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Aging behavior and mechanical properties of 6013 aluminum alloy processed by severe plastic deformation

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Abstract: Structural features, aging behavior, precipitation kinetics and mechanical properties of a 6013 Al–Mg–Si aluminum alloy subjected to equal channel angular pressing (ECAP) at different temperatures were comparatively investigated with that in conventional static aging by quantitative X-ray diffraction (XRD) measurements, differential scanning calorimetry (DSC) and tensile tests. Average grain sizes measured by XRD are in the range of 66−112 nm while the average dislocation density is in the range of 1.20×10^{14}−1.70×10^{14} m^{-2} in the deformed alloy. The DSC analysis reveals that the precipitation kinetics in the deformed alloy is much faster as compared with the peak-aged sample due to the smaller grains and higher dislocation density developed after ECAP. Both the yield strength (YS) and ultimate tensile strength (UTS) are dramatically increased in all the ECAP samples as compared with the undeformed counterparts. The maximum strength appears in the samples ECAP treated at room temperature and the maximum YS is about 1.6 times that of the statically peak-aged sample. The very high strength in the ECAP alloy is suggested to be related to the grain size strengthening and dislocation strengthening, as well as the precipitation strengthening contributing from the dynamic precipitation during ECAP.

Key words: Al−Mg−Si aluminum alloy; severe plastic deformation; equal-channel angular pressing; aging behavior; precipitation kinetics; mechanical properties; strengthening mechanisms

1 Introduction

Over the last two decades, bulk materials with ultrafine-grained (UFG) alloys processed by severe plastic deformation (SPD) have attracted widespread interest in scientific and technological communities [1]. One of the major SPD methods is equal channel angular pressing (ECAP), which has been widely used to fabricate UFG materials [2]. ECAP processing is an attractive procedure for many advanced structural and functional applications as it allows enhancing significant properties of commonly used metals and alloys [1−3]. Although outstanding progress has been made in this area in recent years, the relationships between theory-based structure and property in SPD metals are not yet fully understood [4].

Al−Mg−Si alloys have been extensively studied due to their superior yield strength (YS) and ultimate tensile strength (UTS) obtained by precipitation hardening [5−8]. The formation of metastable phases influences its mechanical properties. It is important to understand the precipitation sequence of the metastable phases and their kinetics for achieving the superior mechanical properties in Al−Mg−Si alloys. The precipitation sequences of this alloy were reported in Ref. [9] as follows: $\alpha\rightarrow$GP

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zones→β''→β'→β, where α is the supersaturated solid solution; GP zones are generally spherical clusters with unknown structure [10]; β'' precipitates are fine needle-shaped zones with monoclinic structure and are generally present in Al alloys aged to the maximum hardness; β' is rod-shaped precipitates with hexagonal structure and is found in the overaged specimens; β (Mg_2Si) is an equilibrium phase in the precipitation sequence.

Precipitation kinetics in Al alloys has been studied by numerous investigators by differential scanning calorimetry (DSC) [10−12]. Several analytical schemes were used to determine the kinetic parameters from the scan rate dependence of peaks observed in DSC curves [11]. The study on precipitation kinetics and microstructural characterization of heat treatable Al-based bulk alloys is abundant but it is very scarce for ultrafine-grained Al alloys. The knowledge of kinetics of precipitate formation and its dissolution in ultrafine-grained Al−Mg−Si alloys is very essential to understand the thermal stability of its microstructures as well as the role of strengthening mechanisms.

In the present work, a commercial 6013 Al−Mg−Si−Cu aluminum alloy was subjected to ECAP at different temperatures. The structural features, aging behavior, precipitation kinetics in the ECAP alloy were compared with that in conventional static aging by DSC and quantitative X-ray diffraction (XRD) measurements. Mechanical properties were comparatively investigated and the strengthening mechanisms involved in the deformed alloy were interpreted.

2 Experimental

Commercially extruded rods with a diameter of 25 mm of the 6013 Al alloy were purchased from ALCOA in the peak-aged temper (T6-condition). The composition of the alloy is given in Table 1. Square billets cut from the as-received rods were first solution-treated (ST) at 560 °C for 2 h, followed by quenching in water, then immediately processed by ECAP (1 to 4 passes) with route Bc. The ECAP was performed at room temperature (RT), 110 °C and 170 °C, respectively. The ECAP die had a channel intersection angle Φ=90°, arc of curvature Ψ=20.6° and the billet dimensions were 19.5 mm×19.5 mm×100 mm [13]. For comparison, conventional static aging was conducted in the as-received materials which were first solution-treated at 560 °C for 2 h, followed by water quenching, then immediately aged at 191 °C for 10 min to 25 h.

Table 1 Composition of 6013 Al alloy (mass fraction, %)

Mg	Si	Cu	Mn	Fe
0.8−1.2	0.6−1.0	0.6−1.1	0.2−0.8	≤0.5
Zn	Ti	Cr	Al	
≤0.25	≤0.1	≤0.1	Bal.	

To investigate the influence of ECAP on phase precipitation during aging, samples of the processed alloy were also subjected to DSC analyses. Specimens were cut from bulk samples and cleaned with ultrasonic wave. The final mass of each DSC sample was about 30 mg. The sample for DSC testing was equilibrated at 20 °C and then heated to 500 °C with a heating rate of 10 °C/min under an argon atmosphere. The structural characterization was performed by quantitative XRD. Quantitative XRD measurements were performed with a D/max–2500PC diffractometer using Cu K_α radiation at 40 kV and 30 mA. Vickers microhardness (HV) was measured using a HV−1000 microindentation tester under a load of 1.96 N for 20 s. Each hardness was averaged over at least 5 measurements. Tensile tests were precisely performed with a WDW−10 computer controlled electronic universal testing machine at room temperature at a strain rate of 10^{-4} s^{-1} operating with a constant displacement of the specimen grips. The yield strength (YS, $\sigma_{0.2}$), ultimate tensile strength (UTS, σ_{UTS}) and elongation (δ) were determined from the tests not less than three samples. The standard deviation of the tensile tests did not exceed 5%.

3 Results

3.1 Structural features

The XRD peaks of the materials processed by ECAP at different temperatures and the quantitative XRD measurements are shown in Table 2 and Fig. 1, respectively. The X-ray measurements demonstrate that the temperature of ECAP strongly influences the subgrain size of the investigated alloy. The size of coherent domains, D_{XRD}, increases tremendously from 66 to 112 nm as the temperature increases from RT to 170 °C (see Table 2). It should be noted that the grain sizes (d) in the ECAP alloy measured by the dark field images are often larger than the D_{XRD} obtained by the XRD. The emergence of this difference is because the XRD process determines the size of the coherent diffraction domains and this includes both the subgrains and the dislocation cells [14−17]. The microstrain, $\langle\varepsilon^2\rangle^{1/2}$, increases significantly from 0.092% to 0.107% as the temperature increases from RT to 170 °C (see Table 2). For the materials subjected to equal channel angular pressing, the dislocation density is proportional to microstrain and inversely proportional to grain size [14]. Using the experimentally obtained values (see Table 2) of D_{XRD} and $\langle\varepsilon^2\rangle^{1/2}$, the dislocation density in the ECAP treated alloy was calculated by the formula employed in Refs. [16,17]: