MODELING AND SIMULATION OF AN ALUMINUM ALLOY SINGLE-PASS ECAP PROCESSING CYCLE

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Equal Channel Angular Pressing (ECAP) is the most effective severe plastic deformation (SPD) method for microstructural refinement performed by pressing a billet of material through a die that has two channels which intersect at a certain angle. In this paper, a single-pass ECAP processing cycle applied to a commercial aluminum alloy was analyzed, the process being modeled and simulated using the finite elements method (FEM) in DEFORM™ v.10.0 simulation software. In this simulation a 90° ECAP die was considered, the analysis being performed for the first ECAP pass. The processing temperature was 20°C and the domain discretization and meshing was made using 4161 nodes and 3908 polygonal surfaces for the workpiece. The ECAP processing cycle was subdivided into 150 steps (intermediary deformation stages), results regarding the effective stress and strain, force, normal pressure and other parameters can be obtained for each step. These results are crucial for ECAP process analysis and also for the ECAP die design and manufacture.

Keywords: equal channel angular pressing; severe plastic deformation; modeling and simulation; finite elements method; aluminum alloys

1. Introduction

The interest in severe plastic deformation (SPD) has increased extremely over the past decade, due to many remarkable properties that can be achieved in bulk materials by SPD processing [1-3]. More recently, SPD was in the spotlight of researchers and academics around the world as being a technique capable of producing fully dense and bulk submicrocrystalline and nanocrystalline materials. For converting a coarse-grained material into an ultrafine grained material, it is necessary both to impose an exceptionally high strain in order to introduce a high density of dislocations and for these dislocations to subsequently rearrange in order to form an array of grain boundaries [2, 4]. Conventionally, SPD processing may be defined as those metal-forming procedures in which a very high strain is

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imposed on a bulk solid without the introduction of any significant change in the overall dimensions of the solid and leading to the production of exceptional grain refinement so that, typically, the processed bulk solids have 1,000 or more grains in any section [4]. Unlike the classical deformation processes (forging, rolling, die-forging, extrusion etc.), the key benefit of SPD, with equal channel angular pressing (ECAP) as the most emblematic technique, is that SPD involves inducing very large strains in the processed material, without modifying the initial shape of the billet during deformation [2]. The advanced grain refinement obtained by means of SPD processing is leading therefore to the substantial improvement of structural and physicomechanical characteristics for the processed material [5, 6].

From the various SPD techniques, ECAP is especially attractive because it can be applied to fairly large billets, so that there is the potential for producing materials that may subsequently be used in a wide range of structural applications, creating also the potential for scaling-up and developing ECAP at industrial level, for use in commercial metal processing procedures [7]. This technique can be applied to commercial pure metals and metal alloys, with FCC, BCC and HCP crystal structures with coarse grains, to fabricate ultrafine grained materials or nanomaterials that have no porosity and superior mechanical properties compared to the unprocessed material [8-11]. During ECAP, significant grain refinement occurs together with dislocation strengthening (the grain sizes produced by ECAP being typically in the sub-micrometer range), resulting in a significant enhancement in the strength of the alloys. ECAP processing involves pressing the billet (usually round or squared) throughout a die containing two intersecting channels identical in cross-section (which is also the same as the billet). As one can see in Fig. 1, the intersection angle is ϕ (generally ranging between 90° and 150°) and a secondary angle of ψ sets the curvature from the outward intersection point of the channels.

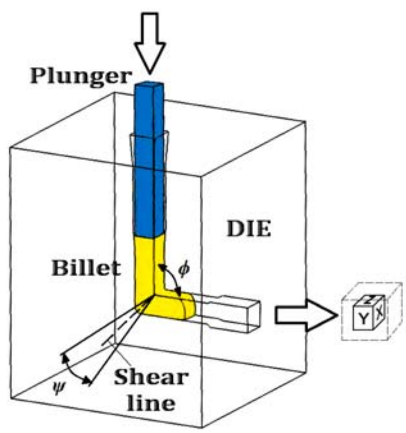


Fig. 1. Schematic illustration of equal channel angular pressing (ECAP) technique

In Fig. 1, the X, Y and Z planes denote the transverse plane, the flow plane and the longitudinal plane, respectively.

