A NUMERICAL AND EXPERIMENTAL ANALYSIS OF ALUMINIUM AA1100 DEFORMED BY DIFFERENT ECAP ROUTES

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Abstract. *The present work reports the influence of two distinct routes (A, and C) on equal-channel angular pressing (ECAP) process via numerical and experimental analyses. Commercial pure aluminium AA1100 was deformed at room temperature to evaluate the distribution of the effective plastic strain. For this purpose, three dimensional (3D) models were developed using the finite element method (FEM). These 3D models were formulated assuming J2 flow theory with nonlinear isotropic work-hardening and Coulomb's friction model. The routes were simulated with the aid of a parametric model. In these simulations the billet rotations can be imposed to the die tooling instead of the material perform some rotation around the strain axis. The experimental part of the work consisted in the validation of the pressing force obtained by two passes FEM models by mean of the billet pressing. The numerical results show a good agreement with the experimental tests. In the case of the second pass, due to the numerical methodology adopted, the pressing forces were higher than the experimental results. In addition, was verified that the redundant strains play an important role on the behaviour of the pressing force and the distribution of the effective plastic strains for the both routes. It could be concluded that the FEM modelling proposed in the present work could be used in the study of the processing routes influence on the billet deformation by the ECAP technique.*

Keywords: *ECAP, Processing Routes, FEM, Aluminium.*

1. INTRODUCTION

The equal channel angular pressing (ECAP) is a repetitive severe plastic deformation technique designated to produce bulk ultrafine materials with improved mechanical properties as reported by Segal (1995). The deformation process consists in the passage of a well-lubricated billet into a die composed by two channels with identical cross-section. This process can induces a continuous deformation into the billet by simple shear during the crossing in the channels intersection region. The principal characteristic of the ECAP technique is that the presence identical channels into the die maintains unaltered the cross-section of the deformed billet, making possible to repeat the pressing for a certain number of passes that will to promote a considerable grain refinement and the improvement of it mechanical properties (Srinivasan, 2001 and Segal, 2004).

The character of the continuity associated to the ECAP technique is due to the activation of the specific material shear planes between successive passes (Valiev, 2000). In this sense, the concept of the processing routes (see Fig.1) was inserted in the study of the great amount of plastic strains imposed on the billet during the deformation. Into this context, one of the first works with this focus was published by Zhu and Lowe (2000), concentrating efforts to establish a relation between the grain refinements, shear planes activation, plastic strains and the texture.

These works marked the most effective use of the numerical simulation in the study of the processing routes effects on the material final mechanical properties. In this sense, the use of the finite element method (FEM) has been very useful in the study of the ECAP processing routes, according to Kim (2002), considering the A and C routes and Rosochowski and Olejnik (2002) pointing out the correct geometric limits to build a multi-pass ECAP die to deform materials via route C.

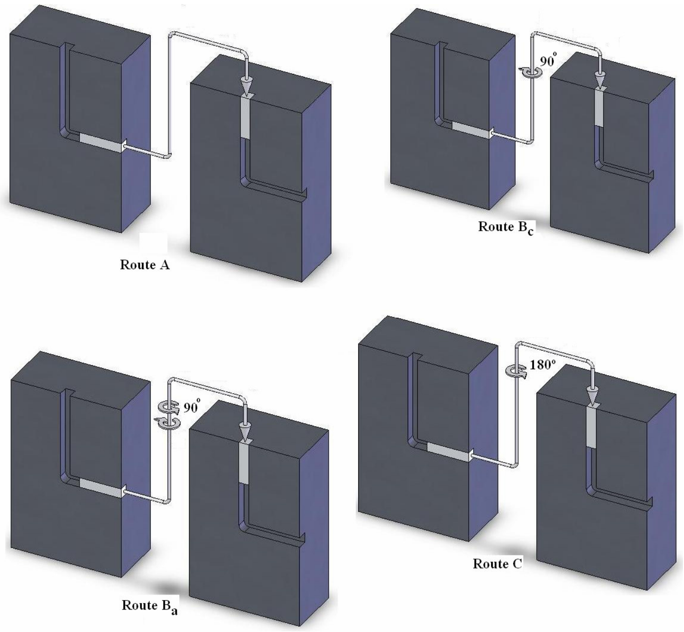


Figure 1. Schemes of the ECAP processing routes (Zhu and Lowe, 2000).

