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MECHANICAL PROPERTIES AND MICROSTRUCTURE OF Al ALLOY PRODUCED BY SPD PROCESS.

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ABSTRACT
Aluminium alloy were subjected to ECAP process for grain refinemed to submicrometer levels. Microstructures after ECAP and subsequent annealing treatments were observed by using transmission electron microscope. Hardness and tensile tests were conducted on ECAP process alloys to examine the strength and elongation at ambient temperature. The hardness and strengths of ECAP processes alloy are higher considerably than those of commercially available respective alloy. Meanwhile, elongation is greatly decreasing after the second cycle and showing no further decrease with increasing the number of cycles. In the range of 5 to 8 cycles in ECAP process aluminium alloy exhibited strain hardening behaviour.
Keywords: ECAP technology, low carbon steel, structure and mechanical properties

1. INTRODUCTION
Influence of magnitude of plastic deformation on properties of metallic materials is connected with increase of internal energy. Internal energy increases right to the limit value, which depends on manner of deformation, purity, grain size, temperature, etc. As a result of non-homogeneity of deformation at ECAP technique the internal energy gain differs at different places of formed alloy [1]. For example the value of internal energy is different in slip planes, at boundaries and inside cells. It is possible to observe higher internal energy also in proximity of precipitates, segregates and solid structural phases. For usual techniques, pure metals, medium magnitude of deformation and temperatures the value of stored energy is said to be approx. around 10 $J.mol^{-1}$ [2]. At cold extrusion density of dislocations increases with magnitude of plastic deformation. Density of dislocations depends linearly on magnitude of plastic deformation in accordance with the well-known equation:

$$\rho = \rho_o + K \cdot \varepsilon \qquad (1)$$

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

Flow stress necessary for continuation of deformation is function of number of lattice defects [3]:

$$\tau = \tau_o + k \cdot G \cdot b \cdot \rho^{\frac{1}{2}} \qquad (2)$$

where τ_o is initial flow stress, k is a constant, G, b is modulus of elasticity in shear and Burgers' vector.

2. EXPERIMENTAL VERIFICATION OF THE ALLOY 2024

The objective of experiments consisted in verification of deformation behaviour of the given alloy, determination of resistance to deformation, formability and change of structure at extrusion of alloys. Experiments were made with use of an apparatus, the diagram of which is shown in Fig. 1. Contents of individual elements in the alloy is given in the Table 1.

Table 1. Chemical composition of the aluminium alloy 2024

Contents of elements	Cu	Mg	Mn	Si	Fe	Zn	Ti	Cr	Zr	Sn
[%]	4.21	1.31	0.62	0.32	0.24	0.20	0.11	0.10	0.05	0.03

2.1 Microstructure

Structure of initial original samples is shown in Fig. 2 and structure of samples after individual passes is shown in Fig. 3. The structure contains ordinary inter-metallic phases corresponding to the given composition of the alloy. Average grain size in transverse direction was determined by quantitative metallography methods and it varied around 150 μm. Change of shape of the front and rear end of the sample and maintenance of integrity at individual stages of extrusion depends on level of lubrication and on radii of rounding of edges (R_v, R_{vn}) of extruding channel [4].

