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EQUAL CHANNEL ANGULAR PRESSING AS A VIABLE MANUFACTURING PROCESS TO INCREASE HARDNESS OF COMMERCIALLY PURE ALUMINUM (AL 1050)

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Abstract. *The current work aims to verify the effects of a severe plastic deformation process named Equal Channel Angular Pressing (ECAP) on commercially pure aluminum (Al 1050). Longitudinal cut samples were generated from specimens that were submitted to four different deformation passes (1, 4, 8 and 20 processing steps) with a 90º counterclockwise rotation between each deformation step. Microhardness tests were conducted on all samples in order to quantify the augment in hardness. Samples' average strain were estimated for each deformation pass, according with an equation developed by previous authors. A gradual increase in microhardness occurred as a result of the increasing number of passes during deformation of the material. Contrary to what was predicted by previous works, microhardness values did not saturate in the fourth pass. Microhardness peaked from the eighth deformation pass onwards, reaching similar values for the last two processing conditions. Additionally, average strain values indicated supportive conditions for the development of a refined grain structure. Also, these values indicated that dislocation density reached saturation between the fourth and eighth conformation stage. In conclusion, the presented work elucidates the positive outcomes and the applicability from applying ECAP processing for improving mechanical properties in Al 1050*.

Keywords: *equal channel angular pressing, microhardness, commercially pure aluminum, effective strain, grain size*

1. INTRODUCTION

Traditional manufacturing techniques of commercially pure aluminum, such as extrusion and drawing, are often employed as main way of metal forming due to its feasibility and popularity. However, there are some other unconventional metal forming process which increase the material's strength, requiring that the workpiece has to be processed at high strain rates and thus increasing the amount of natural strain already present in the mate These conforming processes have become attractive in recent years due to the possibility of implementing them in industrial scale and complementing those classical techniques of mechanical processing (Valiev and Langdon, 2006).

These processes are capable of inducing severe plastic deformation (SPD) in the material, in which the workpiece is plastically deformed at high rates of deformation, developing a structure with finer grains and with greater fracture toughness, besides promoting a possible superplasticity in metals and alloys (Balasubramanian and Langdon, 2005). There are several SPD processes available, such as High Pressure Torsion (HPT), Accumulative Roll Bonding (ARB), Reciprocating Extrusion-Compression (REC), Repetitive Corrugation and Straightening (RCS), Cyclic Closed Die Forging (CCDF), and Equal Channel Angular Pressing (ECAP) [Zrnik and Dobatkin, 2008].

Among these processes, ECAP or Equal Channel Angular Extrusion (ECAE) is one of the most studied, partially due to its feasibility, which can be roughly described as a plastic forming process using an extrusion die in angular shape. Currently, the ECAP process is one of the most used severe plastic deformation processes, mainly because it is an extremely efficient method to produce Ultrafine Grain Materials (UGM), by maintaining the initial dimensions and shapes of the billet at the end of the process, and being applicable in a multitude of metals and alloys with different microstructures (Zrnik, *et al*., 2008).

In the ECAP process, a billet is positioned and rammed into the interior of a modified die having two channels (one vertical and the other horizontal) with equal cross section, which may be square or round, and both interconnected with an angular difference as shown in Fig. 1. The ECAP process is known to induce high strain rates of in materials and specially to cause increased hardness, inducing grain refinement and forming high angle grain boundaries.

In the ECAP process there are extrusion routes (also called processing routes) that can be followed by varying the entry position and subsequent re-entry of the billet, the most commonly used being A, B_A, B_C, and C (Fig. 1).

Figure 1 is an illustration of the main routes of this process. In Route A the billet is continuously pressed from the inlet to the outlet of the die; on Route B_A the billet is rotated alternately (clockwise and counterclockwise) by 90 ° around its longitudinal axis with each pass. Similarly, in route B_C the billet is rotated 90° consecutively with each pass. Finally, in route C the billet is rotated 180 ° and is deformed continuously until it leaves the die. For each processing route there are particularities (grain size, effective strain, linear and angular deformation) acquired by the billet at the end of each process. The channels of the die make angles to each other, where their intersection is said to be φ and the external angle between them (also called relief angle) is ψ. (Zrnik, *et al*., 2008).

