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On the origin of the extremely high strength of ultrafine-grained Al alloys produced by severe plastic deformation

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Ultrafine-grained Al alloys produced by high-pressure torsion are found to exhibit a very high strength, considerably exceeding the Hall–Petch predictions for ultrafine grains. This phenomenon can be attributed to the unique combination of ultrafine structure and deformation-induced segregations of solute elements along grain boundaries, which may affect the emission and mobility of intragranular dislocations.

Keywords: Ultrafine-grained materials; Al alloys; Hall–Petch relationship; Segregation

Grain refinement is well known to result in strength enhancement of metals and alloys, with the experimental relation between yield strength σ_y and mean grain size d described by the classic Hall–Petch relationship [1,2]:

$$\sigma_y = \sigma_0 + k_y d^{-1/2},$$

where $\sigma_0, k_y > 0$ are material-specific constants.

However, for nanosized grains (20–50 nm) this relation is reported to be violated so that the Hall–Petch plot deviates from linear dependence at lower stress values and its slope k_y often becomes negative. In recent years this problem has been widely analyzed in both experimental and theoretical studies [3,4].

At the same time, Hall–Petch relationship breakdown is not observed in ultrafine-grained (UFG) materials with a mean grain size of 100–1000 nm usually produced by severe plastic deformation (SPD) processing [5]. Moreover, we show in this study that UFG alloys can exhibit a considerably higher strength than the Hall–Petch relationship predicts for the range of ultrafine grains. The nature of such a markedly enhanced strength is analyzed by taking into account the grain boundary structure of UFG materials.

The objects of this research were commercial Al alloys 1570 (Al–5.7Mg–0.32Sc–0.4Mn, wt.%) and 7475 (Al–5.7Zn–2.2Mg–1.6Cu–0.25Cr, wt.%), both of which have a considerable Mg content. In order to obtain an UFG structure, solid-solute alloys were subjected to high-pressure torsion (HPT) at room temperature. HPT is known to be one of the most effective techniques for structure refinement by SPD [5]. An applied pressure of 6 GPa and 20 rotations were used to process the alloys. The produced samples had the form of discs with a diameter of 20 mm and 0.6 mm in thickness, which are well suited for mechanical tests [6].

The structural characterization was performed by transmission electron microscopy (TEM), X-ray diffraction (XRD) and atom probe tomography (APT). A mean grain size and a grain size distribution were estimated from TEM dark-field measurements in torsion plane over more than 350 grains from an area situated at the middle of an HPT disc radius. Selected-area electron diffraction (SAED) patterns have been taken from an area 1.3 μm in diameter. XRD was performed with a Pan Analytical X'Pert diffractometer using Cu K_α radiation (50 kV and 40 mA). The lattice parameter a for the initial and HPT-processed alloys was calculated according to the Nelson–Riley extrapolation method [7]. APT samples were prepared by standard electropolishing methods. Analyses were performed using a CAMECA Energy Compensated Atom Probe (ECOTAP) equipped with an ADLD detector [8]. Samples were field evaporated

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in UHV conditions with electric pulses (pulse fraction of 20%, pulse repetition rate 2 kHz). The data processing was performed using the GPM 3D Data software®. Tensile tests have been precisely performed using a laser extensometer at room temperature with a strain rate of $10^{-4}\ s^{-1}$ on a computer-controlled testing machine operating with a constant displacement of the specimen grips. Strength characteristics were estimated by testing samples with a gage of 2.0 × 1.0 × 0.4 mm.

TEM analysis proved that the HPT processing of the alloys resulted in complete refinement of the initial coarse-grained structures into UFG ones. As an example, Figure 1a,b illustrates the homogeneous UFG structure formed in the HPT 1570 alloy. A grain size distribution chart, presented in Figure 1c provides an estimate of the mean grain size of ~97 nm. The SAED pattern (Fig. 1a) exhibits typical Debye–Scherrer rings that are characteristic of ultrafine structures with mainly high-angle grain boundaries. It is also important to note that a low dislocation density inside nanoscaled grains was observed in both alloys processed by HPT (Fig. 1b), in agreement with previous studies on a Al–3%Mg alloy processed by HPT [9].

