

## EFFECT OF ECAP DIE ON STRUCTURE AND PROPERTIES OF AlMg ALLOY

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### Abstract:

The present study was initiated to investigate the influence of an ECAP die on the microstructure evolution and properties of commercial Al-Mg aluminum alloy in as-cast state. To characterize microstructural features an optical microscope was used. The properties of the as processed and initial state material were evaluated based on the hardness measurements. It was found that the applied ECAP die has the meaningful influence on the microstructure as well as the properties of the material.

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Aluminium, ECAP, SPD, Structure, Hardness

### 1. INTRODUCTION

Nanostructured (NS) materials show excellent mechanical, chemical and physical properties in comparison with their conventional coarse-grained equivalents, with an average grain size being in the range of 10 – 1000  $\mu\text{m}$ . Nanostructures or nanostructured materials can be produced by considering either the bottom-up or the top-down strategy. In the bottom-up approach, the nanostructure is obtained through the atoms deposition or the organization of the nanostructure layer-by-layer. The bottom-up strategy often resulted in porosity, which is known to be detrimental to the properties of nanostructured materials. In the top-down approach, the coarse-grained microstructure is transformed into an ultra-fine grained or a nanostructure. The top-down strategy involves severe plastic deformation (SPD), which can be a useful method to produce bulk nanostructured materials. The principle of the SPD methods involves increasing dislocation density through the strain accumulation, a formation of dense dislocation walls and transformation of the dislocation walls into high-angle grain boundaries. One of the most important advantages of the severe plastic

deformation (SPD) methods is their ability to effectively refine microstructure through the introduction of high amounts of shear strain consequently resulting in an increase of mechanical strength. Materials processed through the SPD technologies can find the application mainly in the automotive industry where the high-strength is one of the most desirable properties [1-5, 13-16].

One of the mostly investigated SPD technologies in recent years has become the equal channel angular pressing (ECAP) method. The ECAP is a metalworking process in which a working specimen, usually having the shape of a rod or a bar, is extruded from a die constrained within a channel, which is bent through a sharp angle near the center of the die. Since both parts of the channel have the identical cross-section dimensions, on either side of the bend, the sample emerges from the die having experienced a high shearing strain but without any change in the cross-sectional dimension. For this reason, the specimen can be processed repetitively through the ECAP die to introduce exceptionally high strain into the material [6-9].

The most important processing parameters in the SPD methods, as well as in the ECAP method, is

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the quantity of the introduced plastic strain. This fact was recognized in one of the first studies of the ECAP by Segal [10-13]. Then, the fundamental parameters connected with ECAP plastic working were described in a great number of publications which delineate various processing operations and different ECAP die configurations.

Current investigation was initiated to evaluate the potential for using an alternative design for the ECAP die which may introduce a more homogeneous microstructure. To characterize the microstructure evolution of the AlMg3 aluminum alloy after each ECAP pass, observation under polarized light was used. Mechanical properties were analyzed via the Vickers micro hardness ( $HV_{0.3}$ ) measurements.

## 2. MATERIALS AND METHODS

The material used in the presented manuscript was a commercial Al-3%Mg aluminum casting alloy having a chemical composition given in Table 1. One of the most important characteristics of the Al-Mg alloy is good a corrosion resistance, including when exposed to sea water and marine atmospheres.

**Table 1.** Chemical composition of Al-3%Mg aluminum alloy

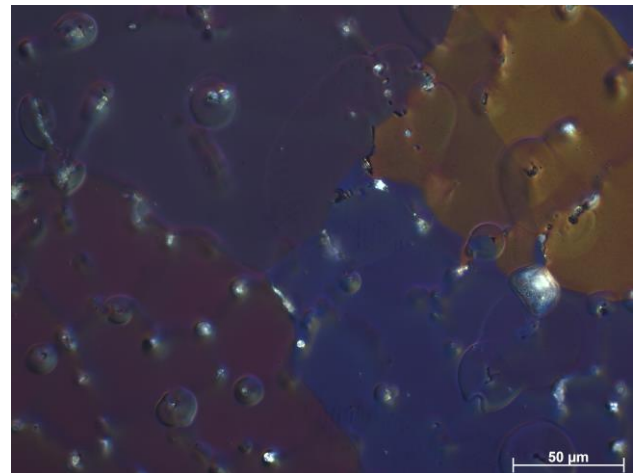
Element	Al	Mg	Si	Fe	Cu
[wt. %]	96.99	2.86	0.07	0.07	0.01

