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The grain size dependence of flow stress in an ECAPed AZ31 Mg alloy with a constant texture

Ho-Kyung Kim*

Department of Automotive Engineering, Seoul National University of Technology, 172 Kongnung-dong, Nowon-ku, Seoul 139-743, Republic of Korea

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ABSTRACT

ECAPed Mg sample with a smaller grain size showed a lower yield stress compared to a unECAPed (as-extruded) sample with a large grain due to texture modification during ECAP process. An equation for the flow stress of an ECAPed alloy with a constant texture as a function of the strain and grain size was derived to quantify the effect of the grain size on the flow stress in this alloy, assuming that 2-, 3-, and 4-passed microstructures have the same texture. According to the predicted flow stress results, the strain hardening is the largest contributor to flow stress and that the solid solution hardening and grain size refinement play relatively minor roles on flow stress in ECAPed samples.

1. Introduction

It is now well agreed that employment of Mg alloys in automobile, airplane and electronic industries is promising due to their superior specific stiffness and strength [1]. Especially, wrought Mg alloys attract attention since they have more advantageous mechanical properties than cast Mg alloys. As Mg alloys have low strength and ductility compared with aluminum alloys because of their hexagonal close packed (HCP) structure with limited slip systems, however, they have been mainly fabricated into mechanical components by die casting. Therefore, strength and ductility of Mg alloys need to be improved for their widespread consumption in industries.

Equal channel angular pressing (ECAP) is an effective method that produces a relatively large volume of bulk material with ultra-fine grains [1–3]. The ECAP process has been proven very effective in enhancing the strength of aluminum [1], steel [2] and copper [3]. This process, however, does not apply to Mg alloys despite the considerable grain refinement it entails [4,5]. For example, an ECAPed Mg sample with a relatively small grain size exhibited a lower yield stress than a unECAPed (as-extruded) sample with a larger grain size [4,5]. This result was reported to be closely related to texture modification during ECAP leading to rotation of the basal planes to the orientations favored for slip [4,5]. The basal planes in most grains are distributed parallel to the extrusion direction in the as-extruded Mg alloys [4,5]. As slip is most prone to occur on basal planes in Mg, the as-extruded alloys are expected to exhibit an increase in the yield stress when the loading axis direction is parallel to the extrusion direction. However, the basal planes in most grains were rotated to the directions oriented more favorably for slip during ECAP pressing [4,5] which caused a reduction of the yield stress even though there was grain refinement. Thus, the effect of texture on strength may prevail over the effect of grain refinement on the strength in Mg alloys with a HCP structure, as these alloys posses limited number of slip systems.

However, practically no studies have focused on quantification of the grain refinement strengthening on the flow stress of ECAPed Mg alloys. In this paper, the effect of the grain size on the flow stress in an ECAPed AZ31 Mg alloy with a constant texture is investigated. An equation for the flow stress of this alloy with a constant texture as a function of the strain and grain size was derived from experimental results. In addition, the contribution of strengthening mechanisms to the flow stress is quantified.

2. Experimental procedures

An extruded AZ31 alloy was cut into rods with a diameter of 14.5 mm and a length of 90 mm. The rod underwent a 2-h solid solution treatment at 693 K followed by quenching into tepid water. ECAP was conducted using a die with an internal angle Φ of 90° and an outer curvature angle Ψ of 30°. This die was designed to give an approximate strain ε of ∼1 upon each pressing [6]. Repetitive pressings of the same sample were carried out using the procedure designated as route B_c [6]. The first and second pressings were

* Tel.: +82 29706348; fax: +82 29797032.
E-mail address: kimhk@snut.ac.kr.

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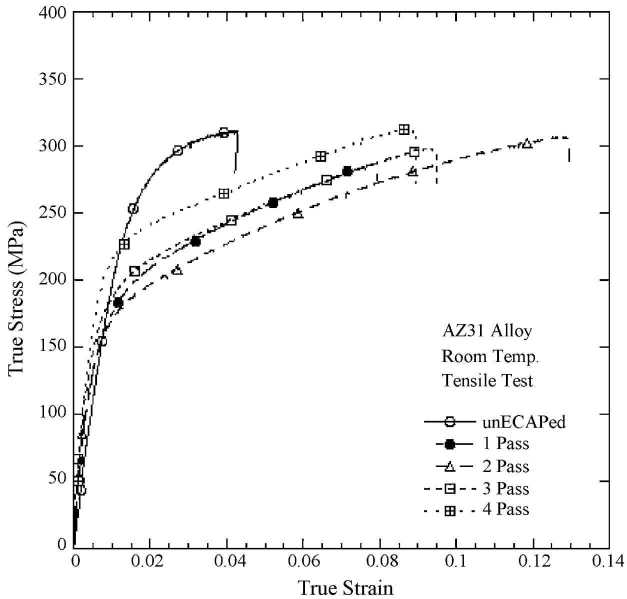

Fig. 1. True stress against true strain curves of the unECAPed and ECAPed AZ31 alloys.

