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STRUCTURAL AND MECHANICAL PROPERTIES OF EN AW 6082 ALUMINUM ALLOY PRODUCED BY EQUAL-CHANNEL ANGULAR PRESSING

STRUKTURNE IN MEHANSKE ZNAČILNOSTI ALUMINIJEVE ZLITINE EN AW 6082 PO STISKANJU SKOZI ORODJE S PRAVOKOTNIM KANALOM

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At the VSB-TU Ostrava a piece of equipment was installed for verifying the equal-channel-angular-pressing (ECAP) technology, used for investigating the effect of deformation on the evolution of the structure and mechanical properties of alloy EN AW 6082. This alloy was subjected to ECAP consisting of four passes. During the pressing deformation forces were measured and the pressure in the die was calculated. Higher values of strain hardening were found and a higher pressure was measured in the matrix with smaller radii of the curvature of the edges. After the third pass, the tension in the matrix with a diameter of 0.5 mm reached the values of up to 1560 MPa. As a result of the extrusion, a grain refinement was achieved resulting in the development of a substructure. The ultimate strength of alloy EN AW 6082 was determined to be in the range from 220 MPa to 230 MPa. Moreover, a penetration test was performed, determining the values of the mechanical properties to be from 250 MPa to 260 MPa. The investigated samples were then subjected to light microscopy and to a SEM analysis. Numerous deformation slip bands were observed. Fracture surfaces resulting from a transcrystalline permanent ductile failure manifested indistinctive shearing borders, and they contained numerous pits with small particles.

Keywords: microstructure, properties, aluminum alloy, ECAP

Na VSB-TU Ostrava je bila postavljena naprava za preverjanje tehnologije stiskanja skozi pravokotni kanal enakih prerezov (ECAP), uporabljena pri preiskavi vpliva deformacije na razvoj strukture in mehanskih lastnosti zlitine EN AW 6082. Ta zlitina je bila štirikrat stisnjena skozi orodje (ECAP). Med stiskanjem so bile merjene deformacijske sile in izračunan je bil tlak v orodju. Višje vrednosti napetostnega utrjevanja osnove so bile ugotovljene pri višjih tlakih pri manjših radijih krivin na robovih. Napetosti v osnovi so pri premeru 0,5 mm dosegle po tretjem prehodu vrednosti do 1560 MPa. Kot rezultat ekstruzije se je pojavila udrobnitev zrn in razvila se je podstruktura. Za natezno trdnost zlitine EN AW 6082 so bile določene vrednosti od 220 MPa do 230 MPa. Izvršen je bil tudi preizkus vtiskovanja, ki je pokazal, da so vrednosti za mehanske lastnosti 250-260 MPa. Vzorci so bili preiskani tudi s svetlobno mikroskopijo in vrstično elektronsko mikroskopijo (SEM). Opaženi so bili številni deformacijski trakovi. Površine preloma kažejo transkristalni žilavi prelom, ki se kaže v nejasno izraženih strižnih robovih, in imajo številne jamice, v katerih so drobni delci.

Ključne besede: mikrostruktura, lastnosti, zlitina aluminija, ECAP

1 INTRODUCTION

Extrusion with the ECAP method enables obtaining a fine-grained structure in larger volumes. The products made with this technique are characterised by high strength properties (**Figure 1**)[1] and they have the potential to be used during the subsequent superplastic forming. The magnitude of deformation, the development of the structure and the resulting mechanical properties achieved with this technique depend notably on: homologous temperature T_h, size of the grain d_g, deformation speed $\varepsilon°$, homologous tension in the die (σ/E), the density of structural failures, the purity, etc[2]. Obtaining the required final structure depends primarily on the geometry of the tool, the number of the passes through the die, the obtained magnitude and strain rate and the temperature.

