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Evolution of Adiabatic Shear Band in Ultra-Fine-Grained Iron under Dynamic Shear Loading

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Abstract: Ultra-fine-grained (UFG)/Nanocrystalline (NC) materials usually show reduced strain hardening and limited ductility due to formation of adiabatic shear band (ASB) under dynamic loading. In the present study, evolution of ASB in UFG Fe under dynamic shear loading was investigated. The UFG Fe was processed by equal-channel angular pressing (ECAP) via route B_c. After 6 passes, the grain size of UFG Fe reaches ~ 600 nm, as confirmed by means of Electron Back Scatter Diffraction (EBSD). Examination of micro-hardness and grain size of UFG Fe as a function of post-ECAP annealing temperature shows a transition from recovery to recrystallization at 500 ^{0}C. The high-strain-rate response of UFG Fe was characterized by hat-shaped specimen set-ups in Hopkinson bar experiments. The characteristics of ASB as a function of shear displacement, such as thickness of shear band and micro-hardness inside the shear band, were examined by SEM and Vickers micro-indentation respectively.

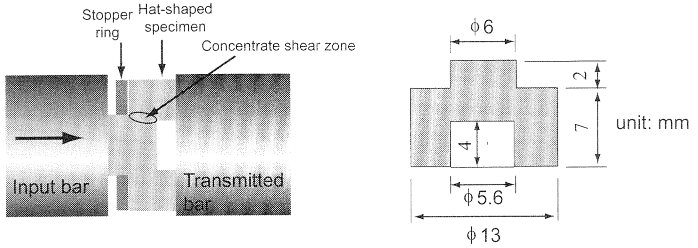
Introduction

UFG/NC materials have unique mechanical properties, such as increased strength/hardness, improved toughness and enhanced diffusivity compared to their coarse grained counterparts [1]. However, UFG/NC materials usually show reduced strain hardening and limited ductility, especially under high strain rate deformation. One of the reasons is the ASB formation during dynamic impact [2]. The strain rate effects in UFG/NC metals with different lattice structures have been summarized in [3]. The experimental results consistently indicate that strain rate sensitivity of FCC metal has been remarkably enhanced in the UFG/NC regime, while that of BCC metals has been considerably reduced. UFG/NC BCC metals are prone to ASB formation due to reduced strain-hardening rate and strain rate sensitivity [4]. As for BCC metals such as Fe, the first observation of localized deformation in the form of shear band has been reported for consolidated UFG/NC Fe under both quasi-static and dynamic compressive loading [5]. In the consolidated samples, the impurity and porosity during powder preparation and subsequent compaction are hard to exclude completely, so the formation of shear band is mainly due to such impurity and porosity, not adiabatic nature. Severe plastic deformation (SPD), such as ECAP, has been proven to be an effective method for production of bulk and fully contamination-free dense metals with sub-micron grain sizes [6, 7]. Although the propensity and the properties of ASB in UFG Fe produce by ECAP have been investigated in [4], the evolution of ASB in UFG Fe is still poorly understood. In the present study, hat-shaped specimen set-ups in Hopkinson bar experiments are used to study the evolution of ASB by controlling dynamic shear displacement. The thermal stability of UFG Fe is also investigated by examination of micro-hardness and grain size as a function of post-ECAP annealing temperature. The results of the present paper will help to not only understand the origin and characteristics of

ASB in UFG BCC metals, but provide insights for improving ductility in such materials.

Materials and Experimental Procedures

The UFG Fe used in the present study was made by ECAP. The origin materials were received in the form of rods of 60 mm in diameter. The rods with a length of 60 mm were extruded for six passes using route B_c at room temperature. After ECAP, thermal stability, the microstructure and the grain size distribution as a function of post-ECAP annealing temperature were examined by micro-hardness testing and EBSD. Small pieces were annealed for half hour at different temperatures after ECAP. Then the annealed sample surfaces were polished with 0.5 μm diamond paste. For each annealing temperature, the Vickers micro-hardness (HV) was measured using a micro-hardness tester with a diamond indenter under a load of 10 g, for 15 s dwell time.



