Development of the Structure and Properties of Aluminium Alloy EN AW 6082 after Severe Plastic Deformation

Vývoj struktury a vlastností slitiny hliníku EN AW 6082 po extrémní plastické deformaci

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Microstructure and texture development of an EN AW6082 alloy during equal channel angular pressing (ECAP) was investigated and correlated with the mechanical properties. The micro-structure was effectively refined by ECAP, and the original fibre texture of the extruded aluminium alloy was disintegrated, and a new texture was gradually developed by repetitive ECAP pressing. After 6 ECAP passes following the route B_c*, the yield stress was lower than that of the as-extruded aluminium alloy, indicating that the texture softening was dominant over the strengthening due to grain refinement. Cross-section of original samples was 20 x 20 mm and their length was 125 mm. Deformation forces were measured during extrusion, resistance to deformation was calculated and deformation speed was determined approximately. Analysis of structure was made with use of light microscopy, TEM and SEM. Mechanical properties of the samples after extrusion were determined by tensile test and by the so-called penetration test.*

***Key words**: micro-structures; properties; aluminium alloy; ECAP*

Experimentálně byl ověřován vývoj mikrostruktury a mechanických vlastností slitiny hliníku EN AW 6082 při aplikaci extrémní plastické deformace protlačováním úhlovými kanály (ECAP) a stanoven vztah mezi strukturou a mechanickými vlastnostmi. Příčný průřez výchozích vzorků byl 20 x 20 mm, délka vzorků 125 mm. Vzorky byly protlačovány při teplotě místnosti. Pro zvýšení koncentrace a zrovnoměrnění deformace v objemu vzorku byly vzorky po jednotlivých protlačeních pootočeny kolem podélné osy o 90° a znovu protlačovány (cesta B_c*). Při aplikaci extrémní plastické deformace technologií ECAP probíhá intenzivní zjemňování zrna, už v počátečních průchodech vzorků matricí, ale deformace je v objemu vzorků nerovnoměrná. Se zvyšujícím se počtem průchodů vzorků matricí je intenzita zjemňování zrna menší, avšak velikost jednotlivých zrn je rovnoměrnější. Jednotlivá zrna jsou přednostně orientována ve směru hlavní deformace. Po šesti průchodech ECAP tažnost slitiny EN AW 6082 klesá i když zjemnění zrna bude pokračovat i při zvýšeném počtu průchodů ECAP. Při aplikaci ECAP byly měřeny deformační síly, vypočítány deformační odpory v jednotlivých průchodech, stanovena optimální deformační rychlost a teplota deformace se pohybovala pod teplotou rekrystalizace zpracovávané slitiny EN AW 6082. Rozbor struktury byl proveden pomocí světelné mikroskopie, pomocí TEM a SEM. Mechanické vlastnosti vzorků po protlačování byly stanoveny zkouškou tahem a provedením penetračního testu. Využití extrémní plastické deformace pro zvýšení mechanických vlastností Al slitin je v současné době stálé ve stádiu laboratorních zkoušek.*

***Klíčová slova**: micro-structures; properties; aluminium alloy; ECAP*

1. Introduction

Extrusion by ECAP method enables to obtain a fine-grained structure in larger volumes. Products made by this technique are characterized by high strength properties, Fig. 1.

$$\sigma_y = \sigma_o + k\, d_g^{-\frac{1}{2}} \tag{1}$$

where σ_y is the yield stress, σ_0 is a material constant for the starting stress of dislocation movement (or the resistance of the lattice to dislocation motion), k is the strengthening coefficient (a constant unique to each material), and d_g is the average grain diameter.

The Hall–Petch relation (1) predicts that as the grain size decreases, the yield strength increases. The Hall–Petch relation was experimentally found to be an effective model for materials with grain sizes ranging from 1 millimeter to 1 micrometer [2-4]. Consequently, it was believed that if the average grain size was decreased even more to the nanometer length scale, the yield strength would increase as well [5-7]. However, experiments on many nano-crystalline materials demonstrated that if the grains reached the critical grain size, which was typically less than 100 nm, the yield strength would either remain constant or decrease with the decreasing grain size [8]. This phenomenon has been termed as reverse or inverse Hall–Petch relation. A number of different mechanisms have been proposed for this relation. As suggested by Poková et al. [9], they fall into four categories: (1) Dislocation based, (2) Diffusion based, (3) Grain boundary shearing based, (4) Two phase based [10, 11]. Other explanations, that have been proposed to rationalize the apparent softening of metals with nano-sized grains, include poor sample quality and suppression of dislocation pileups. Many of the early measurements of reverse Hall–Petch effect were likely the result of unrecognized pores in samples. The presence of voids in nano-crystalline metals would undoubtedly lead to their weaker mechanical properties. The pileup of dislocations at grain boundaries is a signature mechanism of the Hall–Petch relationship [12, 13]. However, once grain sizes drop below the equilibrium distance between dislocations, this relationship should no longer be valid. Nevertheless, it is not entirely clear what exactly the dependency of yield stress should be on grain sizes below this point.