The influence of the magnitude of the plastic deformation on the properties of metallic materials is asso-

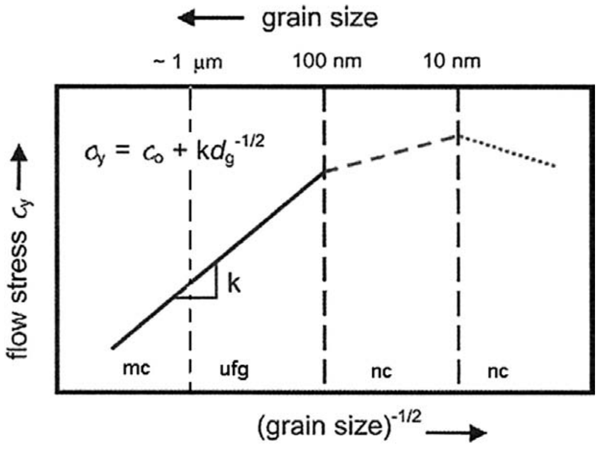

Figure 1: Schematic diagram of the variation in the yield stress as a function of grain size for: mc – coarse-grained materials, ufg – ultra-fine-grained materials and nc – nanocrystalline metals and alloys[1]

Slika 1: Shematski diagram spreminjanja meje tečenja v odvisnosti od velikosti zrn: mc – materiali z velikimi zrni, ufg – materiali z ultra drobnimi zrni in nc – kovine in zlitine z nanokristalnimi zrni[1] ciated with the increase in the internal energy[3–5]. Internal energy increases right to the limit value, which depends on the manner of deformation, purity, grain size, temperature, etc. As a result of the non-homogeneity of the deformation caused with the ECAP technique, the internal-energy gain differs between different places of the formed alloy. For example, the value of internal energy is different in the slip planes, at the boundaries and inside the cells. It is also possible to observe a higher internal energy in the proximity of precipitates, segregates and solid structural phases. For the usual techniques, pure metals, the medium magnitude of the deformation and temperatures, the value of stored energy is said to be approximately around 10 J mol^{-1}.[6] During cold extrusion, the density of dislocations increases with the magnitude of the plastic deformation. The density of dislocations depends linearly on the magnitude of the plastic deformation in accordance with the well-known equation[7,8]:

$$\rho = \rho_0 + K \cdot \varepsilon \tag{1}$$

where ρ_o is the initial dislocation density, K is the constant, ε is the magnitude of the deformation.

The flow stress necessary for the continuation of the deformation is a function of a number of lattice defects[9]:

$$\tau = \tau_0 + k \cdot G \cdot b \cdot \rho^{1/2} \tag{2}$$

where τ_o is the initial flow stress, k is the constant, G is the modulus of elasticity in shear, b is the Burgers vector, and ρ is the dislocation density.

The objectives of the experiments were a verification of the deformation behaviour of the given alloy and a determination of the resistance to deformation, the formability and the change in the structure during the extrusion of the alloys.

2 EXPERIMENTAL PROCEDURE

The AW 6082 alloy was used as the initial material. The amounts of individual elements in the alloy are given in **Table 1**.

Table 1: Chemical composition of the AW 6082
Tabela 1: Kemijska sestava zlitine AW 6082

Amounts of elements	Mg	Si	Mn	Fe	Cu	Zn
(%)	1.10	0.88	0.92	0.45	0.09	0.20

The experiments were made with an apparatus, the diagram of which is shown in **Figure 2**. Two types of matrices were used for the extrusion: with larger radii of the edges' rounding, $R_v = 2$ mm and $R_n = 5$ mm, and with smaller radii of the edges' rounding, $R_v = 0.5$ mm and $R_{vn} = 2$ mm. R_v is the inner rounding radius and R_n is the outer rounding radius of the channel angles.

During the process a metal billet is pressed through a die consisting of two channels with equal cross-sections, intersecting at the β angle. Essentially, the billet undergoes a simple shear deformation, but it retains the same cross-sectional geometry, so that it is possible to repeat the pressing for a number of passes, refining the grain to the extent, determined with the material characteristics.

