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THE TEXTURE STRENGTHENING EFFECT IN A MAGNESIUM ALLOY PROCESSED BY SEVERE PLASTIC DEFORMATION

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Abstract. It is well-known that plastic deformation of hcp-metals leads to both grain refinement and development of crystallographic texture. As a result, enhancement of mechanical properties and their significant anisotropy can be expected. In this work the microstructure of the magnesium alloy Mg-6%Al-0.5%Zn-0.13%Mn has been investigated using transmission electron microscopy, X-ray diffraction and optical microscopy. Mechanical properties have been studied using tensile tests. For the sake of comparison, the samples were subjected to both equal channel angular pressing (ECAP) with additional rolling and hot compression.

1. INTRODUCTION

It is known that magnesium alloys are used as lightweight materials with high strength-to-weight ratio in automotive and aerospace industry. However, most of lightweight components from coarse grained magnesium alloys are produced by casting in order to avoid problems with low ductility leading to poor formability. At the same time, it is well recognized that the formability of metallic materials can be essentially improved by grain refinement down to a grain size of less than 1 mm [1]. Recently it has been demonstrated that processing by equal channel angular pressing (ECAP) can be used to successfully produce bulk UFG metals and alloys [2], thereby providing a potential for achieving the enhanced mechanical properties [3]. For example, significant grain refinement down to 0.5–1 μm was observed in several magnesium alloys processed by ECAP [4,5], in particular in the commercial AM60 magnesium alloy [6,7].

At the same time the grain refinement should lead to increase of a number of grains with favorable orientation of the crystal lattice for development of basal slip. In addition one can expect the strong crystallographic texture and corresponding anisotropy of mechanical properties after grain refinement by equal channel angular pressing [8].

Application of ECAP to materials with a hexagonal close-packed (hcp) lattice leads not only to grain refinement but also to formation of basal texture (0001) [9]. In this case the mechanical properties of magnesium alloys will depend on both the grain size and crystallographic texture contributing to strengthening or softening of material.

The aim of this work is to study the effect of both the grain refinement and crystallographic texture on the mechanical properties of the magnesium alloy subjected to various treatments including ECAP, warm rolling and hot upsetting.

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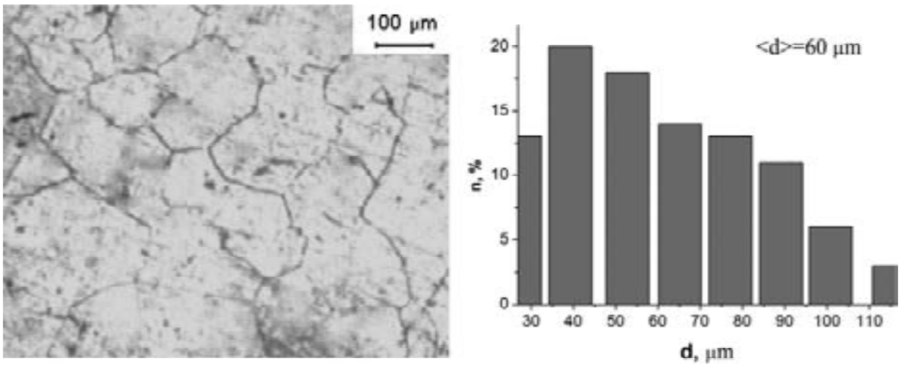


Fig. 1. Initial microstructure of the magnesium alloy.

Table 1. The treatment regimes for the magnesium alloy.

Treatment	n_{ECAP}	$n_{rolling}$	T_{treatm}, °C	e_{Σ}	$T_{rolling}$, °C
Compression 30%	0	—	350	0.35	—
8 ECAP passes	8	—	350 + 300	3.2	—
12 ECAP passes	12	—	350 + 300 + 210	7.2	—
12 ECAP passes + rolling	12	16	350 + 300 + 210	8.5	300

2. MATERIALS AND EXPERIMENTAL PROCEDURE

Cast billets of the magnesium alloy Mg – 6%Al - 0.5%Zn – 0.14%Mn were selected as initial material for investigations. Homogenization at 415 °C for 14 hours with subsequent quenching was used to produce both supersaturated solid solution and coarse-grained structure with a grain size of 60 µm (Fig. 1).