Hat-shaped specimen set-up in Hopkinson bar experiments

Geometry and dimensions of hat-shaped specimen

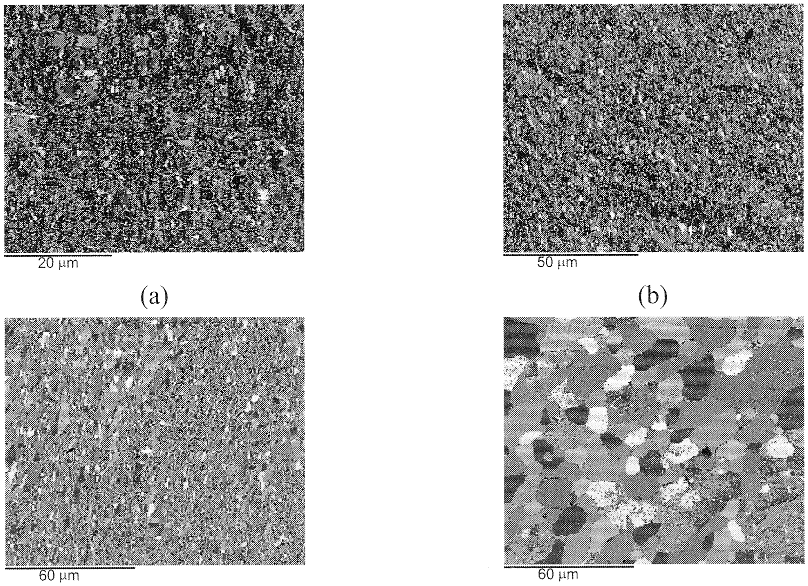
Fig. 1 Hat-shaped specimen set-up in Hokinson bar experiments.

All specimens for mechanical testing were machined from the extruded billets by wire saw with loading direction parallel to the direction of pressing. The hat-shaped specimen set-up for Hopkinson-bar testing is shown in Fig. 1. The hat shape is designed to concentrate shear deformation in a narrow zone facilitating the formation of a shear band [2]. Details of the Hopkinson-bar technique can be found in [8]. Following impact, the hat-shaped specimens were sectioned in half along the impact axis. The half sections were then polished to 2000 grit and final polished with 0.5 μm diamond paste. This was followed by etching with 5% Nital. The etched half sections were then examined by SEM. Micro-hardness measurements were also made on these polished half sections using a Vickers diamond indenter at a load of 10g for 15s dwell time. The light load is especially compatible with measurements within adiabatic shear bands which have widths ranging from roughly 30 μm to 150 μm. Three groups of measurements traversing an ASB are made, and the average value is taken for reducing the physical error.

Results and Discussions

The evolution of microstructure and grain size after annealing for half hour at different temperatures is shown in Fig. 2. After pressing for 6 passes, the average grain size is approximately 600 nm (Figure 2a). At annealing temperature 400 ^{0}C, because only recovery occurs, there is no much difference in microstructure from that of ECAP-6 Fe, and the average grain size slightly increases to 900 nm. At annealing temperature 500 ^{0}C, the microstructure consists of both ultra-fine grains and newly recrystallized larger grains. The bimodal structure has an average grain size of approximately 2 μm. At annealing temperature 600 ^{0}C, because recrystallization is complete, the microstructure consists of mostly larger grains with an average grain size of approximately 12 μm.

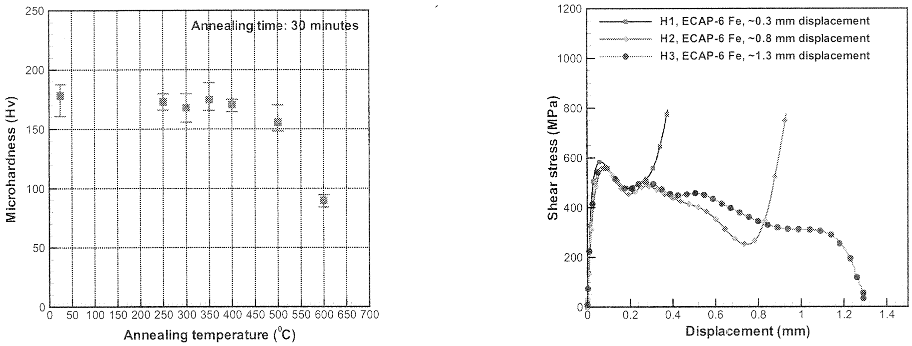
The evolution of micro-hardness of ECAP-6 Fe after annealing for half hours at different temperatures is shown in Fig. 3a. The micro-hardness decreases with annealing temperature, revealing a transition from recovery to recrystallization. The critical transition temperature is approximately 500 ^{0}C, which has a good correlation with EBSD results.



(a) (b)

(c) (d)

Fig. 2 EBSD maps of (a) ECAP-6 Fe; (b) 400 ^{0}C post-ECAP annealing Fe; (c) 500 ^{0}C post-ECAP annealing Fe; (d) 600 ^{0}C post-ECAP annealing Fe.

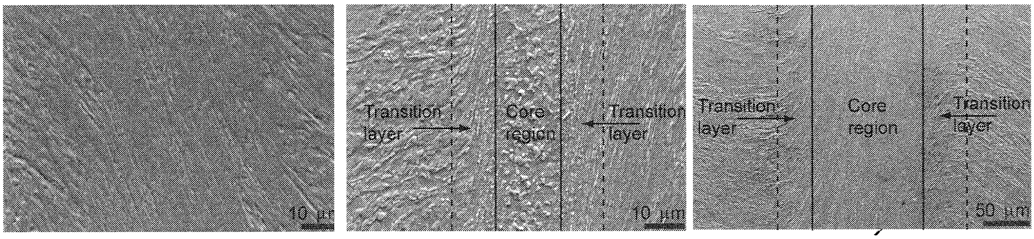


(a) (b)

Fig. 3 (a) Evolution of micro-hardness with annealing temperature; (b) Shear stress vs. displacement plot for the hat-shaped specimen.