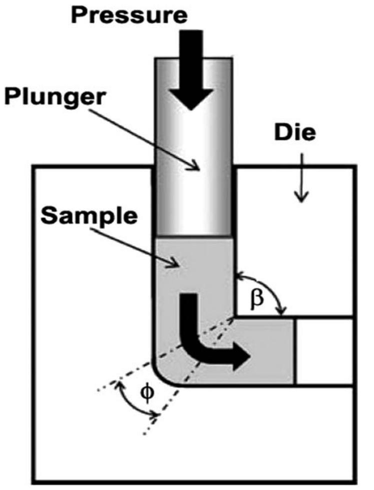

Figure 2: Schematic illustration of a die used in the present investigation, with $\beta = 90°$ and $\phi = 20°$
Slika 2: Shematski prikaz orodja, uporabljenega v preiskavi z $\beta = 90°$ in $\phi = 20°$

The samples for a metallographic determination of the structure were cut in the transverse direction for the alloy in the initial state and then again for the same alloy after the application of the ECAP technology. A partial sample was taken after each extrusion for a continuous evaluation of the microstructure. The samples were cut by a saw of the type MTH (Materials Testing Hrazdil) Mikron 110 using carbide cutting discs. An intense flow of the cooling emulsion prevented possible changes to the structural properties of the sample. After the cutting, the samples were pressed into dentacryl at a pressure of 18–24 MPa (180 bar to 240 bar) at elevated temperatures. The pressing was performed in the matrix of the type MTH Standard 30 for approximately 10 min. The grinding and polishing of the samples pressed into dentacryl were performed on a multi-functional automatic device, MTH Kompakt 1031. The roughness of the abrasive emery papers varied from 60 μm, through (120, 180, 200, 400, 600, 800, 1000, 1200, 2000) μm, to 2500 μm. The polishing pastes, used for the following polishing had a fineness of (0.09, 0.07, 0.06, 0.04, 0.03 and 0.01) μm. The microstructures of the samples were developed with an etching agent: 30 mL H_2O, 10 mL HF, 60 mL H_2O_2. The observations of the microstructures were made using an inverse metallographic microscope GX51 with a digital camera DP12.

A fractography analysis of the rupture surfaces was performed with a scanning electron microscope JEOL – JSM 5510.

The verification of the influence of equal-channel angular pressing on the mechanical properties was realised with a conventional mechanical tensile test and with the so-called penetration test. The samples were tested before and after the application of the ECAP

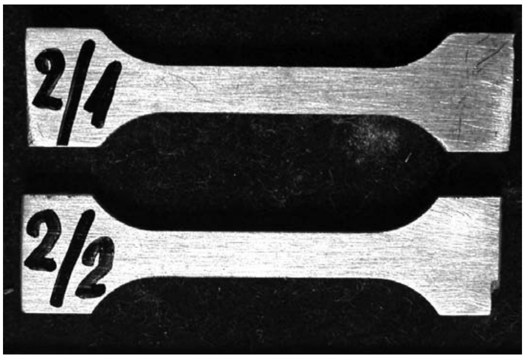

Figure 3: Miniature test specimens for the tensile test
Slika 3: Miniaturni vzorec za natezni preizkus

technology. A total of four miniaturised test specimens with a cross-section of 2.5 mm × 5 mm (**Figure 3**) were prepared for the tensile test and they were tested at the laboratory temperature and at the rate of movement of the cross member of 0.2 mm/min.

The samples for the penetration test were manufactured with the equipment SSamTM-2 of the Rolls-Royce company. Three test specimens in the form of a disc with a diameter of 8 mm and thickness of 0.5 mm were manufactured from the samples after the application of the ECAP technology, and they were subjected to the penetration test at the laboratory temperature. The principle of a small-punch test is a penetration of a special puncher with a spherical surface through a flat disc-shaped sample, which is fixed between the upper holder and the lower die.

3 RESULTS AND DISCUSSION

Deformation forces were measured during the extrusion and the pressures in the die were calculated. For the extrusion with the larger radii of the rounding of the edges (R_v = 2 mm; R_n = 5 mm) the pressure in the die during the first pass varied around τ_{max} = 620 MPa, and it gradually increased in such a manner that during the fourth pass its magnitude was approximately τ_{max} = 810 MPa. For the extrusion through the die with the smaller radii of the rounding (R_v = 0.5 mm; R_n = 2 mm) the pressure during the first pass was approximately τ_{max} = 780 MPa, and during the third pass it was approximately τ_{max} = 1560 MPa.[10,11]

Significantly higher values of the resistance to deformation and the strengthening during the extrusion are related to the high absolute value of the octahedral stress, which either makes the formation of dislocations more difficult or decelerates their movement.