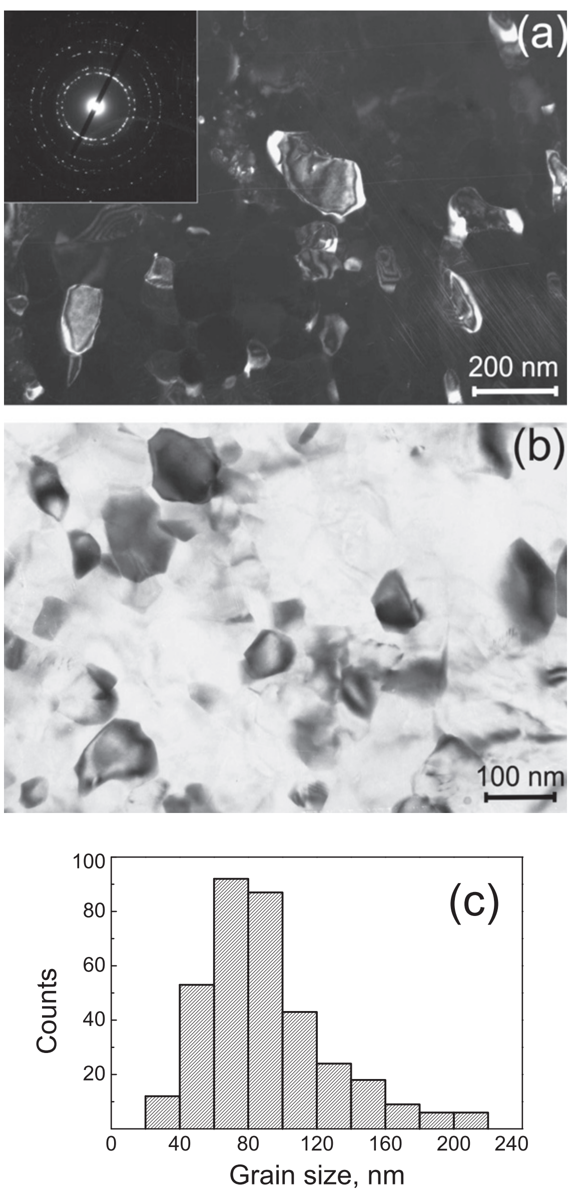

Figure 1. A typical TEM dark-field image of the UFG 1570 alloy with a corresponding SAED (a), a bright-field image (b) and a grain size distribution (c).

Figure 2 shows the results of mechanical tests of the 1570 and 7475 alloys in coarse-grained and HPT-processed states. It should be noted that deformation curves for coarse-grained states are given for 1570 alloy in the solid-solution state and for 7475 hardened by conventional T6 treatment. The plot demonstrates that UFG alloys manifest an outstanding strength accompanied by reduced uniform elongation. Both yield stress and ultimate tensile stress values exceed by almost three times those of initial solid-solution 1570 alloy, and are almost twice as much as those of T6-treated 7475 alloy.

Let us analyze the obtained data in terms of the Hall–Petch relation to estimate to what extent the exhibited strength of UFG alloys may be determined by their grain size, with special attention to 1570 alloy. There are no reference data available to construct a reliable Hall–Petch plot for the investigated alloys. In order to perform a correct comparative study we relied on the literature data for the other Al alloys.

As is known, for deformed alloys a number of factors contributes to overall hardening. For the 1570 Al alloy these include hardening caused by deformation-induced structures and solid-solution hardening. This means that the Hall–Petch slope for the materials processed by deformation techniques would be changed, as confirmed, for example, by Ref. [10] for 1100 Al alloy. The same considerations are valid for solid-solution hardening as well.

Since the investigated UFG materials have been produced by SPD, for a valid comparison we need to analyze the data obtained for Al alloys also subjected to severe straining. For that purpose two sets of data are presented (Fig. 3). The first one is for the 1100 Al alloy produced by accumulative roll-bonding [10] in order to highlight the increased k_y determined from deformation-induced structures. The second one is for UFG Al–Mg alloy produced by another SPD technique – equal-channel angular pressing [11], and shows the simultaneous effect of both deformation and solid-solution hardening. Thus, one can expect that the Hall–Petch line for Al–3%Mg alloy will demonstrate a slope typical for Al alloys, accounting for solid-solution and deformation-induced hardening.

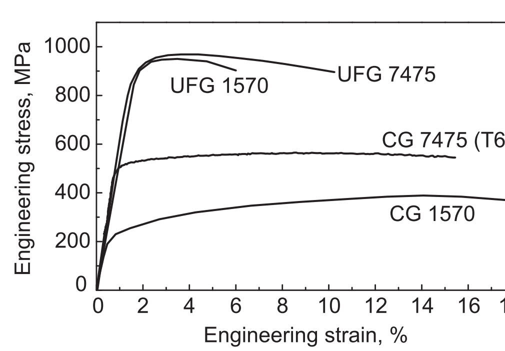

Figure 2. Engineering stress–strain curves for 1570 and 7475 alloys in UFG and coarse-grained states.