Improvement of Mechanical Characteristics in Severely Plastic-deformed Mg Alloys

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The commercial pure Mg, AZ31 and AZ61 alloys were severely plastic-deformed through equal channel angular pressing (ECAP). The grain size of pure Mg was decreased from 400 to 80 µm after ECAP and the 4 ECA pressed AZ31 alloy revealed the mixed microstructure of fine grains of less than 5 µm and coarser grains of approximately 5 ~ 10 µm. Newly formed grains were attributed to dynamic recrystallization during ECAP at temperatures of higher than 1/2 T_m, where T_m is melting temperature. There was small increase of microhardness, yield stress and tensile strength in the ECA pressed pure Mg, while those of AZ31 and AZ61 alloys drastically increased after 1 pressing. The yield stress in the ECA pressed AZ31 and AZ61 alloys gradually decreased with increasing the number of pressings, but the tensile strength increased slightly. In particular, there was a typical tensile characteristic when compared with the other ECA pressed metals; a marked improvement in elongation was found concurrent with the pronounced strain hardening, without sacrificing the tensile strength, in the 4 ECA pressed AZ31 and AZ61 alloys. These tensile deformation characteristics were explained based on the observation of the deformed microstructure in the vicinity of fracture surface.

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1. Introduction

Mg alloys have become attractive as a light and highly efficient eco-material for high performance applications such as the components of automobile and electronics because of their low density, high specific strength, relatively excellent dent resistance, damping capacity and shield capacity of electromagnetic waves when compared with plastics and Al alloys. However, they have poor plastic workability due to limited slip systems available only on basal plane in hexagonal close packed (hcp) crystal structure, limiting to the expanded applications. Therefore, most of Mg alloy components have been fabricated by casting method. If the poor plastic workability is improved, the further applications of Mg alloys can be expected.

In order to improve the poor plastic workability in Mg alloys, the change of crystal structure by addition of Li¹,²) and the grain refining by additional elements 3,4) have been attempted. However, these ways depend strongly on the chemical composition of alloys, leading to the limitation of improvement of workability. Recently, it has been known that the improvement of workability can be obtained concurrent with drastically increased strength, without adding the additional elements, by the grain refining through severe plastic deformation (SPD) techniques. Among SPD techniques, particularly, the ECAP has been well used to obtain the bulk ultra-fine grained materials without residual porosity and volume change.⁵,⁶) However, the limited approaches have been attempted for Mg alloys.⁷-¹⁰)

Yamashita et al.⁸) showed that grain refining by ECAP increased strength in pure Mg and Mg alloy containing 0.9% AI. For a commercial AZ91 alloy, Mabuchi et al.⁷) reported that ultra-fine grains were obtained by the ECAP. In addition, Yoshida et al.⁹) showed the substantial increase of strength in commercial Mg alloys after ECAP. However, it is generally difficult to attain the high ductility without sacrificing strength in grain-refined Mg alloys. Therefore, the aim in this study is to manifest tensile deformation characteristics of the ECA pressed Mg alloys to achieve high toughness much higher than that which be expected in commercial Mg alloys.

2. Experimental Procedure

The commercial pure Mg, AZ31 and AZ61 alloys (Mg-3, 6%Al-1%Zn (in mass%), respectively) were supplied in the form of cast ingots. The ingots of AZ system alloys were solution-treated at 693 K for 16 h and hot-rolled under a condition of rolling ratio of 20% at 673 K, followed by annealing at 693 K for 1 h. Cylindrical samples of φ18 mm × 130 mm and φ10 mm × 130 mm were prepared from the ingots, as stating materials for ECAP of pure Mg and AZ system alloys, respectively. The ECAP was carried out using route C and a press speed of 2 mm s⁻¹ at 573 K (pure Mg), 493 K (AZ31) and 523 K (AZ61). Much information for ECAP adopted in this study has been previously report-ed.¹⁰,¹¹)

Microhardness was measured using a vickers microhardness tester at a load of 0.05 kg for 15 s. Tensile tests were carried out using the tensile specimens with 25 mm in gauge length at the initial strain rate of 1.00 × 10⁻³ s⁻¹ at room temperature. In this study, tensile strength was comparable to fracture strength. Microstructures of samples were examined with an optical microscope (OM) and a transmission electron microscope (TEM) utilizing a JEOL 2010 operated at 200 kV. In particular, the microstructure of Y and Z planes in the vicinity of fracture surface in samples after tensile test was observed with OM and a field emission scanning electron microscope (FE-SEM); where the Y and Z planes denote the planes parallel and perpendicular to the longitudinal axis of the sample, respectively.