In these circumstances, the material moves like a rigid body, the deformation being performed in a quasi-ideal way by simple shear in a thin layer (a plane) at the intersection of the two channels of the die (the shear plane), this phenomenon occurring as the billet passes throughout the ECAP die [12-14]. Maintaining the same cross section during ECAP processing, despite the introduction of a very intense strain, is the most important characteristic of SPD processing and, moreover, is a distinguishing feature of this method compared to conventional metal-working operations, such as rolling, extrusion, forging or drawing. Since the cross-sectional area remains unchanged, the same sample may be pressed repetitively in order to attain exceptionally high strains [15-17]. 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 [18-21]. Based on the sample rotation manner, different deformation routes can be applied. Route A has no rotation of the billet, route B_A is rotated counter clockwise 90° on even number of passes and clockwise 90° on odd number of passes, route B_C is rotated counter clockwise 90° after every pass and route C is rotated 180° after each pass [22-25].

A series of recent studies are showing that microstructural refinement via ECAP processing may result in an unique combination of strength and ductility in case of aluminum alloys [26-31]. Such superior mechanical properties are highly desirable when manufacturing advanced structural materials. However, achieving these properties is associated with creating some specific microstructures, which are related themselves with the specific processing regim and with the nature of any further treatment. Therefore, the main difficulty elements in ECAP processing are related to the judicious design and manufacture of the working tools used in the severe plastic deformation process and to the accurate evaluation of specific processing parameters, these aspects being easily addressed through computer modeling and simulation.

2. Materials and Methods

This study was applied to a standard 6063 aluminum alloy (cold working 20-250°C), which is generally known as an architectural alloy. Mostly used for complex extrusions, 6063 Al 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, 6063 Al alloy is widely used for structural applications, in constructions, in transportation, for extreme sports equipment etc. Therefore, comprehending his mechanical behavior under various experimental conditions (strain rates, loadings, temperatures and so on) becomes a crucial issue.

The considered single-pass ECAP processing cycle was modeled and simulated using the finite elements method (FEM) in DEFORM™ v.10.0 simulation software, which enables designers to analyze metal forming, heat treatment, machining and mechanical joining processes on the computer rather than the shop floor using trial and error. For this simulation, a 90° ECAP die was considered (maximum pressure), the analysis being performed only for the first ECAP passage through the die. Also, in this study, a value of 20° for the ψ angle was adopted. The initial dimensions of the ECAP billet were 60 x 10 x 10 mm. The processing temperature was 20°C and the pressing speed was 1 mm/s, no strain hardening and temperature rise being generated during deformation and consequently, an iso-thermal simulation model being applied. The ECAP die and the plunger were considered as rigid elements, the workpiece alone having a plastic behavior.

All three objects in this simulation (the ECAP die, the plunger and the workpiece) were firstly designed in CATIA V5R19, being subsequently exported to DEFORM™ v.10.0, where the domains discretization and meshing was made using 50 points and 100 polygons for the ECAP die, 80 points and 156 polygons for the plunger and 4161 nodes and 3908 polygonal surfaces for the workpiece. The ECAP processing cycle was subdivided into 150 steps (intermediary deformation stages) and for each step a series of results regarding the effective stress and strain, force, normal pressure and other factors can be obtained, these results being crucial for the working tools design and manufacture and especially for ECAP process parameters evaluation and analysis.

3. Results and Discussions

All the results being presented for this model are based on the current configuration of the elements (ECAP die, plunger and workpiece) and on the described domain discretization and meshing system.

As the ECAP die does not allow for lateral expansion and there are no precipitous changes in the cross-sectional area of the billet, the deformation being performed just by simple shear at die channels intersection, the effective strain is insignificant; Fig. 2 showing results regarding the effective stress distribution within the workpiece.