Upsetting of cylindrical billets of ∅20×30 mm with the coarse grained structure was performed under uniaxial compression at a temperature of 350 °C.

Quenched samples of 40 mm in diameter and 150 mm in length were pressed through the ECAP die containing two channels (circular in cross-section) intersecting at an angle of 120%. The ECAP was carried out via the route B_C at temperatures of 350 °C (4 passes), 300 °C (additional 4 passes), and 210 °C (additional 4 passes).

The billets processed by 12 ECAP passes were subjected to rolling at 300 °C with reduction of 50% and subsequent rolling at room temperature to a thickness of 3 mm.

Table 1 illustrates the treatment details for the samples selected to investigations their microstructure and mechanical properties.

Microstructural changes associated with the ECAP processing at different temperatures and additional treatments were investigated by an optical microscope Olympus and a transmission electron microscope JEM-100B. To prepare TEM foils, discs with a diameter of 3 mm were cut from the ECAP-processed samples of 0.15 mm in thickness and subjected to twin-jet electropolishing on Tenupole-5.

X-ray diffraction analysis of the phase composition was carried out on a DRON-4 diffractometer using CuK_{α} radiation and graphite monochromator. Texture investigations were performed on a Rigaku diffractometer with a goniometer focused according to the Bragg-Brentano method and equipped with an automatic texture device. Bragg reflections were scanned in the radial angular spacing from 10 to 90 degrees and in the azimuth interval from 0 to 360 degrees. The experimental data obtained for incomplete pole figures were processed by a software package provided by a supplier.

The specimens with a gage length of 4mm and a cross-section of 1.0×0.4 mm were subjected to tensile tests at room temperature and a constant strain rate of 10^{-3} s^{-1}.

Misorientations of grain boundaries were examined in a Quanta 600 scanning election microscope equipped with an electron back scattering diffraction (EBSD).

3. RESULTS AND DISCUSSION

The alloy after homogenization has the coarse-grained structure with the mean grain size of 61

