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Strain rate sensitivity studies in an ultrafine-grained Al–30 wt.% Zn alloy using micro- and nanoindentation

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ABSTRACT

The characteristics of plastic deformation of an ultrafine-grained (UFG) Al–30 wt.% Zn alloy were investigated using depth-sensing micro- and nanoindentation. Emphasis was placed on the effects of grain boundaries and the unusually high strain rate sensitivity. It is shown that there is a close relationship between enhanced strain rate sensitivity and ductility in this UFG material and this is associated with grain boundary sliding and enhanced diffusion along the Al/Al grain boundaries which appear to be wetted by Zn-rich layers.

1. Introduction

It is now well established that bulk ultrafine-grained (UFG) materials may be achieved by using severe plastic deformation (SPD) techniques such as equal-channel angular pressing (ECAP) or high-pressure torsion (HPT) [1–3]. As a consequence of the severe deformation, the UFG materials generally have reasonably saturated microstructures with a steady-state dislocation density [4]. Furthermore, in the UFG materials the role of the grain boundaries is generally enhanced in post-SPD deformation processes thereby leading to high strength [5,6]. There is direct evidence suggesting that grain boundary sliding (GBS) may occur more easily at room temperature (*RT*) in UFG metals [7–9]. At the same time, the UFG materials produced by SPD typically exhibit very low – about only 5–10% – tensile ductility at ambient temperature due to an exhaustion in the work hardening capacity. In addition, the low ductility is correlated with the extremely low strain rate sensitivity (SRS) of only about 0.01–0.03 characterizing these materials [10].

Because the low ductility limits the practical applications, several attempts have been made to improve the tensile ductility of the UFG materials. As the ductility is controlled mainly by work hardening and/or the strain rate sensitivity [9], it was possible to successfully improve the tensile ductility of some UFG metals up to ∼40–50% by enhancing the work hardening [11–13]. Recently, it was demonstrated that SPD is capable of increasing the room temperature ductility of an HPT-processed UFG Al–30 wt.% Zn alloy leading to unusually high elongations up to 150% while maintaining an enhanced strength [9]. Thus, the objective of the present investigation was to study and analyze the main plastic characteristics which delineate the high ductility of this UFG Al–30 wt.% Zn alloy. In order to demonstrate the unusual mechanical properties of the alloy, the mechanical characteristics are compared also with results obtained for UFG pure Al processed by HPT.

2. Experimental materials and procedures

As-cast high purity (4 N) Al and an Al–30 wt.% Zn alloy were homogenized at 500 °C for 1 and 5 h, respectively. Disks having thicknesses of ∼0.8 mm with diameters of 10 mm for Al and 20 mm for Al–30 wt.% Zn were prepared for the subsequent HPT processing. The disks were processed by HPT at room temperature under

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an imposed pressure of 6.0 GPa. The straining was continued up to a total of 5 turns at a rotation speed of 1 rpm. Samples for investigation were cut from the HPT disks at a distance of approximately one-half radius from the center where this distance corresponds to a shear strain of ∼6 [3]. The microstructure of the Al–30 wt.% Zn alloy after HPT contained equiaxed ultrafine Al grains having an average size of ∼380 nm with smaller Zn grains located mainly at the triple junctions of the Al grains [9]. The microstructure of the HPT-processed pure Al consisted also of equiaxed grains having an average size of ∼1.2 μm where this grain size is consistent with that reported earlier for high-purity Al using ECAP [14,15] and HPT [16].

The mechanical properties were studied using both depth-sensing micro- and nanoindentation tests controlled by computer. The data of depth and load were recorded as a function of time. The microindentation measurements were carried out using a Shimadzu machine with Vickers microindenter operating under a force, F, that increased linearly with time, t, through an imposed loading rate between 0.25 and 70 mN s^{-1}. It may be estimated from an earlier analysis [17] that the equivalent strain rate, $\dot{\varepsilon}_{eq}$, around the edge of the indenter at the end of the indentation process is proportional to the loading rate. Applying microindentation at a maximum load of 2000 mN, the equivalent strain rate, $\dot{\varepsilon}_{eq}$, was varied between 6.25×10^{-5} and 1.75×10^{-2} s^{-1}. The size of the indenter patterns was ∼50–100 μm, covering at least 5000 grains so that quasi-macroscopic behavior may be observed. The reported microhardness values are the averages of at least 5 individual measurements. The error bars on these average values were estimated as <5%. The equivalent yield strengths, σ_{eq}, were taken as one-third of the hardness values in the present analysis.

Nanoindentation was applied to monitor the effect of the grain boundaries. The nanohardness measurements were carried out using a UMIS nanoindentation device with a Berkovich indenter and applying maximum loads of 0.5 and 1 mN with loading rates of 10^{-2} and 2×10^{-2} mN s^{-1}. A series of 400 indentations was recorded with the indents arranged in a 20 × 20 matrix with a neighbor-spacing of 20 μm at a given maximum load and loading rate. The maximum indentation depth, h_{max}, was between 60 and 180 nm depending on the applied maximum load and also on the local hardness.