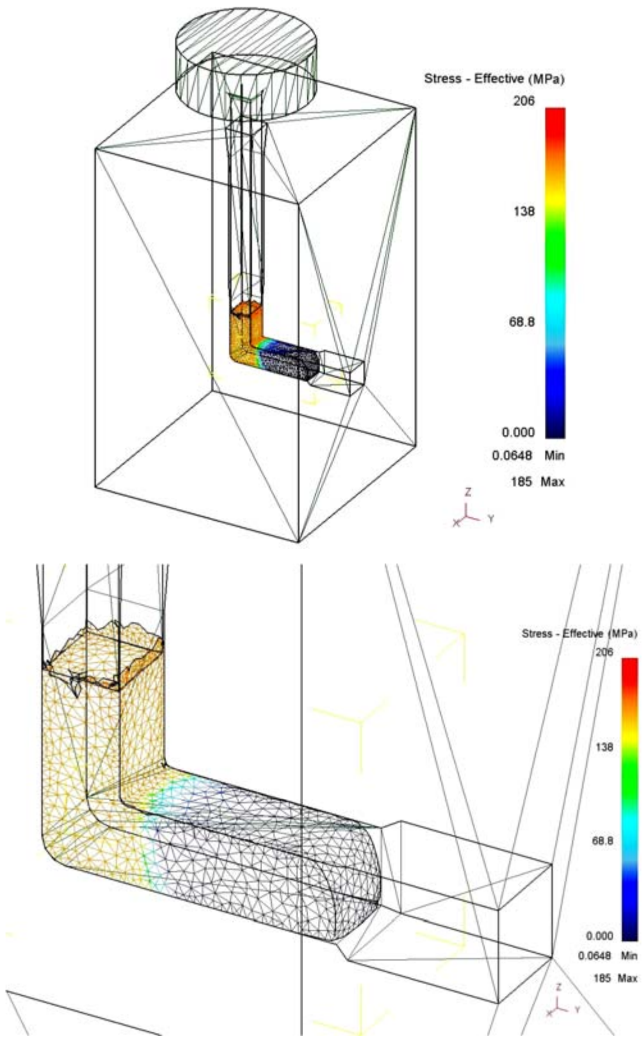
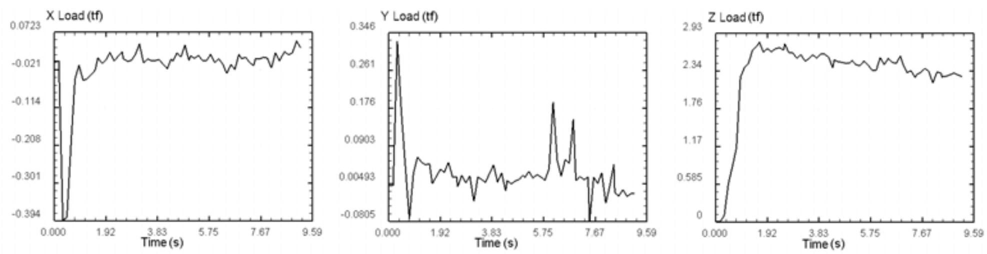


Fig. 2. Effective stress distribution within the Al 6063 workpiece (step 97)

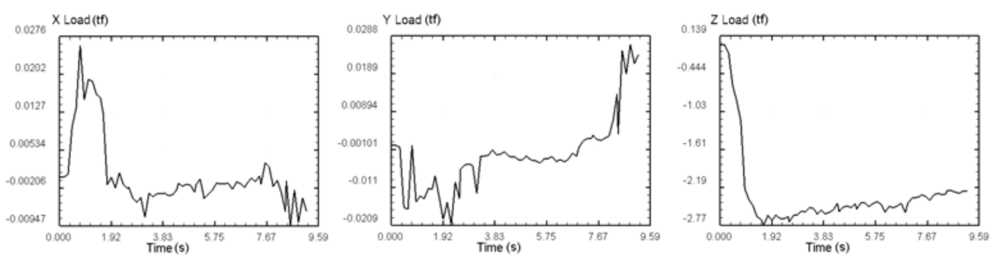
In Fig. 2, one can observe that the maximum recorded value for the effective stress within the Al 6063 billet is 206 MPa. Nevertheless, for more than 90% of all intermediary deformation stages, the maximum value estimated for this parameter was approximately 185 MPa. Fig. 2 shows the effective stress distribution within the workpiece for step number 97. Thereby, considering the specimen area through the theoretical shear plane and the maximum estimated value for the effective stress, the required ECAP pressing force can be evaluated as being approximately 30 kN (3 ton-force). Therefore, equipment and machinery which are readily available in most laboratories can be used for the designed

ECAP processing cycle, given the current configuration of the die, plunger and workpiece; even if the strain hardening behavior of the processed material is to be considered for a higher number of ECAP passes.

In order to predict the stress that the ECAP working tools will endure during the pressing process, the load versus time variation, in the X, Y and Z directions, was also estimated via computer simulation for the ECAP die and the plunger. The obtained results are shown in Fig. 3.



a.



b.