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3. Results and Discussion

3.1 Microstructural characteristics

Microstructure of as-ECA pressed pure Mg is shown in Fig. 1. The initial grain size of pure Mg supplied in the form of cast ingots was approximately 400 \( \mu m \). The grain size decreased to approximately 80 \( \mu m \) after 1 ECAP, and it remained unchanged until 4 ECAPs. Distinct grain boundaries were observed, indicating the occurrence of dynamic recrystallization during ECAP. In addition, twinning was observed in the grain interior. Figure 2 shows typical microstructures of as-ECA pressed AZ31 alloy. The average grain size of as-annealed AZ31 alloy before ECAP was approximately 200 \( \mu m \). The single ECA pressed AZ31 alloy showed no uniform microstructure of locally large grains above 10 \( \mu m \). However, there exist fine grain (\( < \sim 5 \mu m \)) region and coarser grain (approximately 5 \( \sim 10 \mu m \)) region with a volume fraction of \( \sim 50\% \) in the 4 ECA pressed AZ31 alloy, which was similar to the bimodal microstructure, unlike the reports that equiaxed ultra-fine grains of \( \sim 0.3 \mu m \) in the Al alloys and Fe alloys were introduced by 4 repetitive ECAPs.\(^{11-15} \) This is attributed to the dynamic recrystallization and grain growth during the ECAP at temperature of higher than 1/2 \( T_m \), where \( T_m \) is melting temperature.

Typical TEM micrographs of as-ECA pressed pure Mg are shown in Fig. 3. The subgrain bands parallel to shear direction were observed in pure Mg after 1 ECAP, which were much wider than those formed in FCC and BCC materials, \( >0.2 \mu m \).\(^{15-17} \) In addition, the SAD pattern indicates that the subgrain boundary would be low-angled. The dislocation density, as observed in the pure Mg when compared with Al alloys\(^{18} \) after ECAP, was relatively low. On the other hand, it was previously reported\(^{10} \) that the microstructure characteristics in pure Mg after 1 ECAP remained unchanged after 4 repetitive ECAPs, unlike the FCC and BCC materials\(^{15-17} \) and the dislocations within bands were of basal and non-basal slips characteristics. In addition, the twinning on \{10\overline{1}2\} plane occurred in the 4 ECA pressed pure Mg, as indicated by arrow drawn in Fig. 3(b). Figure 4 shows TEM micrographs of as-ECA pressed AZ31 alloy. The AZ31 alloy after 1 ECAP revealed the microstructure of the elongated band parallel to the shear direction. No twinning was observed and the dislocations were of basal and non-basal slips characteristics from the corresponding SAD pattern. However, the dislocation density was much reduced after 4 ECAPs (Fig. 4(b)) and the microstructure was similar to that of the reannealed Al alloys after ECAP.\(^{11} \) It has been previously known that the unclear
grain boundaries in severely plastic-deformed metallic materials include many facets and steps of regular or irregular alignment, and the lattices near grain boundaries are severely distorted. Additionally, the extrinsic dislocation density is high in the grain boundaries, leading to the drastic increase of grain boundary energy. Such grains with non-equilibrium grain boundaries could have pronounced experience of the dynamic recrystallization and grain growth during repetitive ECAP at the higher half of melting temperature, $T_m$.

3.2 Micro hardness and tensile deformation behavior

The microhardness, tensile strength, yield stress and elongation of as-ECA pressed pure Mg are summarized in Table 1. There was a slight increase of less than 20% in microhardness, tensile strength and yield stress without sacrificing elongation. And also, the microhardness of AZ31 and AZ61 alloys revealed drastic increase after single pressing and it was nearly constant with the number of pressings as shown in Fig. 5. This phenomenon is well comparable to other ECA pressed metals.

In addition, the yield stress and tensile strength of AZ31 and AZ61 alloys, as observed for the stress-strain curves shown in Fig. 6, drastically increased after single pressing.
This is well known to be attributed to the work hardening that is caused by the formation of subgrain bands and the increase of dislocation density occurring with the shear deformation in the initial grain interior.\textsuperscript{11,12,20} Such microstructural characteristics were also shown in this study (Fig. 4(a)). The yield stress gradually decreased with increasing the number of pressings, which was considered to be due to the reduced dislocation density with the number of pressings as shown in Fig. 4, while the tensile strength became slightly high. In particular, nearly 3 times higher elongation when compared with that of as-annealed one was found concurrent with pronounced strain hardening, with satisfying the strength, in the 4 ECA pressed alloys. These phenomena stand in stark contrast to the behavior of conventional materials and the ECA pressed materials.

As shown in Fig. 7, it was found that the deformed...
the pronounced strain hardening. Such concurrent matrix of nano-sized grains. In addition, nano-crystalline Ni consisting of micrometer-sized grains embedded inside a uniform elongation was found, without sacrificing much of grains. Recently, Koike et al. reported that in Mg alloys with fine grains of less than approximately 10 μm introduced by ECAP the cross slip on non-basal plane as well as basal slip were activated through grain interior during only 2% deformation. In addition, they clarified that the recovery and grain boundary sliding occurred even at room temperature, which contributed to approximately 8% of total amount of deformation. This indicates that at least the fine grains play an additional role in the uniform deformation for high ductility.

Wang et al. reported that a marked improvement in uniform elongation was found, without sacrificing much of strength, in pure Cu with the bimodal microstructure consisting of micrometer-sized grains embedded inside a matrix of nano-sized grains. In addition, nano-crystalline Ni with a bimodal microstructure was recently known to exhibit the pronounced strain hardening. Such concurrent strengthening and toughening, as also observed for the 4 ECA pressed AZ31 and AZ61 alloys when compared with as-annealed one, could be attributed to the fine grains that reduce the size of nucleating defects and increase the resistance to crack propagation, leading to the higher fracture stress, and the larger (softer) grains that might accommodate strains preferentially. Consequently, the inhomogeneous mixed microstructure induces the strain hardening mechanisms that stabilize the tensile deformation accompanied with grain boundary sliding, leading to the high tensile ductility.

4. Conclusions

The microstructure and mechanical characteristics of severely plastic-deformed commercial Mg alloys through ECAP were investigated. The grain size of pure Mg was decreased from 400 to 80 μm after ECAP. In particular, the 4 ECA pressed AZ31 alloy revealed the mixed microstructure consisting of the recrystallized fine grains of less than 5 μm and coarser grains of approximately 5 ~ 10 μm. TEM micrographs of the ECA pressed AZ31 alloy revealed the dislocation characteristics on basal and nonbasal planes. However, the dislocation density was much reduced in the 4 ECA pressed one. There was small increase of microhardness, yield stress and tensile strength in the ECA pressed pure Mg, while those of AZ31 and AZ61 alloys drastically increased compared with those of as-annealed ones after ECAP. The yield stress in the ECA pressed AZ31 and AZ61 alloys gradually decreased with increasing the number of pressings, but the tensile strength increased slightly. In particular, a marked improvement in elongation was found concurrent with the pronounced strain hardening, without sacrificing the tensile strength, in the 4 ECA pressed AZ31 and AZ61 alloys. The inhomogeneous mixed microstructure, which induces the strain hardening mechanisms that stabilize the tensile deformation, was maintained to failure in the 4 ECA pressed AZ31 alloy, leading to the marked improvement in elongation.

REFERENCES