# INFLUENCE OF MICROSTRUCTURE ON TENSILE PROPERTIES OF MAGNESIUM ALLOY AZ91

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**Abstract**

This paper deals with influence of microstructure of magnesium alloy AZ91 on its mechanical properties. Tensile characteristics and microstructures of cast and extruded state of the alloy, and both of these initial states after equal channel angular pressing (ECAP), were compared. It was found that tensile properties are not only determined by the grain size but another aspect plays also an important role because the highest values of $\sigma_{0.2}$ proof stress and tensile strength were achieved for the alloy in extruded state despite its higher average grain size compared to both ECAPed states of the alloy. Compared to this, microhardness seems to be related only to grain size.

**Keywords:** AZ91, microstructure, ECAP, tensile properties

## 1. INTRODUCTION

Magnesium as one of the lightest metallic structural materials is very attractive for those industries where weight reduction is demanded, especially in automotive and aerospace. However, mechanical properties of these materials in natural state are not sufficient for many applications and possibilities for improving its properties by mechanical processing are limited due to inherent features of magnesium's HCP crystal lattice [1, 2]. Despite this fact, improving of mechanical properties of magnesium and its alloys is conducted via mechanical processing in different ways. Conventional forging or extrusion is usually sufficient but in some special applications more sophisticated and expensive methods for further improvement of properties are applied. Different methods of severe plastic deformation (SPD) or combination of mechanical processing and heat treatment are usually used [3-6].

Tensile strength of magnesium and its alloys is low but can be improved effectively by grain refinement achieved just by simple extrusion. Further grain refinement can be obtained by SPD methods, but in this case another factors than grain size sometimes come into consideration; therefore the resulting properties are strongly dependent on all processing conditions [6-8] and, moreover, alloys prepared this way usually exhibit lower thermal stability of their microstructure [9,10]. For this reason all conditions (e.g. initial grain size, reproducibility of the method, application temperature) during material processing should be evaluated.

In this paper, the microstructure and its influence on tensile properties and microhardness of Mg alloy AZ91 in as cast state, after extrusion and after equal channel angular pressing (ECAP) of both mentioned states were analyzed.

## 2. MATERIAL AND EXPERIMENTAL METHODS

Two different initial states of the AZ91 alloy were used in this work; AZ91 alloy in as-cast state and AZ91E after extrusion, with chemical composition given in **Table 1**. Billets of material of both these initial states were subjected to ECAP process. Billets of as-cast initial state (state 1) were processed by ECAP in Ufa State University laboratory, Russia, by six passes through ECAP die (the angle between channels Φ was 120°) at temperature 300 °C using route $B_C$ (state 3). Billets of extruded initial state (state 2) were prepared by ECAP (exECAP) in the laboratory of Politecnico di Milano, Italy, by four passes through the die (the angle between channels Φ was 110°) at temperature 200 °C using route $B_C$ as well (state 4). Microstructural analyses of all four states of the alloy were performed using light microscope Zeiss Axio Observer Z1.m and scanning electron microscope Zeiss Ultra Plus 50.

Samples for tensile tests were machined from ECAPed billets so their longitudinal axis was identical with the extrusion and also ECAP direction. Dimensions of the gauge length of the tensile samples differed due to differences in available volume of the billets and were ϕ 6 mm × 30 mm for the alloy in state 1 and 3, ϕ 8 mm × 40 mm for the alloy in state 2 and ϕ 5 mm × 25 mm in state 4. Tensile tests were performed using Zwick Z250 testing machine at room temperature with loading speed 2 mm/min. Microhardness HV0.1 was measured using Leco LM 247AT microhardness tester.