Fig. 3. Load prediction (load vs. time) in the X, Y and Z directions for:
a. the ECAP die; b. the plunger

As one can see in Fig. 3, the loadings in X and Y directions are very low (0.3-0.4 tf in the initial stage), the maximum loading being estimated, as expected, in the Z direction (the pressing direction), reaching a value of approximately 2.8 tf at the beginning of the ECAP process and decreasing gradually to about 2.3 tf at the end of the pressing process, as the material leaves the input channel and passes through the shear plane to the output channel. Also, one can observe that the variations estimated for the plunger are relatively similar, being approximately equal and opposite, with the predicted loadings for the ECAP die, in each of the three directions. These results are also consistent with the estimates made for the required pressing force and for the effective stress.

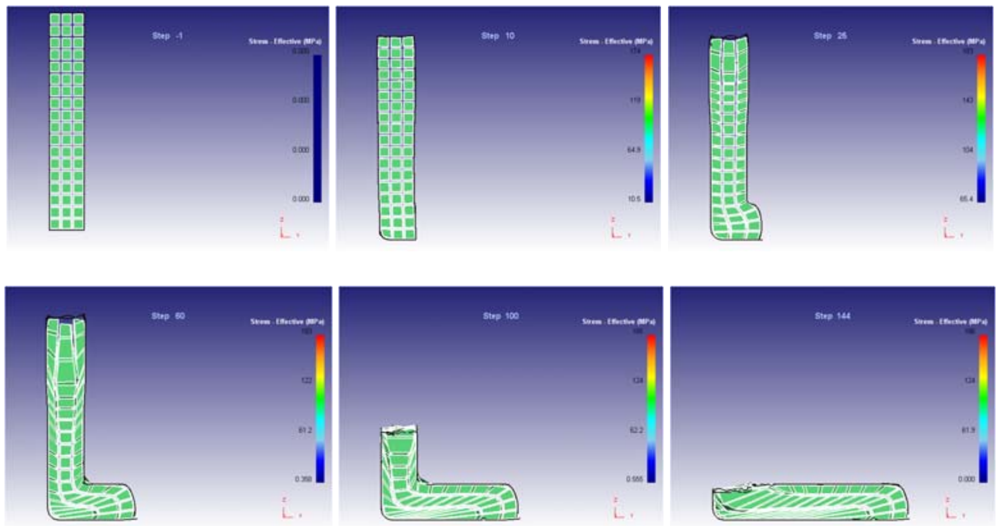


Fig. 4. Material flow characteristics for a single-pass ECAP processing cycle (computer simulation in DEFORM^{TM} v.10.0)

Present study included also an analysis of the material flow character during the first passage of the billet through the ECAP die, eloquent results being presented in Fig. 4. Rectangular meshing technique was used for subdividing the billet into squared elements. From this figure, one can observe that the material flow during ECAP processing is not uniform, mainly because of the effects of friction and of the shearing characteristics associated with the ECAP process. Thus, the material from the front end of the billet and the one passing near the inner corner of the die (the upper region of the processed billet) flows more easier than the material passing near the outward intersection corner (the bottom region of the processed billet), the elements in this area being the most distorted and so the deformation the most inhomogeneous. Also, as the initial rectangular elements are passing through the theoretical shear plane, they are becoming elongated and aligned with the shearing direction, Fig. 4 showing that the material deforms by simple shear at the intersection of the two channels.

4. Conclusions

In this study, a single-pass ECAP processing cycle applied to the 6063 aluminum alloy was modeled and simulated using the finite elements method in DEFORM^{TM} v.10.0. A series of results regarding the effective stress and strain, the required force, the loadings, the material flow and other parameters were obtained from this simulation. A maximum value for the effective stress within the Al 6063 billet of 206 MPa and a required ECAP pressing force of about 30 kN

(3 ton-force) were estimated, being found that the equipment and machinery which is readily available in most laboratories can be used for the designed ECAP processing cycle. The maximum loading was estimated for the pressing direction, of approximately 2.8 ton-force at the beginning of the deformation, this result being consistent with the estimates made for the required pressing force and for the effective stress. It was also found that the deformation occurs by simple shear at the intersection of the two channels of the die, the material flow during ECAP being not uniform and resulting in an inhomogeneous deformation, mainly in the bottom region of the processed billet. These results, obtained via FEM in DEFORM™ v.10.0 simulation software, are crucial for ECAP process analysis and also for the ECAP die-sets design and manufacture. The entire experimental setup was validated through this simulation; thus demonstrating its viability.

Acknowledgements

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