The possibility of a successful use of the plane-strain FEM modelling to study the ECAP technique and the effects of the processing routes started a very important theme of analysis, or rather, the appearance of a uniform plastic strain zone in the middle portions of the billet, after the deformation. Besides, the favourable conditions to the existence of this zone in a most homogeneous form were also explored. The works that are inserted in this context were ones published by Oh and Kang (2003), Kim and Namkung (2005), Raab (2005), Xu *et al.* (2006) and most recently by Zhang *et al.* (2007).

Although the mentioned works referred in this brief review present both experimental and numerical results about the ECAP technique employed in the deformation of bulk materials and the effect of the processing routes on the final mechanical properties, the necessity of to quantify the pressing force in a most realistic mode becomes evident. In this way, the focus of the present work is to establish the pressing force needed to deform an Al-1100 alloy by mean of two passes of processing. To achieve these objectives, 3D (three-dimensional) models were developed with the help of the finite element method and the simulations were carried out implicitly, at room temperature. Finally, experimental tests were performed also at room temperature to validate the numerical models by comparison between the respective pressing forces.

2. MATERIALS AND METHODS

2.1. Materials

The aluminium AA1100 billets was supplied by Novelis do Brasil Ltda. and the Tab.1 shows the nominal chemical composition. The material was machined with dimensions about 50 mm x 10 mm x 10 mm.

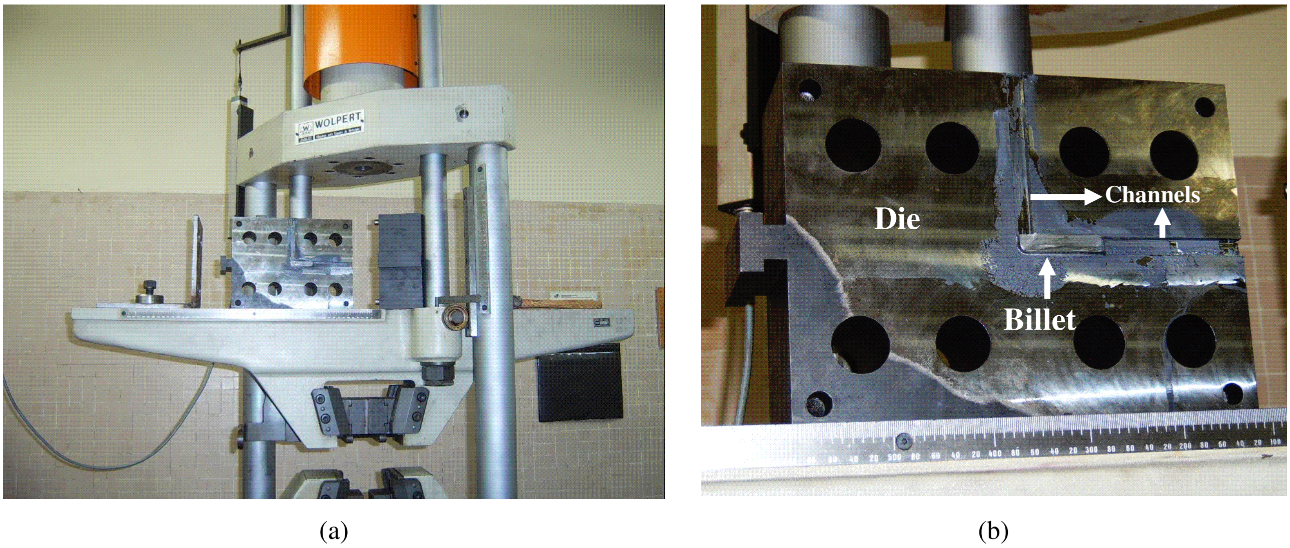
Table 1. Chemical composition of aluminium AA1100 (wt - %).

