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FINITE ELEMENT MODELLING AND ANALYSIS OF PROCESSING ROUTES BY USING EQUAL CHANNEL ANGULAR EXTRUSION

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ABSTRACT
Equal Channel Angular Extrusion (ECAE) is an innovative technique which allows us to obtain an improvement in the mechanical properties of the processed materials, such as: yield stress, ultimate tension stress, toughness, and hardness, among others. These improvements in the mechanical properties are based on the metallographic grain refinement, as a consequence of the plastic strain accumulation inside the processed materials. In this process the material is extruded through two channels that intersect at an angle usually comprised of between 90º and 115 º. As the material crosses the intersection between both channels, it is deformed by a deformation process where shear deformation and a high hydrostatic pressure are involved. As a consequence of this, the material can reach severe plastic deformation (ε>1) in each passage. Although, it is possible to achieve this plastic deformation levels by using conventional deformation processes, such as extrusion or rolling, the changes on the cross section would make the final products unusable for structural applications. The channels are manufactured with almost the same cross section, and hence when the part is extruded the change in its initial dimensions is negligible. As the shape of the part does not change in the process, the billet can be extruded as many times as it is needed in order to achieve the desired plastic strain. In the ECAE process there exist many parameters to be controlled such as friction, die geometry and processing route. The way that the part is introduced inside the die is called route. In route A the part is introduced with out any rotation, in route B the part is rotated 90º around the longitudinal axis and in route C the billet is rotated 180ª between each passage of ECAE. In this work, a comparative analysis between route A and C is performed by using finite element method. This has been done with the objective of determining the most suitable processing route for performing the ECAE process in order to obtain a more uniform strain field inside the billets. The three-dimensional FEM model considers a circular section, a shear friction coefficient between the part and the die that has been experimentally determined, the material strain hardening behaviour and a rigid-deformable contact between the billet and the die.
Keywords: ECAE, SPD, FEM, Forming

1. INTRODUCTION
The equal channel angular extrusion or pressing (ECAE or ECAP) was first developed in the former Soviet Union by V. Segal in 1981 [1]. The process is used to improve mechanical properties by refining the grain size due to severe plastic deformation (SPD) and heat treatments [2]. This refinement allows processed material to increase its mechanical properties. In order to impart the deformation to the material, the billet is extruded thought two channels that intersect at an angle between 90º and 115º, as can be observed in Figure 1.

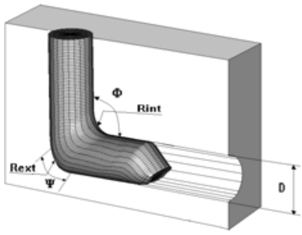


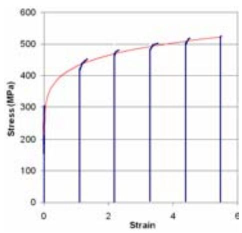
Figure 1. ECAE process.

As the material crosses the intersection between the channels, shear deformation is introduced within it. The accumulated deformation leads to grain refinement in two different ways: discontinuous recrystallization or continuous recrystallization [3]. In the discontinuous recrystallization the billet is deformed at room temperature by using ECAE until a desired value of deformation, and then a thermal treatment is used to reduce the grain size. In the continuous recrystallization the ECAE dies and the part are heated before the extrusion, so the deformation process and the thermal treatment to achieve the grain size reduction are performed together [3].
As the channels are manufactured with the same cross section the part does not change its dimensions in the extrusion. This means that the part can be processed as many times as it is desired in order to achieve the desired deformation. There are different ways of introducing the part in the die to perform the passes and these ways are called routes. The part can be rotated between each pass 0º, 90º or 180º, these routes are called route A, route B and route C. In [4] and [5] experiments of processing routes were carried out and also a measurement of the grain size reduction. These works recommended using route C instead of route A, because the grain size reduction is achieved quicker.
The higher the plastic strain the higher the grain size reduction and the improvement in the mechanical properties [6]. Nevertheless, the strain homogeneity is as important as the strain value. If the strain field is homogeneous, then the mechanical improvement of the processed material is approximately the same in the whole part. For structural applications the global mechanical improvement in the entire part is much more important than obtaining a local grain size reduction which is obtained when using route A, which means that ECAE routes must be carefully studied to achieve the desired strain field. In this work a study of the strain homogeneity of routes A and C is made.

2. FINITE ELEMENT MODELLING

To perform the FEM analysis a ECAE die geometry with internal radius (R_{int}) of 0.5 mm, external radius (R_{ext}) of 1.5 mm, diameter (D) of 10 mm and intersection angle (Φ) of 90º was selected. The extrusion was performed at a velocity of 10 mm/s.
A conventional tension test cannot accurately predict the behaviour of the material in the ECAE process because of the obtained deformation which is much higher than that attained in the tension test. So in order to obtain more accurate results the methodology developed in [7] has been considered. Figure 2 (a) shows the ECAE press used to perform the experiments and Figure 2 (b) shows the flow stress curve of the 5083 AA.

(a)ECAE press to develop the process



(b) 5083 AA Flow stress curve obtained by using the methodology developed in [6]

Figure 2.

