Sustainable Lightweight 6063-T1 Aluminium Alloy Processed by Equal Channel Angular Pressing for Low Environmental Impact Applications

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Nowadays, scientists are making great efforts towards increasing fuel efficiency and for this, aluminium and its alloys are one of the best available options, sustainable aluminium items being able to lower greenhouse gas emissions and save energy expenses in a wide range of structural applications. Equal-channel angular pressing (ECAP) is the main severe plastic deformation (SPD) technique for obtaining ultra-fine grained (UFG) and nanostructured materials (NM), the advanced grain refinement obtained by SPD substantially enhancing microstructural and physicomechanical characteristics for the processed material, therefore arising the potential for minimizing the weight and dimensions of the items being produced. In our study, a commercial 6063 Al alloy (T1 condition) was pressed at room temperature for several passes, the ECAP processed and as-cast samples being microstructural investigated and mechanically tested. Ultimate tensile strength, yield strength, strength to fracture and maximum elongation to fracture were determined. The obtained fracture surfaces were investigated using scanning electron microscopy. For the severely deformed 6063 Al alloy, multiple correlations between the key processing parameters and the resulting microstructure and mechanical behaviour were determined. It was shown that SPD/ECAP can be used as an advanced tool in fabricating sustainable lightweight aluminium products for low environmental impact applications.

Keywords: aluminium alloys; equal-channel angular pressing; environmental impact; ultra-fine grained materials; sustainable materials

Aluminium alloys are used in a wide range of industries, therefore they are considered to be vital materials for nowadays society. Actually, they are extremely important for every aspect of living, from shelter and mobility to food and entertainment. The main features making aluminium alloys such significant materials in our present times are their superior mechanical properties and low density, as well as the fact that they have a high corrosion resistance and a great processability [1]. In our modern times, aluminium alloys are preferred mainly because they are leading to the reduction of the product weight. However, aluminium was constantly highly demanded since the vast majority of its alloys are age-hardenable and easily processable. A large number of consumer goods and products involves nowadays the use of Al-Mg-Si alloys (especially the 6063 alloy), be it in transportation and buildings or for pipes, furniture, railings and so on and so forth [2-5].

Sustainable development is considered to represent a series of best practices for satisfying the humanity present needs without endangering the capability of next generations to meet their own needs. Given this nowadays focus on sustainable development, energy security and climate changes, companies, manufacturers and service providers around the world must adapt the way they do business and create products in order to help and promote sustainability [1, 6]. For example, the use of aluminium alloys in transports for reducing the weight of the vehicle also reduces fuel consumption and greenhouse gas emissions. A vehicle downweighting study [7] found that on average, each kilogram of aluminium used in substitution for mild and high-strength steel or cast iron in passenger cars and light trucks saves 120-1000 MJ of primary energy, or about 0.8-6.9 gallons of crude oil, throughout the lifetime of the vehicle, with a reduction in greenhouse gas emissions varying from 8 to 73 kg CO_2 equivalent. It must be mentioned that the variations in vehicle lifetime mileage and driving cycles are the main causes of these savings variations. Also, according to [1, 7], for commercial vehicles, lifetime energy savings are varying between 150 and 1048 MJ, equivalent to 1.0-7.2 gallons of crude oil, in this case the reduction in greenhouse gas emissions being 10-76 kg CO_2 equivalent.

Since aluminium is considerable lighter than steel, several industries, such as aeronautics and the car industry, have chosen to use aluminium alloys, whereas each kilogram diminution in weight of the vehicle generates important fuel economy and larger payloads [8]. In the same time, considering the current global economic context, when oil resources are increasingly limited and fuel prices higher and higher each day, it is clear that the need to reduce vehicles weight is of paramount importance.

Mostly used for complex extrusions, 6063 aluminium alloy features a high corrosion resistance, a good surface finish and has a medium strength. Also, this alloy can be subjected to anodization and is well suited for welding. Consequently, the 6063 Al alloy is widely used for structural and architectural applications, in constructions, in transportation, for extreme sports equipment etc. Therefore, comprehending his mechanical behaviour under various experimental conditions (strain rates, loadings, temperatures and so on) becomes a crucial issue. Only by fully understanding these aspects, one can anticipate the material behaviour for all these conditions, in order to design his microstructure and estimate the mechanical characteristics [9, 10].

