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Effect of strain rate on the ductility of a nanostructured aluminum alloy

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Abstract

Nanostructured materials normally exhibit enhanced ductility at higher strain rate. In this paper we report the observation that a cryomilled nanostructured 5083 Al alloy exhibits the opposite behavior, i.e., higher ductility at lower strain rates. This phenomenon was rationalized by a diffusion-mediated stress relaxation mechanism that effectively delayed crack initiation events.

Keywords: Nanostructured; Aluminum alloy; Cryomilling; Ductility; Strain rate

1. Introduction

The mechanical properties of nanostructured or ultrafine-grained (UFG) materials are of interest within the context of nanotechnology as applied to structural materials [1]. There are a number of reported trends in behavior that deserve detailed study since they may provide insight into the underlying mechanisms. For example, a strong influence of strain rate on mechanical properties has been observed in many nanostructured/UFG materials [2–4]. Most studies have reported an increase in tensile strength and ductility of nanostructured materials with increasing strain rates [3,5–7].

Deformation at higher strain rates has been proposed as a strategy for improving the ductility of nanostructured materials [3]. Indeed, face-centered cubic (fcc), body-centered cubic (bcc) and hexagonal close-packed (hcp) metals have been found to exhibit higher ductility at higher strain rates [6]. The accepted reason for improved ductility at higher strain rates is higher work hardening rates [8]. Work hardening delays necking, the onset of failure under tension for most metals and alloys. It is caused by the accumulation of crystalline defects, such as dislocations, which make further deformation more difficult [9]. At the same time, dynamic recovery lowers the defect density, and consequently lowers the work hardening rate. Higher strain rates generate crystalline defects at a higher rate to compete with dynamic recovery and therefore increase the work hardening rate, which leads to higher ductility. Another strategy for improving the ductility of nanostructured fcc metals is to increase the strain rate sensitivity [3].

Despite the above findings, published results sometimes reveal contradictory behavior. For example, a nanostructured Cu processed via ball milling was found to have a higher ductility at lower strain rates, while its tensile strength follows the same trend as other nanostructured materials, i.e., lower strength at lower strain rates [4]. The higher ductility at lower strain rates in the nanostructured Cu [4] cannot be explained by the above two strategies and therefore it likely involves a new mechanism. It is the objective of this study to investigate the mechanism of higher ductility at lower strain rate in nanostructured metals. We selected nanostructured 5083 Al alloy produced by cryomilling and subsequent consolidation via hot extrusion for this study as a result of recent interest in this synthesis route. For the past several years, cryomilling has evolved into a viable technology for processing UFG or

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nanostructured materials for engineering applications [10–12]. However, in spite of numerous published studies on cryomilled materials, the influence of strain rate on their ductility has not been investigated. As shown later, this material exhibits higher ductility at lower strain rate, similar to the nanostructured Cu produced by ball milling.

2. Materials and experimental procedures

The cryomilled 5083 Al alloy (Al–4.2 wt.%Mg–0.67 wt.%Mn) was produced following the processing sequence of cryomilling, cold isostatic pressing and hot extrusion. Spray-atomized powder was mechanically milled for 8 h in a liquid nitrogen slurry. The cryomilled powder was canned and compacted by cold isostatic pressing at a pressure of ~400 MPa. The compacts were extruded into round bars with a diameter of 19 mm at 823 K.

High-resolution electron microscopy (HREM) of a JEOL 3000F microscope was operated at 300 kV. HREM samples were prepared via mechanical grinding using sandpapers with different grades to a thickness of approximately 50 μm. Final thinning and perforation were conducted with ion milling until a small perforation was made in the center.

The as-extruded materials were machined along the extrusion direction into flat dog-bone specimens with a gauge length of 12 mm, a width of 4 mm and a thickness of 2 mm. Tensile tests at various crosshead velocities from 0.012 mm/s to 0.0001 mm/s until failure were performed using a universal testing machine, loaded with a load cell with an accuracy within 0.5% of the indicated load and a dual-camera video extensometer to directly measure the displacement of the tensile gauge section with an accuracy of 5 μm. The fracture surface of the tensile specimens was studied using a scanning electron microscope (SEM) operated at 10 kV. A compression specimen of 5 mm cubes was loaded along the extrusion direction at a crosshead velocity of 0.0005 mm/s.