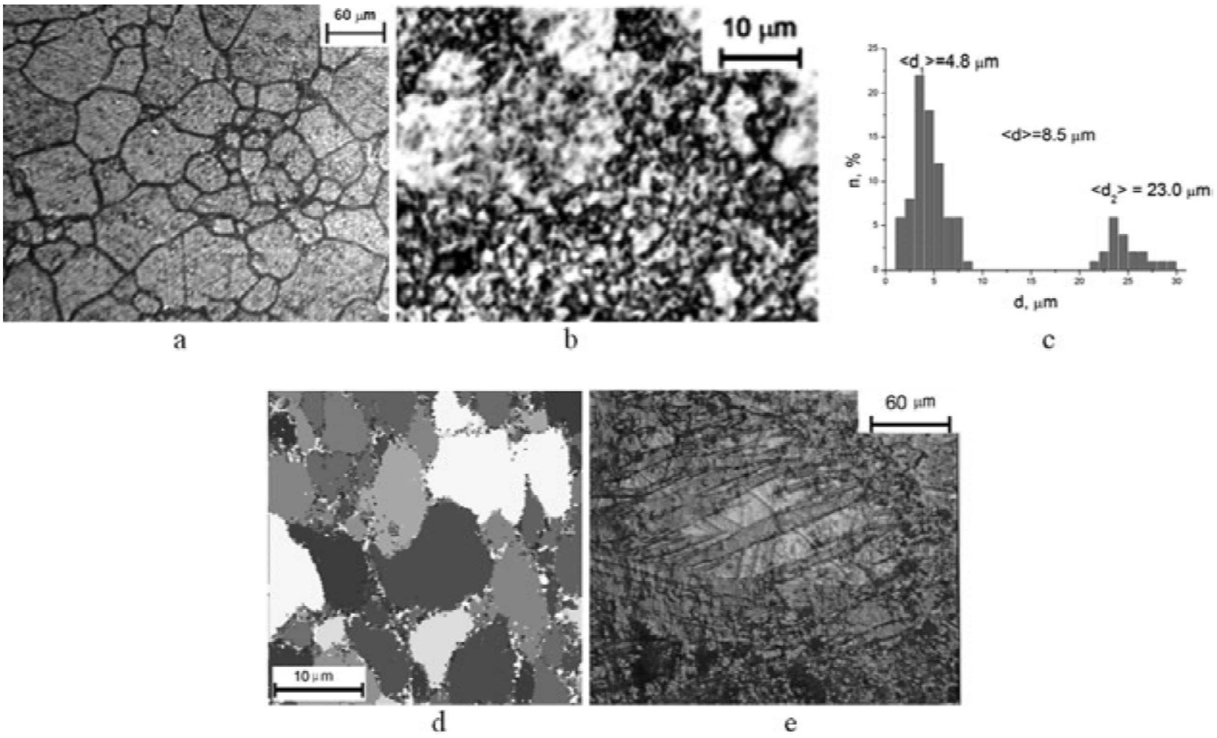


Fig. 2. Microstructure of the magnesium alloy subjected to: (a) 8 ECAP passes; (b,c) 12 ECAP passes; (d) 12 ECAP passes with additional rolling; (e) hot compression.

mm. The equiaxed grains with a size of 23 μm in both the cross section and longitudinal direction were observed after 8 ECAP passes (Fig. 2a). The microstructure after 12 ECAP passes was bimodal, with two peaks at 23 μm and 4.8 μm on the grain size distribution (Fig. 2b). The average grain size in this sample was about 8.5 μm, whereas the additional rolling led to the mean grain size of 3.6 μm (Fig. 3c).

For the sake of comparison, numerous twins inside coarse grains were a typical feature of the microstructure in the alloy subjected to upsetting at a temperature of 350 °C (Fig. 2d).

Precipitates of γ-phase $Mg_{17}Al_{12}$ were detected in the alloy processed by 12 ECAP passes (Fig. 3). Appearance of the corresponding X-ray diffraction peaks indicated that additional rolling did not lead to dissolution of precipitates, which were observed as small particles with a size of 0.4 μm in the TEM micrographs**.**

The texture evolution in terms of (0001) pole figures for the samples subjected to ECAP is demonstrated in Fig. 4. To the right of pole figures, one can see diametrical sections convenient for comparison of pole densities. Directions TD (toward direction), ED (extrusion direction), ND (normal direction) are shown to the left of pole figures. The EBSD investigation results of the alloy subjected to 12 ECAP passes are presented as well for estimation of crystallographic orientations.

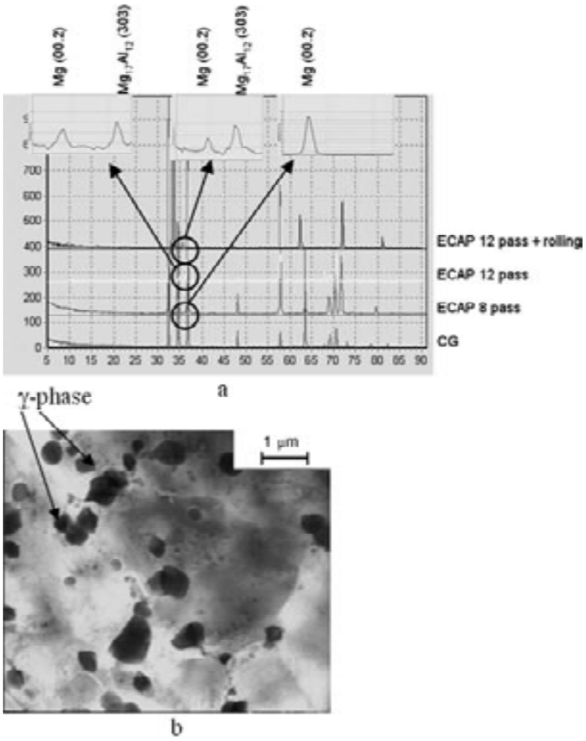
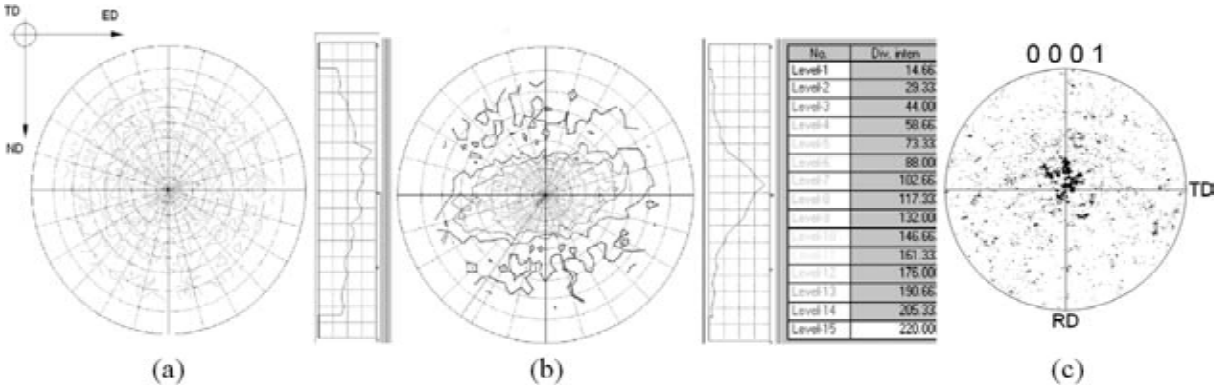