Mn	Mg	Si	Pb	Fe	Ti	Cu	Sb	Al
0.0012	0.0018	0.04	0.001	0.14	0.005	0.0003	0,001	balance

2.2. Methods

The aluminium alloy were deformed via equal channel angular pressing using an apparatus at room temperature. The process was done using two distinct routes (A and C) at strain rate about 1 mm /s. The apparatus used consisted of a Wolpert universal test machine with the maximum load capacity of the 200 kN, a plunger and a H13 tool-steel die (Fig. 2). The die was designed with two rectangular channels intersected at Φ angle equal to 90°.

In the bottom intersection of the channels was inserted an outer fillet radius of 5 mm to reduce the pressing force and to facilitate the flow of the billet. Before the deformation, the channel and each sample were lubricated using a commercial MoS_2 spray.



(a) (b)

Figure 2. (a) Apparatus used in the experimental tests and (b) H-13 tool-steel die.

2.3. The FEM three-dimensional modeling of the ECAP processing routes

The numerical analyses were carried out at room temperature neglecting the heating effects due to the friction in the billet-die contact. The initial material was considered as isotropic and its plastic flow was described by the von Mises plasticity yield criterion. In relation to the 3D finite element modeling, the die geometry employed to deform the billet for one pass is presented in Fig. 3. Fig. 4 shows the model employed to simulate the pressing for two consecutive passes to both A and C routes. This model was similar that was proposed elsewhere by Zhang *et al.* (2007). The effect of each route was attributed on the billet by means of different geometric configurations of the die. To represent the second pass using the route A the billet was forced to upward (Fig. 4a). The second pass of route C was simulated by the rotation of the billet around 180º, as shown in Fig. 4b. In the FEM modeling, the die outer fillet radius and the channels cross-sections were identical to the tooling used in the experimental tests.

In relation to the mechanical properties, the die was designed as an elastic-rigid H 13 tool-steel piece (E = 210 GPa, $\nu = 0.3$). The material considered to the billet was an elastic-plastic aluminium alloy AA1100 with dimensions about 10mm x 10 mm x 50 mm and the isotropic hardening described by the Hollomon law in a uniaxial stress condition. This relation was proposed by Nagasekhar and Tick-Hon (2004), according to Eq. (1).

$$\sigma_y = 173.79\,(\varepsilon_{eq}^{p})^{0.304} \tag{1}$$

where σ_y and ε_{eq}^{p} represent the uniaxial yield stress and the effective plastic strain, both defined by mean of the von Mises yield criterion.

In the billet mesh were employed 5,000 incompressible quadrilateral solid elements with full integration and adjusted aspect ratios to permit that the mesh undergoes high distortions.

The finite element simulation was carried out with the quasi-static implicit solver of commercial ANSYS code (Swanson Analysis Systems Inc., 1994). The plunger action was replaced by displacements imposed on the billet top surface. In order to assure the quadratic convergence of the full Newton-Raphson method, the top billet displacements during the first pass were fixed in increments of 0.25 mm up to a total displacement of 45 mm, in the case of one pass. In the case of the routes A and C the total displacement regarded was 30 mm. This procedure can maintain the same increments mentioned previously due to the convergence aspects.

To represent the friction behavior, the generalized Coulomb's law was used in the FEM model and a value of 0.055 was stated to the friction coefficient. It is well known that the generalized Coulomb's law states the relation between yield stresses in pure shear and uniaxial tension as given by Eq. (2):

$$\kappa = \sigma_y / \sqrt{3} \tag{2}$$

where κ represents the pure shear yield stress according to the von Mises yield criterion.

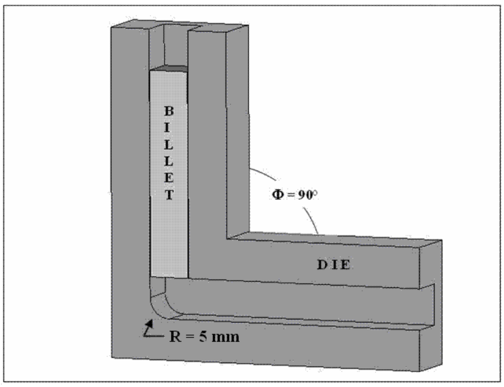


Figure 3. Die geometry containing the outer fillet radius used in the FEM simulation.