The steps of the method which are developed in [7] are: first the material is pre-deformed to a known deformation value and then a tension test is performed on the material. After that, the tension test curve is shifted to the pre-deformed value. Then the stress-strain curve can be fitted as Figure 2 (b) shows. The material shown in Figure 2 (b) is a 5083 aluminium alloy, and this is the one used to simulate the ECAE process. The fitted material model can be observed in Equation 1.

$$\sigma = 428.18 \cdot \varepsilon^{0.1161} \tag{1}$$

In this work two ECAE passages considering route A were simulated. Because of the symmetry of the process only half of the part was meshed and a symmetry plane was employed. A shear friction model with a friction coefficient of 0.125 was used. This coefficient and the model of friction were determined in [7].
An initial three-dimensional meshing which has elements of 0.25 mm of edge was employed and an overlay global remeshing in the whole part was used. In order to reduce the computational cost, the remeshing criterion makes the mesh twice as coarser in the inside than in the outside of the mesh. The remeshing criteria were: (a) by penetration, which means that, remeshing is done if the distance between the polygonal created by the edges of the elements and the contact surface is greater than 5% of the element edge, (b) by grid distortion, where remesh algorithm is run if the angle between the edges of the hexahedral elements are not between 50º and 130º and (c) if the increment of strain between each increment is greater than 0.4 (this is used in order to represent all the strain gradient). If no criterion is satisfied a remeshing is done every 10 increments.
A rigid-deformable contact between the part and the die was chosen because of the difference of rigidity between them (the part is in plastic zone $\varepsilon \approx 1$ and the die deformations are in elastic zone $\varepsilon < 0.003$).
A first passage of ECAE was simulated and then the strain field was determined. In order to perform the second passage, the meshing, the plastic strain and the stress field of the last increment were recovered in a new FEM modelling which was considered as an initial condition used to perform the second ECAE passage. The recovered meshing of the first passage is introduced inside the entrance channel without rotation, so route A is performed. In [8] route C was simulated by the authors of this work by using the same material model, friction coefficient, die geometry and hence in this work the routes A and C are to be compared.

3. RESULTS

In [6], [7] and [8] FEM modelling was validated with the actual results obtained by using the ECAE press. The discrepancy between FEM modelling and actual results were close to 6% for the extrusion force and 1.2% for the strain, so the FEM modelling agrees well with the reality.
In Figure 3 (a) and (b) a cross section of the first and the second passage of route A are shown.

(a) Cross section after the 1st ECAE extrusion *(b) Cross section after the 2nd ECAE extrusion*

Figure 3. Strain field in the work-piece processed by ECAE using route A

In order to compare route A with route C studied in [8], the strain fields of Figure 4 were statistically analysed by using a Kolmogorov-Smirnov test. 160 randomized strain values were extracted from the strain field of the first passage and 127 from the second passage.
The selected null hypothesis of the Kolmogorov-Smirnov test was that deformations can be expressed by using a Gaussian distribution with average $\mu = 1.1$ and a standard deviation $\sigma = 0.13$ for the first passage and average $\mu = 2.53$ and $\sigma = 0.27$ for the second passage. These average and standard deviation are the average and standard deviation from the randomized values. The probability that the null hypothesis cannot be rejected is around 0.9999 in both cases.

This means that the strain distribution can be represented as a distribution with an average and a standard deviation which are $\mu = 1.1$ $\sigma = 0.13$ and $\mu = 2.53$ and $\sigma = 0.27$ for the first and the second passage respectively, when route A is used.
As was obtained in [8], the mean value and the standard deviation for the second passage of route C was $\mu = 2.14$ and $\sigma = 0.09$. This means that, higher local values of strain can be obtained by using route A instead of using route C, although the homogeneity of the strain field is lower than using route C, as can be graphically observed in the Figure 4.

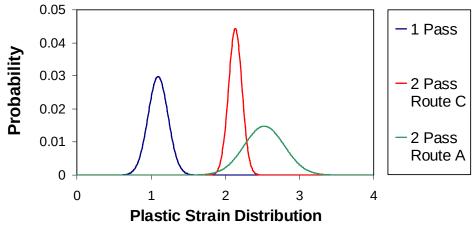


Figure 4. ECAE strain distribution of the different processing routes.

The attained plastic strain is directly associated with the mechanical improvement. It can be stated that by using route A, as can be observed, the attained deformation is higher in route A than in route C. Nevertheless the variability of the attained deformation when using route A is much higher than that obtained by using route C. This means that an orthotropic material is achieved by using route A.
By using route C the obtained material has almost the same mechanical improvement in the whole work-piece because the strain value is almost the same over all the part. This means that an isotropic material is achieved by processing material by using route C.

4. CONCLUSIONS

In this work, a comparative study of the strain field obtained by using route A and C have been made. It has been demonstrated that the strain fields obtained after performing route A and C can be expressed by using a normal distribution and hence, by using FEM modelling, the strain field of first and second passages of route A and C have been obtained and mean values and standard deviation have been calculated.
It has been shown that route A leads to higher average of deformation values but it has higher variability than route C. This means that route A gives higher local values of deformation but lower homogeneity in the strain field.
In industrial processes the improvement of the mechanical properties should be homogeneous so it can be concluded that route C is much more useful to improve mechanical properties equally in the whole processed part.

5. ACKNOWLEDGEMENTS

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