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Short communication

An insight into the strain rate dependence of tensile ductility of an ultrafine grained Cu matrix nanocomposite

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ABSTRACT

In this study, we observed a strong strain rate dependence of tensile ductility for an ultrafine grained Cu-5vol% Al_2O_3 nanocomposite prepared by powder compact extrusion. This dependency of tensile ductility of the material to strain rate, combined with detailed materials characterization, suggests that the strain at which nearly ideal plastic deformation occurs is associated with the magnitude of the flow stress. The measured apparent activation volume and observed alignment of Cu grains suggest that plastic deformation during this nearly perfect deformation stage is dominated by the co-operative grain boundary sliding.

1. Introduction

The lack of sufficient tensile ductility has been recognized as a major barrier to the application of high strength nanocrystalline (NC) (grain sizes≤100 nm) and ultrafine grained (UFG) (100 nm < grain sizes≤1 μm) metallic materials [1–4]. It appears that most high strength NC and UFG alloys exhibit an elongation to fracture of less than 10% at room temperature. This is much lower than that of their coarse grained (CG) counterparts [5,6]. It has been accepted that for processing artifact-free NC and UFG alloys, their low tensile ductility mainly results from the lack of strain hardening capability. Such limited strain hardening ability is associated with both insufficient dislocation accumulation inside nanograins/ultrafine grains and high dynamic recovery rate at grain boundaries [7]. In addition, the instability of crack nucleation and/or propagation also causes NC and UFG metallic materials to fail at a very small plastic strain in tension [2–4]. However, for strain rate sensitive UFG metals, although the strain hardening effect decays rapidly with plastic strain and soon becomes trivial, the strain rate hardening effect is still capable of delaying the onset of severe localization of plastic deformation and, hence, could render materials with enhanced tensile ductility [8,9].

It has been shown that the strain rate sensitivity of the flow stress of face centered cubic (FCC) structured metals, such as Cu, can be elevated by approximately an order of magnitude through reducing grain sizes from the micron level to the nanometer/sub-micron level [10–13]. Such drastically increased strain rate sensitivity allows NC/UFG Cu to achieve good tensile ductility at a relatively low strain rate of $1\times10^{-5}\ s^{-1}$ or lower [9,10,14–17]. For instance, a NC Cu sample, with an average grain size of 54 nm, exhibited a tensile strain rate sensitivity of 0.0272 in the strain rate range of 1×10^{-2} to $1\times10^{-4}\ s^{-1}$, and its elongation to fracture increased from 6% to 12% by decreasing the strain rate from 1×10^{-2} to $1\times10^{-4}\ s^{-1}$ [15]. Similarly, the strain rate sensitivity of an UFG Cu, with an average grain size of around 300 nm produced by equal channel angular pressing (EACP), was measured to be 0.025 by strain rate change tensile test (tensile jump test) at $6\times10^{-7}\ s^{-1}$ [9,18]. The sample showed a perfectly flat true stress-strain curve over the first 12% of strain without exhibiting necking at a low strain rate of $1\times10^{-6}\ s^{-1}$.

In our investigation of the strain rate dependence of the tensile ductility of an UFG Cu-5vol%Al_2O_3 nanocomposite, which was prepared by powder compact extrusion and had grain sizes in the range of ~70 to ~800 nm and Al_2O_3 nanoparticle sizes in the range of ~5 to ~350 nm, we observed an interesting phenomenon. The elongation to fracture of the sample increased drastically from 8.1% to 15%, i.e. by a factor of about two, as the strain rate decreased from 1×10^{-4} to $5\times10^{-5}\ s^{-1}$, while it only increased slightly from 6.5% to 8.1% with

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decreasing the strain rate by three orders of magnitude, from 1×10^{-1} to 1×10^{-4} s^{-1}. This paper is to probe the underlying origins responsible for this strong strain rate dependency of the tensile ductility of an UFG Cu-5vol%Al_2O_3 nanocomposite sample.

2. Experimental procedure

A nanostructured Cu-5vol%Al_2O_3 nanocomposite powder was prepared by high energy mechanical milling (HEMM) of a mixture of Cu powder and a γ-Al_2O_3 nanopowder. Reference [19] provides details of the ball mill used. The vial, which was loaded with a powder mixture of 50*g* and 250*g* stainless steel balls with diameters of 20 and 16 mm, was sealed in a glove box filled with argon. Prior to HEMM, 6 h powder mixing at 200 rpm was conducted, and then the mixed powder was milled at 500 rpm for 36 h without any stop during milling. Subsequently, the milled powder was pressed into a cylindrical compact with a diameter of 52 mm and a height of about 50 mm at room temperature in air. The powder compact was heated with an induction coil to 900 °C, held at this temperature for 2 min, and then extruded with an extrusion ratio of 24:1 to produce an extruded rod of 11 mm in diameter and 99% in relative density. The heating and extrusion of the powder compact were conducted in a glove box filled with argon. Tensile test specimens with a gauge length of 20 mm and a cross-sectional area of 2×3 mm^2 were cut from the as-extruded rod using an electric discharge wire cutting machine. The tensile tests were conducted using a Zwick-100 universal mechanical testing equipment and with four strain rates: 1×10^{-1}, 1×10^{-2}, 1×10^{-4} and 5×10^{-5} s^{-1}, respectively, and for each strain rate, at least two specimens were tested. The strain of each specimen during testing was measured using an extensometer attached to the specimen. After tensile testing, the fractured tensile specimens were directly put in scanning electron microscopy (SEM) to examine their longitudinal surfaces. Referring to [15], the strain rate sensitivity of the flow stress of the tensile tested samples was evaluated at a certain plastic strain of 2.5%. SEM (Nova NanoSEM 230) and transmission electron microscopy (TEM) (Philips/FEI CM200 and JEM2100) were used to characterize the microstructures of the as-extruded rod and tensile tested specimens.

