# Development of Mechanical properties of an Al–Mg alloy through Equi-Channel Angular Pressing

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## Abstract

**Equal channel angular Pressing (ECAP) is an innovative technique for developing ultrafine-grained microstructures first developed by Segal et al in 1981 in the former Soviet Union. The ECAP method consists of two channels that intersect at an angle, generally comprised between 90◦ and 135◦ . The deformation is produced by shear as the billet is extruded through the channels. One of the geometrical properties of the process is that the cross-section of the billet remains constant and so, it is possible to repeat the process over many cycles. Therefore, very high plastic strains can be accumulated in the billet. Thus, the ECAP process allows us to produce ultrafine-grained materials and hence to improve the mechanical properties of the material.**

**This work presents a study of the mechanical and optical properties of the AA5083 processed by equal channel angular extrusion. Vickers microhardness and tensile tests were carried out after processing the AA5083 up to N = 5 at room temperature. The improvement obtained in mechanical properties is shown.**

**Keywords: ECAP; Microstructure; Vickers microhardness; Tensile test; Optical microscopy**

## 1. Introduction

Ultra fine-grained materials are currently of great scien- tific interest due to their unusual mechanical properties. One method for developing ultra fine-grained materials in metal alloys is equal channel angular extrusion or Pressing (ECAE), which initially was developed by Segal et al. [1].

In this process, the cross section of the extruded material is not modified significantly, so there is no geometric restric- tion on the deformation that could be achieved. Although a restriction obviously exists as a consequence of the cracks, which appear in the surface and may damage the billet, as shown in Fig. 1.

The ECAE method consists of two channels that intersect at an angle, usually between 90° and 135°. A billet of material is placed into one of the channels. Then, the billet is extruded with a punch into the second channel. The material is de- formed by shear as it crosses the intersection channel. The billet deformed by ECAE retains the same cross-sectional area, so it is possible to repeat the process over several cy- cles.

Some authors have studied different routes to process the material by ECAE [2,3], where some of them are: route A, the specimen orientation is kept the same in successive pas-sages; route B, the specimen is rotated 90° around its axis between consecutive passages and route C, the specimen is rotated 180° around its axis between consecutive passages, where the microstructure obtained is different depending on the processing route [2,4].

In this study, tensile strength and Vickers Hardness are studied in Al–Mg alloy. The ECAE process was repeated five times through route C. Moreover, the present work examines strengthening as related to grain size. In order to do this, the evolution of the microstructure was studied by means of optical microscopy.

## 2. Experimental procedure

As was previously mentioned, the aluminium alloy 5083 (Al–Mg) was used for this study. The alloy was analyzed by

Fig. 1. Billets with cracks in the surface after $N = 6$ ECAE passages.

Table 1
Chemical composition of AA5083

| | % |
|---|---|
| Zn | 0.02 |
| Mg | 4.40 |
| Cu | 0.05 |
| Si | 0.35 |
| Mn | 0.093 |
| Fe | 0.20 |
| Cr | 0.12 |
| Zr | 0.02 |
| Ti | 0.01 |

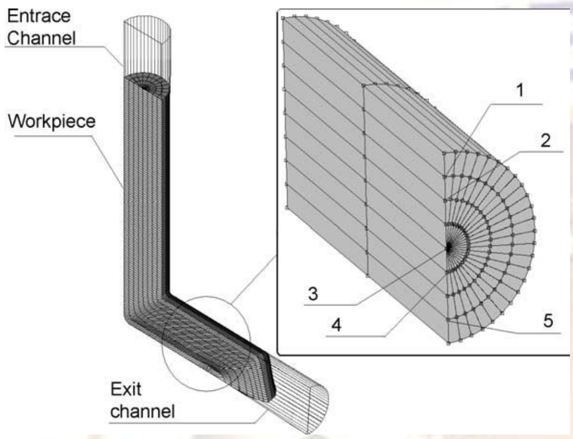


Fig. 2. ECAE process and considered zones within the billet, from reference [6].

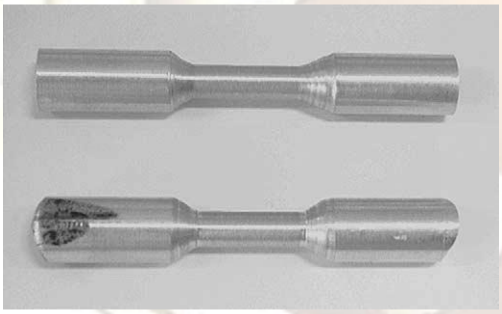

Fig. 3. Machined specimens for tensile test.