Strengthening can be described in several manners. Grain boundaries have a very distinct impact. The influence of grain radius d_g on the yield strength is usually described with the Hall-Petch relation:

$$\sigma_y = \sigma_0 + k \cdot d_g^{-1/2} \tag{3}$$

For an aluminium alloy of the type similar to the AW 6082 alloy the constants in the equation (3) vary around these values: σ_0 = 15.2 MPa, k = 2.35 N mm$^{-3/2}$.

Another factor, which significantly influences the flow stress and the development of the microstructure is angle β, formed between the axes of the vertical and horizontal channels. This angle determines the magnitude of the shearing strain during individual passes and it can be expressed with the following relation:

$$\gamma = 2 \cot g \, (\beta/2) \tag{4}$$

The shearing strain at the angle β = 90° achieves the value of 2 and the normal deformation has the value of 2.3. A smaller angle β leads to a higher shearing stress at each pass. We checked the size of the angle β in the range from 90° to 125° using the technological route B_C.

We ascertained that grain refining is the most efficient (under the same magnitude of deformation) at the angle of 90°. This is due to the fact that, in this case, two slip planes in a sample form an angle of 60°. For the materials, whose formation is more demanding, it is more advantageous to apply the angle β = 120° together with a higher extrusion temperature. It is possible to calculate the magnitude of the accumulated deformation from the following relation:

$$\varepsilon_N = \frac{N}{\sqrt{3}}\left[2 \cot g\left(\frac{\beta}{2}+\frac{\phi}{2}\right)+\phi \cos ec\left(\frac{\beta}{2}+\frac{\phi}{2}\right)\right] \tag{5}$$

where N is the number of the passes through the die, β is the channel angle, ϕ is the additional angle.

With the passes, we achieved the magnitude of the total accumulated deformation in a sample (**Table 2**).

Table 2: Effective strain intensity and equivalent reduction after ECAP
Tabela 2: Intenziteta efektivne napetosti in ekvivalentna redukcija po ECAP

Number of passes	Total strain intensity (ε)	Equivalent area reduction (%)
1	1.15	69
2	2.30	90
3	3.45	97
4	4.60	99
5	5.75	99.8
6	6.90	99.9

On the basis of the realised experiments we determined the tensile strength, which was found to be R_m = 175 MPa for the AW 6082 aluminium alloy before ECAP (**Figure 4**). The tests were carried out at the ambient temperature at a crosshead speed of 1 mm/min.

The obtained values of the tensile strength for the aluminium alloy after ECAP varied in the range of R_m = 220 MPa to 230 MPa. The obtained values of the tensile strength correspond very well to the values obtained with a simulation and the approximate values based on the results of the measurements of the hardness. As it follows from a comparison of the strength properties, as a result

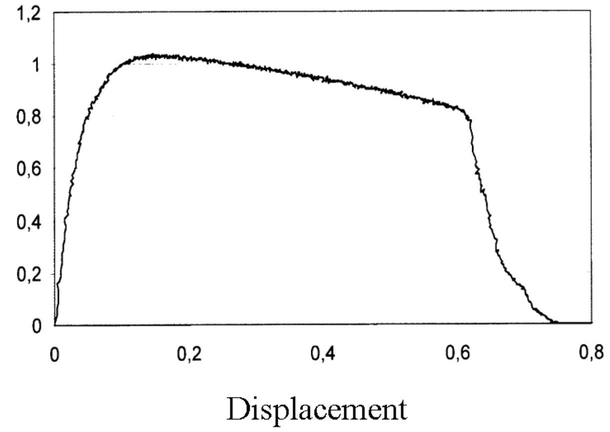

Figure 4: Stress-strain record of the tensile test
Slika 4: Napetost – raztezek pri nateznem preizkusu

of the rectangular extrusion the strength of the aluminium alloy was increased by approximately 25 %. On the basis of the realised experiments it is possible to state that the tensile strength of the aluminum alloy obtained with the small-punch test varies in the range from R_m = 250 MPa to 260 MPa, demonstrating very good agreement with the values of the tensile strength obtained with the standard tensile test (R_m = 220 MPa to 230 MPa). We performed fractography analyses on the broken halves of the test specimens. The results of the above-mentioned analyses, including their graphical presentations are given below.