The pre-machined samples from an as-cast ingot in an initial state, having a diameter of 10 mm and a length of 45 mm, were subjected up to four ECAP passes using a deformation route A and two different ECAP dies with 30° twist angle and conventional one. The internal die channel angle was 90°. The work samples were processed at room temperature with a constant deformation rate. To decrease the friction between samples and the ECAP die, molybdenum sulfide was used as a coating lubricant. Microstructural investigations were carried out using a light microscopy on the cross sections of the samples that were polished using standard metallographic techniques (grinding and polishing using diamond pastes). Samples were electrolytically etched using the Barker's reagent (20 V, 90s) and using Keller's reagent. The microstructure of samples was observed on the light optical microscope Zeiss Axio Observer under bright field and polarized light. The Vickers micro

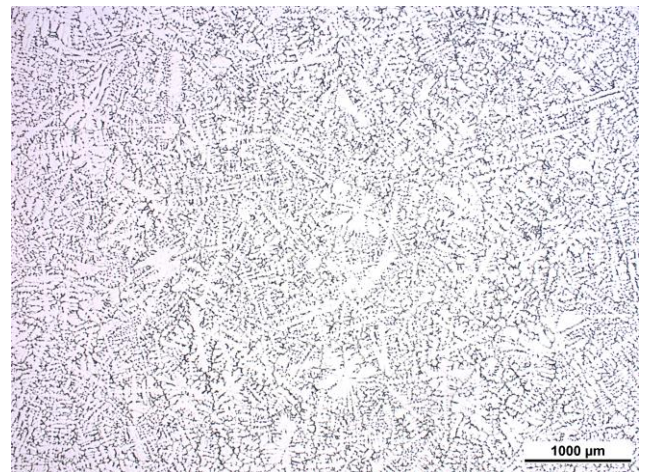
hardness ( $H_V$ ) was measured on a cross-section plane designated as the X-plane by imposing a load of 300 g and using a dwell time of 15 s using the Vickers hardness tester Future-Tech FM-ARS.

## 3. RESULTS AND DISCUSSION

The representative light optical microscope images, showing the microstructure of Al-3%Mg alloy in the as cast state, are presented in Figures 1 and 2. It is clearly visible that the microstructure of the alloy is characterized by the fine dendritic structure. Moreover, it can be observed also that a large majority of the  $\beta$ -phase is distributed in the inter-dendritic region as result of the non-equilibrium solidification. The initial state microstructure consists of three phases  $\alpha$ -Al primary phase (matrix of an alloy),  $Al_3Mg_2$ ,  $Mg_2Si$  and  $Al_3Fe$  phases that are present on the grain boundaries [13]. The structure is coarse grained with an average grain size of about 330  $\mu m$ .



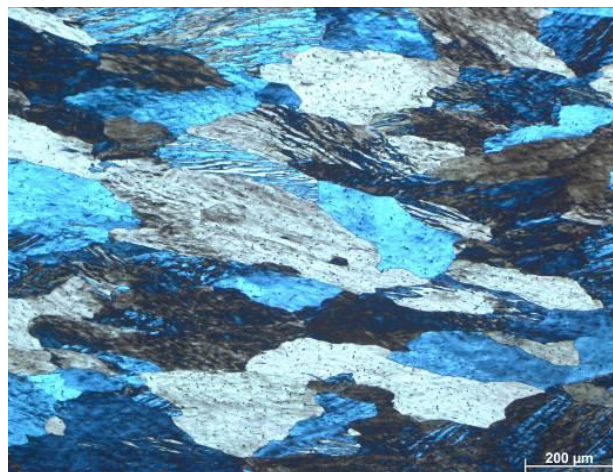
**Fig. 1.** Initial microstructure of investigated alloy (observed under polarized light)



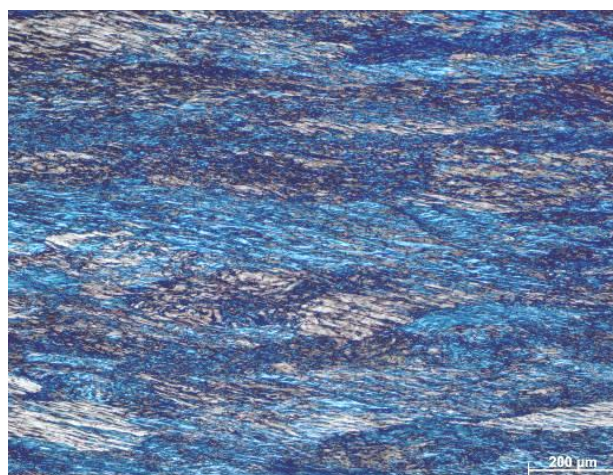
**Fig. 2.** Initial microstructure of investigated alloy (observed under bright field)



