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MECHANICAL BEHAVIOUR COMPARISON BETWEEN UN-PROCESSED AND ECAP (Equal Channel Angular Pressing) PROCESSED 6063-T835 ALUMINUM ALLOY

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Presarea în canale la unghiuri egale (Equal Channel Angular Pressing) – ECAP – este o metodă de modificare a microstructurii materialelor, având ca scop obținerea de structuri ultra fine şi nanostructuri. Metoda constă în presarea unei probe de material printr-o matriță care conține două canale, de secțiune egală, care se intersectează sub un anumit unghi ϕ, între canale existând şi un unghi de racordare ψ. Ca un rezultat al presării, materialul se deformează numai datorită forfecării din zona de deformare. În urma procesării prin metoda ECAP a unei probe de aliaj de aluminiu 6063-T835, într-un număr de 6 presări, s-au constatat creşteri seminificative în valorile caracteristicilor mecanice, atât pentru limita de curgere, rezistența maximă cât şi pentru limita de rupere a materialului.

Equal Channel Angular Pressing (ECAP) is a very interesting method for modifying microstructure in producing ultra fine grained materials (UFG) and nanomaterials (NM). It consists of pressing test samples through a die containing two channels, equal in cross section and intersecting at an angle ϕ and a corner angle ψ. As a result of pressing, the sample theoretically deforms by simple shear and retains the same cross sectional area to repeat the pressing for several cycles. The 6063-T835 aluminum alloy was examined after six pressing operations by route BC in a $\phi = 90°$ and $\psi = 20°$ die. The specimens were processed for a number of six passes. Mechanical behaviour of the ECAP processed material was investigated by uniaxial tensile tests. It was found that, the ECAP process increases the mechanical properties. The significant increase in ultimate tensile strength (σ_{UTS}), yield strength (σ_{YS}) and strength to fracture (σ_F) after ECAP was observed and discussed by two strengthening mechanisms.

Keywords: Mechanical processing, Mechanical behaviour, Aluminium alloys, Nanocrystalline materials, Fracture surfaces

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1. Introduction

Aluminium alloys, like Al 6063, are some of the most widely used materials today which spans the entire range of industries. They are used in many consumer products, including pipes, railings, furniture, architectural extrusions, irrigation pipes, and transportation. The aircraft and aerospace industry uses aluminium alloys because it is much lighter than steel and every kilogram of weight reduction results in greater fuel savings and higher payloads. The car industry has increased its use of aluminium over the years as the price of gasoline has increased and the need to reduce vehicle weight has been of paramount importance. Today, much of aluminium's use is to reduce the weight of the item being produced, but it has always been popular because it is easy to machine, cast, extrude, roll, etc. and many alloys are age-hardenable [1-3].

Because of the widespread use of these alloys, it is important to understand their mechanical behaviour when exposed to different loading conditions, strain rates and temperatures, and to be able to model the behaviour and later, to predict the behaviour for any of these conditions. In order to improve mechanical properties of these alloys many processing routes can be applied. During the last decade, the equal-channel angular pressing (ECAP) route proved to produce ultrafine-grained bulk samples in a fully dense condition without changing the cross-sectional dimensions of the samples. During ECAP, significant grain refinement occurs together with dislocation strengthening, resulting in a significant enhancement in the strength of the alloys [4-6].

Equal channel angular pressing (ECAP) is a technique using severe plastic deformation to produce ultra-fine grain sizes in the range of hundreds of nanometers to bulk course grained materials [7-9]. ECAP is performed by pressing a billet of material through a die that has two channels which intersect at an angle. The billet experiences simple shear deformation, at the intersection, without any precipitous change in the cross section area because the die does not allow for lateral expansion. This means the billet can be pressed more than once and can be rotated about the pressing axis during subsequent pressings. A single pass with channels 90° to each other, induces approximately 1.15 equivalent strain in the billet.

