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# Microstructural evolution in adiabatic shear bands of copper at high strain rates: Electron backscatter diffraction characterization

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ARTICLE DATA

*Article history:*
Received 2 August 2011
Received in revised form
17 November 2011
Accepted 19 November 2011

*Keywords:*
Copper
High strain rate
Adiabatic shear band
Electron backscatter diffraction
Dynamic recrystallization

## ABSTRACT

The microstructural evolution of adiabatic shear bands in annealed copper with different large strains at high strain rates has been investigated by electron backscatter diffraction. The results show that mechanical twinning can occur with minimal contribution to shear localization under dynamic loading. Elongated ultrafine grains with widths of 100–300 nm are observed during the evolution of the adiabatic shear bands. A rotational dynamic recrystallization mechanism is proposed to explain the formation of the elongated ultrafine grains.

## 1. Introduction

Adiabatic shear bands (ASBs) are specific regions of highly localized deformation occurring in numerous metals and alloys during dynamic loading. ASB formation is often a precursor to catastrophic failure. The microstructural characterization of ASBs is highly important to understand the thermo-mechanical evolution during shear localization. Researchers have investigated the microstructure of ASBs in copper using transmission electron microscopy (TEM), and found equiaxed fine grains, indicating the possibility of dynamic recrystallization (DRX) [1–4]. Many similar results have also been found in the ASBs of other materials including tantalum [5], steel [6], titanium [7], aluminum alloys [8], titanium alloys [9] and magnesium alloys [10]. However, the mechanism of fine grain evolution remains unclear because the small width of ASB (of the order of 1–300 μm) makes microstructure examination difficult [11]. Compared with transmission electron microscopy, electron backscatter diffraction (EBSD) enables the observation of larger areas and the collection of more statistically significant data on crystal orientations, boundary misorientations, etc. However, the high defect densities and small-scale of substructures caused by the large deformations in ASBs lead to difficulty in obtaining good backscattered pattern quality. Therefore, only a few researchers have examined ASB microstructure by electron backscatter diffraction. Pe´rez-Prado et al. [12] first reported the characterization of shear band structures in Ta alloys by electron backscatter diffraction. In recent investigations, Kad et al. [13], Lins et al. [14] and Martinez et al. [15] have characterized DRX within the ASBs in zirconium, interstitial-free steel and Ti–6Al–4 V, respectively, using high-resolution electron backscatter diffraction. Xue et al. [16] investigated shear band region of 304 stainless steel, but did not map the structures within the ASBs. More recently, electron backscatter diffraction (EBSD) characterization of the fine grains within shear bands of Fe–Cr–Ni monocrystal and polycrystalline Zn were reported in

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doi:10.1016/j.matchar.2011.11.011

Ref. [17,18]. On the other hand, ASB evolution, which is correlated with strain, has not been extensively discussed in literatures. The present study aims to investigate the microstructural evolution of ASBs in copper at high strain rates using electron backscatter diffraction.

## 2. Experimental

In the present work, as-received pure copper (99.9 wt%) with dimensions of 200 mm × 80 mm × 60 mm was kept at a temperature of 700 °C for 60 min and then cold rolled from a 60 mm to 12 mm thick sheet, yielding a cumulative rolling reduction of 80%. The cold-rolled sheet was then annealed at 450 °C for 2 h, giving an equiaxed grains size of 10–20 μm with some annealing twins present (Fig. 1a). Hat-shaped specimens were prepared along the normal direction of the sheet for the dynamic deformation. The hat-shaped specimens, originally developed by Meyers et al. [19], as shown in Fig. 1b, were used to produce well-controlled shear bands at high strain rates.

