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A quantitative experimental study on non-homogenous deformation behaviors of nanocrystalline Ni sheet

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ABSTRACT

A quantitative experimental study on the non-homogenous plastic deformation of fully dense electrodeposited nanocrystalline Ni sheet under a quasi-static uniaxial tensile load was carried out in this paper. The sheet sample exhibited high strength simultaneously with a decrease in tensile strain. To investigate the early failure of the nanocrystalline Ni, the strain fields was quantified with digital image correlation algorithm. Based on the experimental results, the non-homogenous in form of shear bands was analyzed. Some critical points, such as shear band nucleation, broadening process and failure point were recognized. Then the inclination and width of full-developed shear band were discussed quantitatively. Finally, the failure mode, deformation mechanism and some impact factors on the non-homogenous deformation were discussed in detail.

1. Introduction

One of the great interests in nanocrystalline (NC) materials originates from the observations of their unique mechanical properties, such as high yield and fracture strengths [1–2], better wear resistance [3–4], and superplasticity at some special cases [5–6]. However, it should be noted that its strength increases simultaneously with a decrease in tensile strain due to high propensity to non-homogenous deformation [7–8]. This has been a major obstacle in the development and application of the NC materials. While the limited ductility was previously attributed to be pre-existing flaws, such as impurities and porosity [9], recent examples of good quality still show a little ductility in tension [10–12]. Several scientists [11–18] have associated it to non-homogenous plastic deformation in the form of shear band in a wide range of deformation operations based on their novel experimental and numerical investigations. Dalla Torre et al. [11] and Cheng et al. [12] investigated the tensile properties of NC electroplated Ni and consolidated Cu, and reported that shear localization was observed in the two samples during the tensile plastic deformation. Wang et al. [8] and Hung et al. [18] also found the non-homogeneous behaviors in ultra-fine grained copper and aluminum sample under tensile testing. Meanwhile, the non-homogenous deformation in NC or ultra-fine grained metals was reported in bcc structure materials under compressive testing, rather than in fcc structure ones. Jia et al. [13] observed that the deformation of the NC Fe progressed by shear band nucleation, propagation and broadening under compressive load, and Carsley et al. [17] reported intense shear banding was the first and only mechanism of non-homogenous plastic deformation in NC bulk, fully dense Fe–10Cu bcc alloy under compression. Similarly, bulk NC W and Fe were tested under dynamic and quasi-static compression loading respectively by Wei et al. [14–16], the increased propensity for non-homogenous plastic deformation due to the ultra-fine grain structure were demonstrated. From these reports, it can be recognized that a transition from homogenous to non-homogenous plastic deformation, which suggest a gradual deformation mechanism transition, appeared with a reduction in grain size under both tension and compression. However, the evolution process of this non-homogenous deformation has not been given quantitatively and the potential mechanisms of this non-homogenous deformation behavior (i.e. shear localization) in NC materials have not been clear so far. Though results of previous atomic simulation [19–22] and molecular static simulations [23] confirmed that grain boundary mediated plasticity substituted for conventional dislocation nucleation and motion as the dominant deformation mechanism when grain sizes are reduced below a certain value, this grain boundary mediated mechanism has not been verified experimentally. Based on the special deformation mechanisms that different from conventional mechanism in coarse-grained metals with the decreasing of grain size, Joshi et al. [24,25] have established a grain size dependent model to describe the non-homogenous plastic deformation in NC materials, but quantitative experimental data covering the whole area of the sample during the non-homogenous deformation have not been reported to support this model.

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In this paper, the non-homogenous plastic deformation in form of shear bands was studied in details. A quantitative experimental study on the non-homogenous plastic deformation of NC Ni sheet under a quasi-static uniaxial tensile testing was carried out, and the evolution process of shear bands, which may develop with strain and contribute to the early failure during plastic deformation, were discussed. First, the mechanical properties of the NC Ni sheets were investigated and the strain fields of the NC samples were quantified with digital image correlation (DIC) algorithm during the plastic deformation. Then, the non-homogenous in form of shear bands was analyzed and the inclination and width of full-developed shear band were discussed quantitatively. Some critical points, such as shear band nucleation, broadening process and failure point were recognized. Finally, the details of non-homogenous deformation mechanism that can be used to explain and describe the critical condition for shear band nucleation and propagation were discussed.

