Acta Polytechnica **56**(5):353–359, 2016
doi:10.14311/AP.2016.56.0353

available online at http://ojs.cvut.cz/ojs/index.php/ap

IMPACT OF PLASTIC DEFORMATION ON THE PROPERTIES OF A SELECTED ALUMINIUM ALLOY

Anna Lišková*, Petra Lacková, Mária Mihaliková, Robert Kočiško

Institute of Materials, Faculty of Metallurgy, Technical University of Košice, Slovakia

* corresponding author: anna.liskova@tuke.sk

Abstract. This paper reports on an experiment to assess the influence of plastic deformation on the microstructure and properties of EN AW 6012 (AlMgSiPb) aluminium alloy in two states. The first was the initial state with heat treatment T3, and the second was the state after intensive plastic deformation by ECAP (Equal Channel Angular Pressing) technology. The ECAP process was carried out repeatedly at room temperature. In the initial state of the alloy, the process redistributed eutectic Si-particles and increased the strength of the alloy. The mechanical properties and the hardness increased due to intensive plastic deformation (the yield strength increased by 15 %, the tensile strength by 6 %, and the hardness by 23 %). The fracture cracks initiated and propagated mainly along eutectic particles. The fracture area of the ECAPed specimen displayed a typical ductile cavity characteristic.

Keywords: intensive plastic deformation; aluminium alloy; tensile test.

1. Introduction

The AlMgSiPb alloy investigated here belongs to the AA6xxx (AlMgSi) series of aluminium alloys, where magnesium and silicon are the principal alloying elements. Commercial alloys of this type contain mass fractions of 0.5 % to 1.5 % of Si and 0.5 % to 1.5 % of Mg, and are used in great quantities. They are universal aluminium alloys which can be extruded into sections, rods and tubes. Their characteristics are a high level of workability, strength properties, corrosion resistance and machinability. Their mechanical and technological properties depend on the chemical composition and the heat treatment of the castings, i.e., cast blanks and extruded pieces [1, 2]. Free machining aluminium alloys are well known in the literature [3, 4]. These alloys typically include free machining constituents that are insoluble but soft and nonabrasive. They are beneficial, assisting in chip breakage and tool life [3]. More specifically, at the point of contact between the tool and the material, softening and melting occur. As a result of these changes, breakage occurs, chips are formed and material removal is enhanced. It is well known that chip breaking is promoted by the addition of Pb to conventional aluminium alloys, since Pb has poor solubility in solid aluminium and forms a soft, low melting point phase [5, 6].

Apart from the major alloying elements, standard aluminium alloys for free cutting also include additions (lead, bismuth), which form softer phases in the matrix. These “free machining” phases improve the machinability of the alloys, because the chips break more easily, they have a smooth surface, lower cutting forces and cause less tool wear. Since lead is poisonous, there is a tendency to replace it with other elements: tin and, to some extent, indium are the most frequently-used substituents.

Alloys with tin must have similar or better properties than standard alloys as regard microstructure, workability, mechanical properties, corrosion resistance, and machinability [7]. In recent time, tin has been added mainly to Al-Mg-Si (AA 6000 series) alloys and to Al–Cu (AA 2000 series) alloys, which normally contain lead and bismuth, or only lead. Semi-finished products made from these alloys in the form of bars are used for free cutting or, more precisely, for turning [8–10]. Equal-Channel Angular Pressing (ECAP) is a very useful method for producing ultra-fine microstructures of Al-based alloys with significantly improved mechanical properties [11–16]. During the last two decades, intensive plastic deformation (SPD) techniques have been widely applied to obtain an ultrafine-grained (UFG) structure, which can significantly improve the mechanical properties of Al–Mg–Si alloys [17, 18]. Among various SPD techniques, equal channel angular pressing (ECAP) is the most promising method for fabricating large bulk UFG materials [19, 20]. A significant increase in strength is obtained during ECAP processing [21]. In addition, some ultrafine- grained Al-based alloys produced by the ECAP procedure have shown a superplastic forming capability [16]. Intensive plastic deformation by the ECAP process also significantly increases the density of lattice defects in a solid solution of Al-based alloy, and can therefore accelerate the precipitation process of strengthening particles during the post-ECAP ageing treatment applied to an age-hardenable alloy [22–24]. Al–Mg–Si alloys can be strengthened by precipitation hardening. It is essential to study the precipitation sequence and the precipitation behavior. The precipitation sequence in Al–Mg–Si alloy is

$$\text{atomic clusters} \rightarrow \text{GP zones} \rightarrow \beta'' \rightarrow \beta' \rightarrow \beta,$$

where the atomic clusters are the supersaturated solid solution; GP zones are generally spherical clus-

Si	Fe	Mn	Mg	Cr	Bi	Pb	Al
1.13	0.37	0.53	0.83	0.2	0.51	0.83	bal.