Depending on the billet rotation, different deformation routes can be applied. Route A has no rotation of the billet, route BA is rotated counter clockwise 90° on even number of passes and clockwise 90° on odd number of passes, route BC is rotated counter clockwise 90° after every pass, and route C is rotated 180° after every pass [10]. This technique can be applied to commercial pure metals and metal alloys, with FCC, BCC and HCP crystal structures, with coarse grains to fabricate ultra-fine grained materials that have no porosity and higher strength than the non-processed material [11-14].

2. Experimental procedure

Material

A 6063-T835 aluminum alloy was investigated in this study. The chemical composition (wt%) of Al 6063-T835 alloy used in the experiment was: Si 0.467; Mg 0.488; Fe 0.602; Cu 0.103; Mn 0.086; Zn 0.133; Ti 0.012; Ni < 0.02; Cr < 0.08; balance is Al.

The Al 6063-T835 specimens were obtained from 100 cm round billets stock, obtained by continuous casting, hot extruded and heat treated. The specimens were machined such that the specimen axis was perpendicular to the continuous extrusion direction of the billets. The specimens machining for the ECAP processing was performed using an abrasive cutter Metkon SERVOCUT M300, in order to cut specimens from the initial continuous extruded billets. The final specimens dimensions for the ECAP process was 60 x 9.6 x9.6 mm.

From the un-processed and ECAP processed specimens, samples for mechanical testing were cut. For the samples subject to ECAP process, the axis was parallel to the ECAP direction. A precision cutter Metkon MICRACUT 200 was used to obtain samples with 30 x 1.5 x1 mm dimensions.

Equal channel angular pressing procedures

The ECAP die had a channel angle of ϕ = 90° and a corner angle of approximately = 20° (Fig. 1). The accumulated equivalent strain values was calculated using the die-channel and relief angles in Eq. (1) [15]:

$$\varepsilon_N = N \cdot \frac{1}{\sqrt{3}}\left[2\cot\left(\frac{\phi}{2}+\frac{\Psi}{2}\right)+\Psi\operatorname{cosec}\left(\frac{\phi}{2}+\frac{\Psi}{2}\right)\right] \tag{1}$$

were N is the number of passes, ϕ is the channel angle and ψ is the corner angle.

According to Eq. (1) the equivalent strain depends on both ϕ and ψ angles. It decreases when ψ increases and the maximum ($\varepsilon_N \sim 1.15$) is obtained for ϕ = 90° and ψ close to zero [16]. Eq. (1), proposed by Iwahashi et al. [15], is an analytical expression for calculating the equivalent strain imposed in each ECAP pass only in terms of die geometric parameters. The assumptions in this geometric analysis include simple shear, a frictionless die surface, a uniform plastic flow on a plane, a complete filling of the die channel by the workpiece and a rigid perfectly plastic material (no strain hardening behaviour is included). With this assumptions, Eq. (1), doesn't take into account for the effect of friction, strain hardening, strain distribution and deformation gradient, providing a homogeneous value of strain in the whole workpiece.

For channel angle of $\phi = 90°$ and a corner angle of approximately $\psi = 20°$, the equivalent strain for each pass subjected to each specimen is about 1.05.

No lubricant was used during ECAP material processing. The specimens were pressed at room temperature in six passes, using a pressing speed of 10 mm/s and ECAP route BC.

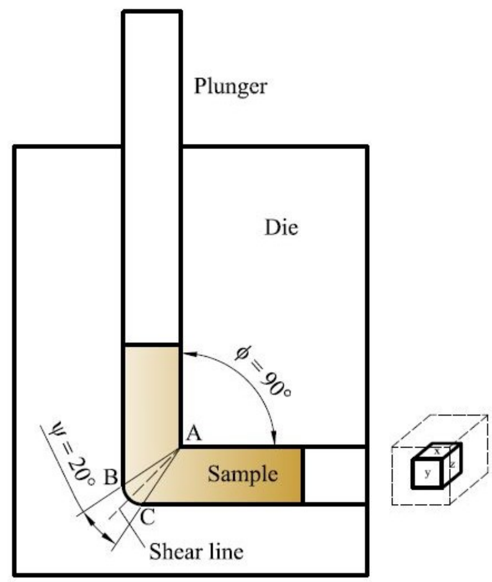


Fig. 1. ECAP die geometry showing the scheme of the process
(ABC is the plastic deformation zone - PDZ)

Mechanical testing

All samples were mechanical investigated in tensile tests using a Gatan MicroTest 2000N module, mounted inside of a Tescan VEGA II – XMU SEM. Ultimate tensile strength (σ_{UTS}), yield strength (σ_{YS}), strength to fracture (σ_F) and maximum elongation to fracture (ε_F) were obtained. Main testing parameters were as follows: testing speed 0.4 mm/min; testing temperature 20°C; testing environment: high vacuum.