An analysis of the microstructure before and after the application of the ECAP technology was performed with light optical microscopy. The structure of the initial original samples is shown in **Figure 5** and the structure of the samples after individual passes is shown in **Figure 6**.

The structure contains ordinary intermetallic phases corresponding to the given composition of the alloy. The average grain size in the transverse direction was determined with quantitative metallography methods and it varied around 150 µm.

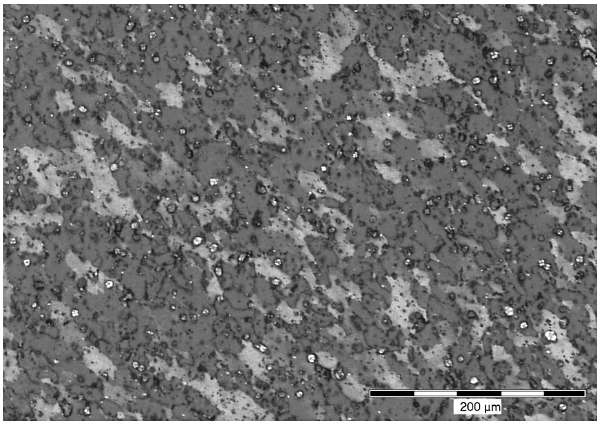

Figure 5: Structure of the initial sample of the AW 6082 alloy
Slika 5: Struktura začetnega vzorca zlitine AW 6082

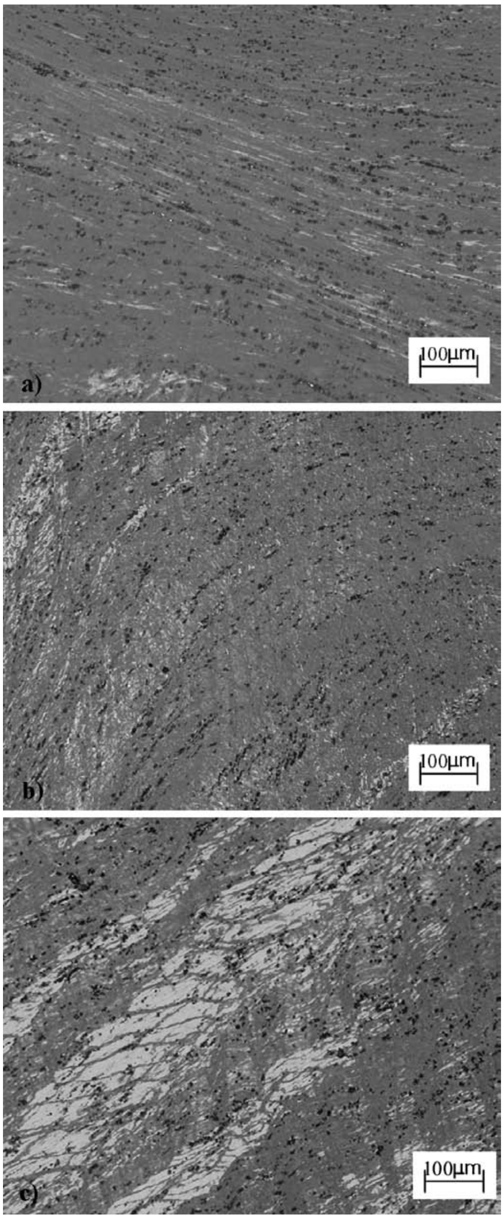

Figure 6: Structure of the samples after the ECAP extrusion in the longitudinal direction: a) after the 1st pass, b) after the 2nd pass, c) after the 3rd pass
Slika 6: Struktura vzorca po ekstruziji ECAP v vzdolžni smeri: a) po prvem prehodu, b) po drugem prehodu, c) po tretjem prehodu

Figure 6 shows the microstructure of the samples after the application of the ECAP technology. It shows deformation bands, the density of which is the highest in **Figure 6c** due to the largest plastic deformation.