Table 1. The chemical composition of AW 6012 [wt.%].

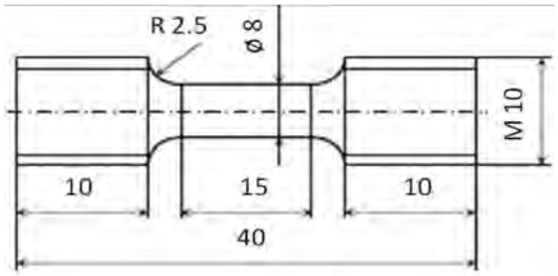

Figure 1. The shape and the parameters of the short specimen for the tensile test.

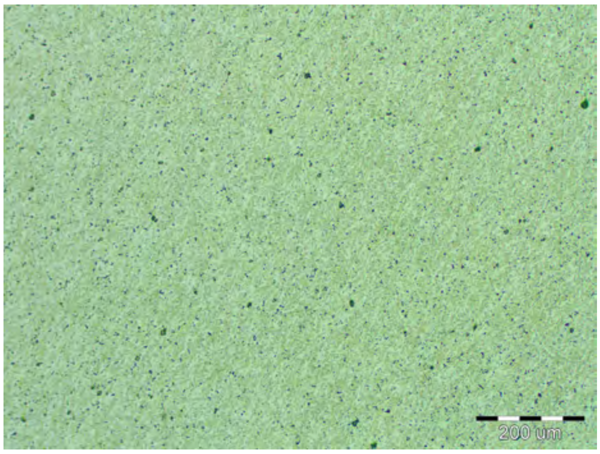

Figure 2. Microstructure of the aluminium alloy in the initial state.

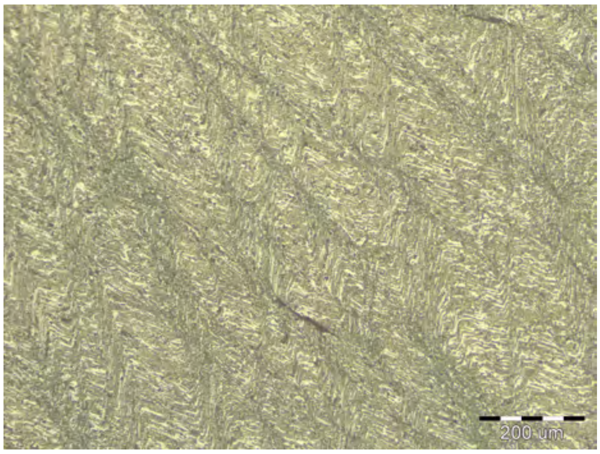

Figure 3. Microstructure of the aluminium alloy after ECAP and heat treatment.

ters with unknown structure; β'' precipitates are fine needle-shaped zones with a monoclinic structure. They are generally present in Al alloys aged to maximum hardness; β' are rod-shaped precipitates with a hexagonal structure and are found in overegged specimens; β (Mg_2Si) is an equilibrium phase in the precipitation sequence. Among these, the β'' phases are considered to make the main contribution to strength. The significant improvement in the strength of Al alloy upon SPD is due to the dynamic ageing effect, as reported in earlier work. The strength and the ductility of an Al alloy were further improved by static ageing [25].

Our study has been aimed at understanding the influence of the ECAP process on the microstructure and the mechanical properties of AlSiMgPb alloys.