Table 2
Vickers microhardness measured with a load of 1 kg and with duration of the tests of 15 s

| Zone | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| N1, HV | 118 | 132.7 | 133.7 | 134 | 136. |
| N2, HV | 131.7 | 144.2 | 145 | 140.2 | 118 |
| N3, HV | 138.7 | 155 | 152.5 | 151.5 | 133. |
| N4, HV | 146.5 | 163 | 157 | 163.5 | 146 |
| N5, HV | 150 | 153.7 | 158 | 156.5 | 149. |

Microhardness measured after 1, 2, 3, 4 and 5 ECAE passages in different zones within the processed billet.

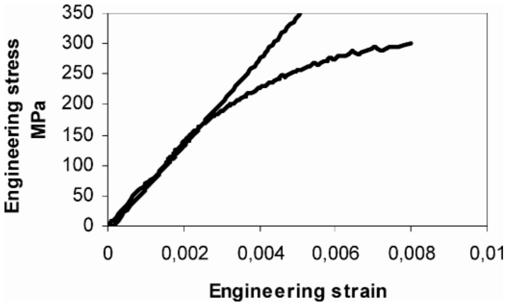


Fig. 4. Tension test for $N = 0$.

ICP-AES. The chemical composition of the alloy is shown in Table 1.

The die used for ECAE consists of two channels of equal cross section intersecting at an angle of 90° as shown in Fig. 2.

The friction during the extrusion was minimized using $MoS_2$ lubricant for both the rods and the die. The ECAE process was carried out at room temperature and during the extrusion, the punch speed was 10 mm/min.

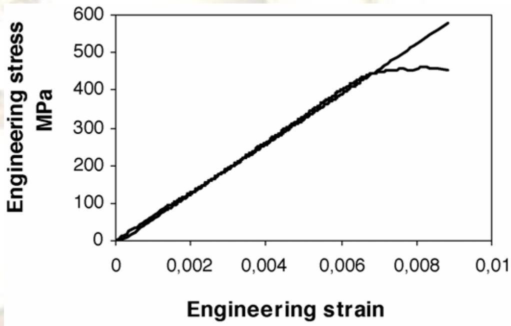


Fig. 5. Tension test for $N = 1$.

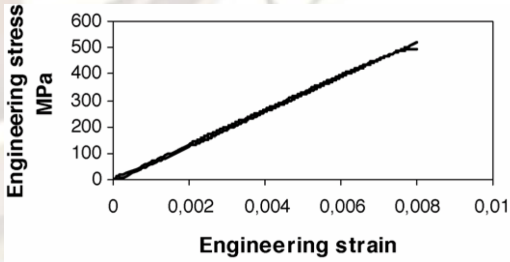


Fig. 6. Tension test for $N = 2$.

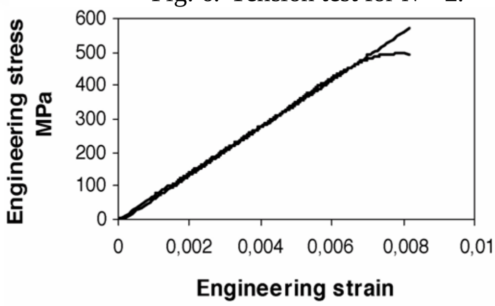


Fig. 7. Tension test for $N = 3$

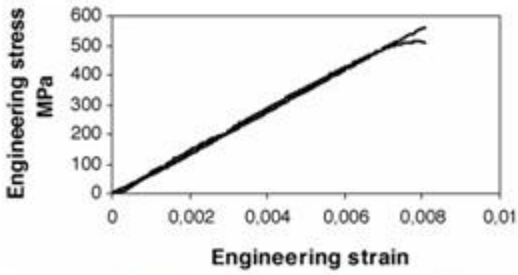


Fig. 8. Tension test for $N = 4$.

