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Strain rate dependence of tensile strength and ductility of nano and ultrafine grained coppers

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ABSTRACT

An ultrafine grained Cu with a wide distribution of grain size and an average grain size of d= 110 nm was prepared by electric brush-plating technique. Tensile properties, microstructure and deformation surface morphologies of this ultrafine grained Cu were compared with two results on an electric brush-plated nanocrystalline Cu (d= 59 nm) and an electrodeposited ultrafine grained Cu (d= 200 nm) previously prepared by our group. Based on these comparisons, the strain rate dependences of strength and ductility of these three materials and underlying mechanisms were studied. It was revealed that the pronounced strain rate sensitivity (larger m value) of these three materials is a result of the competition between the dislocation and grain boundary mediated deformations. The grain boundary mediated deformation plays a very important role in controlling the tensile ductility of these three materials, which affects the deformation accommodation by promoting different modes of strain localization and hence leads to the completely different strain rate dependences of tensile ductility (the elongations decrease, remains unchangeable and increase with increasing strain rate).

1. Introduction

Nanocrystalline (NC) (with grain size of $d\leq$ 100 nm) and ultrafine grained (UFG) (100 nm $<d\leq$ 500 nm) metals and alloys have attracted considerable interest over the past two decades due to their ultra-high strength and hardness [1–11], but insufficient tensile ductility greatly restricts their practical application. It is noted that most high strength NC and UFG metals and alloys usually exhibit an elongation to fracture less than 10% at room temperature (RT), which is far lower than that of their coarse grained (CG) counterparts [6,7]. Over the past decades, several strategies have been proposed to improve the tensile ductility of NC and UFG metals and alloys [1–7,12], e.g., developing mixed grain structures with coarse grains being embedded in a matrix of nano or ultrafine grains [1,3,5–8,12], producing nano-structures with a mixture of nano grains and twins [4,13–15] and introducing tiny second-phase particles into a matrix of nano or ultrafine grains [8,16]. All of these strategies are based on the manipulation of various deformation mechanisms to suppress strain localization and plastic instability via elevating the strain hardening and strain rate hardening capabilities of materials.

It has been suggested [6,7,9–11,17–24] that for NC metals with smaller grain size (e.g., $d\leq$ 30 nm), grain boundary (GB) mediated deformation processes, such as thermally activated GB sliding, grain rotation and GB diffusion, play a very important role in controlling the plastic deformation of such NC metals. Meanwhile, dislocation activity, which mainly involves emission of complete or partial dislocations from GB sources, their propagation across grains and eventual absorption in opposite GBs, can also occur concurrently with the GB mediated deformation. In the recent years, several investigators [25–30] found that the GB mediated deformation can also operate effectively in NC metals with larger grain size (30 nm $\leq d\leq$ 100 nm), even in UFG metals and alloys, which takes a form of the cooperative GB sliding in a group mode and can promote the formation of micro shear bands. These investigators suggested [25–27] that if such micro shear bands can form in large numbers and do not develop immediately into catastrophic macro shear bands, the strain localization would be suppressed, the tensile ductility of these materials could be significantly improved. Since the cooperative GB sliding in NC and UFG metals and alloys also needs to be accommodated by dislocation activity, the strain localization and resultant tensile ductility would depend on strain rate and temperature and would be also influenced remarkably by microstructure (grain size, grain size distribution and GB property, etc). Significantly increased tensile ductility with decreasing strain rate (normal ductility-strain rate dependence) has been widely reported in

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many NC and UFG metals and alloys [25–30]. However, the reverse (abnormal) tensile ductility-strain rate dependence was also found in some UFG materials, e.g., in the electrodeposited UFG Cu at RT [31,32] and equal-channel angular pressing UFG Cu at 77 K [33]. In fact, the abnormal tensile ductility-strain rate dependence was also observed in superplastic CG metals and alloys [34–38]. The above experimental results imply that systematical experimental investigations are still needed to understand further how the microstructure affects the strain localization process and resultant strain rate dependence of tensile ductility of NC and UFG metals and alloys and what are underlying mechanisms.

In the present work, a UFG Cu with a wide distribution of grain size and an average grain size of 110 nm was prepared by the electric brush-plating technique. Tensile properties were tested at RT over a range of strain rate from $1 \times 10^{-4}s^{-1}$ to $1 \times 10^{0}s^{-1}$. The results of the tensile testing, microstructure characterization and deformation surface observation were compared with those obtained on an electric-brush-plated NC Cu [30] and an electrodeposited UFG Cu [32] previously prepared by our group, the effects of the microstructure on the strain localization and strain rate dependence of tensile ductility of these three materials were studied systemically.

2. Experimental procedures

Bulk UFG Cu samples with a size of ~ 1.2 mm × 100 mm × 100 mm were prepared by the electric brush-plating technique with bath only containing $CuSO_4 \cdot 5H_2O$ (180–220 g/l). Cathode is a poly-crystalline copper sheet with a thickness of 1.2 mm and stylus (anode) is a stainless steel (AISI304) wrapped with cotton and poly-propylene fabric with proper thickness. The brush-plating voltage of 3–5 V was supplied by a direct current power pack (DSD-75-S). In order to remove the produced heat and avoid the contact of the deposition surface with air circumstance during the brush-plating operation, the cathode surface was always covered by sufficient bath and the bath temperature was kept at RT (298 K). Moving speed and contact pressure between the anode and cathode were optimized to ensure a mirror finish deposition surface. The resultant deposition rate was about 0.06 mm/h. The as-brush-plated UFG Cu had a purity of about 99.977 wt% detected by energy dispersive spectroscopy (EDS) (SUPRA-40).