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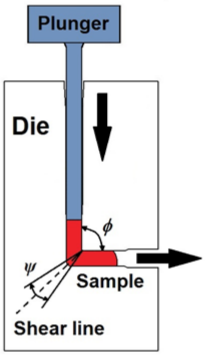


Fig. 1. ECAP concept with emphasis on the main technological elements

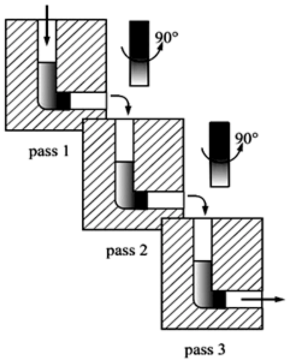


Fig. 2. Overview of the SPD/ECAP deformation route used in the experiments

Contrastive to classical deformation processes (forging, rolling, die-forging, extrusion etc.), the key benefit of severe plastic deformation (SPD), with equal channel angular pressing (ECAP) as an emblematic technique, is that SPD involves inducing very large strains in the processed material, without modifying the initial shape of the billet during deformation [11]. Lately, SPD was in the spotlight of researchers as a technique capable of producing fully dense and bulk submicrocrystalline and nanocrystalline materials. Significant grain refinement obtained by means of SPD processing is leading to the improvement of physical, mechanical and microstructural properties [12-20]. As a result of enhanced mechanical characteristics, the possibility of reducing the overall dimensions for the finished products arises, reflected in vehicle downweighting and thus in fuel economy or increasing payloads. Furthermore, special aluminium alloys, with relatively high prices, could be replaced with common, cheaper alloys, for a variety of items. All this emphasizes the importance of SPD in terms of sustainable development and positive environmental impact.

Experimental Part

Equal channel angular pressing involves passing the billet (usually round or squared) throughout a die containing two intersecting channels identical in cross-section. As shown in figure 1, the intersection angle is ϕ and a secondary angle of ψ sets the curvature from the outward intersection point of the channels.

Since ECAP is also suitable for processing large billets, we consider that from the various SPD procedures, this is the most appealing technique, mainly because of its high potential in manufacturing materials for a variety of structural applications. This way, ECAP could be scaled up and used for industrial purposes, especially in processing sustainable metals and metal alloys for the next generation. Maintaining the same cross-section during ECAP, despite the introduction of a very intense strain, is the important characteristic of SPD processing and, moreover, is a distinguishing feature of this method compared to conventional metal-working operations. Since the cross-sectional area remains unchanged, the same sample may be pressed repetitively in order to attain exceptionally high strains [21]. By simply rotating the samples on each consecutive passage through the die, therefore by changing the shear plane and the shear direction, controlling the microstructure and the texture of processed material is made possible, therefore becoming possible to control its mechanical properties [22, 23].

In ECAP, four major processing routes (schemes) are possible based on the sample rotation, as described by Furukawa et al. [24]. Route A is defined when the billet is not subjected to any rotation between passes. If the sample is alternately rotated 90° in opposite directions, after each passage through the die, then the deformation is performed following route B_A. Also, by rotating the sample after every pass 90°, but preserving the same direction (as shown in fig. 2), route B_C is established. Finally, a 180° billet rotation between passages defines the processing route C. In our study, ECAP route B_C was used, as it was found to be the most effective for microstructural control and consequently for mechanical properties improvement [25-28].

In our study, we examined a 6063 Al alloy, in the T1 condition, which is generally known as an architectural alloy. This average strength material exhibits a very good surface finish and has a high corrosion resistance. Also, it is liable to anodization and well suited to welding. Usually, the 6063-T1 Al alloy is applied in complex extrusions. By using a GNR metal-LAB 75/80V optical emission spectrometer (OES), the chemical composition for the investigated Al alloy samples was established (as shown in table 1).

