CHANGES IN MECHANICAL PROPERTIES OF AS-CAST MAGNESIUM ALLOY AZ91 AFTER EQUAL CHANNEL ANGULAR PRESSING

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Resume

This paper deals with differences in mechanical characteristics of AZ91 magnesium alloy in the as-cast state and after the subsequent equal channel angular pressing (ECAP) and with measurement of local microhardness. According to the obtained results, the tensile properties increased by a factor of two due to the ECAP procedure. The proof stress, $\sigma_{0.2}$, increased to 160 MPa and the ultimate tensile strength, σ_{UTS}, to 321 MPa. The local microhardness of ECAPed alloy varied between 70 and 91 HV 0.025 due to microstructural bimodality.

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1. Introduction

Magnesium and its alloys as one of the lightest structural material seem to be suitable for application in industries where weight reduction is required. In fact, the properties of magnesium alloys in their most common as-cast state are not sufficient for many advanced applications [1]. In many cases, theconventional extrusion of magnesium alloys leads to satisfactory properties. However, a further grain refinement is required for special applications.

One of the possible ways is processing via severe plastic deformation (SPD) methods. One of the most used processing method is equal channel angular pressing (ECAP). This method provides homogenous microstructure of processed alloy and whole process of grain refinement can be very well controlled [2, 3, 4].

Although ECAP provides further grain refinement compared to conventional methods (e.g. extrusion), mechanical properties enhancement is not always guaranteed. The final properties are dependent on various factors, such as the initial state of the material or type of the alloy [5, 6]. Resulting mechanical characteristic is usually attributed to specific texture in the particular material [6].

Even though ECAP leads to mostly homogenous microstructures, the final microstructure often exhibits certain degree of bimodality depending on the processing conditions and specific material [4, 7, 8]. This bimodality leads to significant differences between local material properties and causes differences in the local response to mechanical loading. It can be postulated that plastic deformation in larger grains is easier contrary to areas of smaller grains which are rather resistant to plastic deformation [9].

This paper deals with enhancement of the tensile properties of as-cast magnesium alloy AZ91 after subsequent ECAP and with differences between the overall and local microhardness HV 0.025 of the alloy in the ECAPed state.

2. Material and experimental methods

AZ91 magnesium alloy with chemical composition given in Table 1 in as-cast state was used in this work. The evaluated alloy was processed by ECAP in Ufa State University laboratory, Russia. The material was prepared by six passes through ECAP die at 300 °C using B_C route, the angle between intersecting die channels was of 120°. Material after ECAP processwas machined into cylindrical billets with diameter of 15 mm and length of 100 mm. Metallographic analysis was performed using light optical microscope Zeiss Axio Observer Z1.m. Samples for tensile tests were machined from billets so their longitudinal axis was identical with the ECAPed billets axis. Dimensions of the gauge length of the cylindrical testing specimens were of ∅ 6 mm × 30 mm. The tensile tests were performed using Zwick Z250 testing machine at room temperature with loading speed 2 mm/min. Microhardness was measured using Leco LM 247AT hardness tester. Different loads for hardness measurement were used, 0.05 kg (HV 0.05) for measurement of overall microhardness and 0.025 kg (HV 0.025) for measurement of microhardness in individual grains. For microstructural analysis at higher magnification, determination of grain size (EBSD), chemical microanalysis of particles (EDS analysis) and fractographic analysis on specimens failed during the tensile test for both states the analytic system Zeiss Ultra Plus (SEM) was used.

3. Results

The microstructure of the investigated alloy in the as-cast state exhibited typical features of a cast material (in this case dendrites in Fig. 1a) with eutectics along grain boundaries of solid solution (Fig. 1b) with grain size of about 500 μm. The bimodal microstructure after ECAP consisted of fine grains (usually less than 5 μm in diameter) in areas rich in $Mg_{17}Al_{12}$ phase (Fig. 2a – dark areas) and of areas with coarse grains (more than 15 μm in diameter) practically without $Mg_{17}Al_{12}$ particles (Fig 2a – light areas, Fig. 2b – solid arrows). The average grains size determined by EBSD was 6.1 μm. The material in both states also contained relatively large amount of manganese-based particles (determined by EDS analysis) homogenously distributed through the whole volume of samples (Fig. 2b – dashed arrow).

Fig. 3 shows typical engineering stress-strain curves (tensile testing at room temperature) for the analyzed alloy, in the as-cast state, and after the ECAP process. The obtained results (average values determined from three tensile tests) are summarized in Table 2. The mechanical properties of the as-cast material, i.e. $\sigma_{0.2}$ proof stress and the ultimate tensile strength were 87 MPa and 168 MPa respectively. The elongation of the as-cast alloy reached 3.1%. The ECAPed alloy exhibited a significant increase of all the measured properties; $\sigma_{0.2}$ proof stress of 160 MPa, ultimate tensile strength of 321 MPa, and elongation of 15.6%. The reduction of area was 5.1% for as-cast alloy and 14.3% for ECAPed alloy.