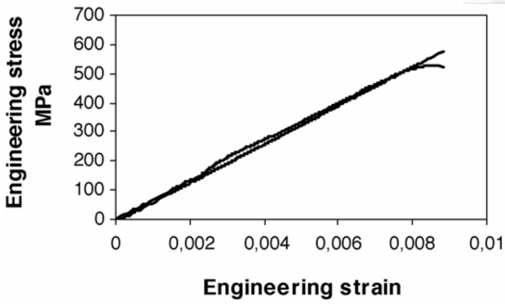


Fig. 9. Tension test for $N = 5$.

Optical images, showing the deformed grains developed after the different ECAE passages, were taken of different zones within the processed billet as shown in Figs. 10–11. The different zones are: zone 1 (inner radius), zone 2 (between zone 1 and 3), zone 3 (central zone), zone 4 (between zone Each billet was extruded up to five times, since cracks appeared at the end of the deformed specimen as shown in Fig. 1. The dimensions of the billet were 10 mm in diameter and 80 mm in length.

The deformed billets were cut in the extrusion axis direc- tion to perform the Vickers measurements, and polished, in order to analyze the microstructure by optical microscopy. Tensile tests were carried out to characterize the mechanical properties of the deformed billets.

The microhardness measurements were obtained with a Micromet microhardness tester. A Vickers diamond pyrami- dal indenter was used. The load used was 1 kg and the duration of the tests was 15 s. The processed billets were machined af- ter each ECAE passage, as shown in Fig. 3, in order to attain the flow stress curves shown in Figs. 4–9.

Afterwards, the polished samples were etched using the

Barker attack. [5].

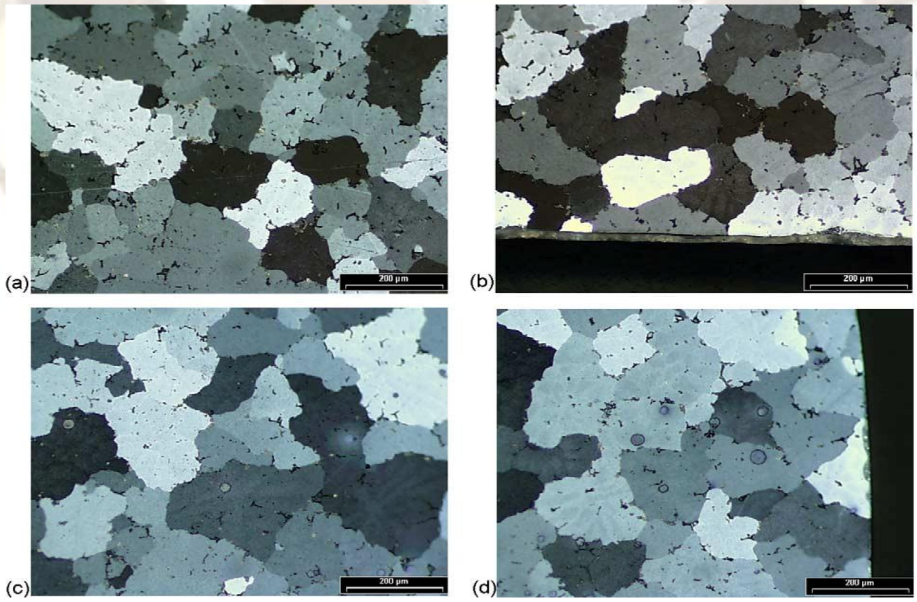


Fig. 10. Optical micrographs showing the original grains in different zones within the unprocessed billet.