Fracture surfaces analysis

Samples fracture surfaces subjected to ECAP process and un-processed state were investigated using a Tescan VEGA II – XMU SEM microscope.

3. Results and Discussion

All of the stress–strain results for all experiments are based on the current configuration of the specimen.

Uniaxial tensile experimental results for 6063-T835 aluminum alloy

As sown in Fig. 2, one can observe significant improvement in mechanical properties for ECAP processed specimens.

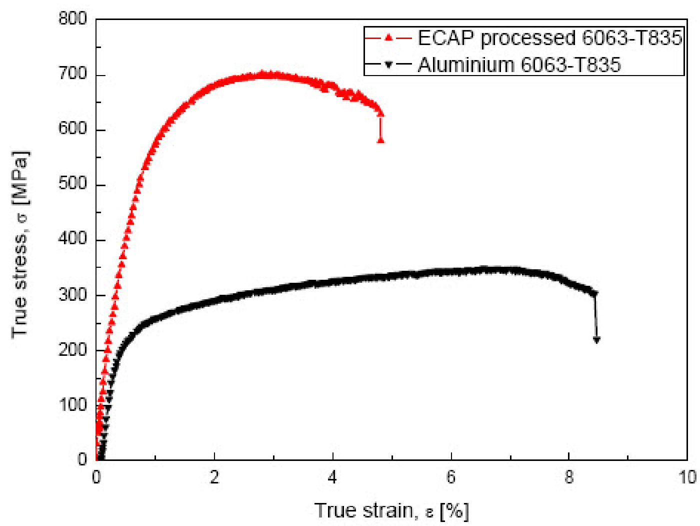


Fig. 2. True stress – true strain diagram for unprocessed and ECAP processed 6063-T835 aluminum alloy

Fig. 2 shows an increasing in ultimate tensile strength (σ_{UTS}) from 348.86 MPa to 699.78 MPa for 6 passes ECAP processed Al 6063-T835 alloy, aprox. 100% increasing. The same behaviour is observed for yield strength (σ_{YS}) and strength to fracture (σ_F), for which aprox. 129% and 107% increasing was obtained. Concerning maximum elongation to fracture (ε_F) an inverse behaviour is observed, from 8.43 % to 4.81 % for 6 passes ECAP processed Al 6063-T835 alloy, aprox. 43 % decreasing.

The observed behaviour can be explained by two strengthening models.

According to the first one, plastic flow in a nanocrystalline material is considered to be controlled by the stress required to attain dislocation loops (from Frank-Read sources) in a set of larger grains with the critical semicircle configuration [17]. This model can also be applied to discuss the plastic flow of a

UFG material. The critical stress to activate the Frank-Read source is expressed by [18]:

$$\sigma = \frac{M \cdot G \cdot b}{2\pi \cdot L(1-\upsilon)}\left[\left(1-\frac{3\cdot\upsilon}{2}\right)\ln\left(\frac{L}{b}\right)-1+\frac{\upsilon}{2}\right] \tag{2}$$

where M is the Taylor factor, G the shear modulus, b the Burgers vector, v the Poison's ratio and L is the average length of dislocations which varies with the dislocation density ρ as $L = 1/\sqrt{\rho}$, [16]. As shown in Eq. (2), the critical stress to activate the Frank-Read source increase due to decreasing crystalline domains size, from micro to nanoscale, also the L value decreases.