Fig. 3. (a) X-ray analysis of the magnesium alloy subjected to various treatments; (b) precipitates after 12 ECAP passes and rolling (b), TEM.



(a) (b) (c)

Fig. 4. (1010) pole figures for the magnesium alloy after: (a) 8 ECAP passes, (b) 12 ECAP passes illustrating the (1010) texture; (c) EBSD analysis indicating to sharp basal microtexture in the rolling direction for the sample subjected to ECAP and additional rolling.

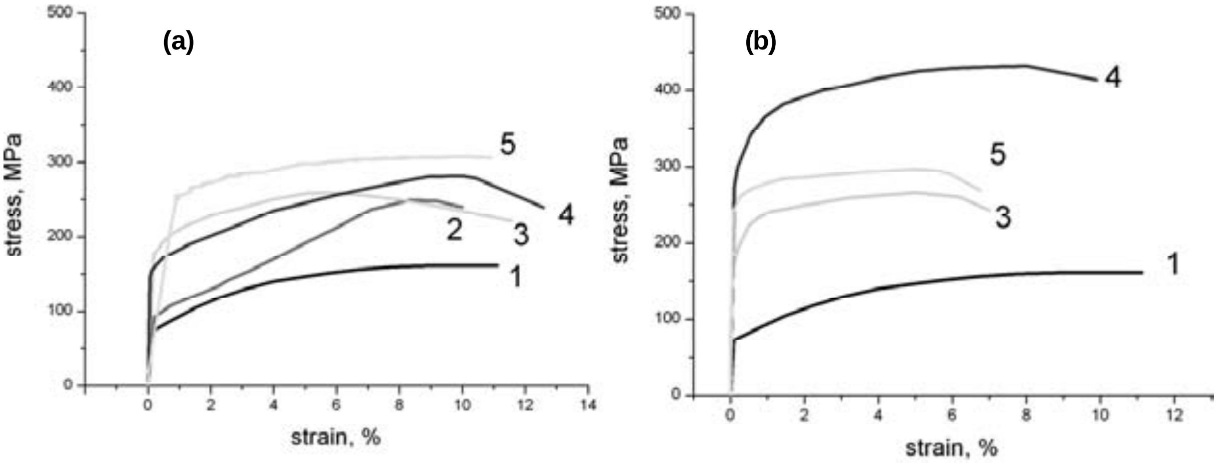


Fig. 5. Stress-strain curves for the magnesium alloy for longitudinal section (a) and cross section (b) after: (1) homogenization; (2) compression to 30%; (3) 8 ECAP passes; (4) 12 ECAP passes, (5) 12 ECAP passes + rolling.