The experimental set-up used for our research is shown schematically in figure 3. The investigated material originated from a 120 mm round extrusion billet, industrially manufactured using a continuous casting and heat treating technology. A METKON Servocut M300 abrasive cutter was used in order to obtain 60 x 9.6 x 9.6 mm initial dimensions for the ECAP samples. Cutting was done in such a manner that the sample and the billet axis are perpendicular.

Three ECAP processing dies [29] with Õ, the intersection angle, being 90°, 100° and 110° respectively, were assayed for 6063-T1 alloy processing. Secondary angle, ø, was around 20° for all three cases. When using the 90° ECAP die [12, 27], the most valid experimental results were obtained and this is the reason why this paper presents only these results. As lubricant, graphite powder was used. By using a 200 tnf (1.96 MN) hydraulic press, the specimens were ECAP-ed at ambient temperature for multiple passes (up to nine), at a pressing speed of 10 mm/s. The sample 90° rotation was conducted following the SPD/ECAP deformation route B_C, preserving the same direction after each passage through the die (as shown in fig. 2).

From all the specimens (as-received and SPD/ECAP processed), multiple samples intended for metallography and mechanical investigations were taken. For the ECAP-ed samples, in order for the microstructure to be examined only in the longitudinal plane, the cutting direction was

Table 1
OES DETERMINED CHEMICAL COMPOSITION (wt. %) FOR THE EXPERIMENTAL ALLOY

Si	Mg	Fe	Cu	Mn	Zn	Ti	Pb	Ni	Cr	Al
0.458	0.616	0.326	0.091	0.089	0.074	0.014	0.013	0.002	0.010	remainder

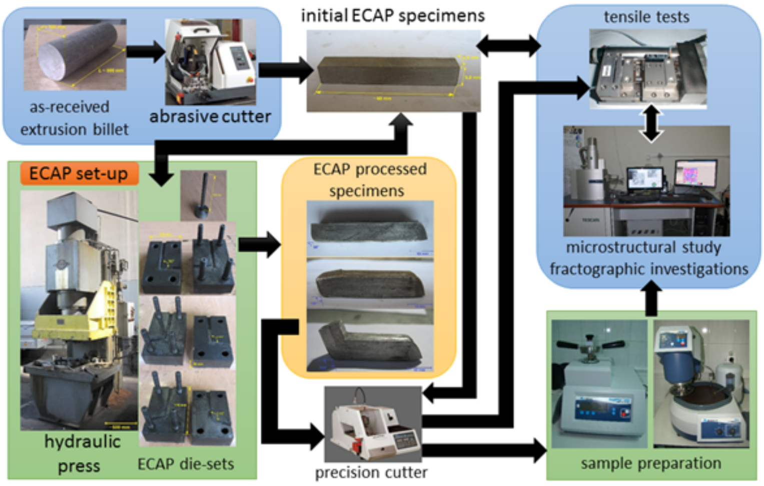


Fig. 3. Schematic illustration of the employed experimental set-up

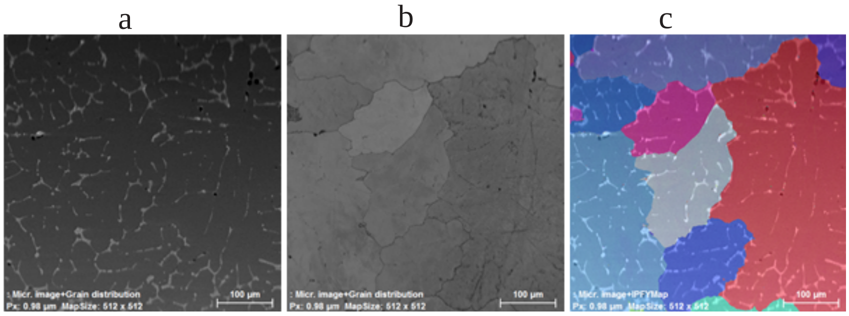


Fig. 4. SEM micrographs of the as-cast 6063-T1 aluminium alloy: a. BSE image; b. grain distribution; c. EBSD orientation map

parallel to the ECAP direction. A precision cutter METKON Micracut 200 was used for obtaining these samples, which were later hot mounted on a BUEHLER Simplimet 1000 automatic mounting press and metallographically prepared on a semiautomatic machine BUEHLER Phoenix 4000 Beta/1 Single. Using Keller's reagent, all samples were etched for 20 s. For the microstructural study of the ECAP processed and as-cast samples, scanning electron microscopy – SEM (BSE detector – TESCAN Vega II XMU) was used. For the as-cast samples, the microstructure was also analysed via electron back scattered diffraction (EBSD detector of TESCAN Vega II XMU SEM).