The microhardness was 64 HV 0.05 for the as-cast alloy and 89 HV 0.05 for the material after ECAP process. The specific values for the corresponding state of the alloy were determined as an average value from linear indentation measurements, each consisting of fifty imprints spanning all different microstructural areas. The local microhardness of the ECAPed alloy was measured in selected areas with fine grain clusters and in the areas of coarse grains. The microhardness of the fine grain areas obtained from three individual measurements was of 91 HV 0.025, while the microhardness of the coarse grains reached value of 74 HV 0.025. It is necessary to note that the area fraction of coarse grained regions was 20 % only.

Fracture surfaces of the samples failed during the tensile test were analyzed by means of SEM. In the case of the as-cast samples, the fracture surface consisted of transgranular, quasi-cleavage fracture in which the cleavage planes and tearing edges appeared (Fig. 4a). Observation using higher magnification has shown that the ductile dimples are tiny and shallow (Fig. 4b).

The material after six ECAP passes exhibited more ductile fracture. The fracture surface consisted of tiny and shallow dimples of substantial larger amount in comparison with the as-cast state, while the presence of cleavage planes/facets was rather poor (Fig. 5).

Table 1

Chemical compositions of the analyzed alloy in wt. %.

	Al	Zn	Mn	Si	Fe	others	Mg
AZ91	8.700	0.650	0.250	0.006	0.003	0.002	balance

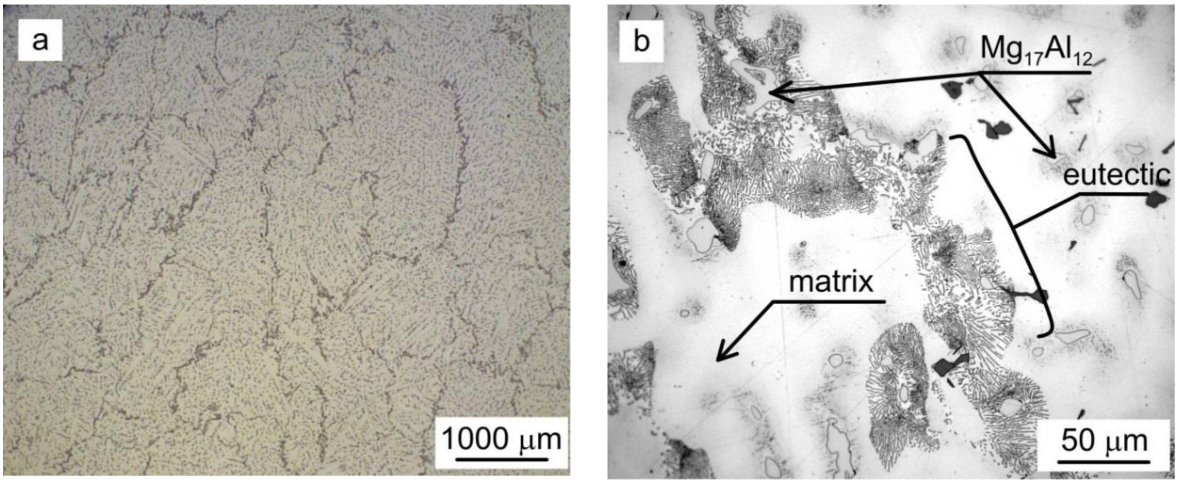

Fig. 1. Microstructure of the as-cast alloy, a) typical microstructure, b) detail of the eutectic.
(full colour version available online)