2. Material and methods

EN AW 6012 aluminium alloy on the basis of AlMgSiPb was used as the experimental material. In the initial state, the experimental material was treated with T3 — solution annealing and natural ageing. Prior to deformation in an ECAP die, the specimens of the initial states were solution annealed for 1.5h at 550 °C. The alloy was then subjected to intensive plastic deformation by heat treatment: the solution was annealed for 1.5h at 550 °C, followed by 4 passes of ECAP and artificial ageing for 30h at 100 °C. The ECAP process was performed in a die with the following parameters: channel intersection angle $\Phi = 90°$, and arc of curvature $\Psi = 37°$. Repetitive pressing of specimens $\varnothing\,10\,\mathrm{mm} \times 80\,\mathrm{mm}$ in size was attempted in the ECAP die at room temperature, using the B_C route (the sample was rotated in direction by 90°). The chemical composition of the aluminium alloy is shown in Table 1. Figure 1 shows the parameters of the specimens that were used for the tensile test.

Microstructures were prepared by standard metallographic methods (special enhanced etching – etchant: modified Kroll – 92ml distilled water, 6ml HNO_3, and 2ml HF) and were observed using an OLYMPUS optical microscope. The fracture surfaces were studied by means of a Scanning electron microscope (a JEOL model JSM 7000F microscope operated at an accelerating voltage of 300kV). Particle identification was carried out using EDX quantitative analysis with the INCA-sight analyser.

The influence of severe plastic deformation by the ECAP process and post-ECAP artificial ageing on the mechanical properties of the analyzed alloys was evaluated with a Vickers hardness measurement (HV 10) and a tensile test. The hardness was estimated in a cross-section by the Vickers test with a dwell time of 10s. The test was carried out according to the EN ISO 6507-1 standard [26]. The hardness was estimated in a cross-section. The pre-ECAP and post-ECAP state of the samples was evaluated by 10 measurements in 2 lines. For the Vickers test, a very small diamond indenter with pyramidal geometry is forced into the surface of a specimen of AlMgSiPb aluminium alloy [27].

The mechanical properties (yield strength — YS, ultimate tensile strength — UTS, elongation — A, and

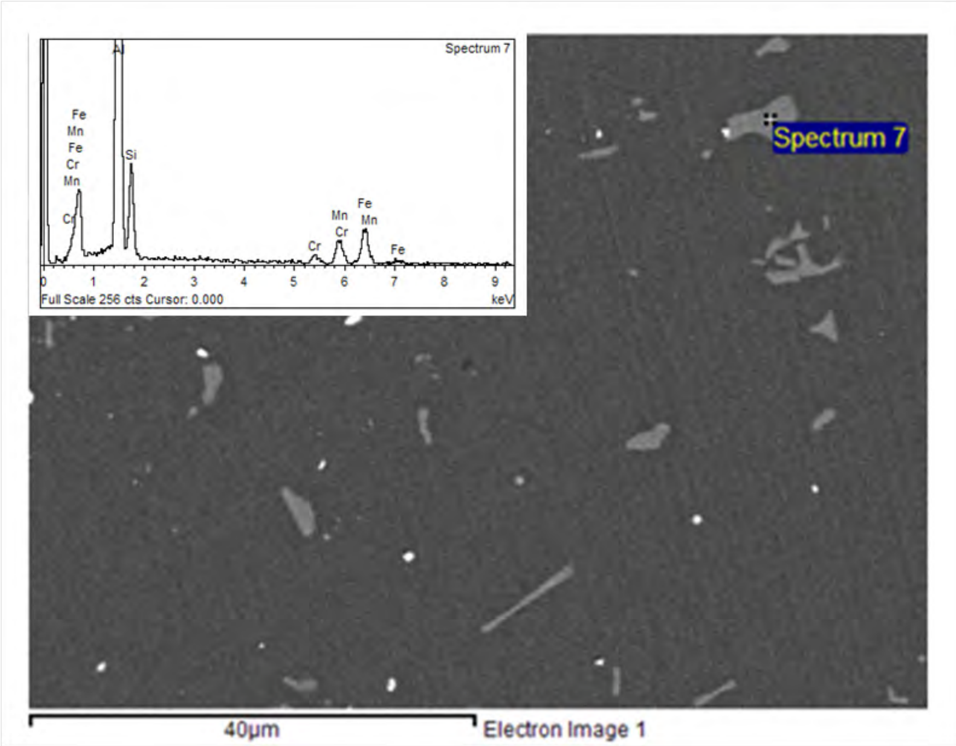

Figure 4. The EDX analysis of the aluminium alloy in the initial state.

reduction of area — Z) were measured by a uniaxial tensile test carried out using a ZWICK 1387 machine, according to STN EN ISO 6892-1 [28], for samples 8mm in diameter (Figure 1). The tension test can be used to ascertain several mechanical properties of materials that are important in mechanical engineering. The tensile test (the initial strain rate of $2.5 \cdot 10^{-4}\,\mathrm{s}^{-1}$) was carried out on specimens made from quenched, ECAP-processed and post-ECAP specimens. The tensile testing machine is designed to elongate the specimen at a constate rate using an extensometer [27, 29]. The Young modulus was measured using a WN2 52497 extensometer. A LEICA WILD M 32 microscope was used to observe the macrostructure after a tensile test had been applied.