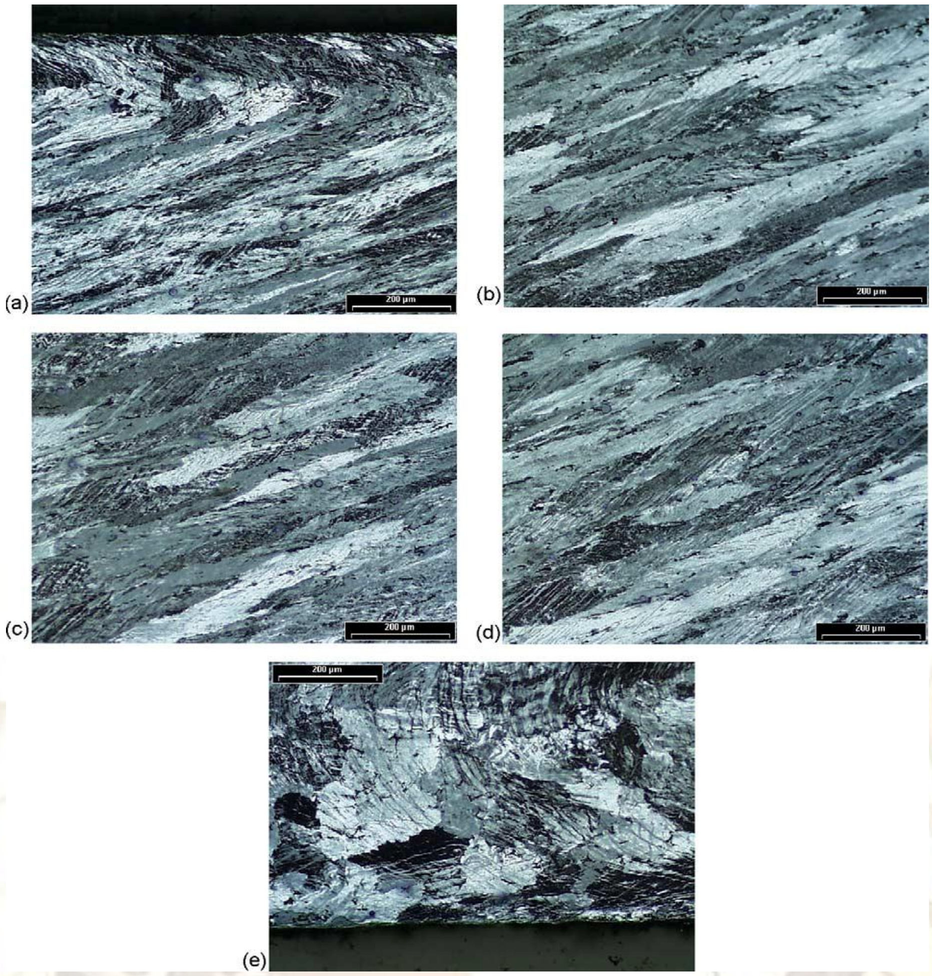

Fig. 11. Optical micrographs showing the deformed grains developed after three ECAE passages and route C, in different zones within the processed billet. (a) Zone 1 inner radius, (b) Zone 2, (c) Zone 3 central zone, (d) Zone 4 and (e) Zone (5) corresponding to the outer zone

not homogenous and the central zone of the billet has higher deformation than the elements close to the surface. The grains of the material after the first passage have the same distortion as the element grid of the simulation, as can be appreciated by comparing .

If a second passage of ECAE is simulated, then more de- formation is accumulated within the billet, where the different deformation zones can be seen in Fig. 12.

Comparing Figs. 12 and 10, it can be stated that grains have recovered the original shape as well as the element grid of the simulation. As an accumulative plastic deformation procedure has been selected, then the elements have higher deformation, where this is related to the deformation bands which have dislocations in the same direction.

Therefore, it can be observed in the simulation of Fig. 11 that different deformation zones exist in the billet after one ECAE passage. This results fits with the experimental results obtained processing the billet with the ECAE machine that exists in the Mechanical, Energetics and Materials Engineer- ing Department of the Public University of Navarre.

The idea of considering route C is to obtain a more ho- mogeneous deformation in all the billet, although the value of the deformation in a located zone could be higher using another route, for example, route A.

The effects of route C in the grains of the material are as follows: tendency to straighten, accumulation of the previous deformation and appearance of a high number of deformation bands in the grains of the original material, as can be observed in Figs. 11–12.

Moreover, it can be seen that the grains from zone 1, which is described in Fig. 2, are deformed after one ECAE passage in the opposite direction to that expected in advance. Therefore, a border effect exists, where this means that the deformation in the zones closest to the surface is less intense than in the central zone of the billet.

In the first ECAE passage, total equivalent plastic strain values are ε = 1.2 and ε = 0.4 in the middle of the cross-section and in the outer part of the billet, respectively.