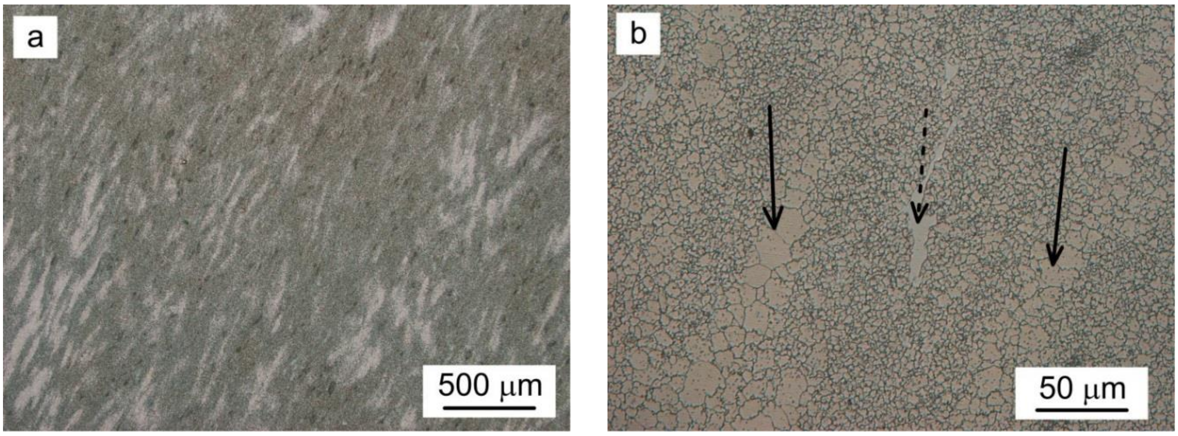

Fig. 2. Microstructure of ECAPed alloy, a) longitudinal plane, b) detail of bimodal area – longitudinal plane.
(full colour version available online)

Table 2

Grain size and mechanical properties at room temperature (average values).

State of material	Average grain size (μm)	Proof stress $\sigma_{0.2}$ (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Reduction of area (%)	Microhardness (HV 0.05)
as-cast	>500	87	168	3.1	5.1	64
ECAPed	6.1	160	321	15.6	14.3	89

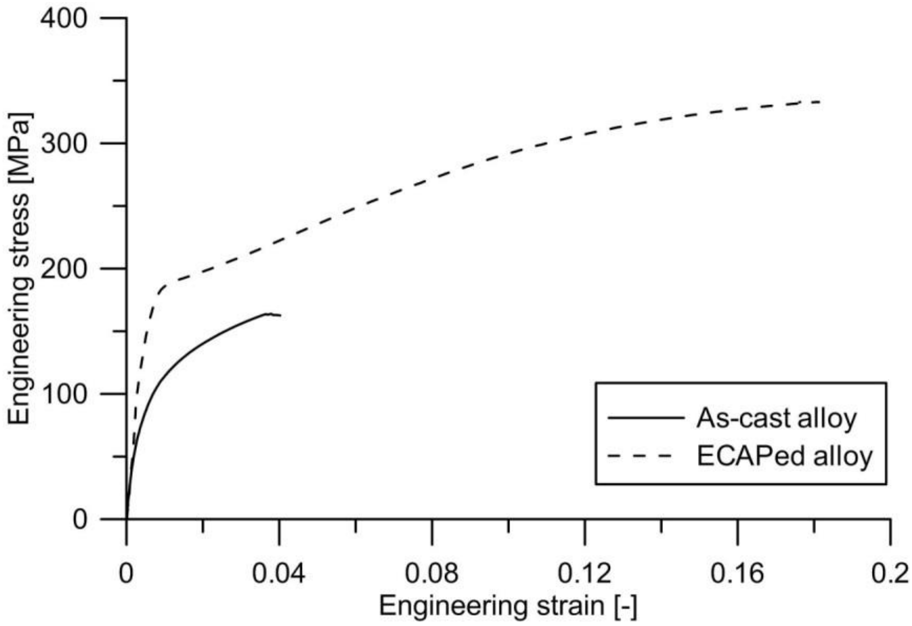

Fig. 3. Engineering stress-strain curves of the samples tested at room temperature [9, 10].

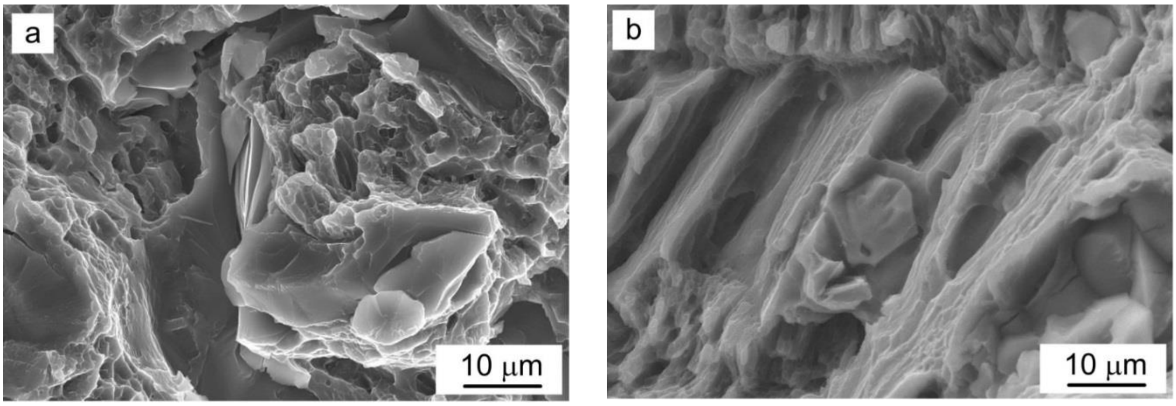

Fig. 4. Fracture surface of as-cast specimen failed during the tensile test a) quasi-cleavage fracture micromechanism, b) detail of shallow dimples close to cleavage facets.

