Owing to shear strain variation along radial direction, one can examine the microstructure characteristics in the same sample at different shear strain regions to reveal the underlying mechanism of grain refinement in the nanocrystalline regime.

2. Experimental procedure

The material for HPT used in this work is Cu-30 wt% Zn rod with diameter of 10 mm. Disks were prepared from the as-received samples with diameters of 10 mm and thickness of 0.8 mm. These disks were processed by HPT using a facility in which each disk was placed in turn between two anvils, a pressure was applied and torsional straining was then achieved by rotation of lower anvil. All processing was conducted at room temperature using an imposed pressure of 5 GPa, at a rotation speed of 1 rpm and a total of five revolutions.

The microstructural evolution of the HPT Cu-30 wt% Zn samples was characterized by using JEM-3000F TEM operated a voltage of 300 kV. TEM observations were conducted on each specimen in the center, at the half radius position and near the edge of each HPT disk, where these separate positions are designated the 0R, 0.5R and 1R positions, respectively, R is the radius of the disk. TEM sample was prepared as follows: (1) HPT disk was mechanically ground to 100 μm on abrasive paper; (2) Cutting a piece with a diameter of 3 mm and grinding carefully it to about 30 μm thickness; (3) Pre-thin the TEM samples using dimple grinder; (4) Finally using a Gatan Fischione 3000 system with an Ar+ accelerating voltage of 4 kV and with liquid nitrogen for cooling of the sample. The measurements of grain sizes were made directly from TEM observations and the reported values are averaged from several hundred grains selected randomly.

3. Results

3.1. Microstructures of three typical samples

Fig. 1 shows typical TEM bright field images and the corresponding selected area electron diffraction (SEAD) patterns at different positions from the center to the edge of HPT disk. At the center of sample, i.e., 0R position (Fig. 1a), the microstructure is

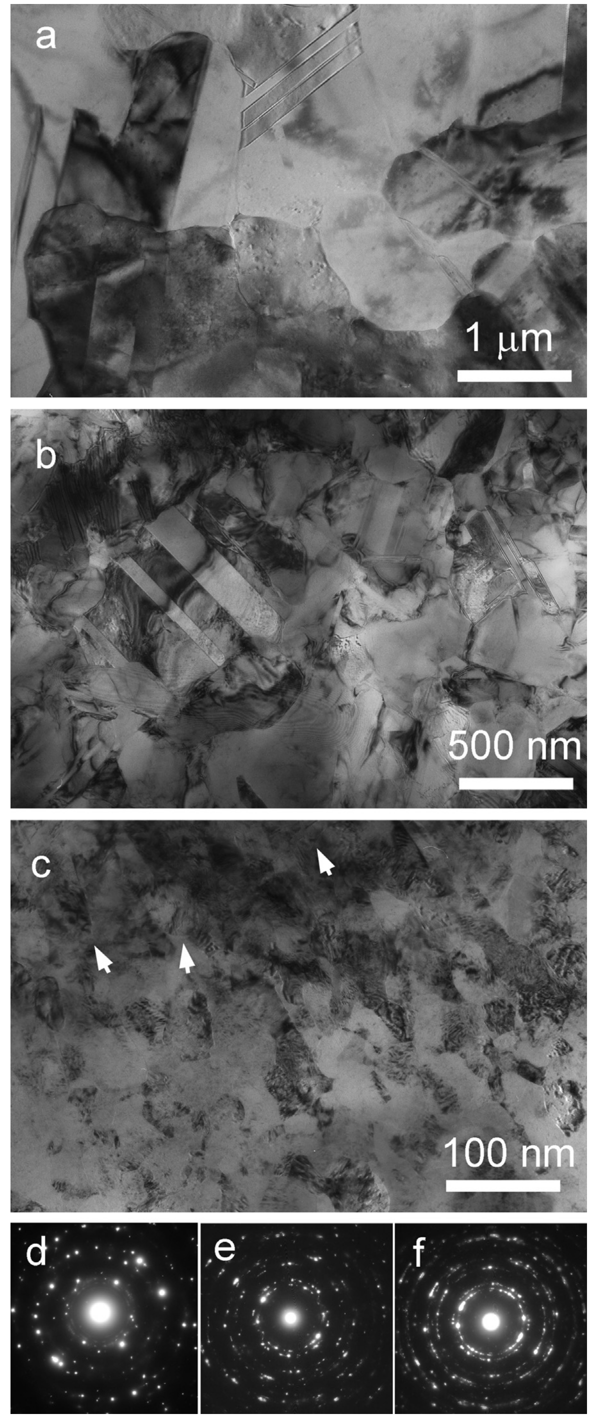

Fig. 1. Typical TEM images (a, b, and c) and corresponding selected area electron diffraction patterns (d, e and f) of 0R, 0.5R and 1R of HPT disks.

characterized by uniformly distributed micrometer grains with an average grain size of ~ 1.5 μm, where some twins are shown within grains, which is in accordance with earlier reports [21–25]. Corresponding SEAD pattern (Fig. 1d) shows its equiaxed grains with random orientations.

With shear deformation increasing, the microstructure of micrometer regions will be refined further. The microstructure at the half radius position (0.5R) of HPT disk shown in Fig. 1b revealed grain size and defect density along the direction of radius. It can be obviously seen that sub-micrometer grain regions with an average grain size of ~ 600 nm are visible relative to that of 0R position. The corresponding SAED (Fig. 1e) demonstrated that the grain size