(a) (b)

Figure 4. Three dimensional FEM model employed in the ECAP simulation corresponding to: (a) route A; (b) route C.

3. RESULTS AND DISCUSSIONS

Fig. 5 shows the validation of the three-dimensional FEM modelling developed to simulate the process of the billet after one pass. The experimental force versus displacement curve was valid to all the routes once the first ECAP deformation pass follows the same procedure to the undeformed material. Analyzing the Fig. 5, it can be noted that the maximum force obtained in the numerical analysis and in the experimental tests was very close. It suggests that the simulation was validated. Conversely, the adoption of a constant value to the friction factor in the die-billet contact regions can explain the differences observed in the numerical results when one compares to the experimental procedure. It is very clear at the first 8 mm of displacement and after 20 mm that the principal reason that justify these differences are the heterogeneity in the machining realized on the die channels surfaces associated with the unequal action of the MoS_2 during the pressing. Thus, due to the disregarding of both channels superficial conditions and the role of the lubricant during the deformation, the comparison between numerical and experimental results of force versus displacement curves showed the mentioned differences. In addition, these aspects also contributed by achieving of the maximum force via numerical analysis in a smaller displacement value than observed in the experimental tests.

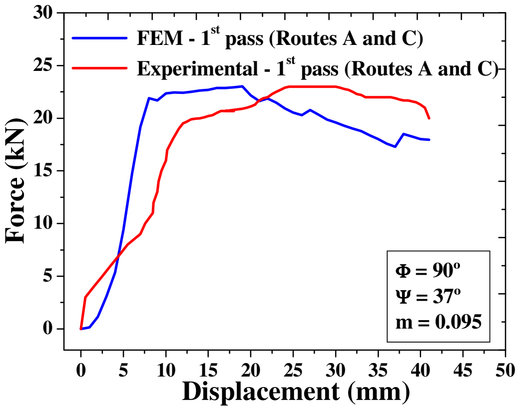


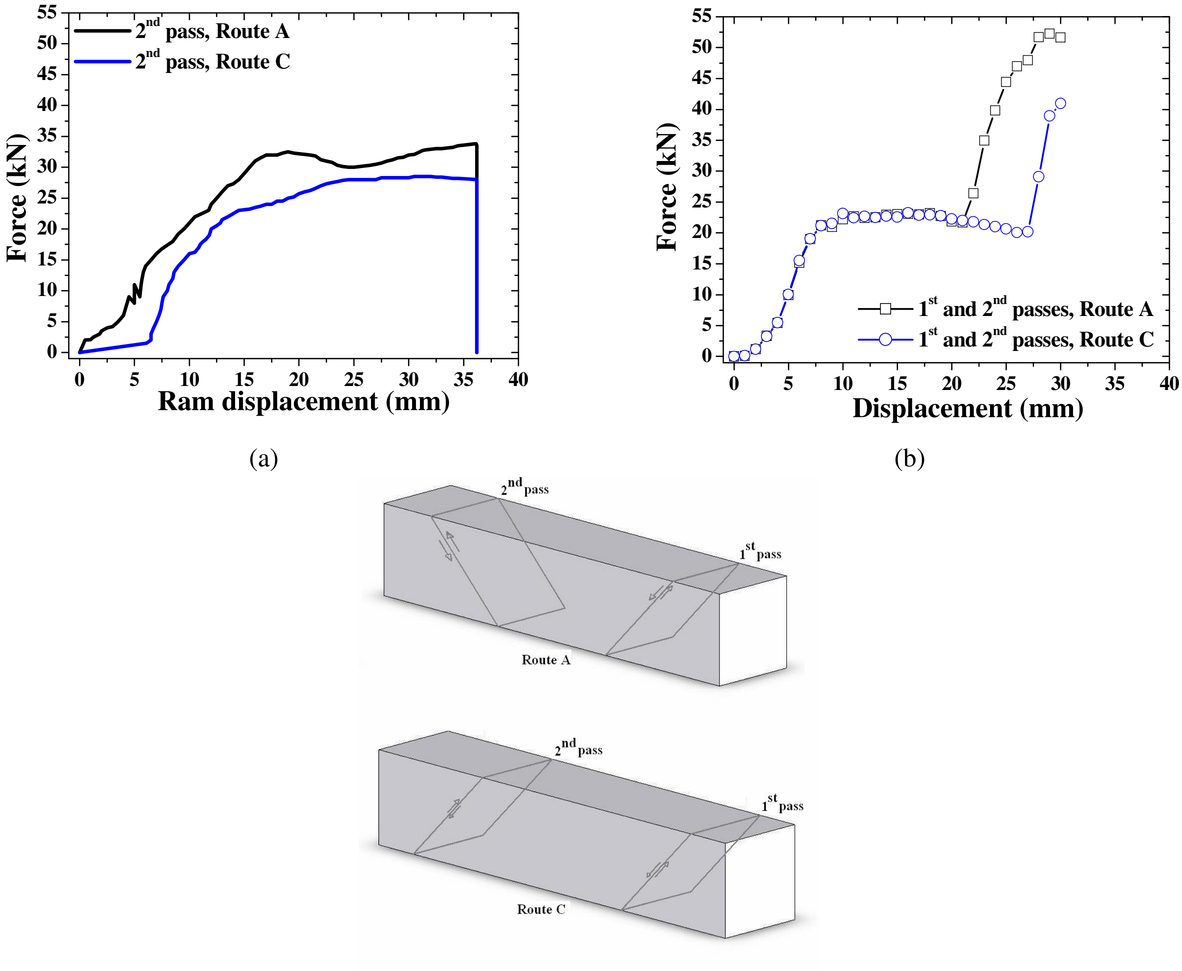
Figure 5. Validation of the FEM modelling comparing the numerical and experimental pressing forces after one pass of an AA1100 billet deformation by mean of the ECAP technique.

Figure 6a compares the experimental forces obtained after the second pass via A and C routes while Fig. 6b shows the numerical results obtained by two successive passes following the same routes. In the case of the experimental results, the deformation of the billet by means of the route A exhibit the high load values when compared to route C due to the absence of the redundant strains and the activation of different shearing planes between the passes, as mentioned by Valiev and Langdon (2006) and depicted in the Fig. 6(c).