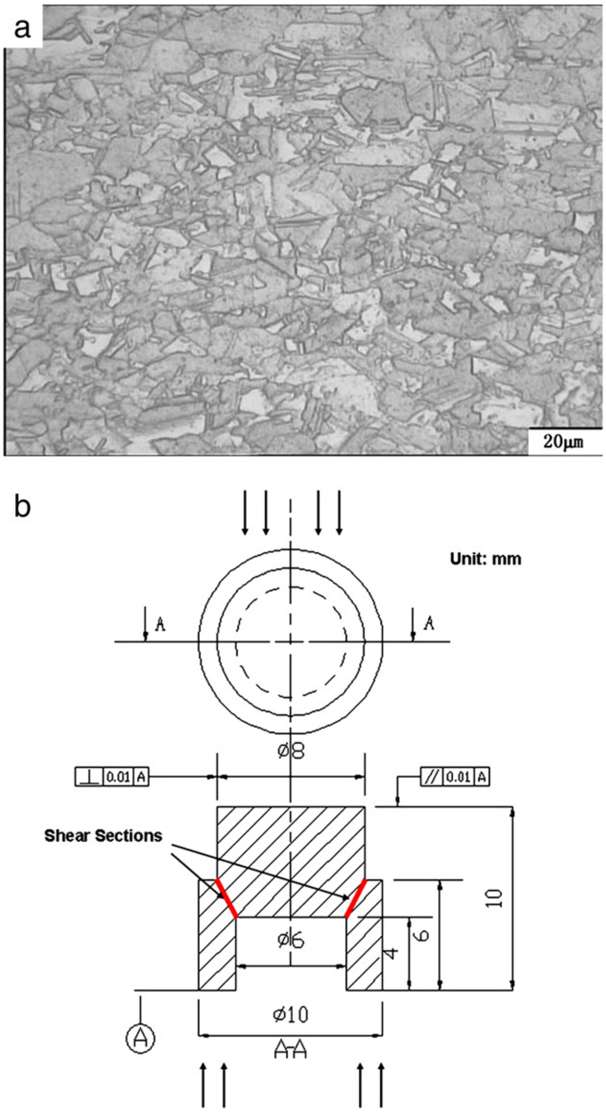

**Fig. 1 – (a) Initial microstructure of samples before deformation and (b) schematic configuration of the hat-shaped specimens and loading condition.**

The dynamic compression of hat-shaped specimens was carried out using a modified split-Hopkinson pressure bar. A striker bar with a length of 200 mm, which was accelerated by an adjustable air brake cylinder, was used to generate different strains in samples. The specimens were compressed up to three high shear strains (about 3.2, 4.6 and 5.8) at a strain rate of about $4\times10^4\ s^{-1}$.

After dynamic compression, the samples were sectioned along the compression axis by Electrical Discharge Machining (EDM). The sectioned axial cross-sections surfaces were polished to a mirror finish and then etched with 5 g $FeCl_3$, 10 ml HCl, and 85 ml $H_2O$ for metallographic observation. Electron backscatter diffraction observations were also conducted on the axial cross-sections surfaces using a FEI Sirion200 scanning electron microscope. The scanning areas focus on the rejoins including the shear bands and the adjacent areas. EBSD data were analyzed using commercially available TSL-OIM software.

## 3. Results and Discussion

### 3.1. *Forced Shear Response and Metallographic Observation*

Fig. 2 shows the force-shear responses of the samples with different strains. The oscillations observed in the stress–strain curves (Fig. 2a) are a result of the nature of the dynamic loading. The curves exhibit distinct work hardening, which is an inherent feature of annealed copper. The peak stress is reached only in the sample with a final strain of 5.8. The peak of dynamic shear stress curves often represents the onset of unstable deformation, suggesting that DRX may occur under this condition. From the metallographic images (Fig. 2b–d), it can be seen clearly that the high shear deformation localizes in the shear band, while the matrix experiences no deformation. The widths of the shear bands are almost the same for the different deformation strains, while the ASBs appearances show a little different. The shear localization region becomes more clearly defined with the increasing of shear strain.

### 3.2. *Electron Backscatter Diffraction Characterization*

Fig. 3 shows the electron backscatter diffraction maps of the microstructure from the area adjacent to the shear band to the band interior. Fig. 3a shows the microstructural features of the sample with a strain of 3.2. The shear localization region is diffused with many elongated substructures present. Some grains have subdivided into several parts, indicating severe deformation in these grains. At a strain of 4.6 (Fig. 3b), the grains are elongated to a lamellar structure and rotated to the shear direction (SD), similar to that found in the ASBs of IF-steel in the study by Lins et al. [14]. Some elongated grains and fine grains coexist in the area of ASB. Few of the fine grains result from recrystallization; most are fragmentized grains, as depicted in the inverse pole figure (IPF) map, which shows that the fine grains are distributed along the elongated grain and both are similar in color, implying that they evolve from the fragmentation of elongated grains. The electron backscatter diffraction characterization of the sample with a final strain of 5.8 is shown in