**Table 1** Chemical composition of raw materials

| Material | Al (wt.%) | Cu (wt.%) | Fe (wt.%) | Mn (wt.%) | Si (wt.%) | Zn (wt.%) | Other (each) (wt.%) | Other (total) (wt.%) | Mg (wt.%) |
|---|---|---|---|---|---|---|---|---|---|
| as-cast (state 1) | 9.043 | - | 0.003 | 0.144 | - | 0.748 | - | - | Balance |
| extruded (state 2) | 8.70 | 0.001 | 0.003 | 0.20 | 0.04 | 0.67 | <0.01 | <0.03 | Balance |

## 3. RESULTS

Microstructure observations showed that the material in state 1 had typical appearance of a cast structure with really large grains (even larger than 1 mm) with eutectic on the grain boundaries (**Fig. 1**). Microstructure of the material in state 2 consisted of equiaxial grains with average grain size of 15.9 μm (**Fig. 2a**), $Mg_{17}Al_{12}$ particles aligned along extrusion direction were also present as expected (**Fig. 2b**). Microstructures of both processing variants exhibited significant grain refinement after ECAP: microstructure of the material in state 3 was bimodal with smaller grains in areas rich in $Mg_{17}Al_{12}$ particles and coarse grains in areas free of those particles, having average grain size of 6.1 μm (**Fig. 3**). Microstructure of the material in state 4 was rich in $Mg_{17}Al_{12}$ particles and almost unimodal with average grain size of 1.2 μm retaining just a few larger grains (**Fig. 4**).