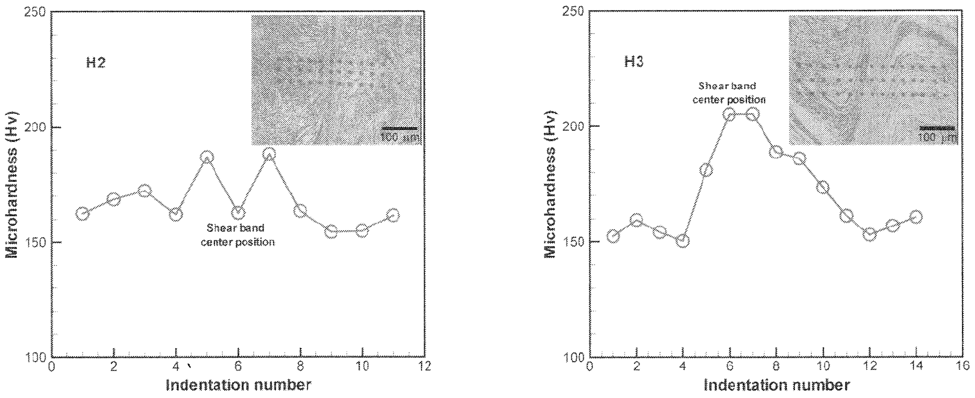
The shear stress-displacement response UFG hat-shaped samples tested by Hopkinson bar is shown in Fig. 3b. Three ECAP-6 specimens were tested with displacements of 0.3, 0.8 and 1.3 mm. The peak shear stress for ECAP-6 Fe sample is about 550 MPa, which translates to a normal stress of 950 MPa by Von Mises criterion. This stress level is in the same range of strength tested by uniaxial dynamic compression (the result is not shown here). At the end of curve H1 and H2, the stress rises because the incident bar is in contact with the stopper ring, the pressure is now being applied on the whole area of both the hat and the stopper ring.

Fig. 4 shows close SEM observations of the shear band for experiments H1, H2, H3. Fig. 5 shows Vickers micro-hardness traversing an ASB for experiments H2, H3. As shown in Fig. 4a, when the shear displacement is small (0.3 mm for H1), the shear deformation is not enough to form a shear band, but only distort the origin texture produced by ECAP. As the shear displacement is increased, the evolution of the shear band is found to be a two-stage process, namely an initiation stage (Fig. 4b) followed by a thickening stage (Fig. 4c). In the initiation stage, the shear band occurs within a thickness 30 μm. As shown in Fig. 4b and 5a, the initial shear band consists of two regions: a core region, which shows a similar micro-hardness with the matrix; on the two sides of the core region, two transition layers exist where the origin texture produced by ECAP is bended, and the micro-hardness of transition layers is 190 Hv in contrast to the surrounding matrix micro-hardness of 160 Hv. In the thickening stage (as shown in 4c, 5b), ASB evolution is accompanied by increasing in both thickness and micro-hardness of the core region. ASB width is increased from 30 to 150 μm, and micro-hardness of the core region is increased from 160 to 210 Hv. This increasing micro-hardness in the core region indicates that grains in the shear band are further refined by severe shear deformation and temperature rise (dynamic recrystallization), which will be further identified by TEM in the future work.



(a) (b) (c)

Fig. 4 SEM micrographs of the shear band as observed for (a) H1; (b) H2; (c) H3.



(a) (b)

Fig. 5 Vickers micro-hardness traversing an ASB (shown in inserts) for (a) H2; (b) H3.

Summary

The thermal stability and evolution of ASB in ECAP-6 Fe under dynamic shear loading were investigated systematically. Examination of micro-hardness and grain size of UFG Fe as a function of post-ECAP annealing temperature shows a transition from recovery to recrystallization at approximately 500 ^{0}C. With increasing dynamic shear loading, the evolution of ASB could be identified by two characteristic stages: initiation and thickening. In the initiation stage, ASB consists of a core region surrounded by two transition layers, and the interface boundary separating the core region and the transition layer are characterized by very large shear strain gradients. Increasing shear strains lead to thickening of shear bands by transforming the transition layers into core region. In the thickening stage, ASB evolution is accompanied by increasing in both thickness and micro-hardness of the core region. The increasing micro-hardness in the core region indicates that grains in the shear band are further refined by severe shear deformation (dynamic recrystallization). Once the shear band is initiated, cracks also nucleate and propagate within the ASB, which produces failure in the material. In the future work, we will focus on the detail TEM characterization of the shear band and the study of dynamic shear deformation for ECAP-6 Fe annealed at different temperatures (400 - 500 ^{0}C).

Acknowledgements

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