Further, a GATAN MicroTest 2000N tensile module, mounted inside the TESCAN Vega II XMU SEM, was used to mechanically test to fracture in tensile tests the ECAP processed samples and one as-cast sample, considering the same experimental conditions. This way, ultimate tensile strength (σ_{UTS}), yield strength (σ_{YS}), strength to fracture (σ_F) and maximum elongation to fracture (ε_F) were determined. Main testing parameters were as follow: testing speed *0.4* mm/min, testing temperature *20*°C, vacuum environment. Also, the obtained fracture surfaces were investigated using scanning electron microscopy (TESCAN Vega II XMU SEM microscope).

Results and discussions

All results presented are based on the current configuration of the specimen. The acquired SEM images (BSE and EBSD) are shown infigure 4 for the as-cast 6063-T1 aluminium alloy and in figure 5 (BSE) for the one, three, six and respectively nine passes ECAP processed material. EBSD pattern quality heavily deteriorates with increasing density of defects like dislocations and accumulated strain in ECAP processed materials, therefore the ECAP-ed material is very difficult to be investigated by EBSD [30]. In the case of SPD processed aluminium alloys, annealing treatments are required for improving the pattern quality [31], which would result in modifying the original ECAP microstructure and for this reason it was preferred only the BSE microstructural analysis for the ECAP-ed 6063-T1 alloy.

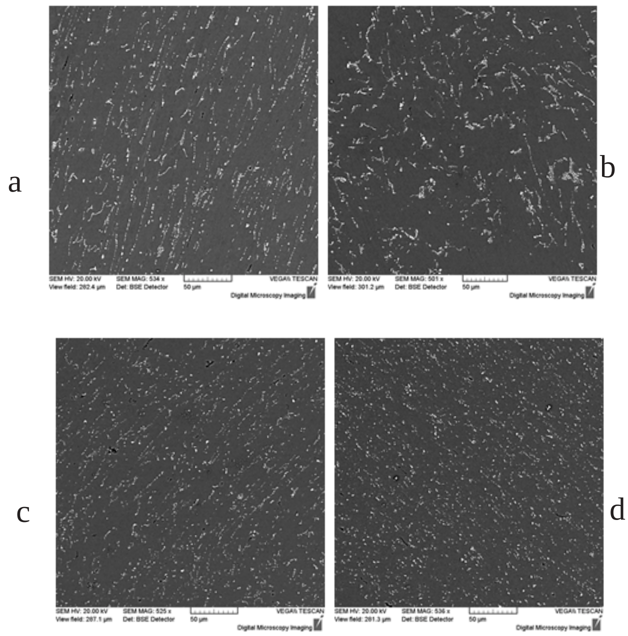


Fig. 5. SEM micrographs of 6063-T1 aluminium alloy: a. one ECAP pass; b. three ECAP passes; c. six ECAP passes; d. nine ECAP passes

From figure 4 it can be seen that the microstructure of the as-cast 6063-T1 aluminium alloy shows a rough appearance, with large grains (an average size of about 300-350µm) of dendritic aspect and with a secondary phase at grain boundaries, which is a typical continuous casting microstructure. The ECAP processed samples (see fig. 5) are characterized by a microstructure with finished and homogeneous aspect, with refined, severely deformed, elongated grains, and also with crumbled and uniformly distributed secondary phase particles (compounds/ precipitates), aligned after a typical ECAP texture. Such microstructure was also referred by other researchers [32, 33] and is described as bands of subgrains elongated and aligned with the shearing direction [34-36]. If the number