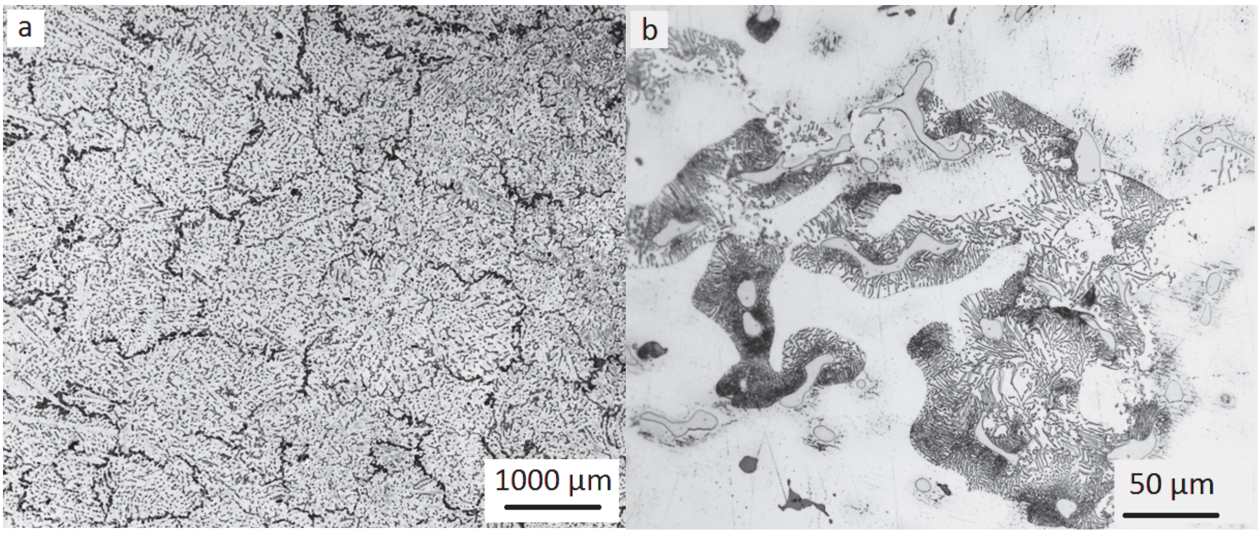


**Fig. 1** a) Microstructure of the cast material (state 1), b) detail of the eutectic (light microscope)

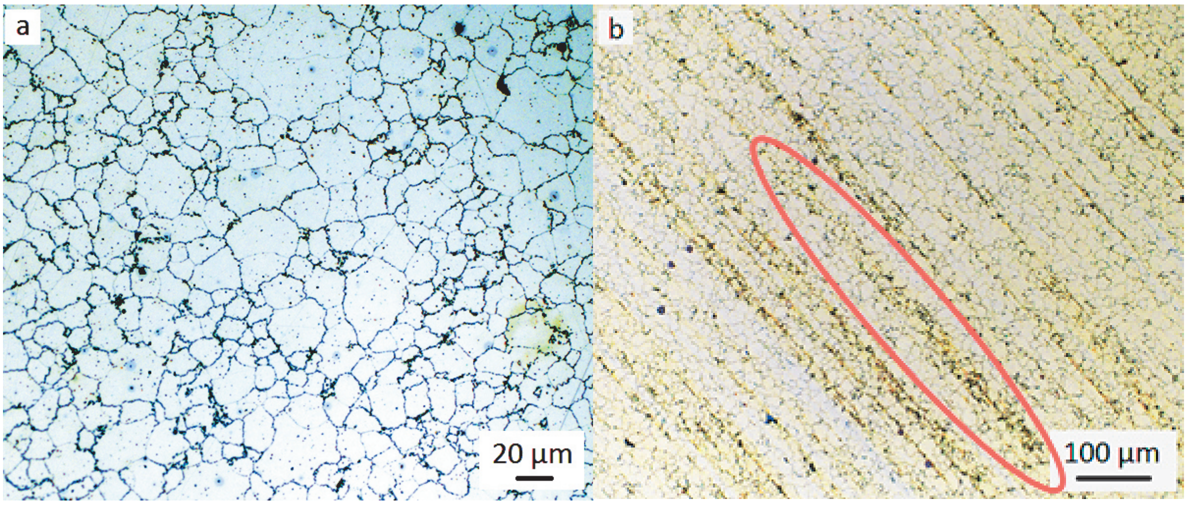


**Fig. 2** a) Microstructure of the extruded material (state 2) - transversal plane, b) morphology of $Mg_{17}Al_{12}$ particles - longitudinal plane (light microscope)

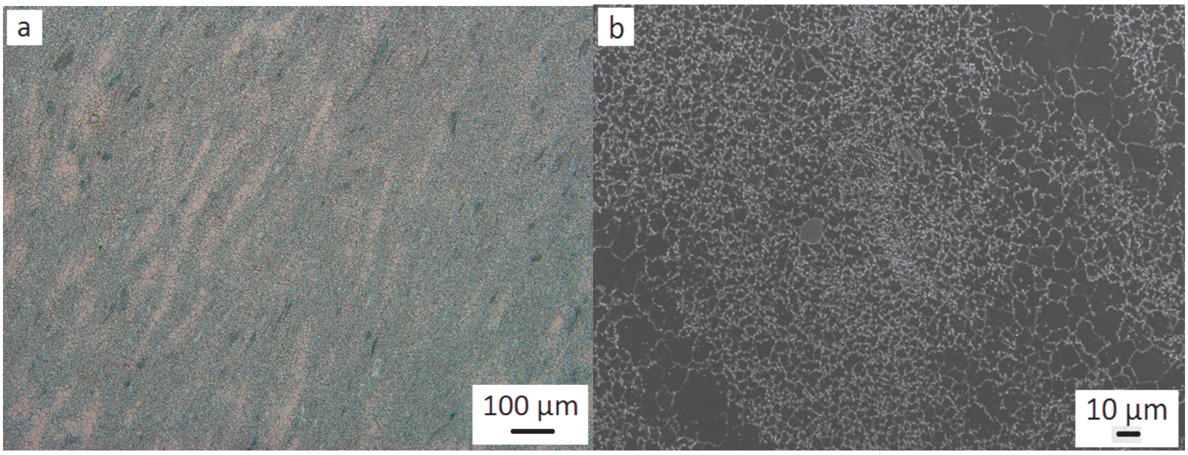


**Fig. 3** a) Microstructure of the ECAPed material (state 3) - longitudinal plane (light microscope), b) Illustration of bimodality of the microstructure - longitudinal plane (secondary electrons)