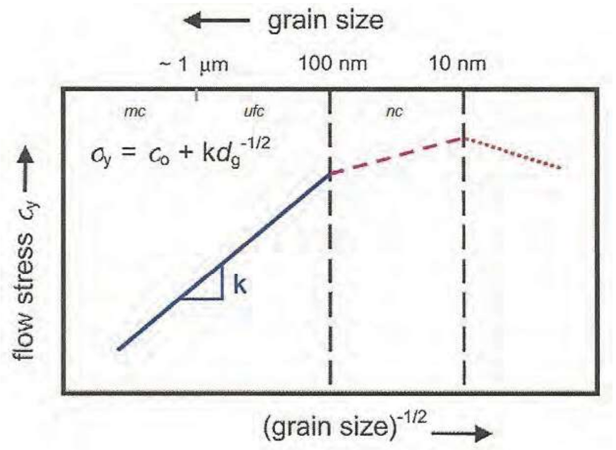

Fig. 1 Schematic representation of the variation of yield stress as function of grain size in mc, ufc and nc metals and alloys

Obr. 1 Závislost meze kluzu na velikosti zrna pro hrubozrnné (mc), ultrajemnozrnné (ufc) a nanostrukturní (nc) materiály

2. Development and structure

Influence of amount of plastic deformation on properties of metallic materials is connected with an increase of internal energy. Internal energy increases right to the limit value, which depends on the manner of deformation, purity, grain size, temperature, etc. As a result of inhomogeneity of deformation caused by the ECAP technique the internal energy gain differs at different places of the formed alloy. 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, segregations and solid structural phases. For usual techniques, pure metals, medium amount of deformation and temperatures, the values of stored energy are said to be approx. around 10 J·mol^{-1} [14]. In cold extrusion density of dislocations increases with magnitude of plastic deformation. Density of dislocations depends linearly on amount of plastic deformation in accordance with the well-known Eq. (2) [15, 16]:

$$\rho = \rho_o + K \cdot \varepsilon \qquad (2)$$

where ρ_o is initial dislocation density (10^{10} to 10^{12} m^{-2}), K is a constant, ε is amount of deformation.

Flow stress necessary for continuation of deformation is function of number of lattice defects as stated by Eq. 3 [17, 18]:

$$\tau = \tau_o + k \cdot G \cdot b \cdot \rho^{\frac{1}{2}} \qquad (3)$$

Where τ_o is initial flow stress, k is a constant (k = 0.3), G, is modulus of elasticity in shear (G ~ 25 GPa) and b is Burgers vector (b = 0.3 to 0.4 nm)

3. Experimental procedures

The objective of experiments was to verify deformation behaviour of the given alloy, determine its resistance to deformation, formability and change of structure in extrusion of this alloys. Experiments were made with use of an apparatus, the diagram of which is shown in Fig. 2. Chemical composition the alloy is given in Tab. 1.

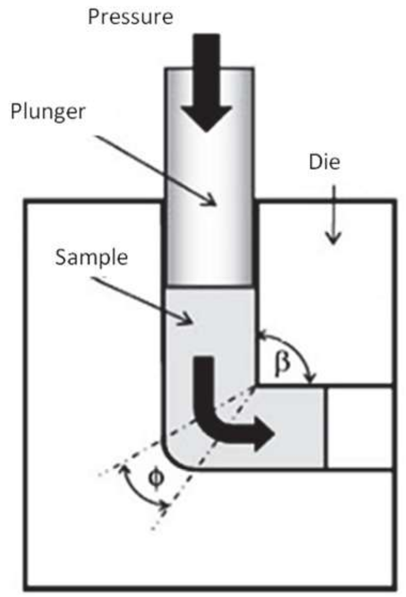

Fig. 2 Schematic illustration of a die used at the present investigation: a) with Φ = 90° and ψ = 20°