In the case of the numerical results, during the first pass the force values were identical to both routes, reinforcing the validation presented in the Fig. 5. Conversely, due to the fact that in the FEM models the billet was maintained into the die (elastic unloading was neglecting) in the subsequent pass, the pressing force increases continuously, independently of the processing route adopted. Thus, the first pass of the route A starts in 0 and ends after 20 mm of the displacement, providing a maximum force of approximately 23kN, whereas the second pass starts in 20 mm and finishes after 30 mm, promoting an increasing of the maximum force about 53 kN.

In the case of the route C, the firs pass was identical to the route A, as mentioned previously. Nevertheless, due to the geometric characteristics of the FEM modelling, the end of the first pass occurred after about 28 mm. The second pass started after 28 mm and also finished after 30 mm of displacement, requiring a pressing force close to 40 kN. This result was significantly small when compared to route A. It is a consequence of the rotation of the 180º realized in the billet between the successive passes by the route C leads to redundant strains and, consequently, the return to the initial configuration. Thus, in the deformation process the material attains to accommodate the great dislocation density imposed during the deformation requiring a less pressing force, as reported by Valiev and Langdon (2006). The redundant strains present in the second pass by route C can be macroscopically represented by the return to the initial form of the billet mesh, as shown in Fig. 7b. On the other hand, the mesh referent to the route A exhibits the elements with a certain tendency to preserve the deformed geometry and, thus, increasing the pressing force necessary to deform the billet.