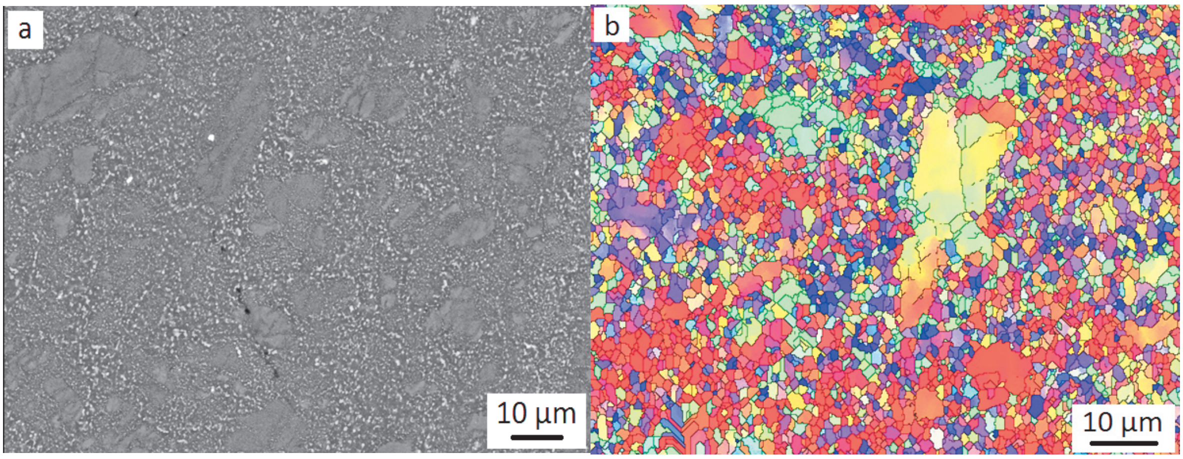


**Fig. 4** a) Microstructure of the exECAPed material (state 4) - longitudinal plane (channeling contrast), b) Orientation map of the microstructure - longitudinal plane (inverse pole figure map - ND - EBSD)

Based on the results of tensile tests (**Fig. 5**, **Table 2**) the lowest values of $\sigma_{0.2}$ proof stress (87 MPa), ultimate tensile strength (168 MPa) and also elongation (3.1 %) were achieved for material in state 1. It was found that subsequent ECAP process (state 3) brought significant improvement to mechanical properties ($\sigma_{0.2}$ proof stress - 160 MPa, ultimate tensile strength - 321 MPa, elongation 15.6 %) as expected.

Material in state 2 exhibited better mechanical properties even compared to the one in state 3 ($\sigma_{0.2}$ proof stress - 260 MPa, ultimate tensile strength - 366 MPa, elongation - 15.7 %) despite higher average grain size.

Mechanical properties of the material in an state 4 were comparable ($\sigma_{0.2}$ proof stress - 251 MPa, ultimate tensile strength - 359 MPa, elongation - 11.9 %) with the same in extruded state. Nevertheless, it is visible in **Fig. 5** that stress-strain curves were of a slightly different shape. This behaviour suggests that the material in state 4 exhibited different character of strengthening than the extruded one (state 2).

Contrary to these results, microhardness increased with diminishing grain size (**Table 2**).