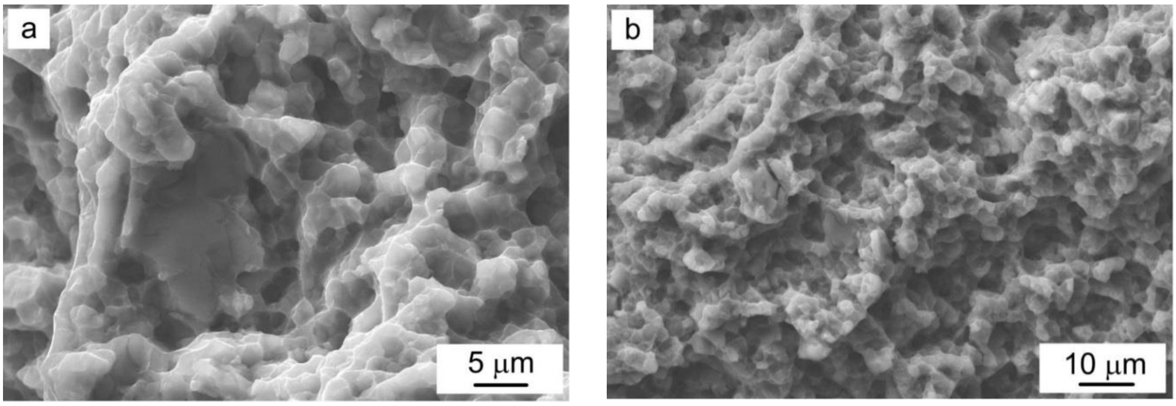

Fig. 5. Fracture surface of specimens in ECAP state failed in tensile test a) quasi-cleavage fracture micromechanism, b) detail of ductile fracture with tiny dimples.

4. Discussion

According to the results, processing the as-cast AZ91 magnesium alloy by ECAP leads to a significant improvement of mechanical properties. Both $\sigma_{0.2}$ proof stress and ultimate tensile strength increased twice by ECAP (from 87 MPa to 160 MPa and from 168 MPa to 321 MPa respectively). The elongation increased more than five times from 3.1% to 15.6%. This finding differs from the extruded state of AZ91 alloy where improvement of mechanical properties is rather insignificant and ambiguous [10]. Such difference is caused by the texture influence. After extrusion, the texture is distinctive and its weakening occurred during ECAP process [5, 6, 10]. Contrary to this, improvement of mechanical properties owing to ECAP of the as-cast alloy was expected [3, 5, 11, 12] due to weak specific grain orientation in this state, significant grain refinement via dynamic recrystallization and much higher dislocation density gained by the used SPD method (i.e. strengthening by dislocation (sub)grain boundaries).

The measured average value of microhardness, 89 HV 0.05, confirmed the findings about partial contribution of the individual areas with different grain sizes to the overall hardness. The average hardness determined by area weighted average from the local microhardness measurements with consideration of both areas ratio (CG area – 20%, FG area – 80%, total calculated microhardness – 87.6 HV) is in good agreement with the obtained overall hardness. It is worth noting that distribution of $Mg_{17}Al_{12}$ particles also contributes to differences in microhardness between fine and coarse grained areas. This partial contribution of different areas to overall mechanical properties is reached for tensile properties, when the fine grains contribute to the overall strength whereas the coarse grains contribute rather to overall ductility expressed by the elongation during tensile test [13].

5. Conclusions

Based on the results, it is obvious that the ECAP process improves the mechanical properties of the investigated AZ91 alloy. Proof stress $\sigma_{0.2}$ and ultimate tensile strength were improved almost twice by ECAP and the elongation was improved five times comparing to the as-cast state.

The microhardness of as-cast state was of 64 HV 0.05. The microhardness of alloy in ECAPed state for coarse grain areas was of 74 HV 0.025 and 91 HV 0.025 for fine grain areas. These values combined with the area fraction of both types of microstructure correspond well with the overall microhardness of 89 HV 0.05. The ECAP process influenced also the fracture behaviour. Grain refinement and introduced internal strain caused changes in micromechanism of fracture. The amount of cleavage facets on the fracture surfaces was reduced on the behalf of ductile dimples. However, the character and the size of the dimples is similar for both states (as-cast and ECAPed).

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