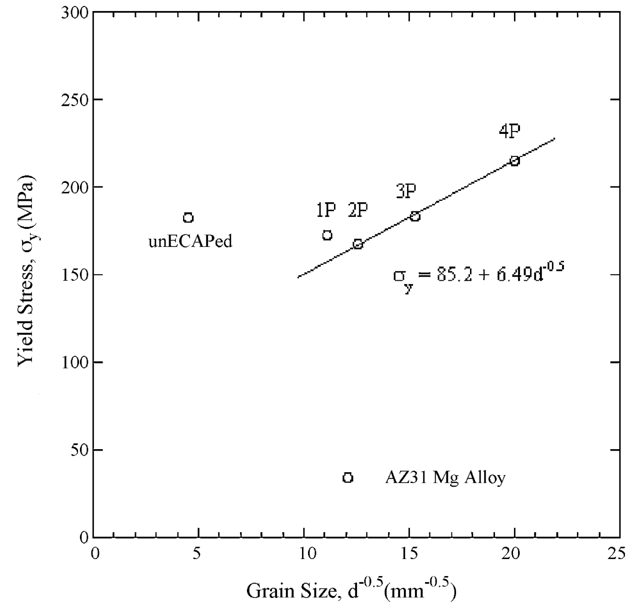

Fig. 2. 0.2% yield stress against $d^{-1/2}$ for the unECAPed and ECAPed AZ31 alloys.

conducted at 593 K, and the third and fourth pressings were conducted at the lower temperatures of 523 K and 473 K, respectively. A detailed description of the tooling is reported in the literature [7].

Tensile specimens with a gage length of 20 mm, a diameter of 4.76 mm, and a shoulder radius of 5 mm with the gauge length parallel to the longitudinal axis were extracted from the unECAPed and ECAP processed materials. A single tensile sample was machined from a single ECAPed billet. Tensile testing was conducted at room temperature under a constant cross-head speed condition (5 mm/min) on a tensile testing machine (Instron 8516). A clip-on extensometer with a gage length of 12.7 mm was attached to the test specimen at the gage section to monitor the strain. The image analysis program Matrox Inspector 2.2 was used to determine the grain size distribution and average grain size from optical micrographs by recording the sizes of more than 200 grains.

3. Results and discussion

Fig. 1 shows the true stress–strain curves of the unECAPed (=0 pass) and ECAPed AZ31 alloys from 1 pass to 4 passes. The true stress–strain curve is converted using the data from the previous work [7]. The data for the yield stress (YS), ultimate tensile strength (UTS), elongation to failure and average grain size are summarized in Table 1. The yield stresses of the ECAPed samples were lower than those of the unECAPed sample despite significant grain refinement during ECAP. This can be attributed to texture modification during ECAP, as mentioned in the previous section. Primary slip occurs on the basal plane in Mg at room temperature with limited non-basal slip activities. For pure Mg and Mg alloys, the basal planes tend to lie parallel to the extrusion direction after conventional extrusion [4,5], indicating that slip on the basal plane would be unfeasible, resulting in an increase of the yield strength, even with the larger grain size in the unECAPed samples.

In Fig. 2, a 0.2% yield stress is plotted against $d^{-1/2}$ for the unECAPed and ECAPed AZ31 alloys. The ECAPed AZ31 alloys show a negative slope between 0, 1 and 2 passes and a positive slope between 2, 3 and 4 passes. The change of the slope sign in YS observed in the results can be attributed to softening due to gradual texture transition during repeated ECAP processing as observed in the ECAPed AZ61 alloys [5,8]. Thus, it appears that the strengthening due to grain refinement is more significant compared to the softening due to texture modification after 3 passes. As mentioned previously, the negative slope of the yield stress against $d^{-1/2}$ in some ECAPed Mg materials was reported [5,8]. This behavior can be explainable by the texture transition that occurs progressively during repetitive ECAP, resulting in a lower yield stress with a smaller grain size. It is well known that the change of the yield stress in Mg alloys is dependent on both the grain size and the texture. In Fig. 2, the standard Hall–Petch relationship (positive slope) observed in the 2–4-pass ECAPed samples can be assumed that the texture remains unchanged after the 2-pass ECAP process. This assumption can be supported by observation that the texture of the ECAPed AZ61 alloy exhibiting a standard Hall–Petch relationship remains constant at different grain sizes [5,8]. In the ECAPed AZ61 alloy, the texture which favors the basal slip is reported to be not well developed and almost constant after 2–4 passes of ECAP as evidenced by relatively low maximum texture intensity. However, after 8 passes, the basal plane is reported to be more favorably oriented for slip as proved by a higher Schmid factor and the maximum texture intensity [5,8]. Thus, if the present ECAPed Mg alloys with different grain sizes exhibit the standard Hall–Petch relationship, it can be assumed that the texture of these alloys are similar as in the ECAPed AZ61 Mg alloys [5,8]. It is worthwhile to quantify the effect of the grain size on the flow stress in the ECAPed AZ31 Mg alloy by excluding the effect of texture, assuming that the 2-, 3-, and 4-passed microstructures have the same texture.

The Hall–Petch relationship correlates the grain size of a material to its yield stress. According the to Hall–Petch relationship, the yield stress σ_y of a material can be expressed as:

$$\sigma_y = \sigma_{oy} + k_y d^{-1/2} \quad (1)$$

Table 1
Average grain size and room temperature mechanical properties of the unECAPed and ECAPed AZ31 alloys.

Condition	UTS (MPa)	YS (MPa)	Elongation (%)	Grain size (μm)
unECAPed	309.8	182.5	4.3	48.3
1-Passed	286.2	172.5	8.3	8.1
2-Passed	306.4	167.5	13.8	6.3
3-Passed	298.1	183.3	10.0	4.3
4-Passed	311.2	215.3	9.4	2.5