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Ultrafine grain formation during equal channel angular extrusion in an Al-Mg-Si alloy

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ABSTRACT

Purpose: The possibility of including a new methods into classical technologies is one of reasons which for writing this paper.
Design/methodology/approach: Microstructural development of aluminium alloy 6082 during equal-channel angular pressing (ECAP). Analysis of structure was made by light microscopy and SEM analysis.
Findings: 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.
Research limitations/implications: In this process (ECAP) was one of head problems a impossibility of application other shapes material. One of eventuality solving in respect thereof is using DECAP process.
Practical implications: Radii of rounding of working edges of extruding channel must correspond to conditions for laminar flow of metal.
Originality/value: Aluminium alloy 6082 was used to ECAP process, and found to be that this material can to change substructure structure, mechanical properties, respectively. Achieved quality level of mechanical properties is a function of number of passes as well as used technological route.
Keywords: Shearing strain; ECAP; Ultrafine grain

1. Introduction

Extrusion by ECAP method enables obtaining of a fine-grain structure in larger volumes. Products made by this technique are characterised by high strength properties (Fig.1), and they can be potentially used at subsequent super-plastic forming. Magnitude of deformation, development of structure and resulting mechanical properties achieved by this technique notably depend on: homologous temperature T_h, size of grain d_z, deformation speed ε, homologous tension in die (σ/E), density of structural failures, on purity, etc. Obtaining of the required final structure depends primarily on geometry of tool, number of passes through die, obtained magnitude and speed of deformation, temperature, etc.

2. Development of structure

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 [2]. 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 around 10 $J.mol^{-1}$, approx. [3]. At cold extrusion density of dislocations increases with magnitude of plastic deformation. Density of dislocations linearly depends on magnitude of plastic deformation in accordance with the well-known equation:

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

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

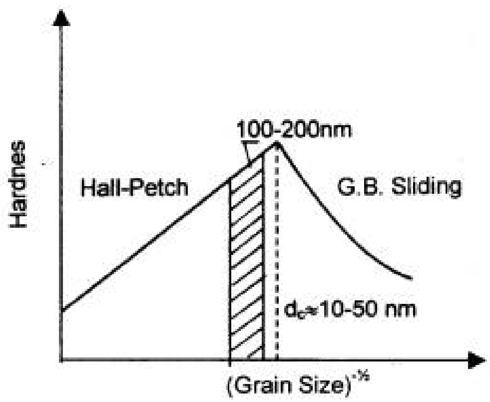


Fig. 1. Predicted dependence of strength on grain size [1]

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

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

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

3. Experimental procedure

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 by of an apparatus, the diagram of which is shown in Fig. 2. Contents of individual elements in the alloy is given in the Table 1.

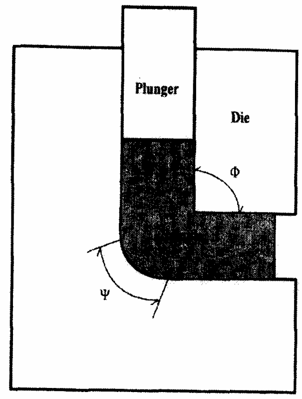


Fig. 2. Diagram of extrusion ECAP

3.1. Microstructure

Structure of initial original samples is shown in Fig. 3 and structure of samples after individual passes is shown in Figure 4. The structure ordinary contains inter-metallic phases corresponding to the given composition of the alloy.

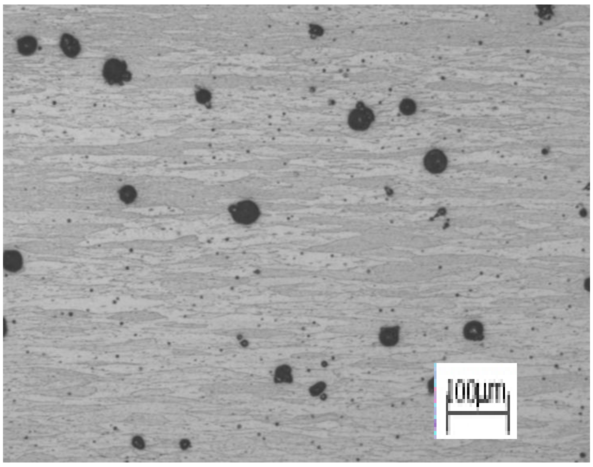


Fig. 3. Structure of initial sample

Average grain size in transverse direction was determined by quantitative metallography methods and it varied around 150 μm. Shape change of the front and rear end of the sample and integrity maintenance at individual stages of extrusion depend on level of lubrication and on radii of rounding of edges (R_v, R_{vn}) of extruding channel [4-6].