Figures 3a-f illustrate changes in the microstructure of Al-3%Mg alloy in the initial state subjected to the ECAP process using two different ECAP dies. Based on the metallographic analysis presented below, it can be concluded that the size of individual grains cannot be clearly distinguished because of the presence of slip, shear and micro-shear bands, which forms the band-like microstructure. The quantity of the shear bands increases with an increase in the ECAP passes – an increase in strain accumulation. These deformation bands also destroy and change the original coarse-grained microstructure of the cast Al-3%Mg alloy. It can be also observed, that the microstructures obtained from two ECAP dies differs. In the conventional ECAP die, grains are elongated parallel to transverse direction, while twist angle in modified ECAP equipment introduces additional shear bands inclined at an angle of 30 degrees in relation to transverse direction. The additional twist angle in modified ECAP die introduces additional shear forces that result in a greater grain refinement (Fig. 3a and d). This statement can be concluded from the observation of the quantity of shear bands. It is obvious that greater amounts of shear and micro-shear bands are in the microstructure presented in the fig. 3d. Further deformation causes an increase in shear bands accumulation which intersects each other (Figs. 3c and f). It is known that each shear band introduced into a polycrystalline structure of aluminum alloy has a preferred orientation, which may result in the non-uniform refinement of the microstructure. In addition, each single shear or micro-shear band causes the lattice rotations lying within the low-to-moderate grain/sub-grain boundary misorientation, thus their interacting and mutual crossing can result in a violent appearance of the deformation bands having a high-angle misorientation. It is believed that this intersection and mutual crossing of shear and slip bands in the polycrystalline material cause the microstructure refinement resulting in a fine-grained microstructure with an increased amount of high angle boundaries.