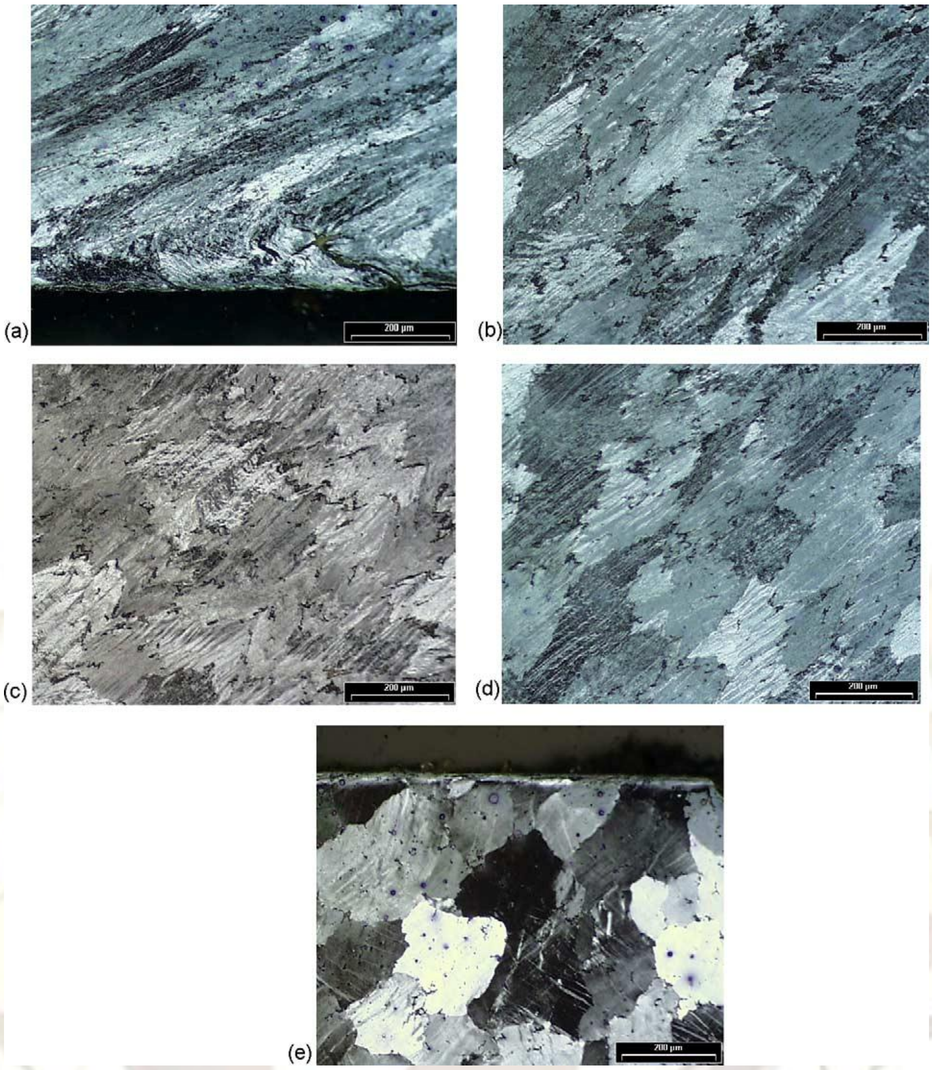


Fig. 12. Optical micrographs showing the deformed grains developed after four ECAE passages and route C, in different zones within the processed billet. (a) Zone 1 inner radius, (b) Zone 2, (c) Zone 3 central zone, (d) Zone 4 and (e) Zone (5) corresponding to the outer zone. (a) AA5083 RC V10 T0 N5. (1). (100×); (b) AA5083 RC V10 T0 N5. (2). (100×); (c) AA5083 RC V10 T0 N5. (3). (100×); (d) AA5083 RC V10 T0 N5. (100×); (e) AA5083 RC V10 T0 N5. (5). (100×)

Also, the grains situated in zone 5 (described in Fig. 2) present lower values of deformation, where this could be due to a higher predominance of bending effect rather than shear.

As can be observed in Fig. 11b–d, the higher deformation appears in the positions 2, 3 and 4. These positions present elongated grains with deformation bands. These results are the same as those obtained with the FEM simulations. A non-uniform result is obtained in all the billet due to the border effect.

After two ECAE passages, it is observed that the material undergoes a straightening mechanism. The structure of the billet after two ECAE passages presents a grain size similar to that observed in the original material. This can be appreciated if both Figs are compared between one another. However, it is clearly seen that the grains shown by Fig.12 contain a high dislocation density. The grains of position 1 (described in Fig. 2) are not so similar to the grains in the starting material because of the border effect.

Figs. 12 show grains highly deformed. Therefore, it is difficult to observe these deformations using optical mi- croscopy.