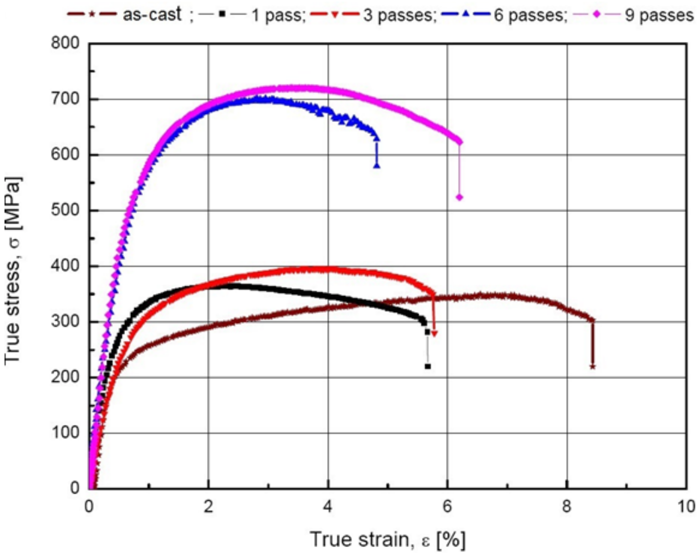


Fig. 6. True tensile stress-strain curves for the 6063-T1 aluminium alloy: as-cast and after one, three, six and nine ECAP passes

of passages through the die is increased (increasing also the value of accumulated equivalent strain), we can observe a higher refining degree for the processed material, with smaller second phase particles, evenly distributed throughout the base metal. An adequate interpretation for the fragmentation of secondary phase particles may be given precisely by taking account of this accumulated equivalent strain incrementing.

For a proper evaluation on the effect of ECAP deformation on 6063 Al alloy mechanical behaviour, the ECAP-ed material was compared to the unprocessed one in a series of mechanical investigations [37]. For all analysed specimens, σ_{YS} (the yield strength), σ_{UTS} (the ultimate tensile strength), σ_F (the strength to fracture) and also σ_F (the maximum elongation to fracture) were determined in tensile tests; the results recorded and computed during these investigations being shown in figures 6 and 7.

In figure 6, the true stress-strain diagrams for the as-cast and the ECAP processed 6063-T1 aluminium alloy, obtained through tensile tests, are given. Also, from this figure one can observe a significant improvement in terms of mechanical properties for the ECAP processed samples, due to the advanced grain refinement achieved with the increase of accumulated equivalent strain, as the number of passages through the die is higher. Also, figure 7a shows an increase of ultimate tensile strength (σ_{UTS}) from 350 MPa for the as-cast state up to 720 MPa for 9 passes ECAP processed 6063-T1 alloy. The increase is nearly 106%. For the yield strength (σ_{YS}) and strength to fracture (σ_F), one can observe the same behaviour; respectively, approximately 138% and 107% increases. However, a relative limitation of σ_{UTS}, σ_{YS} and σ_F is observed after six ECAP passes, meaning that increasing the number of passes furthermore, will result in just a minor increase in mechanical characteristics for the processed material. Contrariwise, an inverse reaction is shown in figure 7b for maximum elongation to fracture (ε_F); namely an overall decrease of approximately 27%, from 8.43% for the as-casted state to 6.18% for 9 passes ECAP processed 6063-T1 Al alloy.

In order to explain the observed behaviour, two strengthening models are to be considered. The first one, described by [38], states that the necessary stress for inducing dislocation loops in a series of coarse grains, having the critical semicircle configuration, is establishing the plastic flow in a nanostructured material, this model being also suitable for evaluating the plastic flow in an UFG material as well. The second strengthening model, referred by [39], describes the combined influence of two mechanisms in the course of heavy deformation of metals and metal alloys, namely grain boundaries strengthening as stipulated through the Hall-Petch equation and dislocation strengthening due to the occurrence of incidental dislocation boundaries having a low misorientation angle. Another possible deformation mechanism is different and more difficult to be proved; it implies no contributions of dislocations and no stress induced phase transformations [40]. In this case, a strange plastic deformation mechanism, considerably different from that of normal metallic materials acts: the deformation progresses by formation of giant faults, crystal lattice local disturbances at nanometer scale are possible, generating localized strain fields. This is a way to gain a dislocation free structure and thus attaining ultra-strength.