3. Experimental results and discussion

Recently [4,8] it was shown for face-centered cubic (f.c.c.) metals with ultrafine-grained structure that plastic deformation during uniaxial compression takes place at the saturation flow stress which corresponds to a dynamic equilibrium between the formation and annihilation of dislocations. The strain rate, $\dot{\varepsilon}$, for the saturation state may be described through the relationship generally applied in steady-state creep [18]:

$$\dot{\varepsilon} = A\frac{DGb}{kT}\left(\frac{\sigma}{G}\right)^{n} \cdot \left(\frac{b}{d}\right)^{p}, \tag{1}$$

where A is a dimensionless mechanism-dependent constant, D is the diffusion coefficient, G is the shear modulus, b is the Burgers vector, k is Boltzmann's constant, T is the absolute testing temperature, n is the stress exponent, and p is the inverse grain size exponent for the grain size, d. The diffusion coefficient, D, is given as $D = D_0 \exp(-Q/RT)$, where D_0 is a frequency factor, Q is the appropriate activation energy for the diffusive process and R is the universal gas constant. In addition, the strain rate sensitivity, m, characterizing the deformation process is the reciprocal of the stress exponent ($m = 1/n$). Using the parameters m and Q, Eq. (1) may be rewritten as:

$$\dot{\varepsilon} = K_1 \cdot \frac{\sigma^{1/m}}{T} \cdot \exp\left(-\frac{Q}{RT}\right), \tag{2}$$

where K_1 is a microstructure-dependent constant for a selected metal having a constant grain size. Assuming a constant strain rate, Eq. (2) may be expressed as

$$\frac{\sigma}{T^m} = K_2 \cdot \exp\left(\frac{mQ}{RT}\right), \tag{3}$$

where K_2 is another constant.

It follows from Eqs. (2) and (3) that the values of m and Q can be determined from the slope of a straight line fit to the $\ln\sigma - \ln\dot{\varepsilon}$ data at a selected temperature and the slope of a straight line fit to the $(\ln\sigma - m \cdot \ln T) - 1/T$ data at a constant strain rate, respectively. Fig. 1 shows such a set of $\ln\sigma_{eq} - \ln\dot{\varepsilon}_{eq}$ and $(\ln\sigma_{eq} - m \cdot \ln T) - 1/T$ relationships using the equivalent strain rate, $\dot{\varepsilon}_{eq}$, and equivalent stress, σ_{eq}, obtained by microindentation using a Vickers indenter. Fig. 1 allows a calculation of the experimental values of m and Q, respectively, for the two HPT-processed UFG samples.

It is apparent that the quantities obtained by indentation ($m \approx 0.03$ and $Q \approx 87$ kJ/mol) for UFG Al are in good agreement with the values reported earlier from compression testing ($m \approx 0.03$ and $Q \approx 82$ kJ/mol) [8]. Although the value of m for UFG Al is very small, it is typical of the low values of the strain rate sensitivities generally recorded in f.c.c. metals deformed at low temperatures [10,19,20]. In addition, the measured activation energy is very close to the value of ∼84 kJ/mol anticipated for grain boundary diffusion in pure Al [21].

For the UFG Al–30 wt.% Zn alloy, the value of the strain rate sensitivity ($m \approx 0.22$) is unusually high and this is consistent with the high ductility at room temperature where elongations to failure were achieved of up to more than 150%. However, the experimentally determined activation energy of 65 kJ/mol is lower than the

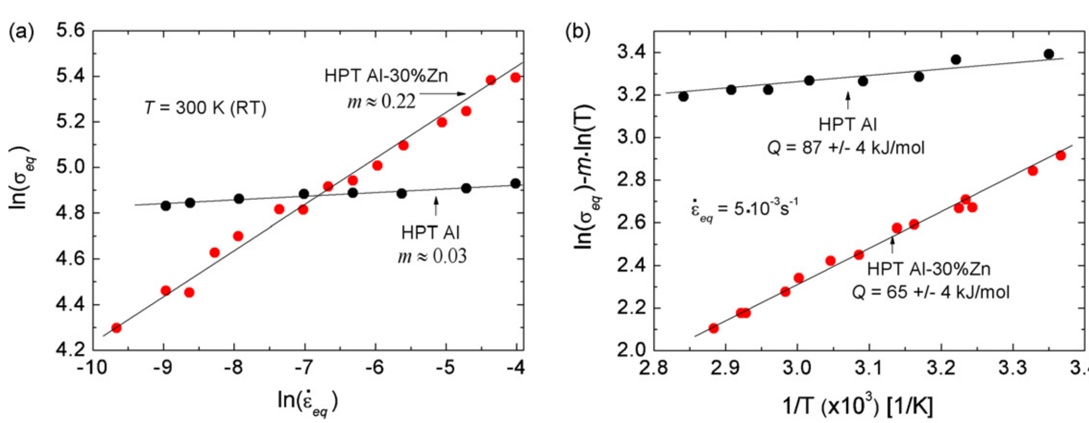

Fig. 1. An evaluation of (a) the strain rate sensitivity, m, and (b) the activation energy, Q, for HPT-processed, UFG Al and Al–30 wt.% Zn alloy.