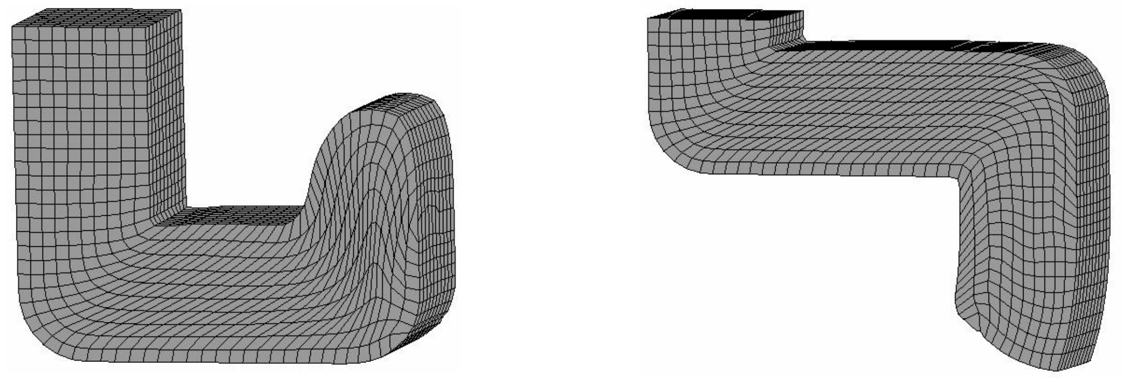
Recently, Suo et al. (2007) also discussed the characteristics of the routes A and C and their consequences on the deformed material. The results obtained in the present work showed a good agreement with the literature.



(a) (b)

(c)

Figure 6. (a) Forces obtained after the second pass of ECAP via A and C processing routes, (b) FEM results of the pressing force after two passes of ECAP via the routes A and C; (c) Shearing planes activated by the ECAP routes.

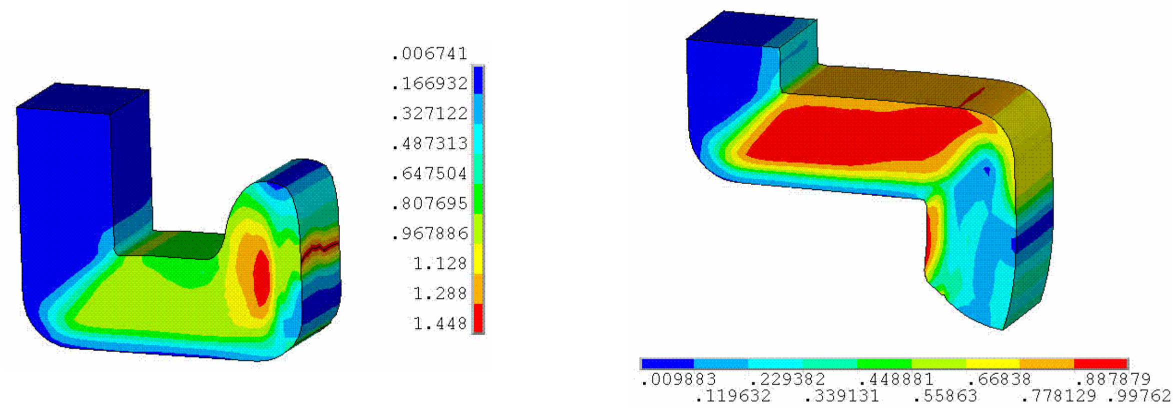


(a) (b)

Figure 7. Representation of the mesh aspect after two ECAP passes according to: (a) Route A and (b) Route C.