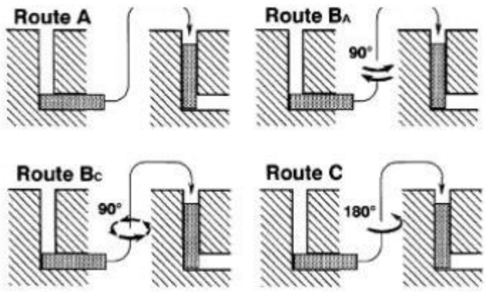

Figure 1. Main routes related to the ECAP mechanical processing. Adapted from Valiev and Langdon (2006).

All these characteristics show that ECAP can be employed to increase Al 1050's strength and hardness, making this material suitable to other applications instead of its traditional one. Commercially pure aluminum is usually employed in transmission lines components, houseware products and heat exchangers. This material may contain up to 0.4 wt% of iron and 0.25 wt% in silicon. These elements are considered two of the most common impurities found in commercial use of aluminum alloys. Other values of residual elements can be found in Tab.1:

Table 1. Chemical composition of commercially pure 1050 aluminum (wt%)

	Al	**Si**	**Mg**	**Mn**	**Fe**	**Cu**	**Zn**	**V**
wt %	99.50 min.	0.25 max.	0.05 max.	0.05 max.	0.40 max.	0.05 max.	0.07 max.	0.03 max.

2. METHODOLOGY

In the present work, commercially pure aluminum Al 1050, with a purity of 99.50 wt% was utilized as the studied material, having been mechanically processed by ECAP. Specimens had billet form of approximately 10.8×10.8×63.0 mm as can be seen in Fig. 2.

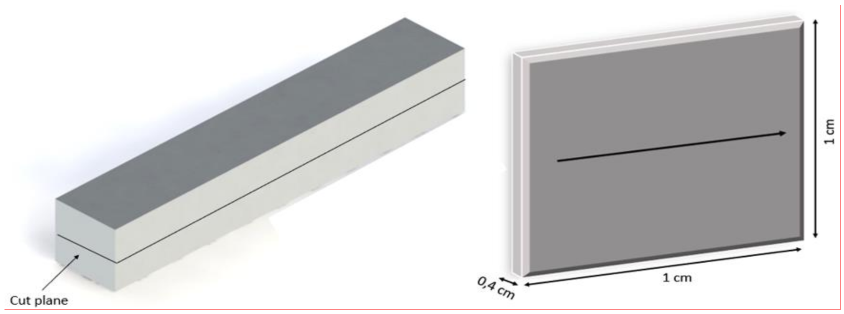

Figure 2. Aluminum specimens: ECAP processing specimen and cut plane (left), and Vickers microhardness indentations along each sample (right).

The ECAP processing was conducted at 25 ° Celsius, following B_C route, in a die with equal channels of 120 ° separation (φ = 120 °), and 20 ° of relief angle (ψ = 20 °), having squared section of approximately 11 mm². The specimens were subjected to multiple passes, which were: 1, 4, 8, and 20 deformation passes for the last conformed workpiece. Specimens were heat treated at 300°C for 20 minutes and then cooled in water before and after ECAP processing.

As-received and ECAP conformed specimens were cut along their longitudinal axis, as in Fig. 2, and provided 5 samples of 1,0×1,0×0,4 cm, as also shown in the same image. The samples were named accordingly to the number of passes and the cut-off direction (RL, 01L, 04L, 08L and 20L). In this way, the samples were called as, respectively: RL, 01L, 04L, 08L and 20L.

Under ideal processing conditions, the effective deformations obtained at the end of the process are cumulative with the increase in number of passes and can be described as a function of the two characteristic angles of the die, *Φ* and *Ψ*. The samples were subjected to total strain evaluation, according with an estimation shown and validated by Iwahashi, *et al.*, 1995 as it follows Eq. (1).

$$\varepsilon = \left(\frac{N}{\sqrt{3}}\right)\cdot\left[2\cot\left(\frac{\varphi}{2}+\frac{\psi}{2}\right)+\psi\ \mathrm{cosec}\left(\frac{\varphi}{2}+\frac{\psi}{2}\right)\right] \tag{1}$$

Additionally, grain sizes of the samples were estimated according with microhardness measurements, rearranging Eq. (2), proposed by Hall (1954), into Eq. (3).

$$H_v = H_0 + \frac{K_H}{\sqrt{d}} \tag{2}$$

$$d = \left(\frac{K_H}{H_V - H_0}\right)^2 \tag{3}$$

In both equations, *d* is the mean grain size (µm), K_H and H_0 are constants associated with the material's hardness (19 HV.µm$^{-1/2}$ and 18 HV, respectively according to Sato, *et al.*, 2003) and H_V is the workpiece's hardness, measured in this work.

