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The orientation and strain dependence of dislocation structure evolution in monotonically deformed polycrystalline copper

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The cross-correlation based HR-EBSD technique was used to derive stored geometrically necessary dislocation (GND) density in the OFHC copper samples deformed under uniaxial tension to true strain of 0%, 6%, 10%, 22.5% and 40%. Large maps (500 μm × 500 μm with 0.5 μm step size) with 1 million points and ~1600 grains were acquired at each deformation level. Detailed studies on dislocation structure and evolution using the HR-EBSD were conducted. Distinct types of dislocation arrangements were revealed in grains with various orientations. For example, dislocation cells were formed in grains of <110> orientation and dislocation bands were generally found in grains of <111> and <001> orientations. The complicated dislocation networks provide vital evidence to understand the deformation mechanisms in polycrystals at mesoscale. Quantitative analyses were also carried out to study this GND density orientation dependence in which Taylor factor was used as an indicator to quantify the grain resistance to deformation. It was found that points with high GND content preferentially accumulated in grains with high Taylor factor ('hard' grains) in deformed samples. This relation becomes stronger with increasing deformation.

1. Introduction

Detailed understanding of the dislocation mechanisms in polycrystals during plastic deformation currently is still elusive in materials research community (Pokharel et al., 2014). For single crystals dislocation slip, interaction and accumulation are relatively well understood and discrete dislocation models can clearly capture many observed dislocation features. For polycrystals satisfaction of geometrical compatibility and stress equilibrium between grains with various orientations lead to longer range patterning in dislocation storage which remains a long standing challenge to understand. The primary challenge is the large number of microstructural variables existing in polycrystal materials such as various grain orientations, different grain boundary types: twin boundary, low misorientation angle or high misorientation angle, triple junctions and so on. This requires a sufficient number of grains to be measured and analysed with detailed dislocation structures to be found in order to provide more insights into this problem.

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The typically used techniques for dislocation density measurement are TEM and X-ray or neutron diffraction. However, the high spatial resolution TEM only probes rather relatively small areas where few grains can be observed (Fultz and Howe, 2012). The dependence of dislocation arrangements on grain orientations using the TEM technique on polycrystal copper and aluminium samples deformed under tension and compression was found by Huang et al. (Huang and Winther, 2007) in 2007. The study was systematic, ~100 grains were selected with care and a series slices were cut to be examined in the TEM. Finally a 3D TEM dislocation network was reconstructed. As a result of TEM's high angular resolution, fine distinctions in various orientations were found. However, the commonly observed dislocation bands with large misorientation were neglected in their TEM study and the study of dislocation patterns near grain boundary were deliberately avoided. The HR-EBSD study presented here was aimed more toward characterising the influence grain boundaries and triple junctions have on perturbing the dislocation patterns.

Although X-ray diffraction can make dislocation measurement on significantly larger areas with deeper interaction volume, the relatively coarse spatial resolution associated with X-ray diffraction prohibits it from mapping fine dislocation structures (Guinier, 2013). Recent developments of high energy synchrotron X-ray beam has overcome this limit and been able to capture developed dislocation structures. However, using it to address the polycrystal plasticity problem and deal with the enormous statistical data are still ongoing (Als-Nielsen and McMorrow, 2011; Ice et al., 2005; Larson et al., 2002).

There is a growing body of evidence from DIC measurements (Abuzaid et al., 2012; Littlewood and Wilkinson, 2012b) that plastic strains are highly inhomogeneous at the microstructural length scale and that the patterns of high plastic strain regions span across many grains. Hence it is very important to capture deformation information on appropriate length scale.

Development of high resolution electron backscatter diffraction (HR-EBSD) by Wilkinson et al., in 2006 has accomplished both high spatial and angular resolution (Wilkinson et al., 2006a, 2006b). By measuring the EBSD pattern shifts using image cross-correlation method, relative residual stress and geometrically necessary dislocation (GND) density can be measured (Wilkinson and Randman, 2010). This has successfully bridged the TEM and X-ray diffraction techniques and allows us to revisit the polycrystal plasticity problem with the hope of providing new evidence to further our understanding.

Recently many research works on polycrystal plasticity problems employing conventional EBSD have been conducted to study the GND density distributions as a function of strain level, grain orientation and Taylor factor in Al alloys, steels and Ni superalloys (Allain-Bonasso et al., 2012; Field et al., 2012). Due to the relatively low angular resolution of conventional EBSD analysis, the dislocation structure was not revealed in lightly deformed specimens. A detailed comparison between the TEM technique and conventional EBSD systems on deformation structures in FCC materials was conducted by Mishin et al. (2009). They found that EBSD was unable to capture the dislocation boundaries with very low misorientation angles and hence this technique was only capable of studying dislocation boundaries with larger misorientation angles formed in heavily deformed samples. This prohibits the observation of dislocation development process. The lowest GND density readily detected by conventional EBSD has been assessed by various authors (Adams and Kacher, 2010; Chekhonin et al., 2014; Field et al., 2012) and is step size dependent. In copper at a 0.5 μm step size GND density below 10^{14} m^{-2} cannot be determined using conventional EBSD (Adams and Kacher, 2010; Jiang et al., 2013b). Mishin et al. (2009) suggested the emergence of HR-EBSD technique might provide promising deformation structure results for a much larger range of plastic deformation.

High angular resolution of the cross-correlation based EBSD analysis allows much improved GND density sensitivity (Wilkinson et al., 2006a). Fortunately issues with reference point selection that complicate extraction of absolute elastic strain values using HR-EBSD do not prevent GND analysis as only relative changes in crystal orientation are required and these do not depend on the specifics of the reference points. Littlewood et al. using the HR-EBSD approach qualitatively investigated the stored GND density distributions in a titanium alloy deformed under tension (Littlewood et al., 2011) and fatigue (Littlewood and Wilkinson, 2012a). However the number of grains included in Littlewood's study was rather small (20–30). This was because data was collected at the full resolution of the EBSD camera which gave a relatively long exposure time per pattern (~1 s). Jiang et al. (2013b) examined the effects of detector binning and step size on GND density mapping and explored the competing effects on the sensitivity and speed of data acquisition and analysis. Greater binning of the detector results in shorter exposure time, allowing acquisition of a larger map in a given time but at lower measurement sensitivity. As the measured mean of GND density in 6% deformed sample is ~$10^{14.1}$ m^{-2}, selecting 4x4 binning is reasonable as this gives a GND measurement sensitivity of $10^{13.5}$ m^{-2}.

This paper follows our previous work on dislocation distributions and evolution in polycrystal copper deformed under tension (Jiang et al., 2013a). In that work, statistical analysis was carried out to establish that the GND density distribution can be accurately described by a log-normal probability function which scales with imposed plastic strain level. The sample averaged GND density increases with increasing plastic deformation and can be used as a single parameter to predict the flow stress according to the Taylor hardening model. GNDs were found to preferentially accumulate adjacent to some microstructure features such as the grain boundaries and triple junctions.

Furthermore, as Merriman et al. measured GND density in pure aluminium samples deformed in channel die compression using conventional EBSD and reported that the development of GND density has strong orientation dependence (Merriman et al., 2008). Our study intends to further investigate the orientation dependent of GND structure.

The first aim of this current paper is to provide direct evidence on dislocation structure, their development with increasing plastic deformation and grain orientation dependence. A comparison with some previous TEM observations of dislocation structure will be made. The second aim is to determine if grain orientation affects the GND density stored in individual grains and how the relationship changes with the increasing tensile strain. Taylor factor is used in this study to define the 'hard' and 'soft' grains.