2. Experimental procedure

2.1. Materials and specimen preparation

Electrodeposited NC metals have been widely used to study the mechanical properties of NC metals due to its high density and purity. Thus, larger dimension (i.e. 76.2 mm × 76.2 mm × 0.2 mm thick), fully dense NC Ni sheets with a purity of 99.9% were purchased from Integran Technologies Inc. (Canada). Their nominal grain sizes are about 20 nm. The sheets had an initial thickness of about 200 μm and were polished on one side using SiC paper with diamond suspensions of 3, 1, and 0.25 μm grain sizes, respectively. After the polishing, the thickness of the specimens reaches to 150 μm. For comparison, fully dense, coarse-grained Ni sheets with a purity of 99.9% were also mechanically polished to a thickness of approximately 150 μm and afterwards annealed at 700 °C. Dog-bone-shaped tensile specimens were electro-discharge machined from the polished NC and coarse-grained Ni sheet. The width and length of the tensile specimen gage section are 10 and 30 mm, respectively, while thickness is approximately 150 μm. These tensile specimens have centimeters in gage section that allow conventional tensile tests. The microstructure of the two sorts of specimens were characterized using a TEM, TEM specimens (thin sheets, 3 mm in diameter) were prepared by the conventional twin-jet polishing technique in an electrolytic bath of 10% perchloric acid and 90% ethanol at −10 °C and 50 V.

2.2. Mechanical testing and image capturing

The tensile specimens were loaded at room temperature with Zwick BZ2.5/TS1S universal test machine at a quasi-static strain rate of $10^{-4}\ s^{-1}$ (displacement control mode). To minimize out-of-plane loading and displacement, two grips of the test machine were carefully aligned. Moreover, the knurl grips were used to minimize slippage between grips and specimen. At the normal of the specimen, a video camera (Model JAI CV-A1) was used to acquire images of the specimen surface during loading and linked to computer to record the images. According to the image resolution (1376 × 1035 pixels), one pixel length represents approximately 10 μm. Sequential images were acquired at a constant frequency of 0.5 Hz during loading. Data acquisition stopped when the specimen was fractured. Finally, fracture surface of the tested NC specimen were examined with a field emission scanning electron microscope (FESEM) operated at 20 Kv.

2.3. Optical strain gage

Full-field quantitative strain evolution of the tensile specimens during deformation was determined by DIC technique. This is an

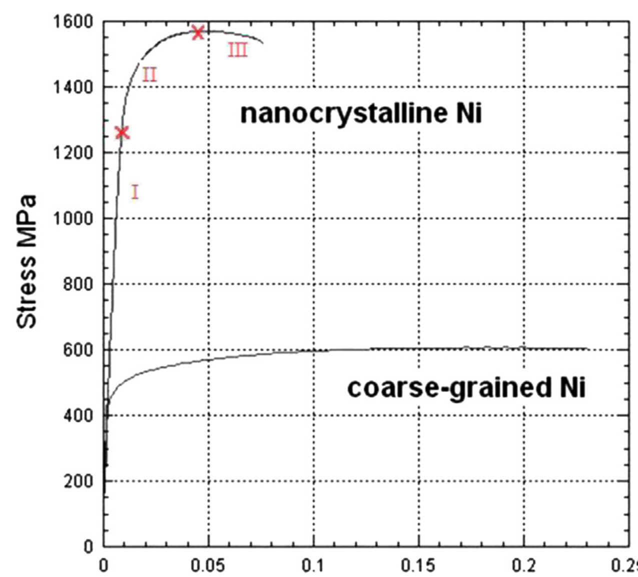

Fig. 2. True stress–strain curves of electrodeposited NC Ni and annealed coarse-grained Ni.

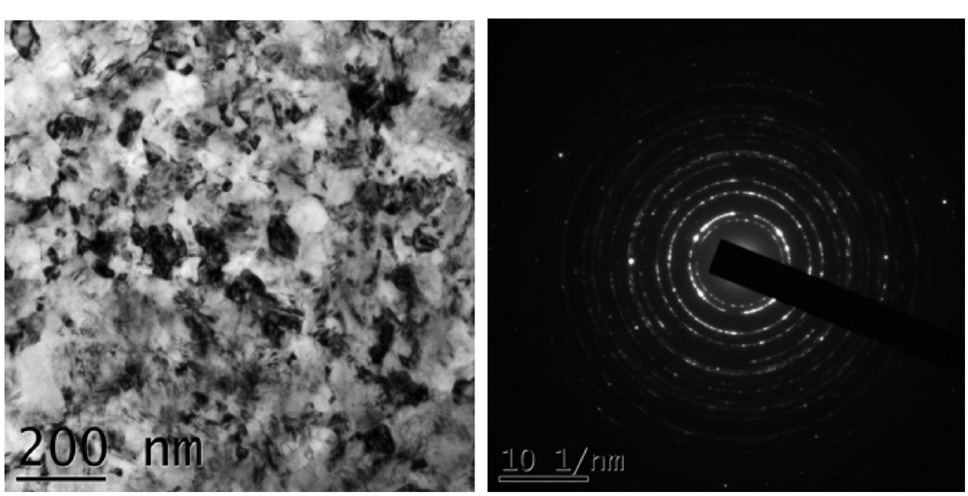

Fig. 1. TEM bright field micrograph accompanying the corresponding SAD pattern of the grain morphology of electrodeposited NC Ni.