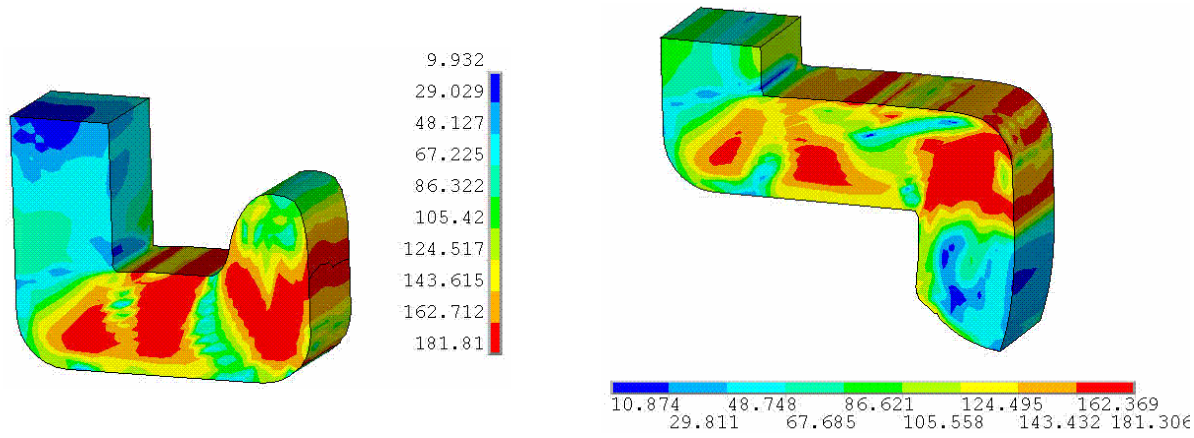
The comparison between the von Mises plastic strains obtained by the FEM simulations to the routes A and C, after two successive passes, can be observed in details in the Fig. 8. The die geometry employed to simulate the two passages of the billet into the die by route A provides higher effective plastic strains than observed in route C. Moreover, the geometric facility to deform the material coupled to the presence of the redundant strains contributed to the decreasing of the effective plastic strains predicted in the case of the route C during the second pass. Also, in both cases analyzed, a common behavior was the appearance of an equivalent plastic strain uniform zone at the die channels intersection region called deformation zone. This region is the responsible by the activation of the shearing planes that promote the plastic deformation of the material, according to the processing route investigated by Suo *et al.* in (Suo *et al.*2006).

The development of the mentioned effective plastic strains uniform zone can be attributed to the observation of the von Mises stress layers just in this region, propagating towards the second channel, as previously suggested by Kim *et al.* (2000). In this context, Fig. 9 shows the distribution of von Mises stresses after routes A and C. After the first pass, it could be observed that the equivalent stress layer placed in the deformation zone and a good spread in the normal direction of the displacement. Specifically in the case of the route A, the fold of the billet in the beginning of the second pass promotes a more significant increasing of stresses in the middle portions of the billet.



(a) (b)

Figure 8. Effective plastic strains distribution in function of the ECAP processing routes: (a) Route A and (b) Route C.



(a) (b)

Figure 9. The von Mises stress distribution associated to the effective plastic strains of the ECAP corresponding to: (a) route A; (b) route C.

4. CONCLUSIONS

The experimental tests of the pressing of an aluminium AA1100 billet via ECAP technique at room temperature were carried out to evaluate the three dimensional (3D) models developed to simulated two distinct processing routes (A and C) using the finite element method (FEM) in an implicit form. It was found that the after the first pass, the maximum value of the force provided by the experiments and the simulations was very close, permitting the validation of the FEM models developed. Conversely, due to the fact that in the numerical analyses the billet was maintained into the die, the pressing force predicted after the second pass was higher than the experimental tests. However, the predictions relative to the route A were superior than observed to route C. In the case of the route C, it can be concluded that the presence of the redundant strains could to explain the results observed. In addition, the predictions of equivalent plastic strains confirmed the severe deformation condition imposed on the billet by the route A, when compared to the route C. In addition, was possible to verify the presence of a strain uniform zone in the middle portions of the billet as a consequence of the equivalent stress field in the normal to the direction of the load application. For the reasons presented here, with the present work was possible to conclude that the redundant strains play a primary role on the route C, leading to the increasing of the pressing force and in the effective plastic strains imposed on the deformed billet. The three-dimensional modelling developed can be used to represent macroscopically the influence of the ECAP processing routes on the plastic deformation levels imposed on the billet at the end of two successive passes of deformation.

5. ACKNOWLEDGEMENTS

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