Dog-shaped tensile specimens with a gauge size of about 0.8 mm × 8 mm × 2.5 mm were cut from the as-brush-plated UFG Cu pieces and then were mechanically polished to a mirror finish in the gauge section. Tensile test was performed on the material test system (MTS-810) with the quasi-static strain rate ranging from $1 \times 10^{-4}s^{-1}$ to $1 \times 10^{0}s^{-1}$ at RT. The stress-strain data were obtained by transforming the output load-(cross-head) displacement data by MTS-810 via the standard relations. In order to ensure the accuracy of the output displacement data, a specially-made clamping apparatus was used to connect the tensile specimens with the grids of the tester. Microstructures of the as-brush-plated and deformed UFG Cu specimens were characterized by using transmission electron microscopy (TEM) (JEM-2100F). TEM samples were prepared by mechanically grinding the bulk materials to a thickness smaller than ~ 30 μm and further thinning to a thickness of electron transparency by using an argon-ion-milling system (EMRES101) at a voltage of 4 kV. Morphologies of the deformation surfaces were observed on scanning electron microscopy (SEM) (JSM-

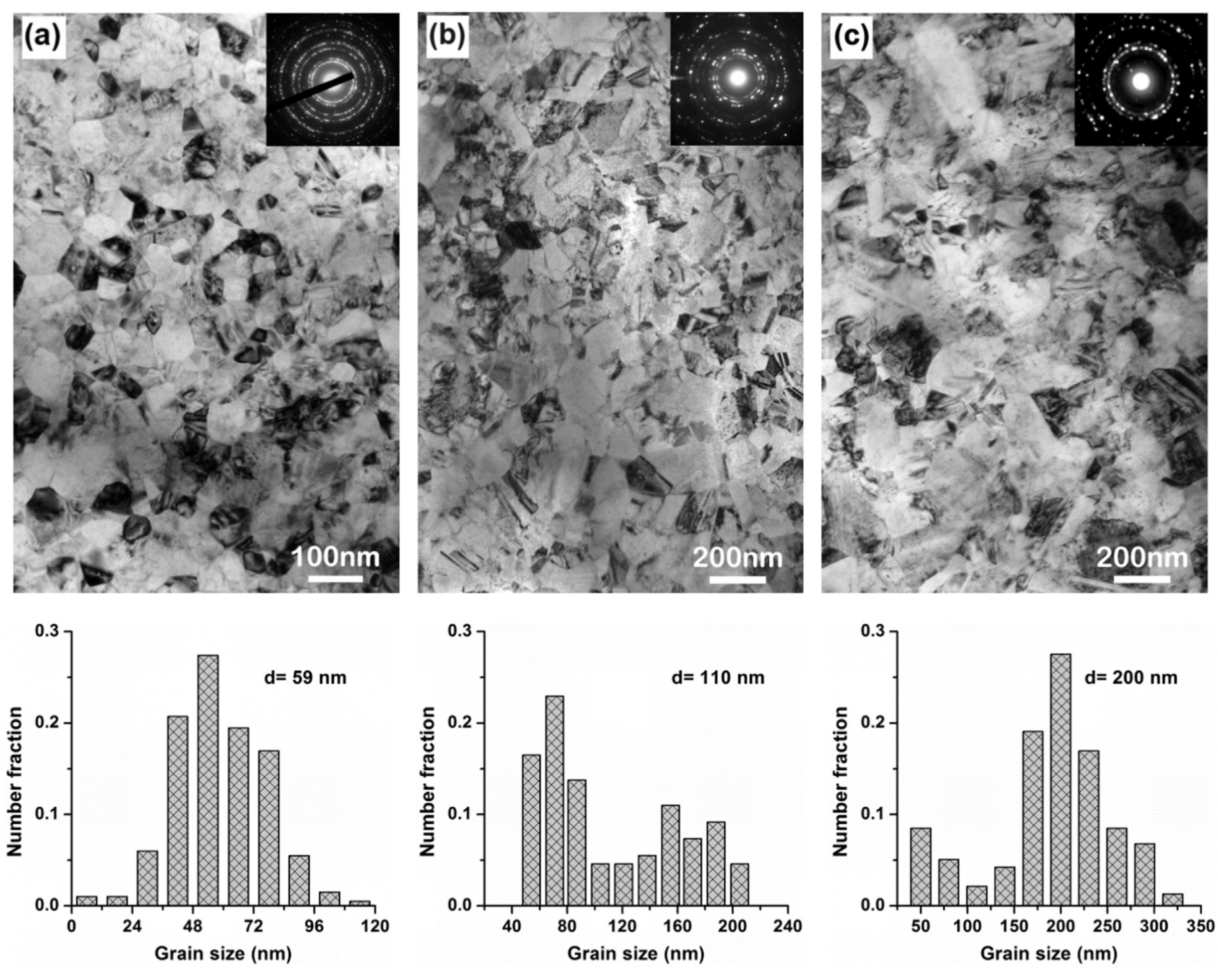

Fig. 1. TEM images of the microstructures, corresponding electron diffraction patterns and grain size distributions of the as-electric brush-plated NC Cu (a), UFG Cu (b) and as-electrodeposited UFG Cu (c).