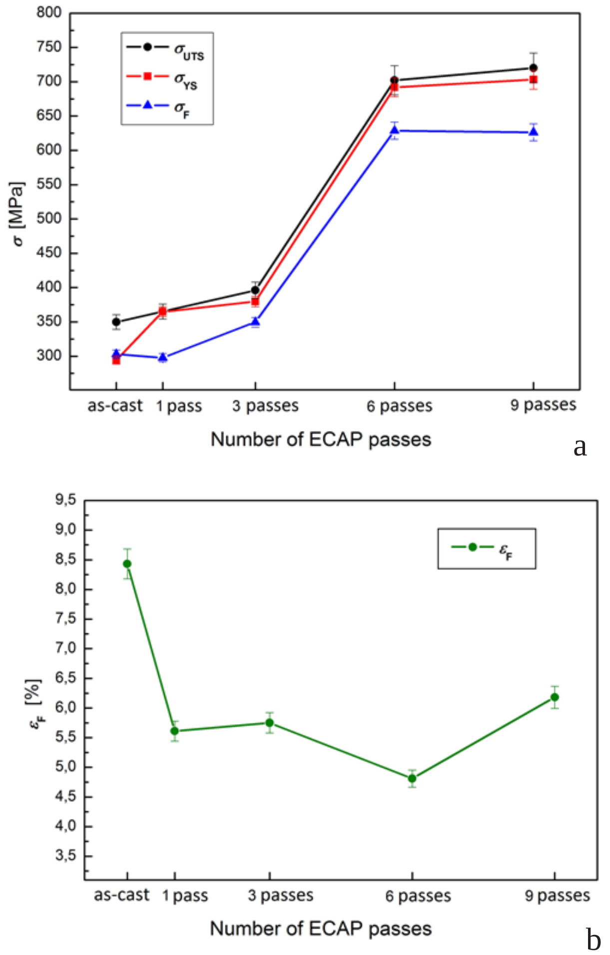
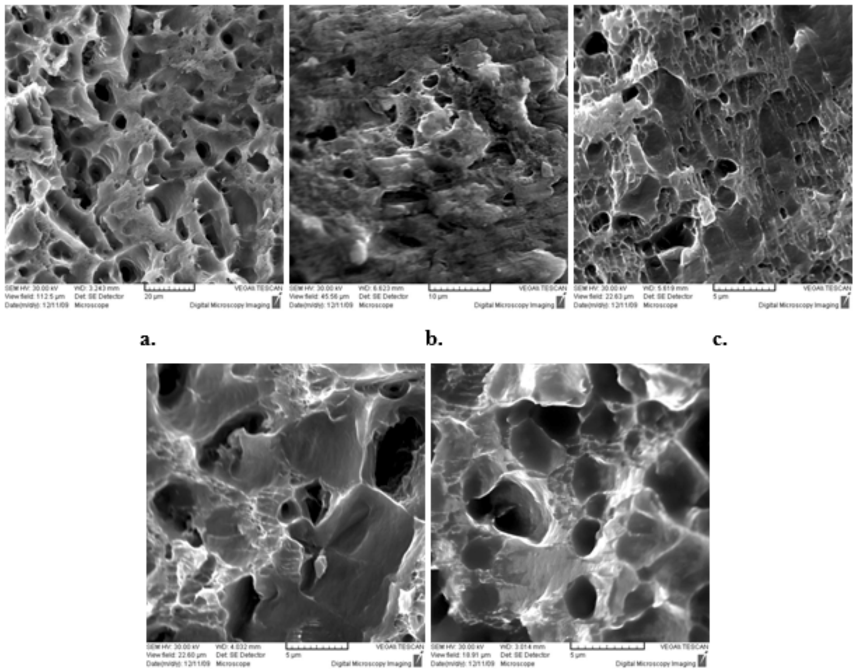


Fig. 7. Mechanical characteristics evolution versus the number of ECAP passes for 6063-T1 Al alloy: a. ultimate tensile strength (σ_{UTS}), yield strength (σ_{YS}) and strength to fracture (σ_F); b. maximum elongation to fracture (ε_F)