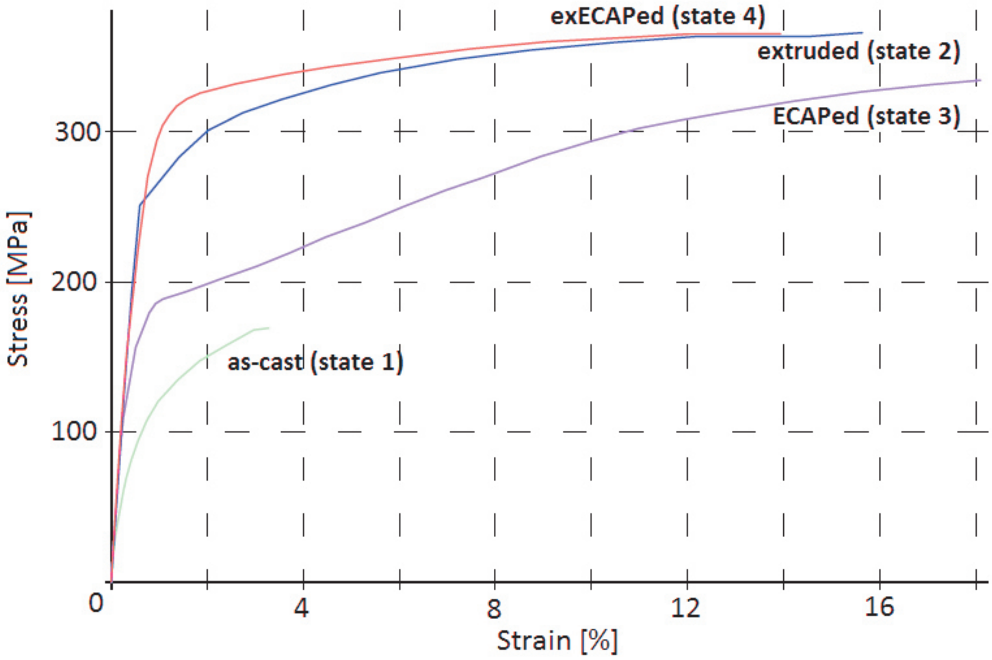


**Fig. 5** Engineering stress-strain curves of the samples at room temperature

**Table 2** Grain size and room temperature mechanical properties of analysed materials (average values)

| Material | Average grain size (μm) | Proof stress $\sigma_{0.2}$ (MPa) | Ultimate tensile strength (MPa) | Elongation (%) | Microhardness (HV0.1) |
|---|---|---|---|---|---|
| as-cast (state 1) | >500 | 87 | 168 | 3.1 | 68 |
| extruded (state 2) | 15.9 | 260 | 366 | 15.7 | 74 |
| ECAPed (state 3) | 6.1 | 160 | 321 | 15.6 | 80 |
| exECAPed (state 4) | 1.2 | 251 | 359 | 11.9 | 101 |

## 4. DISCUSSION

Tensile properties of the analysed materials are not dependent entirely on the average grain size. Whereas there is significant improvement of mechanical properties resulting from ECAP processing of the material in as-cast state (state 3), the quantitative change of mechanical properties after ECAP of the material in extruded state (state 4) is rather insignificant, although grain refinement during ECAP is considerable in both cases. Also the mechanical properties of the material in as extruded state (state 2) are better compared to the material in ECAPed state (state 3 and 4) despite having higher average grain size. This behaviour was already discovered for magnesium alloys prepared under similar conditions: according to literature data this effect is probably caused by texture modification exhibited during ECAP, which counteracts the influence of grain size refinement [4-8]. The bimodality of the material in ECAPed state could also play an important role.

Tensile properties of the material in exECAPed state (state 4) were comparable, or rather slightly lower, than that of the material in extruded state (state 2); but it can be clearly seen that the character of strengthening during plastic deformation differs. This is probably caused by high amount of small $Mg_{17}Al_{12}$ particles in the microstructure of the material in exECAPed state.

The correlation between microhardness and average grain size is much stronger than between tensile properties and grain size, which also corresponds with experiments performed on similar alloys [5, 7].

It is worth noting that according to the mentioned experiments [5, 7, 8] tensile properties improve until some particular number of ECAP passes after which they start to decrease. Without further experiments it is not certain if the analysed material after six passes for the ECAPed state (state 3) and four passes for the exECAPed state (state 4) is already beyond that limit or there will be some improvement with further ECAP passes.

Although no further improvement of mechanical properties by ECAP processing of extruded material was achieved it can be assumed according to Ying et al. [6] that mechanical properties could be improved by additional heat or thermo-mechanical treatment.

## 5. CONCLUSION

- Microstructure and its influence on tensile properties of magnesium alloys after different processing conditions were examined.
- The best $\sigma_{0.2}$ proof stress and ultimate tensile strength was achieved with extruded alloy (state 2) having average grain size 15.9 µm.
- Both examined ECAPed alloys (of different initial states) (state 3 and 4) exhibited smaller average grain size than simply extruded material (state 2) (6.1 µm for material in ECAPed state, 1.2 µm for material in exECAPed state and 15.9 µm for material in just extruded state). Nevertheless, their tensile properties were lower probably due to texture modification during ECAP and microstructural features such as bimodality in grain size distribution.
- Microhardness increased with decreasing average grain size up to 100 HV for material in exECAPed state (state 4).

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