Table 1.
Chemical composition of the aluminium alloy 6082

Contents of elements	Mg	Si	Mn	Fe	Ti	Cu	Zn	Ni	Sn	Cr
[%]	1.106	0.88	0.9	0.21	0.003	0.029	0.026	0.003	0.003	0.002

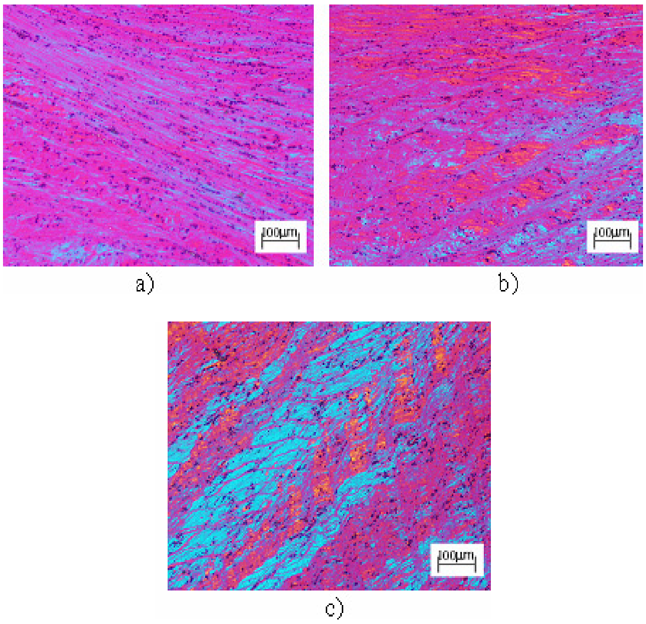


Fig. 4. Structure of samples after extrusion in longitudinal direction: a) after the 1st pass, b) after the 2nd pass, c) after the 3rd pass

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.5 taken by an electron microscope.

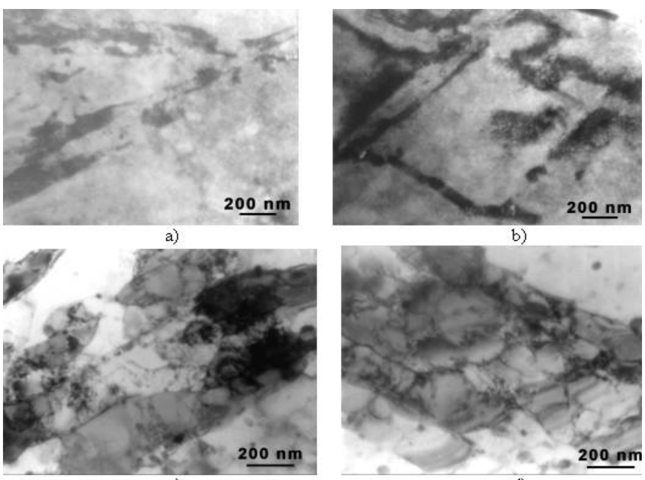


Fig. 5. Substructure aluminium alloy 6082 after extrusion: a) after the 1st pass, b) after the 2nd pass, c) after the 3rd pass, d) after the 4rd pass

Deformation forces were measured during extrusion and pressures in the die were calculated. At extrusion with the radius of rounding of edges (R_v = 2 mm; R_{vn} = 5 mm) the pressure in the die varied around τ_{max} = 620 Mpa at the 1st pass, and it gradually increased in such a manner that at fourth pass its magnitude was τ_{max} = 810 MPa approximately. At extrusion through a die with smaller radii of rounding (R_v = 0.5 mm; R_{vn} = 2 mm) the pressure at the first pass was τ_{max} = 780 MPa, while at the third pass τ_{max} = 1560 MPa approximately.

Significantly higher values of resistance to deformation and strengthening at extrusion are related to high absolute value of octahedral stress [7], 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:

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

Another factor, significantly influencing flow stress and development of microstructure is the angle Φ, which is formed by axis of vertical and horizontal channel. This angle determines magnitude of shearing strain in individual passes and it can be expressed by the relation:

$$\gamma = 2\,\mathrm{cotg}(\Phi/2) \quad (4)$$

Shearing strain at the angle Φ = 90 achieves the value of 2 and normal deformation the value of 2.3. 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° using the technological route **B**$_C$, Fig. 6.