Based on the second model, two strengthening mechanism can contributes to the strengthening during large deformation of materials [19]. The first is the dislocation strengthening due to the presence of incidental dislocation boundaries (IDBs) with a small misorientation (≤3°). These boundaries arise from statistical trapping of dislocations. The second is the grain boundary strengthening via Hall-Petch relationship due to the formation of geometrically necessary boundaries (GNBs) arising from the difference in slip system operating in neighbouring slip systems or local strain difference within each grain. At large strains ($\varepsilon \geq 1$) the misorientation angle of GNBs is composed of high angle grain boundaries ($\theta \geq 15°$) as well as a small fraction of low to medium angle boundaries. The proposed strengthening equation for this model is expressed as [20]:

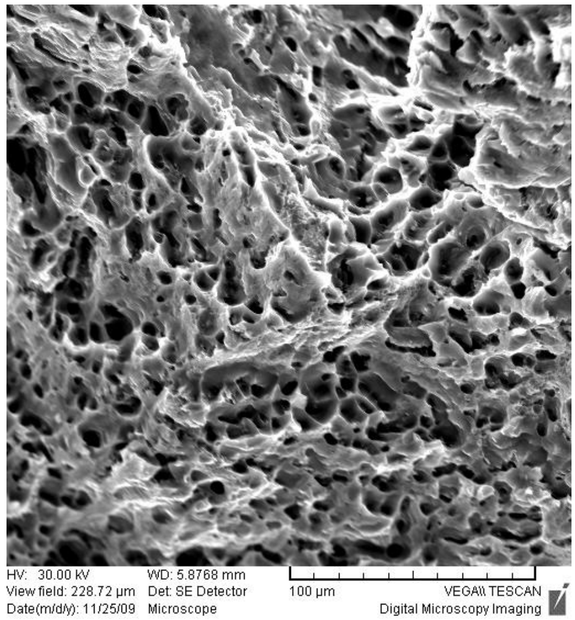
$$\sigma = \sigma_0 + M \cdot \alpha \cdot G \cdot b \cdot \sqrt{\rho} + \frac{k}{\sqrt{d}} \tag{3}$$

where σ_0 is the friction stress, M the Taylor factor, α a constant, G shear modulus, d the average grain size, and k is the Hall–Petch slope of the straight line relating the flow stress to the reciprocal square root of grain size.

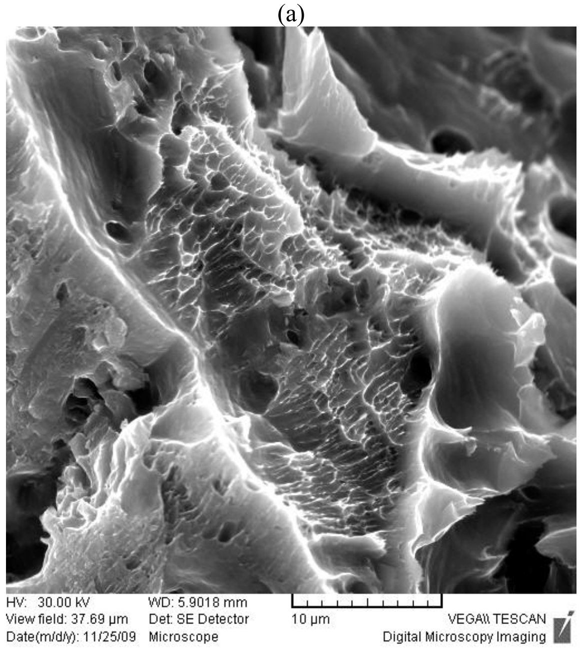
As shown in Eq. (3), one can observe that the σ stress increases due to decreasing in crystalline domains size, from micro to nanoscale ($k/\sqrt{d}$ parameter and dislocation density ρ increases).

Fracture surfaces analysis

SEM observations on fracture surfaces for both un-processed and six passes ECAP processed alloy are shown in Fig. 3 and 4.