The microhardness test was conducted in all samples at room temperature, using a Shimadzu Vickers microhardness tester, employing a 0.2 $HV_{0.2/10}$. The microhardness test was conducted on the 5 samples. A total of 35 indentations were made on each sample, along the line profile. SEM images were obtained from etched samples, using Becker's reagent and a solution of HNO_3 and ethanol (1:3)

3. RESULTS

A considerable increase in microhardness values was found in specimens subjected to ECAP processing. From values of 24,9±0,5 $HV_{0,2/10}$ of RL samples, reaching 44,3±0,9 HV in 01L. Table 2 present higher values computed for 08L and 20L samples. In this case, microhardness values reached saturation values in the last 2 samples.

Table 2. Vickers Hardness values for processed and unprocessed samples

	RL	**01 L**	**04 L**	**08 L**	**20 L**
$HV_{0,2/10}$	24,9±0,5	44,3±0,9	50,9±0,9	117,3±1,3	116,5±1,1

In opposite of what was presented by Alhajeri, *et al.*, 2011, the microhardness values did not saturate in the fourth pass, obtaining significant hardness values for samples of eighth and twentieth passes of up to 2 times higher than the values obtained in the first and fourth pass. On the other hand, the microhardness values obtained for the RL, 01 L and 04 L samples were similar to those obtained in the work of Alhajeri, *et al.*, 2011. In this work, a hypothesis to be followed is that the density of dislocations in these samples saturates before the eighth processing pass, with no further contribution for the hardness.

Al 1050 low hardness and strength is due to its poor solution strengthening, associated to a low presence of alloy elements. Also, the two major impurities in this material (Fe and Si) are not efficiently capable to offer substantial reinforcing to the workpiece's hardness. Thus, hardness' increase may be owned to other strengthening mechanisms, such as grain boundary refinement and dislocation density increase strengthening (work hardening). Evaluating effective strain, according with Eq. (1), provides that strain values are progressive towards greater values of *N*, as this can be seen in Fig. (4). However, there must be a physical limit which strain hardening contributes to strengthening. El Danaf, *et.al.*, 2006 found that microhardness values tend to a saturation state, in which hardness growth decreases with number of processing steps.

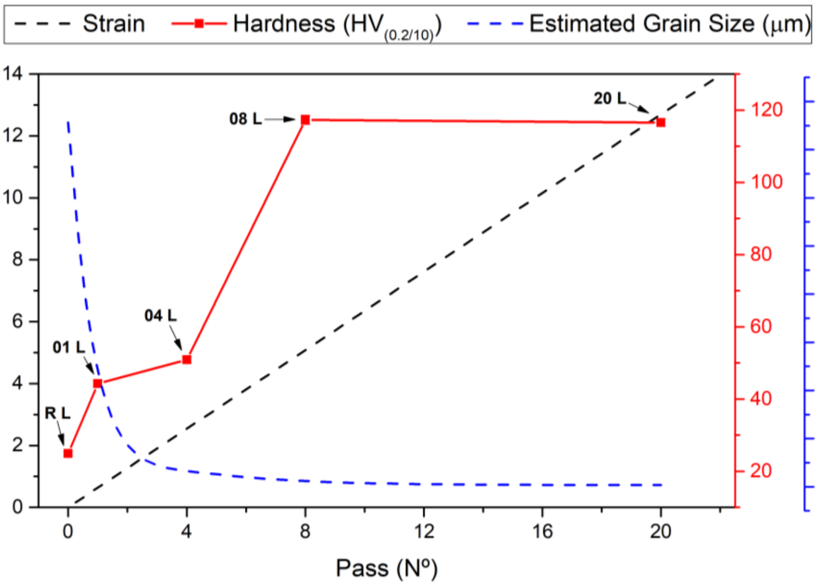

Figure 3. Calculated strain, microhardness values and estimated grain size according to ECAP processed samples

Bratov and Borodin (2015) verified the influence of number of passes in the density of dislocations in the material and concluded that greater effective deformations result in an increase in the density of dislocations, at which a saturation point is reached, being this value subjected to a point of saturation. This fact endorses the hypothesis proposed earlier when we approached the increase and saturation of microhardness values. Baik, *et al*., 2003 found through numerical simulation that little strain hardening occurs during the third and fourth pressings onwards.