3. Results and Discussions

The microstructure (Figure 2) characteristics of the initial state of the investigated alloy, its state after quenching (Figure 3), deformation in the ECAP die and subsequent ageing treatment were analyzed in the central zone of the cross-section of the specimens. Figure 3 shows the ultrafine-grained (UFG) structure with nearly equi-axial morphology, where we can observe the locations of elongated grains. Figure 3 shows the deformed microstructure after intensive plastic deformation with characteristic shear bands along the cross section of the sample. The heterogeneous microstructure of the ECAP-ed alloy indicates a non-uniform deformation along the cross-section of the ECAP-ed specimen. The shear bands are well developed in alloys after plastic deformation, and can be clearly distinguished from the other regions of the microstructure under an optical microscope (Figure 3).

Figure 4 shows the spectrum of the aluminium alloy in the pre-ECAP state, and Figure 5 shows the spectrum of the alloy in the post-ECAP state. It consists of a primary phase a-Al solid solution, which forms the matrix of the material, and secondary phases distributed at the grain boundary and in the interdendritic regions. The secondary constituents, such as Mg_2Si and α-Al(FeMn)Si compounds, as revealed by EDS, are clustered in bands oriented parallel to the extrusion direction. The α-Al(FeMn)Si phase is also present as coarse particles. When the billets were heat treated, the grain segregations and the coarse Mg_2Si particles in the a-Al matrix dissolved. The maximum number of Mg and Si atoms in the alloy are therefore in a solid solution in the extruded section, and are therefore available for precipitating the hardening particles during ageing. Coarse Mg_2Si particles present in the microstructure do not help to strengthen the alloy. Coarse Mn and Cr phases, detected by EDX analyses, are distributed mainly along the grain boundaries. Large Pb bearing particles are normally found adjacent to Fe particles, and sometimes enveloping them [30].

The mechanical properties were evaluated by a static tensile test at room temperature. The dependent force of strain and elongation in static condition is shown in Figure 6. The specimen is deformed, usually to fracture, with a gradually increasing tensile load that is applied uniaxially along the long axis of the specimen. The results for mechanical properties,