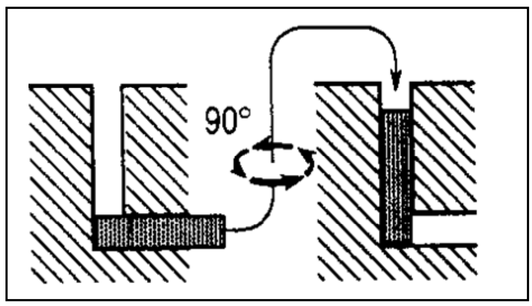


Fig. 6. The technological route

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:

$$\varepsilon = 2N/\sqrt{3}.\mathrm{cotg}(\Phi/2) \quad (5)$$

where:
N - is number of passes through a die.

After passes we achieve in the sample magnitude of total accumulated deformation - Table 2.

3.2. Mechanical properties

Tensile test

We have verified influence of rectangular extrusion on mechanical properties using the 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. 7), being tested at the laboratory temperature and process movement speed 10 mm/min. Obtained values of strength properties varied for the alloy 6082 within the range Rm = 220 to 230 MPa. Obtained strength values correspond with the values obtained by simulation and close calculated on the basis of the hardness tests very well. In the frame of evaluation of influence of the ECAP technique of mechanical properties we have performed 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 were R_m = 175 MPa for the alloy 6058. As it follows from comparison of strength properties as a result of rectangular extrusion the strength of the alloy 608258 was increased approximately by 25 %.

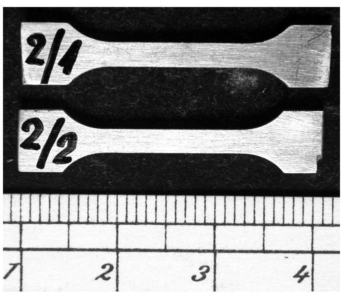


Fig. 7. Miniature test specimens for tensile test

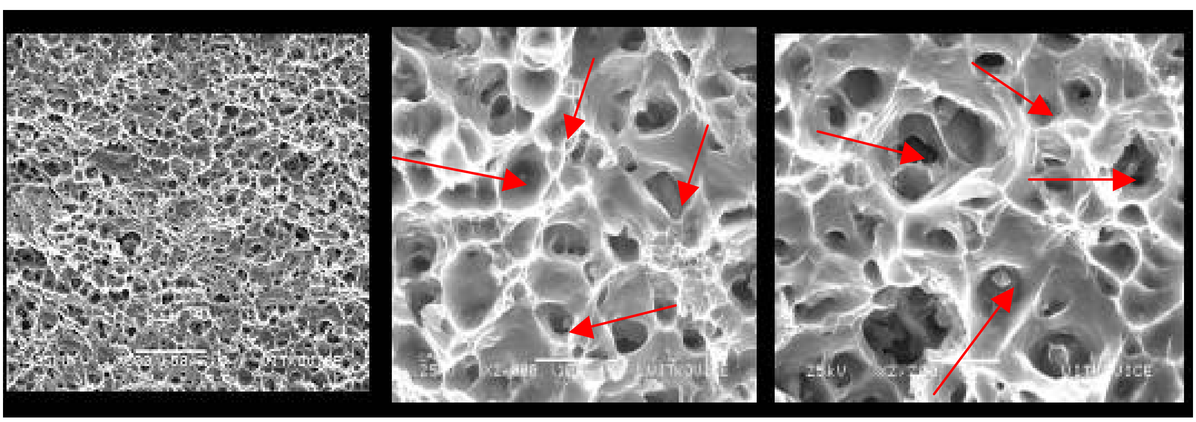
We have performed a fracture analyses on broken halves of test specimens. Results of these fracture analyses, including their graphical presentations are given below.

Mechanical properties determined by penetration test

Taking of material samples for experiment was carried out by the apparatus SSam^{TM}-2 made by Rolls-Royce. 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 6082 obtained by penetration test vary in the range from Rm = 250 to 260 MPa, which demonstrates very good conformity with values of strength properties obtained by classical tensile test (R_m = 220 to 230 MPa).

Fracture analysis of fracture areas in the alloy 6082

Analysis of fracture areas was polished by 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 exclusively formed by mechanism of trans-crystalline ductile failure with morphology of various pits – Fig. 8a. These cavities contained big number of minuscule particles – Fig. 8b, 8c.



a) b) c)

Fig. 8. Fracture areas

Table 2.
Effective strain intensity and equivalent reduction

Number of passes	Total Strain Intensity [ε]	Equivalent Area Reduction [%]
1	1.15	69
2	2.31	90
3	3.46	97
4	4.62	99

4. Conclusions

We have experimentally verified behaviour of the alloy 6082 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 1 μm approx. 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 development of sub-structure occurs there. Using the die with the angle of 90° more intensive deformation is achieved there. Deformation resistance 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.

Acknowledgements

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