In the cases of 08L and 20L samples, the hardness increase indicates that a higher dislocation density is developed by ECAP processing, leading to a finer structure with possible subgrains included.

Estimated mean grain sizes of these samples point towards microscale. In this case, mean grain sizes were calculated to be initially 7.56 µm for RL and to have reached approximately 0.52 µm in 01L sample and 0.33 µm in 04L, as can be observed in Fig. 4. Although, for samples 08L and 20L predicted grain sizes with approximately 0.04 µm, not similar to other works (Sato, *et al.*, 2003). It can be explained that Hall-Petch relation (Eq. 2) only accounts for grain size and, especially for 08L and 20L samples, there are other factors involved in this strengthening mechanism, for example subgrain strengthening and strain hardening.

Figure 4 displays the morphology found for the processed material. The sample's microstructures were not completely visible, but the obstacles indicating the grain limits were detectable. The morphology found in these micrographs corresponds with precipitates outlining a grain size. EDS analysis indicated to be a $FeAl_3$ precipitate. Figure 4 shows a higher amount of precipitates depending on the quantity of deformation steps, being their distribution increased with greater pass number. As the precipitates occurred in grain size boundary, we can infer the reduction of the grain size. The RL micrograph was performed in lower magnification due to having a larger microstructure. On the other hand, 20 L picture was presented in major magnification to identify the precipitate by EDS. Comparing 01L and 08L, it is clear the increase of precipitates delineating a lower grain size, as expected (Subbarayan, *et al.*, 2013).

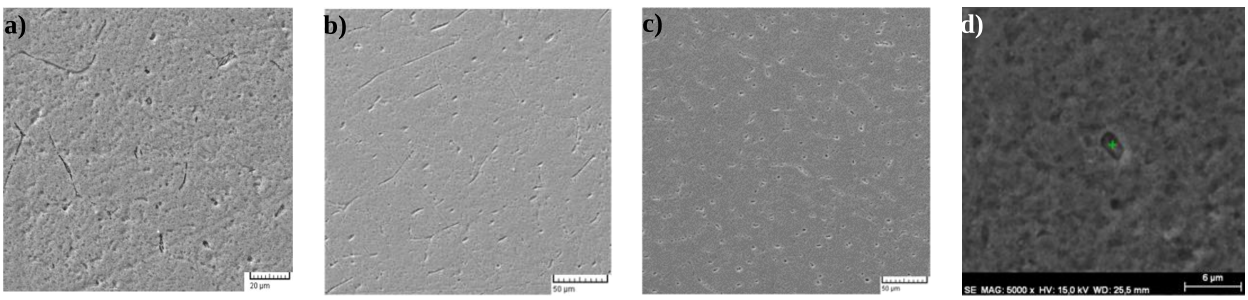

Figure 4. Micrographs of ECAP specimens - a) RL, b) 01 L, c) 08 L and d) 20 L local EDS analysis of a precipitate found throughout the samples' surfaces.

4. CONCLUSIONS

There was an increase in microhardness values related to the number of processing passes. There was a saturation of the microhardness values due to increasing discordance density in samples 08L and 20L. There was no saturation of the microhardness values in the 04L sample in opposite of what was predicted by previous studies.

Progressive values of effective strains for each sample were found to be progressive towards greater values of *N*. The increase in the number of passes influences the density of dislocations present in the material, reflecting the enhancing in mechanical properties. Also, a greater number of passes has shown a decrease in the estimated values of mean grain size. The ECAP process has the potential to alter some of the materials properties in a controlled and significant way, generating applications in areas previously not contemplated.

Grain sizes were estimated using Hall's relation and found to have consistent values, until the 4th ECAP processing pass according to previous works. 08L and 20L mean grain sizes were inconsistent due to other metallurgical factors, such as, and high-density dislocation fields and subgrain formation strengthening, which are non-predicted by the Hall-Petch relation, but still contribute for enhanced mechanical properties. $FeAl_3$ precipitate was found in all samples, presenting an elongated morphology for RL and 01 L samples, and being segregated and evenly located in samples with greater number of processing steps (04 L, 08 L and 20 L). Their shape structure seems to be connected with grain size and processing steps.

5. ACKNOWLEDGEMENTS

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