The samples were then subjected to a SEM analysis. The change in the shape of the front and rear end of a sample and the maintenance of the integrity at the individual stages of the extrusion depends on the level of lubrication and on the radii of the rounding of the edges (R_v, R_n) of the extruding channel. After individual passes an accumulation of deformation strengthening took place, based on the formed substructure, which can be seen in **Figure 7** taken with an electron microscope.

An analysis of the fracture performed on the samples after the tensile test and small-punch test showed that the

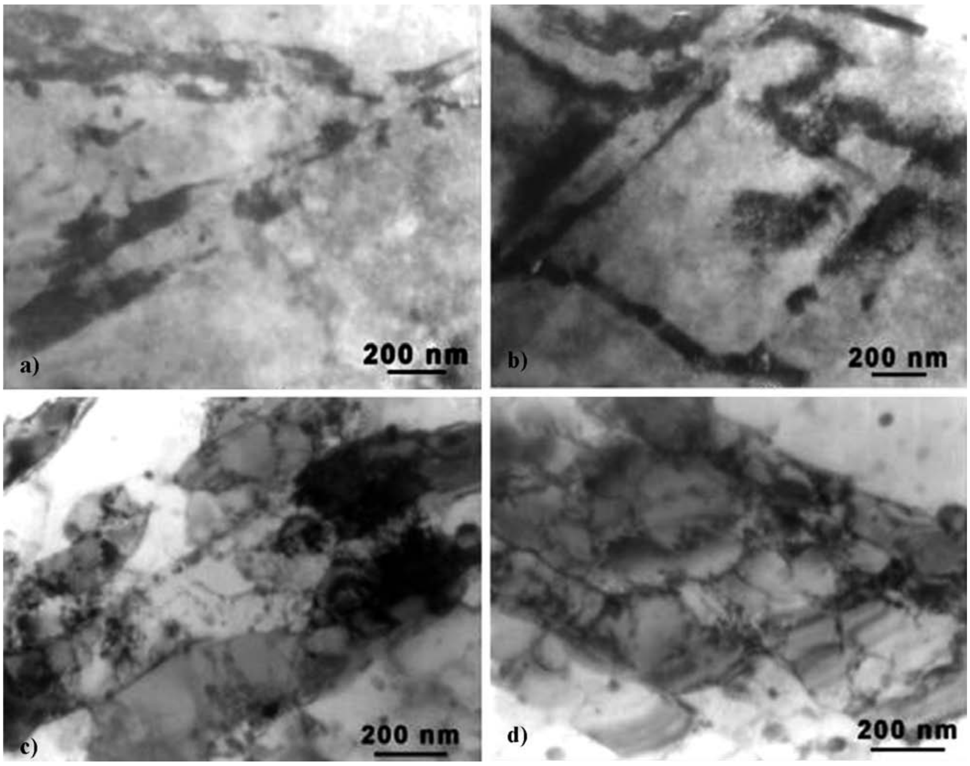

Figure 7: Substructure of the AW 6082 alloy after the ECAP extrusion: a) after the 1st pass, b) after the 2nd pass, c) after the 3rd pass, d) after the 4th pass
Slika 7: Podstruktura v zlitini AW 6082 po ECAP ekstruziji: a) po prvem prehodu, b) po drugem prehodu, c) po tretjem prehodu, d) po četrtem prehodu

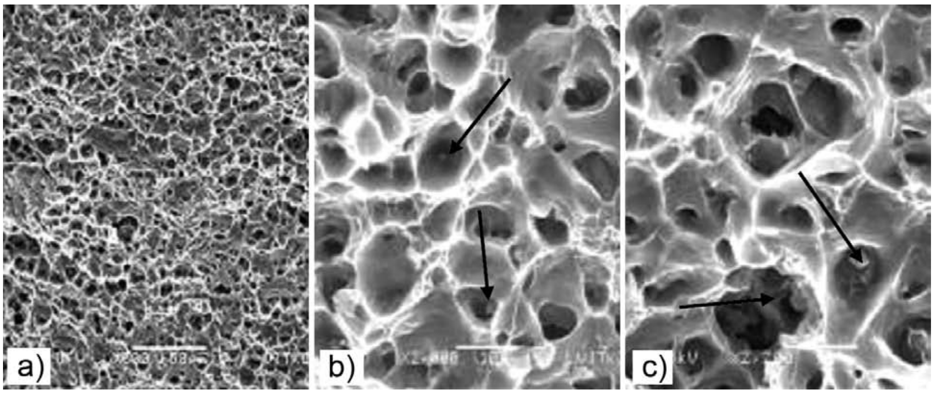

Figure 8: Transcrystalline ductile fracture after ECAP
Slika 8: Transkristalni žilav prelom po ECAP