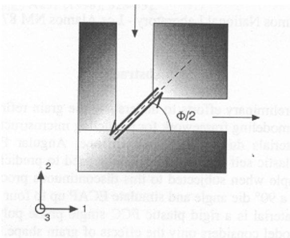


Figure 1. Diagram of extrusion ECAP

Figure 2. Structure of initial samples

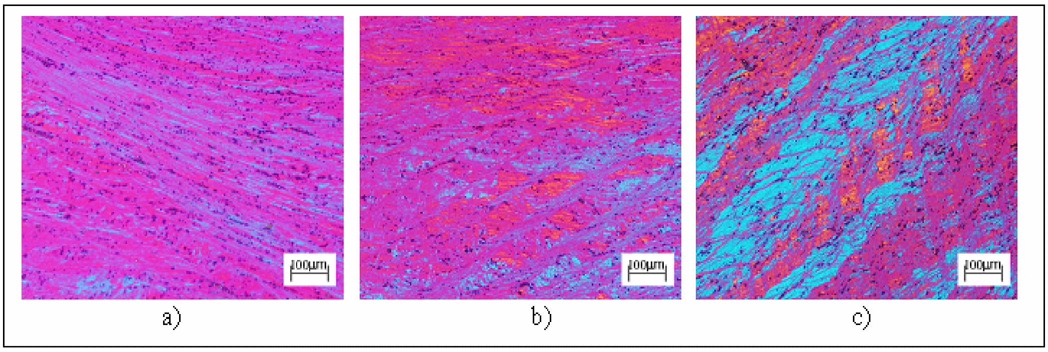


Figure 3. Structure of samples after extrusion in longitudinal direction
a) after the 1st pass b) after the 2nd pass c) after the 4rd pass

After individual passes there occurred accumulation of deformation strengthening, the basis of which was in the formed sub-structure, which can be seen in the Fig.4 taken by an electron microscope.

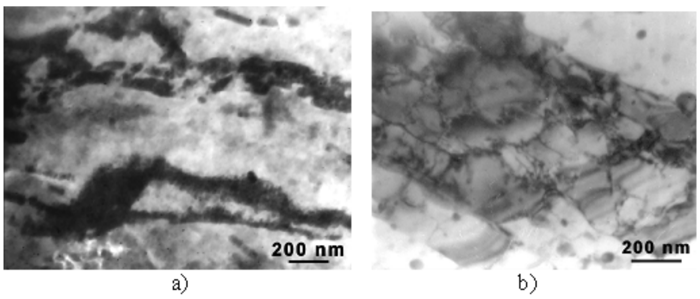


Figure 4. TEM microstructure of 2024 alloy after ECAP : (a)) ε = 1.15 ; (b) ε =4.61

Deformation forces were measured during extrusion and pressures in the die were calculated. At extrusion with the radius of rounding of edges (R_v = 3 mm; R_{vn} = 6 mm) the pressure in the die varied at the 1st pass around τ_{max} = 615 MPa, and it gradually increased in such a manner that at the fourth pass its magnitude was approximately τ_{max} = 810 MPa. At extrusion through a die with smaller radii of rounding (R_v = 1.0 mm; R_{vn} = 2.5 mm) the pressure at the first pass was approx. τ_{max} = 755 MPa, and at the third pass it was approx. τ_{max} = 1520 MPa. Significantly higher values of resistance to deformation and strengthening at extrusion are related to high absolute value of octahedral stress, which either contributes to more difficult formation of dislocations or decelerates their movement.
Strengthening can be described in several manners. Grain boundaries have very distinct impact. Influence of the grain radius d_z on yield strength is usually described by Hall-Petch relation:

$$\sigma_K = \sigma_o + K_y \cdot d_z^{-\frac{1}{2}} \qquad (3)$$

For the aluminium alloy of the type similar to the alloy 2024 the constants in the equation (3) vary around these values: σ_o = 16.4 MPa; K_y = 2.52 N.mm$^{-3/2}$. Another factor, which influences significantly flow stress and development of microstructure is the angle Φ, which is formed by axis of vertical and horizontal channel. Smaller angle Φ leads to higher shearing stress at each pass. We have checked the size of the angle Φ in the range from 90° to 125° with use of technological route B_C. We have ascertained, that refining of grains is the most efficient (under the same magnitude of deformation), at the angle of 90°. This is given by the fact that two slip planes in the sample make in this case the angle of 60°. For materials, forming of which is more difficult, it is more advantageous to apply the angle Φ = 120° together with higher extrusion temperature. It is possible to calculate the magnitude of accumulated deformation from the relation:

$$\varepsilon = 2N/\sqrt{3}.\text{cotg}(\Phi/2), \qquad (4)$$

where N is number of passes through a die.

After four passes we achieve in the sample magnitude of total accumulated deformation equal to 4.61.