Obr. 2 Schématické znázornění tvaru zápustky ECAP: a) s vnitřním úhlem kanálů Φ = 90° a vnějším úhlem kanálů ψ = 20°

Tab. 1 Chemical composition of the EN AW 6082 alloy

Tab. 1 Chemické složení slitiny hliníku EN AW 6082

Contents of elements	Mg	Si	Mn	Fe	Cu	Zn	Ti	Cr	Al
[wt. %]	1.10	0.88	0.92	0.45	0.09	0.20	0.09	0.70	balance

During the process a metal billet is pressed through a die consisting of two channels, equal in cross section and intersecting at an angle **Φ**. The billet undergoes essentially simple shear deformation, but it retains the same cross-sectional geometry, so that it is possible to repeat the pressings for a number of passes, each one refining the grain to the extent, which is determined by the material characteristics.

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

Another factor, which influences flow stress and development of micro-structure significantly, is the angle Φ, which is formed by the axis of vertical and horizontal channel. This angle determines magnitude of in individual passes, and it can be expressed by Eq. (4) [19, 21]:

$$\gamma = 2 \text{ cotg } (\Phi/2) \tag{4}$$

Shear strain at the angle Φ = 90 reaches the value of 2, and normal deformation reaches 2.3. Smaller angle Φ leads to higher shear stress at each pass. We have checked the size of the angle Φ in the range from 90° to 120° 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 Eq. (5) [1, 22]:

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

where N is number of passes through a die, Φ is angle channels, Ψ is additional angle.

Values of total accumulated deformation, grain size and mechanical properties of the sample after increasing number of passes are shown in Tab. 2.

Tab. 2 Effective strain intensity, grain size, and mechanical properties samples EN AW 6082 after ECAP
Tab. 2 Nárůst intenzity deformace, velikost zrna a mechanické vlastnosti vzorků slitiny EN AW 6082 po jednotlivých průchodech ECAP

Number of passes	Total strain intensity	Equivalent area reduction	Grain size	0.2% YS	UTS	$\frac{UTS}{0.2\%YS}$	Elong.	$\bar{\sigma}$ $\bar{\sigma} = C \cdot \varepsilon^n$
	[ε]	[%]	[μm]	[MPa]			[%]	[MPa]
0	-	-	50	120	185	1.50	15.5	175.10
1	1.15	69	3.5	190	230	1.20	8.5	179.95
2	2.30	90	2.0	217	252	1.15	7.5	206.90
3	3.45	97	1.5	230	283	1.20	6.5	224.30
4	4.60	99	1.1	250	312	1.25	6.0	237.65
5	5.75	99.8	1.0	265	325	1.25	5.5	248.30
6	6.90	99.9	0.9	275	340	1.25	5.5	257.50

4. Experimental result and discussion

4.1 Micro-structure

Structure of initial original samples is shown in Fig. 3 and structure of samples after individual passes is shown in Fig. 4.

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 50 μm. Change of shape of the front and rear end of the sample and maintenance of integrity at individual stages of extrusion depend on the level of lubrication and on radii of edges (R_v, R_{vn}) of the extruding channel. After individual passes accumulation of deformation strengthening occurred, the basis of which was in the formed sub-structure, which can be seen in Fig. 5.

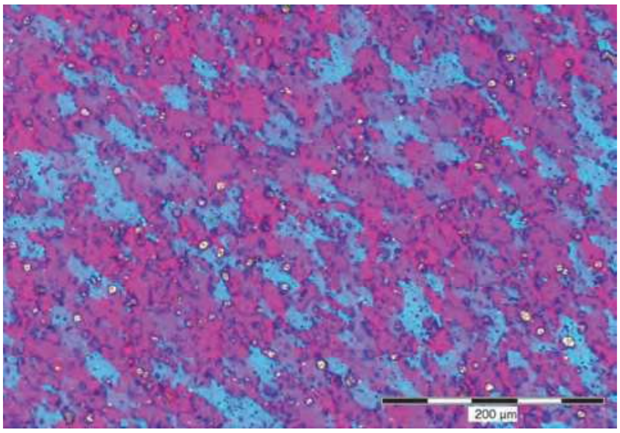

Fig. 3 Microstructure of initial sample EN AW 6082 alloy
Obr. 3 Počáteční mikrostruktura slitiny EN AW 6082