**Fig. 3a.** Microstructure of the AlMg3 alloy subjected to 1 ECAP pass (conventional ECAP die)

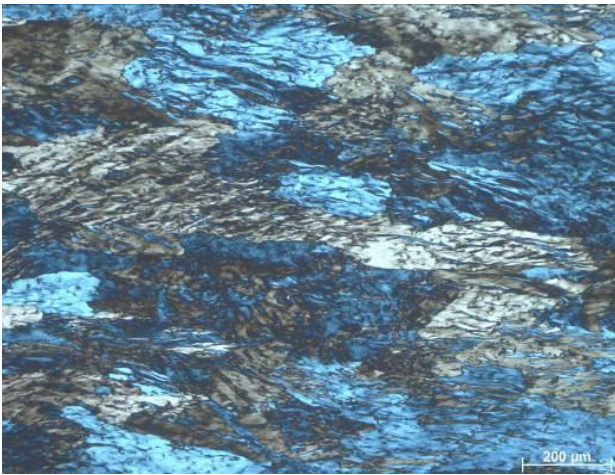


**Fig. 3b.** Microstructure of the AlMg3 alloy subjected to 2 ECAP passes (conventional ECAP die)

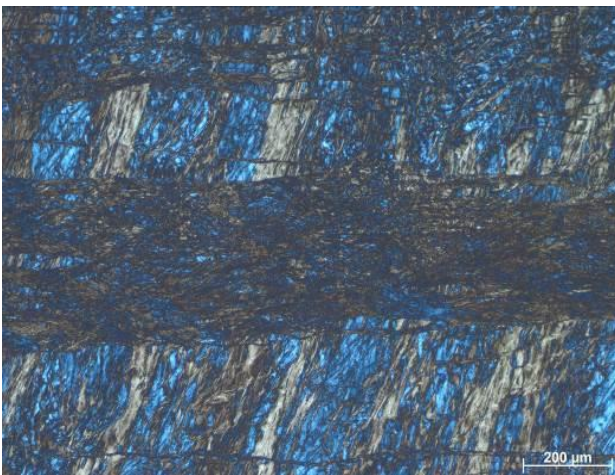


**Fig. 3c.** Microstructure of the AlMg3 alloy subjected to 4 ECAP passes (conventional ECAP die)

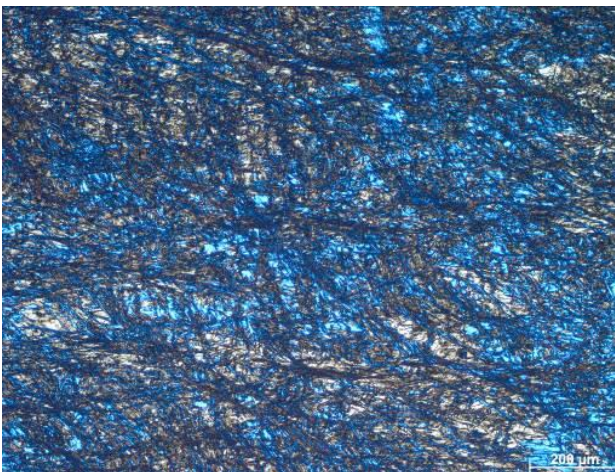




**Fig. 3d.** Microstructure of the AlMg3 alloy subjected to 1 ECAP pass (modified ECAP die)



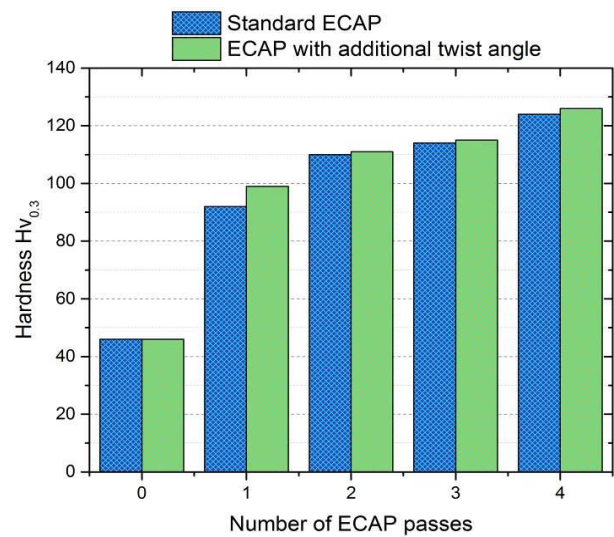
**Fig. 3e.** Microstructure of the AlMg3 alloy subjected to 2 ECAP passes (modified ECAP die)



**Fig. 3f.** Microstructure of the AlMg3 alloy subjected to 4 ECAP passes (modified ECAP die)

Figure 4 presents the hardness evolution of the AlMg3 alloy subjected to the different strain paths using the two ECAP dies. It can be observed that the shear strain accumulation, even after one ECAP pass, causes a rapid and significant increase in hardness of the material. This growth of the

Vickers micro hardness is about 110 % in comparison to a material before the ECAP. It can also be seen that the increase of the mechanical properties after one pass for the sample processed using conventional ECAP equipment is lower than in sample deformed with additional twist angle at the outer channel. The further plastic working results only in a small increase in hardness. The final increase in the Vickers micro hardness after four ECAP passes is about ~ 80 Hv in comparison to the unprocessed state. Moreover, one can observe that the difference between the strength of the material after the four ECAP passes is negligible.



**Fig. 4.** Vickers micro hardness evolution of the AlMg3 alloy subjected to ECAP processing

This phenomenon can be caused by the fact that with an increase of strain accumulation during the ECAP process, the influence of additional twist angle becomes lesser. At the beginning of the deformation, when the alloy is in an unprocessed state and susceptible to plastic working, the additional angle may have greater influence. This new die configuration may introduce more shear and slip bands to the microstructure, which result in obtaining the material with greater mechanical properties. However, greater strain accumulation after several ECAP passes causes that the difference in hardness becomes lesser. The increase in mechanical properties after ECAP process is related to the grain refinement process and increase in dislocation density (dislocation strengthening). The benefits that come from the grain refinement are due to the Hall-Petch relationship. Since the grain boundaries are barriers to dislocation, when dislocation is crossing a grain boundary, its direction of motion must change. There is a discontinuity of slip planes within the vicinity of a grain boundary. In addition,

a metal that has small grains will be stronger than one with large grains because the former has more grain boundary area, and, thus, more barriers to dislocation motion.

#### 4. CONCLUSION

Structure investigations showed that the original coarse-grained dendritic structure consists of the  $\alpha$ -Al primary phase and  $\text{Al}_3\text{Mg}_2$ ,  $\text{Al}_3\text{Fe}$  and  $\text{Mg}_2\text{Si}$  secondary hardening phases. The severe plastic deformation conducted, using the ECAP method with two different dies, changes the microstructure of the alloy. It can be stated that intense plastic deformation induced by equal channel angle pressing can produce significant grain refinement in investigated aluminium alloy. The microstructure achieved gave evidence on the success of such procedure in producing ultrafine grained materials. Most of the grains have been refined to a few micrometers in size and even to submicron scale. It was found that the microstructure is refined through the appearance of shear, micro shear and slip bands. It is believed that this intersection and mutual interaction of shear, micro shear and slip bands in the polycrystalline material causes the microstructure refinement resulting in an ultra-fine-grained microstructure. However, the precise analysis of the grain size and its distribution needs application of higher resolution techniques such as EBSD or TEM investigation which will be a subject of the further studies.

A noticeable increase in hardness of the material even after one ECAP pass was observed. Moreover, it was shown that the greatest influence of the new ECAP configuration – additional twist angle, can be observed when the sample is subjected to low strains. This new die configuration introduces greater quantities of shear and slip bands to the microstructure after one pass, which result in obtaining the material with greater mechanical properties. However, greater strain accumulation after several passes causes that the difference in hardness becomes lesser.

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