2.2 Tensile test

We have verified influence of rectangular extrusion on mechanical properties with use of classical mechanical tensile test and so called penetration test. We made from samples after application of the ECAP technique miniature test specimens for tensile test (Fig. 5), which were tested at the laboratory temperature and speed of movement of crosspiece 0.2 mm/min.

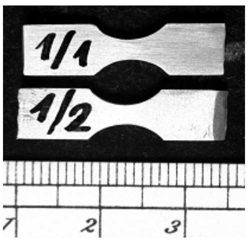


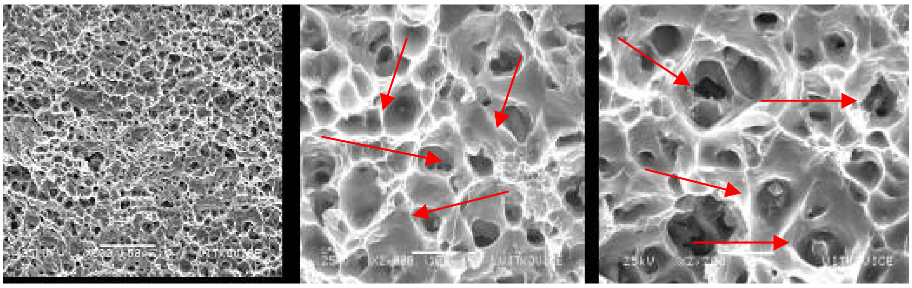
Figure 5. Miniature test specimens for tensile test

Obtained values of strength properties varied for the alloy 2024 within the range Rm = 460 to 470 MPa. Obtained strength values correspond very well with the values obtained by simulation and the values calculated on the basis of the hardness tests. In the frame of evaluation of influence of the ECAP technique of mechanical properties we have made also tensile tests of investigated materials, but without application of the ECAP technique. We have tested altogether 4 test specimens with cross-section 2.5 x 5 mm. On the basis of realised experiments we have determined ultimate strengths, which for the alloy 2024 were Rm = 490 MPa. As it follows from comparison of strength properties as a result of rectangular extrusion the strength of the alloy 2024 was increased approximately by 25 %. We have performed a fracture analyses on broken halves of test specimens. Results of these fracture analyses, including their graphical presentations are given below.

2. 3 Mechanical properties determined by penetration test

We made from the samples after application of the ECAP technique three test specimens in the form of disc with diameter of 8 mm and thickness of 0.5 mm, which were subjected to the penetration test at laboratory temperature. Basic mechanical properties were determined on the basis of penetration test, the principle of which consists in penetration of special punch with spherical surface through the flat disc-shaped sample, which is fixed between the upper holder and the lower die. On the basis of realised experiments it is possible to state that strength properties of the alloy 2024 obtained by penetration test vary in the range from Rm = 430 to 475 MPa, which demonstrates very good conformity with values of strength properties obtained by classical tensile test (Rm = 460 to 470 MPa).

Analysis of fracture areas was made with use of scanning electron microscope JEOL – JSM 5510. From visual viewpoint the fracture area looked as planar and fine-grain with indistinctive shear fractures. It was determined by detail micro-fractographical observation that fracture area was formed exclusively by mechanism of trans-crystalline ductile failure with morphology of various pits – Fig. 6a. These cavities contained big number of minuscule particles – Fig. 6b, 6c (→).



a) b) c)

Figure 9. Fracture areas in the alloy 2024

3. CONCLUSIONS

We have verified experimentally behaviour of the alloy 2024 after extrusion. Method ECAP is a potential tool for refining of grain in poly-crystalline metals. This procedure makes it possible to obtain after 4 passes the grain size of approx. 1 μm. In order to obtain an optimum micro-structure it is necessary to apply more passes with turning of the sample between individual passes by 90° about the longitudinal axis. After 4 passes there occurs development of sub-structure. At use of the die with the angle of 90° there is achieved more intensive deformation and resistance to deformation is higher than at extrusion with higher angles. Radii of rounding of working edges of extruding channel must correspond to conditions for laminar flow of metal.

4. ACKNOWLEDGEMENTS

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