3. Results and discussion

As shown in Fig. 1, the microstructure of the Cu-5vol%Al_2O_3 nanocomposite rod consisted of an UFG Cu matrix with grain sizes in the range of ~70 to ~800 nm and a uniform dispersion of Al_2O_3 nanoparticles with sizes in the range of ~5 to ~350 nm. As shown in Fig. 2(a), the flow stress of the tensile tested specimens increased clearly and monotonically with increasing the strain rate from 5×10^{-5} to 1×10^{-1} s^{-1}. In the meantime, elongation to fracture first increased slightly from 6.5% to 8.1% with decreasing the strain rate from 1×10^{-1} to 1×10^{-4} s^{-1} and then increased sharply from 8.1% to 15% as the strain rate decreased from 1×10^{-4} to 5×10^{-5} s^{-1}. The tensile true stress-strain curves of all specimens tested exhibited a near-ideal plastic flow behavior, similar to those of NC/UFG Cu reported by Champion et al., Cheng et al. and Guduru et al. [14,15,20]. Based on the tensile true stress-strain curves, and the inset shown in Fig. 2(a), the deformation of the tensile tested specimens can be divided into four stages: Stage I is elastic deformation; Stage II is uniform plastic deformation with a high strain hardening rate; Stage III is nearly ideal plastic deformation with a low strain softening rate; and Stage IV is severely localized plastic deformation with a high strain softening rate.

Based on the variation of the flow stress at the plastic strain of 2.5% with the strain rate as shown in Fig. 2(b), the strain rate sensitivity of the flow stress of the material, m, can be determined using the equation below [15]:

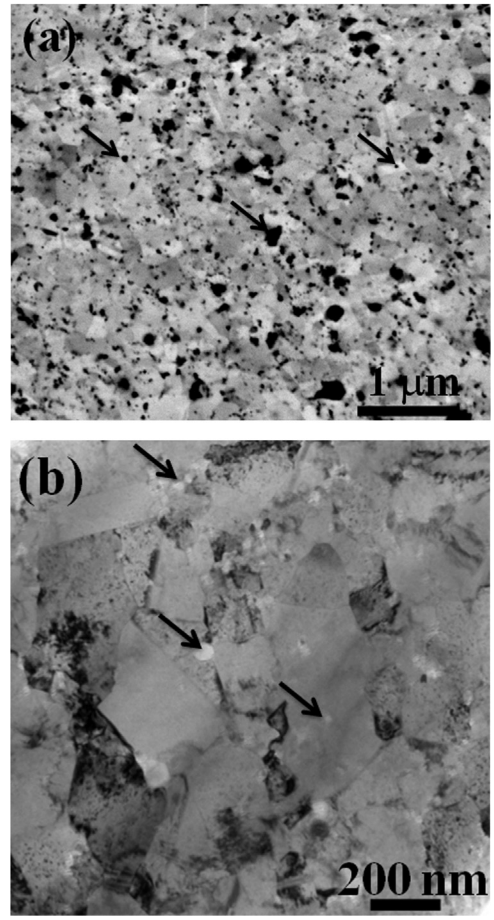

Fig. 1. (a) Backscattered SEM and (b) TEM bright field micrographs showing the microstructure of the as-extruded UFG Cu-5vol%Al_2O_3 nanocomposite. The solid black arrows shown in (a) and (b) point to the Al_2O_3 particles.

$$m = \left.\frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}}\right|_{T,\varepsilon}, \tag{1}$$

where σ is the flow stress at a given plastic strain, $\dot{\varepsilon}$ is the strain rate and the subscript in Eq. (1) means that m is measured at certain temperature, T, and plastic strain, ε. The value of m for the plastic strain of 2.5% was determined to be 0.023.

According to the Considère criterion shown below [7]:

$$\left(\frac{\partial\sigma}{\partial\varepsilon}\right)_{\dot{\varepsilon}} \le \sigma, \tag{2}$$

the plastic deformation would become localized once the Stage II deformation which has a high strain hardening rate terminates, causing the initiation of necking. On the other hand, Hart's criterion [8] for the stable plastic deformation of a strain rate sensitive material is:

$$\frac{1}{\sigma}\left(\frac{\partial\sigma}{\partial\varepsilon}\right)_{\dot{\varepsilon}} - 1 + m \le 0. \tag{3}$$

This criterion requires that an increased strain rate sensitivity can effectively stabilize the plastic deformation and delay the onset of necking. As shown above, the UFG Cu-5vol%Al_2O_3 nanocomposite sample in this study has a strain rate sensitivity of 0.023 which is 4 times higher than that of CG Cu (0.006) [9] and comparable to that of NC Cu (0.027) [15]. The Hart criterion and the high strain rate sensitivity of the material ensure significant plastic deformation with nearly no strain hardening (Stage III), as evidenced by the true stress-strain curves of the specimens tested in this study (Fig. 2(a)).

Here, the Considère and Hart's criteria are not able to explain the