After the tensile tests increase in the ultimate tensile strength (UTS) in all the investigated samples was observed (Fig. 5, Table 2). At the same time there is strong anisotropy of mechanical properties between the cross section and the longitudinal direction. For example, the UTS in the samples subjected to 12 ECAP passes was equal to 430 MPa and 285 MPa, respectively, with the ductility of 10% and 13%.

The strengthening effect of the alloy after uniaxial compression is conditioned obviously by appearance of new deformation twins. It should be noted that the influence of twins on enhancement of strength, for example, in copper was investigated earlier and reported in numerous papers [10].

The strength after 8 ECAP passes is 10-15 MPa higher in comparison with that in the samples subjected to hot compression. It means that strength-

Table 2. Mechanical properties and average grain size after various treatments.

State		YS, MPa		UTS, MPa		δ, %		<*d*>, μm
		long	cross.	long	cross.	long.	cross.	
CG	1	80	80	160	160	11	11	60±3.0
Compression 30%	2	95	-	240	-	10	-	60±3.0
8 ECAP passes	3	180	170	260	265	10	7	23±1.5
12 ECAP passes	4	160	310	285	430	13	10	8.5±0.5
12 ECAP passes + rolling	5	260	240	300	300	7	12	3.6±0.3

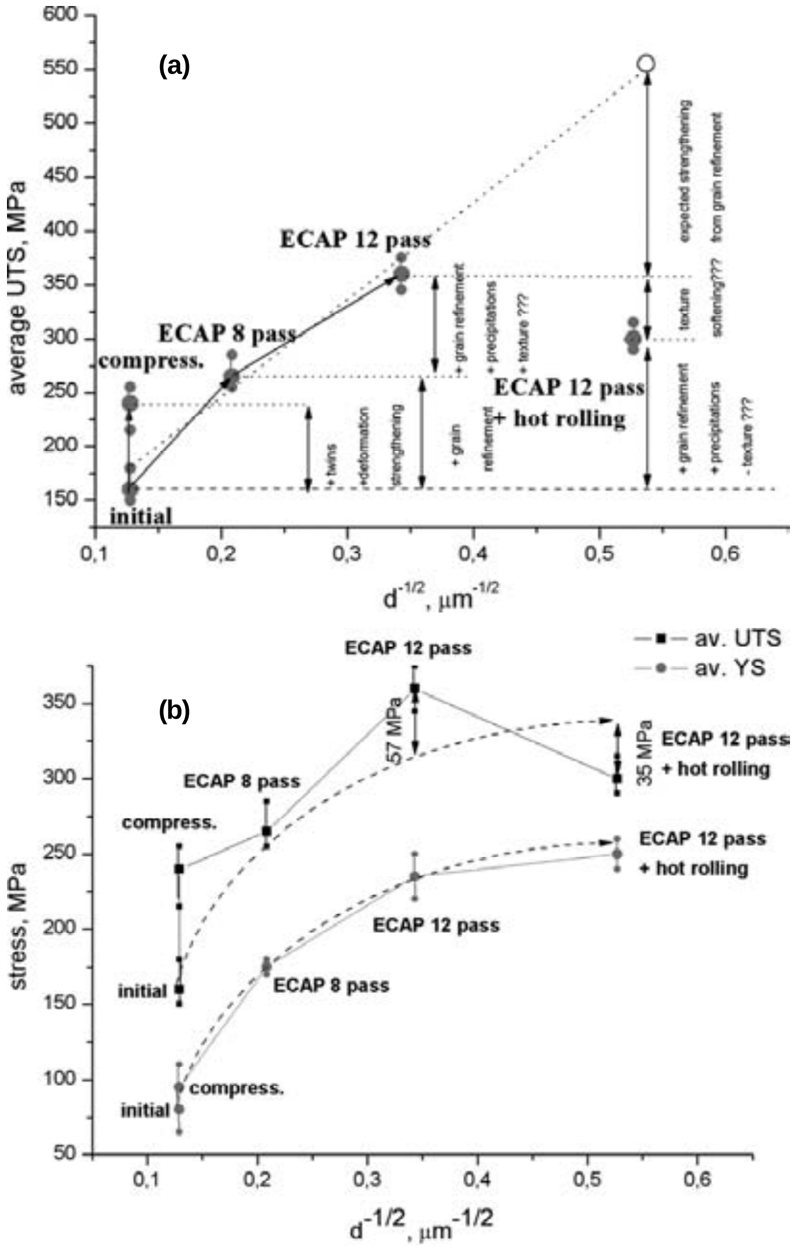


Fig. 6. (a) The UTS dependence on the parameter $d^{-1/2}$ for the magnesium alloy subjected to various treatments; (b) comparison of the UTS and the YS.

ening due to grain refinement to 23 µm has the same effect to be compared with strengthening caused by twins.