Through scanning electron microscopy instrumentality, the specimens were examined as well in a series of fractographic investigations. SEM observations on fracture surfaces for all investigated samples are shown in figure 8. In figure 8a, one can observe that the fracture surface for unprocessed, as-cast 6063-T1 aluminium alloy shows a ductile aspect. Furthermore, considering the grain boundaries appearance, one can observe multiple areas wherein the phenomena of voids nucleation, growth and coalescence are clearly visible. The presence of plastic deformation prior to the occurrence of fracture is shown by the final shear rupture with fibred pull-outs. For the ECAP-ed material (figs. 8b-8e), fracture surfaces show a fragile aspect, with large brittle areas. Internal brittle cleavage



a. b. c.

d. e.

Fig. 8. SEM fractographic investigations on the 6063-T1 Al alloy: a. as-cast; b. one ECAP pass; c. three ECAP passes; d. six ECAP passes; e. nine ECAP passes

fracture emerges in materials due to high strain-hardening rate and low cleavage strength resulted during ECAP processing. Increasing the number of ECAP passes the fraction of voids increases also. After six passes, fibred pull-outs surfaces are visible. Increasing the number of passes, fibred pull-outs surfaces ratio increases.

These observations are consistent with the variation of maximum elongation to fracture (ε_F); presented in figure 7b, in which an increasing of ε_F is visible for more than six passages through the ECAP die. All this allows us to conclude that, even if the strength improvement is negligible after six passes, further ECAP processing (up to nine passes) is leading to an improvement in ductility for the processed 6063-T1 aluminium alloy. Finally, an advanced material, presenting a unique combination of features (high strength and reasonable ductility) is obtained. This unique combination cannot be achieved by any other conventional processing methods.

Conclusions

In our study, the effects of room temperature multi-pass ECAP processing on the microstructure and mechanical behaviour of a commercial 6063 Al alloy were examined in order to assess the possibility of using this alloy as a sustainable downweighting material for low environmental impact applications, especially in aeronautics and for the car industry. Some correlations between the imposed ECAP processing parameters, the resulting microstructure and the mechanical properties obtained for the processed aluminium alloy were established.

It was found that the microstructure of the unprocessed as-cast 6063 Al alloy features a rough appearance, portrayed by coarse grains having a dendritic configuration and a second phase at grain boundaries, this being a typical continuous casting microstructure. In case of ECAP-ed specimens, the microstructure is distinguished by a finished appearance, with severely deformed, refined grains and a homogeneous distribution of crumbled second phase particles. Increasing the number of ECAP passes, secondary phase particle size becomes smaller and its distribution is getting more and more uniform and also the material grain size is more finished.

Considering the mechanical properties, a significant increase was obtained via ECAP, compared to the as-cast 6063-T1 Al alloy. An increasing for ultimate tensile strength (σ_{UTS}) of 106%, in yield strength ((σ_{YS}) of 138% and for the strength to fracture ((σ_F) of approximately 107% was obtained after nine ECAP passes using B_C route. Regarding maximum elongation to fracture (ε_F) an inverse behaviour was noticed; an approximately 27% overall decreasing being recorded.

The fractographic investigations revealed a ductile aspect of fracture surfaces for the unprocessed material, whilst in case of ECAP-ed specimens, a fragile behaviour with wide brittle areas was recorded. Nevertheless, fibred pull-outs surfaces are visible after six ECAP passes and increasing the number of passes, fibred pull-outs surfaces ratio increases also; which correlated with the variation of ε_F demonstrates an improvement in material ductility after six processing passes.

It was shown that grain refining by means of ECAP processing results in a significant improvement of mechanical characteristics for the 6063-T1 Al alloy. Also, a unique combination of strength and ductility is obtained after a certain number of passages through the die. Such superior mechanical properties are highly desirable when manufacturing sustainable lightweight structural materials for low environmental impact applications.

Following the improvement in mechanical properties, it is possible to reduce the dimensions of the products, which leads to a decrease in the weight of the vehicles and therefore to fuel savings and higher payloads. Consequently, the fuel, energy and greenhouse gas emission decreases are a significant environmental gain for our modern society.

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