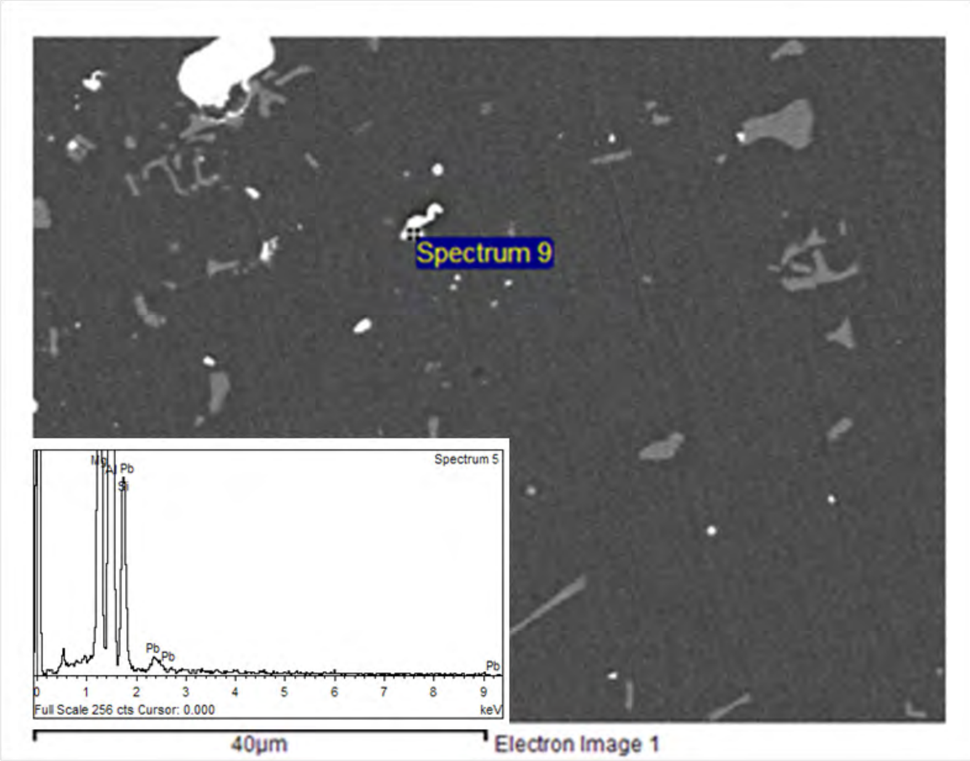

Figure 5. The EDX analysis of the aluminium alloy after ECAP and heat treatment.

State	YS [MPa]	UTS [MPa]	A [%]	Z [%]	E [GPa]	HV10
Initial	309	350	17	23	75	103
ECAPed	355	372	10	8	70	125

Table 2. Mechanical properties of the investigated aluminium alloy.

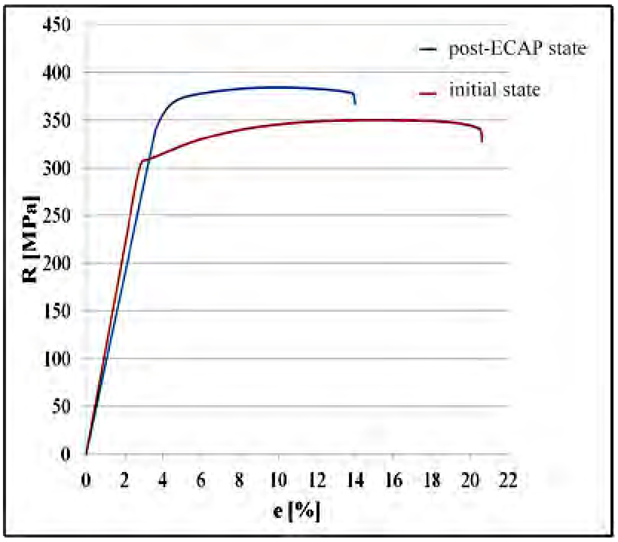

Figure 6. Dependent force of strain and elongation in the static condition of EN AW6012.

evaluated as average values from six measurements, are summarized in Table 2. The intensive plastic deformation realized by ECAP technology increased the yield strength properties from 309MPa to 355MPa, and the ultimate tensile strength from 350MPa to 372MPa. However, the values for the plastic characteristics decreased. The elongation value decreased from 17 % to 10 %, and the contraction decreased from 23 % to 8 %. The decrease in the modulus of elasticity was shown on the samples after intensive plastic deformation in comparison with the initial state. Exhaustion of the plasticity and hardening of aluminum alloy EN AW 6012 was caused by intensive plastic deformation. EN AW 6012 alloy showed a significant increase in hardness HV10 in the post-ECAP state, up to 125 on an average. In its initial state, EN AW 6012 displayed hardness of about 103 (Tab. 2).

A macroscopic analysis of the samples in the initial state and after plastic deformation is shown in Figures 7 and 8. It can be concluded that greater plastic deformation has been replaced by minimum macroscopic deformation. The fracture surface of the sample seems to be slightly rugged. The surface of the fracture on each sample of EN AW 6012 aluminium alloy was in the direction of the axial load. Figure 9 shows a detail of the fracture surface in the initial state, and Figure 10 shows the post-ECAP state.

The fracture surfaces, documented by SEM after a tensile test, are presented in (Figures 9–12). Figure 9 shows the fracture surface of EN AW 6012 in the initial state. Figure 10 shows the fracture surface of the ECAPed state of the aluminium alloy. Details of the fracture surface are shown in Figures 11 and 12. The analysis of the fracture surfaces of the investi-