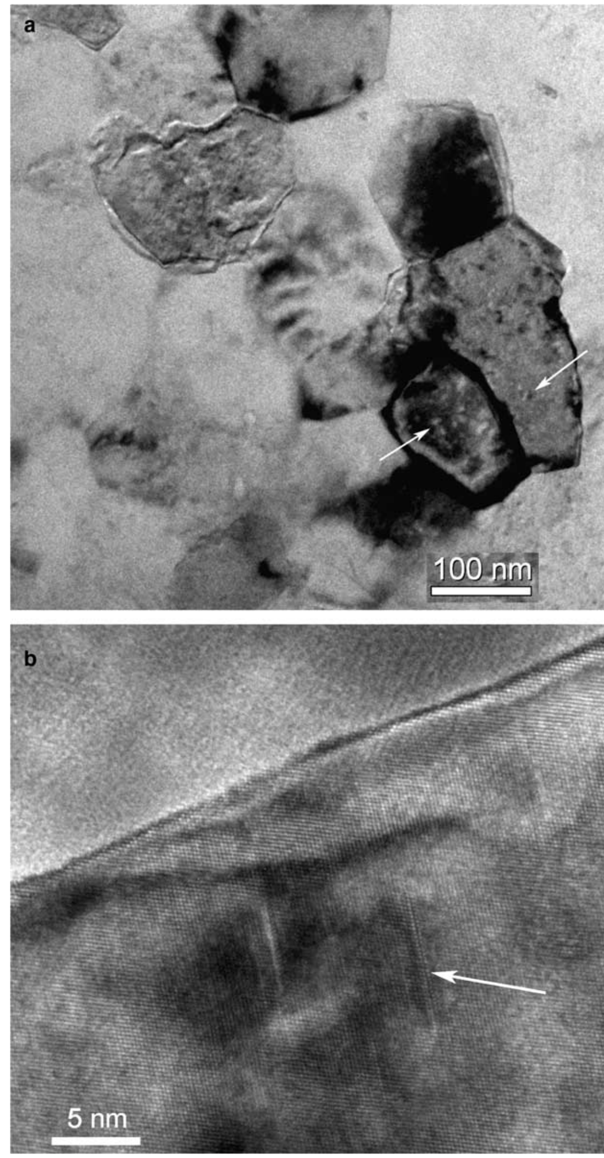

Fig. 1. Microstructure of the as-extruded cryomilled 5083 Al alloy in a section normal to the extrusion direction.

3. Experimental results

The microstructure of the as-extruded cryomilled 5083 Al alloy is shown in Fig. 1(a), a section taken normal to the extrusion direction. The histogram of the grain size distribution of the as-extruded cryomilled 5083 Al alloy was reported in a previous study [13]. The mean grain size is about 207 nm, measured from ≈200 g. It is noteworthy that while most of grains are in the size range of 100 nm and 200 nm, some of the grains are smaller than 100 nm. Although micrometer-sized Al_6Mn is usually observed in coarse-grained conventional 5083 Al alloy [14], this phase is absent in the cryomilled 5083 Al alloy. As shown in Fig. 1(a), a few particles (marked by arrows) with sizes from 2 nm to 10 nm are also observed in the microstructure. In a recent microstructure investigation of a cryomilled 5083 Al alloy, four types of second phases are identified, i.e., grain boundary Mg–O oxides, precipitates of $Al_{12}Mg_2(CrMnFe)$ and $Al_{12}(FeMn)_3Si$, particles of $Al_6(CrMnFe)$, and Al–Si–O dispersoids [15]. We expect these second phases to be present in our current sample as well, given that the material and processing history are identical to the ones used in Ref. [15]. Although the volume fraction of these dispersoids in the microstructure is not high, they play a significant role in stabilizing of microstructure and strengthening of cryomilled Al alloys [10,16]. Fig. 1(b) shows an atomic resolution HREM image of an area near a grain boundary. Marked by a white arrow is a stacking fault, which is frequently observed at grain interiors. Both screw and 60° dislocations are found, typical of fcc metals subjected to heavy deformation [17]. The dislocation density measured from inverse Fourier transformation images is about 8×10^{15} m^2.

Typical tensile stress–strain curves at strain rates of 10^{-3} s^{-1} to 8.3×10^{-6} s^{-1} of the extruded cryomilled 5083