fracture area looked planar and fine-grained with indistinctive shear fractures. It was determined with a detailed micro-fractographic observation that the fracture area was formed exclusively due to the mechanism of a transcrystalline ductile failure having a morphology of various pits (**Figure 8a**). These cavities contained a big number of minuscule particles (**Figures 8b** and **8c**) (→).

4 CONCLUSIONS

We have experimentally verified the behaviour of the AW 6082 alloy after an extrusion. The ECAP method is a potential tool for grain refining in polycrystalline metals. This procedure makes it possible to obtain a grain size of approximately 1 μm after four passes. In order to obtain the optimum microstructure it is necessary to apply more passes while turning the sample by 90° around the longitudinal axis between individual passes. A substructure is developed after four passes. The use of a die with an angle of 90° causes a more intense deformation and a higher resistance to deformation than the extrusion with larger angles. The radii of the rounding of the working edges of the extruding channel must correspond to the conditions for a laminar flow of the metal.

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5 REFERENCES

[1] K. S. Kumar, H. V. Swygenhoven, S. Suresh, Mechanical behavior of nanocrystalline metals and alloys, Acta Materialia, 51 (**2003**), 5743–5774

[2] S. Dadbakhsh, A. Karimi Taheri, C. W. Smith, Strengthening study on 6082 Al alloy after combination of aging treatment and ECAP process, Materials Science and Engineering A, 527 (**2010**), 4758–4766

[3] T. Kovářík, J. Zrník, M. Cieslar, Mechanical properties and microstructure evolution in ECAP processed Al-Mg-Si alloy, Proc. of the conference Metal 2010, Rožnov pod Radhoštem, Czech Republic, 2010, 176–181

[4] F. Parvizian, A. Güzel, A. Jäger et al., Modeling of dynamic microstructure evolution of EN AW-6082 alloy during hot forward extrusion, Computational Materials Science, 50 (**2011**) 4, 1520–1525

[5] M. M. El-Rayes, E. A. El-Danaf, The influence of multi-pass friction stir processing on the microstructural and mechanical properties of Aluminum Alloy 6082, J. Mat. Proc. Techn., 212 (**2012**) 5, 1157–1168

[6] S. Poortmans, B. Verlinden, Mechanical properties of fine-grained AA1050 after ECAP, Materials Science Forum, 503–504 (**2006**), 847–852

[7] N. Q. Chinh et al., Grain boundary sliding as a significant mechanism of low temperature plastic deformation in ECAP aluminum, Materials Science Forum, 503–504 (**2006**), 1001–1006

[8] M. Fujda, T. Kvačkaj, K. Nagyová, Improvement of mechanical properties for EN AW 6082 aluminium alloy using equal-channel angular pressing (ECAP) and post-ECAP aging, Journal of Metals, Materials and Minerals, 18 (**2008**) 1, 81–87

[9] M. Matvija, M. Fujda, T. Kvačkaj et al., The change in microstructure and mechanical properties of hypoeutectic heat treated AlSi7Mg0.3 alloy caused by application of ECAP technology, Strojírenské materiály, 16 (**2011**) 4, 47–53

[10] M. Greger et al., Possibilities of aluminum extrusion with use of the ECAP method, Proceedings of 9th International conference Aluminium in Transport 2003, Institute of Non-Ferrous Metals, Cracow-Tomaszowice, 2003, 165–169

[11] M. Greger, L. Kander, B. Kuřetová, Plastic forming of ECAP processed EN AW 6082 aluminium alloy, University Review, Alexandr Dubček University of Trenčín, 2 (**2008**) 3, 84–90