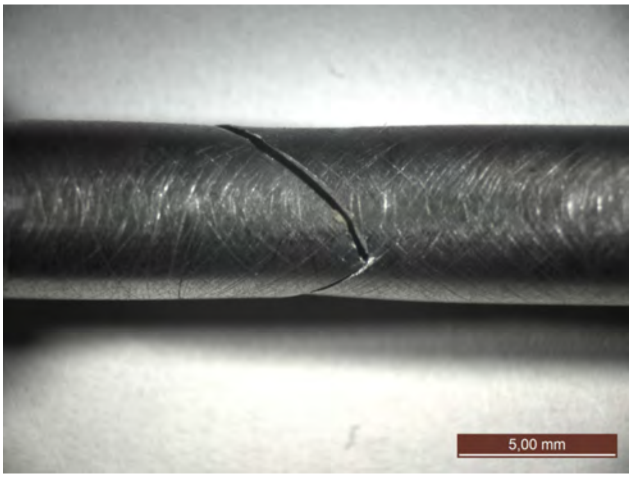

Figure 7. Fracture of EN AW 6012 alloy in pre-ECAP.

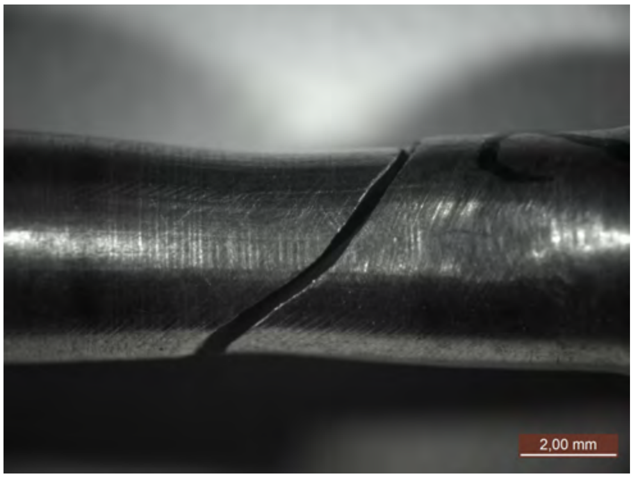

Figure 8. Fracture of EN AW 6012 alloy post-ECAP.

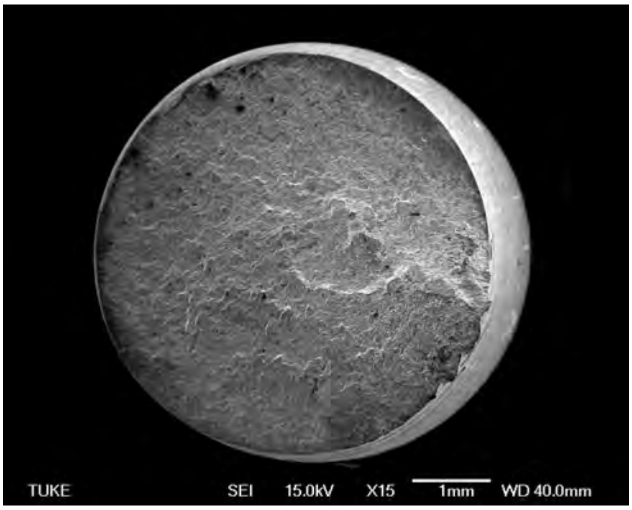

Figure 9. The fracture surface of EN AW 6012 in the initial state.

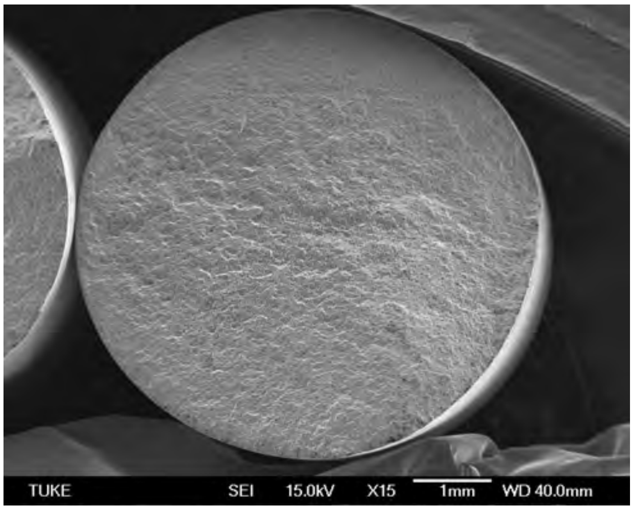

Figure 10. The fracture surface of EN AW 6012 in the post-ECAP state.

gated pre-ECAP and post-ECAP materials showed dominance of transcrystalline ductile fracture. The effect of plastic deformation was revealed in particle cracking for the relevant materials. During plastic deformation, particles were cracked and/or particles were divided from the interphase surface by means of cavity failure systems, which developed from the former dimples. The morphology of the fracture surface was observed as characterized dimples with local presence of striation. The shapes of the fracture surfaces of the samples are characterized by a mixed morphology, which is formed by the surfaces of the particles and the digested holes within a transgranular ductile fracture. The appearance of the surfaces of both surfaces has visible lines, which is an infringement of the guidelines. The fracture was initialized from the surface of the specimen, and the crack growth continued in the perpendicular direction of the axis of the specimen.