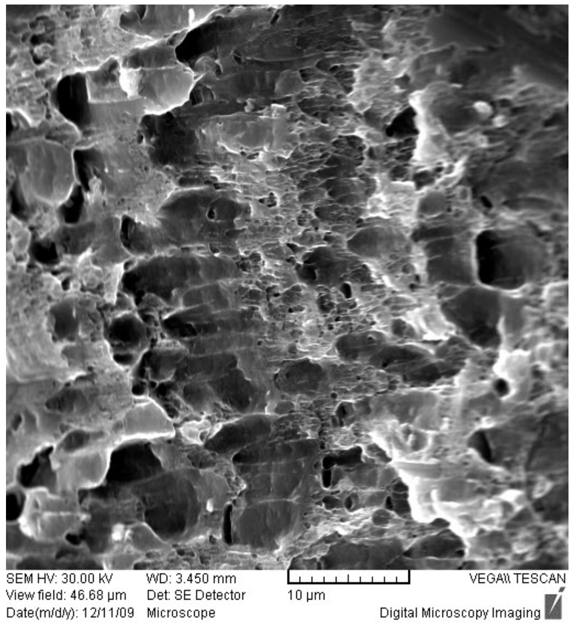


(a)

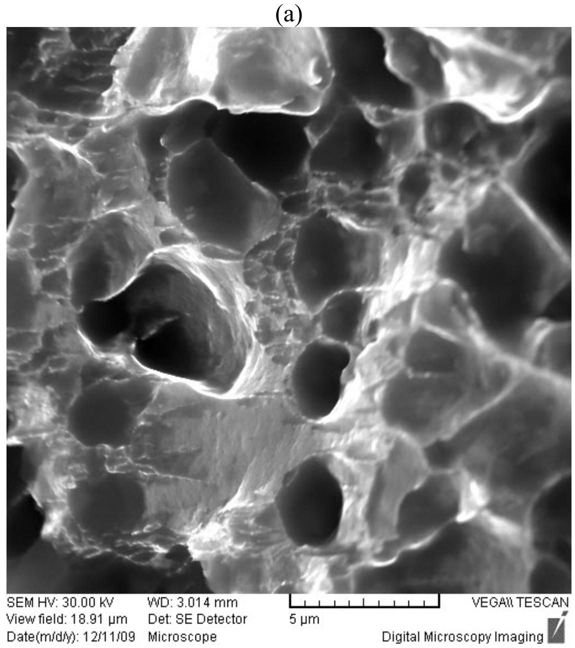


(b)

Fig. 3. SEM fractographies for 6063-T835 aluminum alloy



(a)



(b)

Fig. 4. SEM fractographies for six passes ECAP processed 6063-T835 aluminum alloy

In Fig. 3 one can observe that fracture surfaces show a ductile aspect. One can observe the voids nucleated at grain boundaries, also areas in which void growth and voids coalescence are presented, spherical dimples are observed (fig. 3a). Final shear fracture with fibrous pullout can be observed (fig. 3b), indicating plastic deformation before fracture.

Fig. 4 show ductile-brittle fracture surfaces, also voids nucleated at grain boundaries are observed. As seen in fig. 4a, large areas with brittle fracture surfaces are presented, in fig. 4b one can observe that the voids average dimension is about 2 – 3 μm.

The presence of brittle fracture in materials can be explained due to the high strain-hardening rate and low cleavage strength resulted during ECAP process.

5. Conclusions

In this study, the mechanical behaviour of 6063-T835 aluminum alloy subject to the ECAP process was investigated and compared to the material with no ECAP processing. It was determined that for a number of six passes in an ECAP die with intersecting channels angle $\phi = 90°$ and a corner angle $\psi = 20°$, an increasing in ultimate tensile strength (σ_{UTS}) up to aprox. 100%, yield strength (σ_{YS}) up to aprox. 129% and strength to fracture (σ_F) up to aprox. 107% was obtained in comparison with non-processed 6063-T835 aluminum alloy. Concerning maximum elongation to fracture (ε_F), an inverse behaviour was observed, it was recorded decreasing with aprox. 43 %.

The fracture surfaces for 6063-T835 aluminum alloy show a ductile aspect, voids nucleated at grain boundaries, spherical dimples and shear fracture with fibrous pullout can be observed. For ECAP processed alloy, the fracture surfaces show ductile-brittle fracture surfaces, internal brittle cleavage fracture occurs in materials because of the high strain-hardening rate and low cleavage strength resulted during ECAP process.

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