The alloy after 12 ECAP passes has demonstrated the highest strength and strong anisotropy, which is a result of grain refinement and texture formation. The ultimate tensile strength in the longitudinal direction after 12 passes is lower, than that after 8 passes, which testifies to favorable plane orientations for basal slip in the material volume. The highest ultimate tensile strength of 430 MPa in the investigated alloy has been achieved due to “texture strengthening” observed earlier in other alloys with a hexagonal crystal lattice [10].

It should be noted, that further grain refinement of the alloy by rolling leads to decrease of the tensile strength due to formation of conventional rolling texture [8].

Fig. 6 displays the dependence of the UTS on the parameter $d^{-1/2}$, where d is the average grain size, to analyze contribution of various mechanisms to material strengthening after various treatments. Obviously, twinning and enhanced dislocation density make main contributions to strengthening of coarse-grained alloy after compression. According to the structural investigation results (Fig. 2), grain refinement to 23 µm leads to strengthening according to the Hall-Petch relationship. Additional increase in the yield stress (YS) in the sample subjected to 12 ECAP passes is caused by dispersion hardening due to $Mg_{17}Al_{12}$ precipitates (Fig. 3) and formation of prismatic texture (Fig. 4). Additional rolling leads to softening of the ECAPed samples due to coarsening of precipitates and formation of basal texture.

Fig. 6a demonstrates that there is approximate linear relationship between the UTS and parameter $d^{-1/2}$ for the coarse-grained sample and the samples subjected to 8 and 12 ECAP passes. The dotted line drawn through these experimental points indicates the strengthening of 520-540 MPa for the sample with a grain size of 3.6 μm observed after additional rolling. However, the experimental value of the UTS was 200 MPa lower, probably as a result of both coarsening of precipitates and formation of basal texture.

Another approach for analysis of the strengthening mechanisms can be based on comparison of differences between the UTS and YS (Fig. 6b). For example, the red line fits with the yield stress for all the investigated samples. By shifting the red line to the point corresponding to UTS of the initial material, we can analyze the contribution of deformation mechanisms. In particular, after 8 ECAP passes the UTS fits with the corresponding black dashed line. After 12 ECAP passes the UTS increases by 57 MPa, and it decreases by 35 MPa after additional rolling. One can note that contribution of dispersion hardening in the Mg-Al alloys usually is less than 40 MPa. Therefore softening after additional rolling is caused by coarsening of precipitates and appearance of rolling texture. Taking into account that softening after additional rolling is equal to 92 MPa, we have that the texture strengthening after 12 ECAP passes is about of 50 MPa.

4. CONCLUSIONS

1. Equal channel angular pressing (ECAP) of the magnesium alloy Mg - 6%Al - 0.5%Zn - 0.14%Mn allows reducing the mean grain size from 60 to 8.5 mm and leads to formation of strong crystallographic texture.

2. As a result of both the grain refinement and crystallographic texture after 12 ECAP passes one can observe the strong anisotropy of mechanical properties with UTS of 285 MPa and 430 MPa in the longitudinal and cross sections, respectively. Softening of material in the cross section to UTS of 300 MPa in spite of the smaller grain size of 3.6 μm has been observed after additional rolling due to formation of conventional texture.

3. Coarsening of the $Mg_{17}Al_{12}$ particles up to 0.5 mm during ECAP processing at elevated temperatures is responsible for their low contribution to ultimate tensile strength of the alloy.

4. Production of ultrafine-grained billets with specific texture including axial and rolling components is a promising approach for achievement of enhanced mechanical properties in magnesium alloys.

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