4. Conclusions

On the basis of our experimental work, we have drawn the following conclusions. The intensive plastic deformation carried out by ECAP technology can be summarized as follows:

- Increased strength properties: the yield strength increased by 18 %, and the ultimate tensile strength increased by 16 %.
- There was also a significant 23 % increase in hardness HV10. However, the plastic characteristics decreased: the elongation decreased by 31 %, and the area decreased by 21 %.
- Due to the exhaustion of plasticity and hardening of the EN AW 6012 aluminium alloys, the samples showed a lower elasticity modulus value after the application of intensive plastic deformation.
- A macroscopic examination proved that the surface of the fracture is perpendicular to the load in the

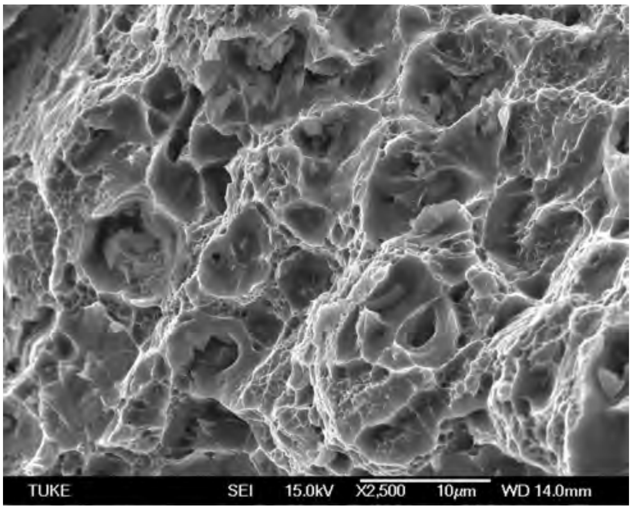

Figure 11. Detail of the fracture surface of EN AW 6012 in the initial state.

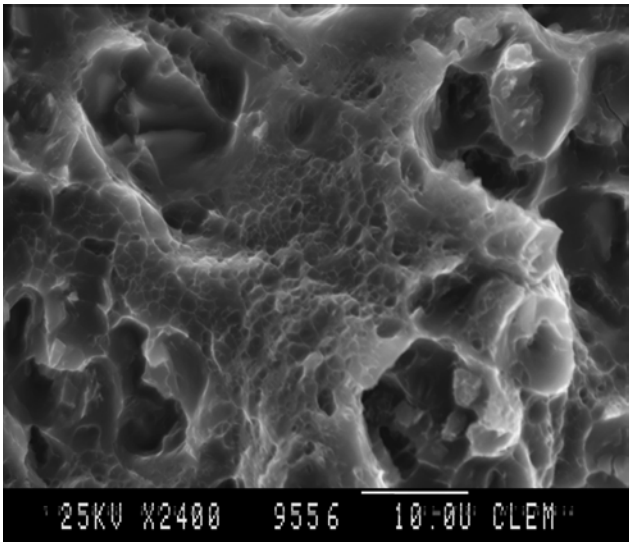

Figure 12. Detail of the fracture surface of EN AW 6012 in the post-ECAP state.

EN AW 6012 alloy in its initial state, and also in the ECAPed state.

- The surface fracture on the composite formed in the direction of the axial load.
- After intensive plastic deformation, shear bands can be observed on the microstructural level. They point to non-uniform deformation along the cross section of the sample. It is evident that there was deformation that led to the formation of shear bands. These shear bands developed, and led to deformation along narrow paths.
- A flat fracture with dimples and local presence of striations was observed on EN AW 6012 in both states (Figures 11 and 12). The surface was highly fractured, with a fine-grained morphology.

Acknowledgements

This study was supported by the Grant Agency of the Slovak Republic, grant project VEGA 1/0549/14.

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