The processed billets can be subjected to an appropriate thermal treatment. Ultrafined grains can be achieved with this kind of treatments. However, this will be studied in a future paper.

Table 3 shows the Vickers measurements on the central position (zone 3), which presents the highest deformation values.
It can be observed in Fig. 13 that the microhardness value increases with the number of passes. The highest increase in hardness occurs when the billet is processed by ECAE once (N = 1). From N =0 to N = 1, the microhardness increases 54 HV. On the other hand, from N =1 to N = 5, a low increase in hardness is observed.The microhardness in the zone corresponding to the inner radius of different billets are shown in Table 4 and the values of microhardness measured in the zone corresponding to the outer radius are shown in Table 5.

Table 3
Vickers microhardness with the number of passes

| N | HV |
|---|---|
| 0 | 79.5 |
| 1 | 133.75 |
| 2 | 145 |
| 3 | 152.5 |
| 4 | 157 |
| 5 | 158 |

Table 4
Vickers microhardness of the inner radius of the different billet

| | | | |
|---|---|---|---|
| HV | 118 | 118 | 138.7 |
| 146 | | | |
| 150 | | | |

Table 5
Vickers microhardness of the outer radius of the different billet

| | | | |
|---|---|---|---|
| HV | 136.5 | 131.7 | 133.5 |
| 146.5 | 149.5 | | |

Vickers microhardness is higher in the central position, due to the high plastic deformation achieved in this position, which agrees with the results from reference [6].
The billet processed the first time presents in the inner radius a value of 118 HV. The second pass, in which this position corresponds to the outer radius, presents the same value of microhardness. The next pass presents a higher value of microhardness due to the higher deformation achieved with the different passages. The value of the microhardness in this position of the billet processed four and five times increases slightly.

Table 6
Yield strength with the number of

| *N* | Yield strength |
|---|---|
| 0 | 167.3 |
| 1 | 442.25 |
| 2 | 481.5 |
| 3 | 481.8 |
| 4 | 482.6 |
| 5 | 504 |

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## 6. Conclusions

Optical and mechanical properties of processed billets by ECAE have been studied in this work. The structure of the processed billets has been examined by employing optical microscopy in different zones of the billet. The experimen- tally obtained results have been compared to those obtained using FEM simulations.
The experimental results fit well with the simulated results in all the deformation zones of the processed material. The highest deformation is achieved in the middle of the billet. The deformation bands in the central zone of the processed billets are easily observed not only in the micrographs but also in the

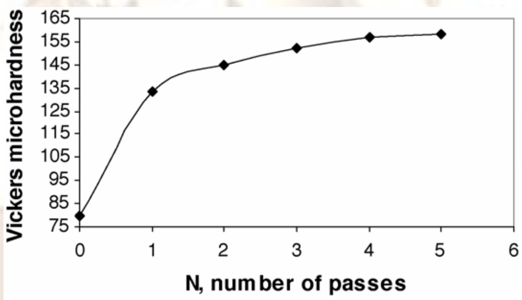


Fig. 13. Vickers microhardness vs. number of passes

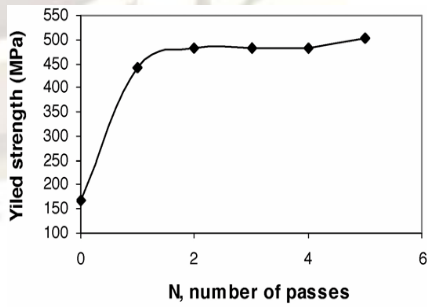


Fig. 14. Yield Strength vs. the number of passes

The tension tests were carried out with the machined billets. The yield strength increases with the number of passes, in the same way as microhardness. The values of yield strength are given by Table 6.

Just as with microhardness, the highest increase occurs when the billet is processed by ECAE first time. The billets with 2, 3, 4 and 5 passes present a yield strength which turn out to be very similar, as can be observed in Fig. 14.

deformation contour map of the simulations.
Microhardness and tension tests were carried out with the processed billets. The values of both parameters increase with the number of ECAE passages. The highest increase occurs from $N = 0$ to $N = 1$. In the different billets, the highest value of microhardness was achieved in the middle of the billet, where this agrees well with the highest deformations achieved in this zone of the billet. This means that the higher the deformation values reached in the material are, the higher the microhard- ness and yield stress reached in the tension test are.

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