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Optimization of the Severe Plastic Deformation Processes for the Grain Refinement of Al6060 Alloy Using 3D FEM Analysis

E. López-Chipres, E. García-Sanchez, E. Ortiz-Cuellar, M.A.L. Hernandez-Rodriguez, and R. Colás

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An analysis in 3D by means of the finite element method was carried out to study three processes for producing bulk fine-grained materials: dual equal channel angular pressing (DECAP), equal channel angular pressing, and multi-axial forging. For this purpose, a commercial Al6060 alloy in solution heat treatment conditions was utilized. The effect of different values of the coefficients of friction (μ), the plastic flow, the strain hardening behavior, and the effective strain were analyzed. The results obtained from the simulation are in good agreement with the experimental studies. The results indicate that the DECAP process improves the plastic flow and promotes homogeneous strain distribution and grain refinement due to an increase in components of the shear deformation, back-pressure effect, and the diminution of the coefficient of friction.

Keywords aluminum alloys, finite element method, severe plastic deformation processes, ultrafine-grained microstructure

1. Introduction

Fine-grained materials have attracted considerable interest among researchers, due to the presence of a large amount of grain boundary area resulting in unusual and extraordinary changes in mechanical and physical properties. Numerous severe plastic deformation (SPD) methods have been proposed to produce fine-grained materials by introducing large plastic strains into bulk materials. Nowadays, the development of aluminum alloys with ultrafine-grained structure is of practical interest. This is explained by the fact that considerable lowering of the grain size gives several technological advantages raising the strength and impact toughness of materials at room temperature (Ref 1-3). The techniques of SPD are defined as metal-forming processes in which a very large plastic strain is imposed on a bulk process to make an ultrafine-grained metal. Some of the applications of these materials produced by these processes are in lightweight parts with high strength for safety and reliability components with less impact in the environment (Ref 4). In conventional metal-forming processes, such as rolling, forging, and extrusion, the imposed plastic strain is limited; due to the reduction of the thickness and diameter. In order to impose an extremely large strain on the bulk metal without changing the shape many SPD processes have been developed.

It has been reported that ultrafine-grained materials could be produced by SPD (Ref 5-8). Several special SPD methods such as equal channel angular pressing (ECAP) (Ref 8-11), high-pressure torsion (HPT) (Ref 12, 13), and mechanical milling (MM) (Ref 14-16) have succeeded in producing ultrafine-grained materials and accumulative roll bonding (ARB) had been used successfully to produce ultrafine grains in many large bulk materials (Ref 17, 18). Multi-axial forging (MAF) is another method to exert large strain on bulk materials and could be the most effective way (Ref 19).

This article proposes a method to produce bulk fine-grained alloys named dual equal channel angular pressing (DECAP), which is a modified ECAP processes. This processing method has the capability of introduce large amounts of plastic strain into bulk material in a relatively uniform manner without reduction in workpiece cross section. The processing concept is defined by the pressing of a block of material through a constant T-cross-section tunnel composed of two intersecting channels. The material undergoes double simple shear in a zone at the crossing plane of the channels. Because workpiece dimensions are nearly the same before and after processing, multiple extrusions of the workpiece are possible. With the rotation of the sample between each extrusion pass different microstructures can be developed. The microstructures produced by DECAP critically depend on a number of experimental factors, including the nature of the slip systems introduced during the pressing operation and the total strain imposed on the sample. DECAP is an effective tool for obtaining ultrafine grain sizes in bulk materials. However, study needs to be done regarding the processing method and the microstructure evolution mechanisms.

On the other hand, FEM simulations are important for understanding and predicting results of experimental studies. Meanwhile, experiments provide valuable data for improvement of physical and phenomenological models of materials to

E. López-Chipres, Facultad de Ciencias Quimicas, Universidad Juárez del Estado de Durango, Durango, Mexico; and **E. García-Sanchez, E. Ortiz-Cuellar, M.A.L. Hernandez-Rodriguez,** and **R. Colás**, Facultad de Ingenieria Mecánica y Eléctrica, Universidad Autónoma de Nuevo León, Monterrey, Mexico. Contact e-mail: egs7710@gmail.com.

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be used in calculations, the simulations can provide an opportunity to considerably reduce the number of required future experiments by optimizing the specimen shape/size, as well as, conditions to be provided by experimental installation (Ref 19, 20). Friction plays a very important role on the distribution of strain in SPD process. Researchers have used coefficients from μ = 0 to μ = 0.3 for various materials. In general, operating with a good lubrication conditions the friction coefficient for metals is between 0.05 and 0.1 (Ref 21). A range of 0.03 to 0.08 for cold aluminum extrusion under lubricated condition was used by Altan et al. (Ref 22).

The finite element software Deform 3D®, which has the capability to model nonlinear engineering simulations accurately and reliably, was used. In this study, the plastic deformation behavior of an Al6060 alloy in solution heat treatment conditions during the SPD processes of ECAP, MAF, and DECAP was simulated using FEM with the aim to study the strain distribution in the workpiece, the friction effect and to

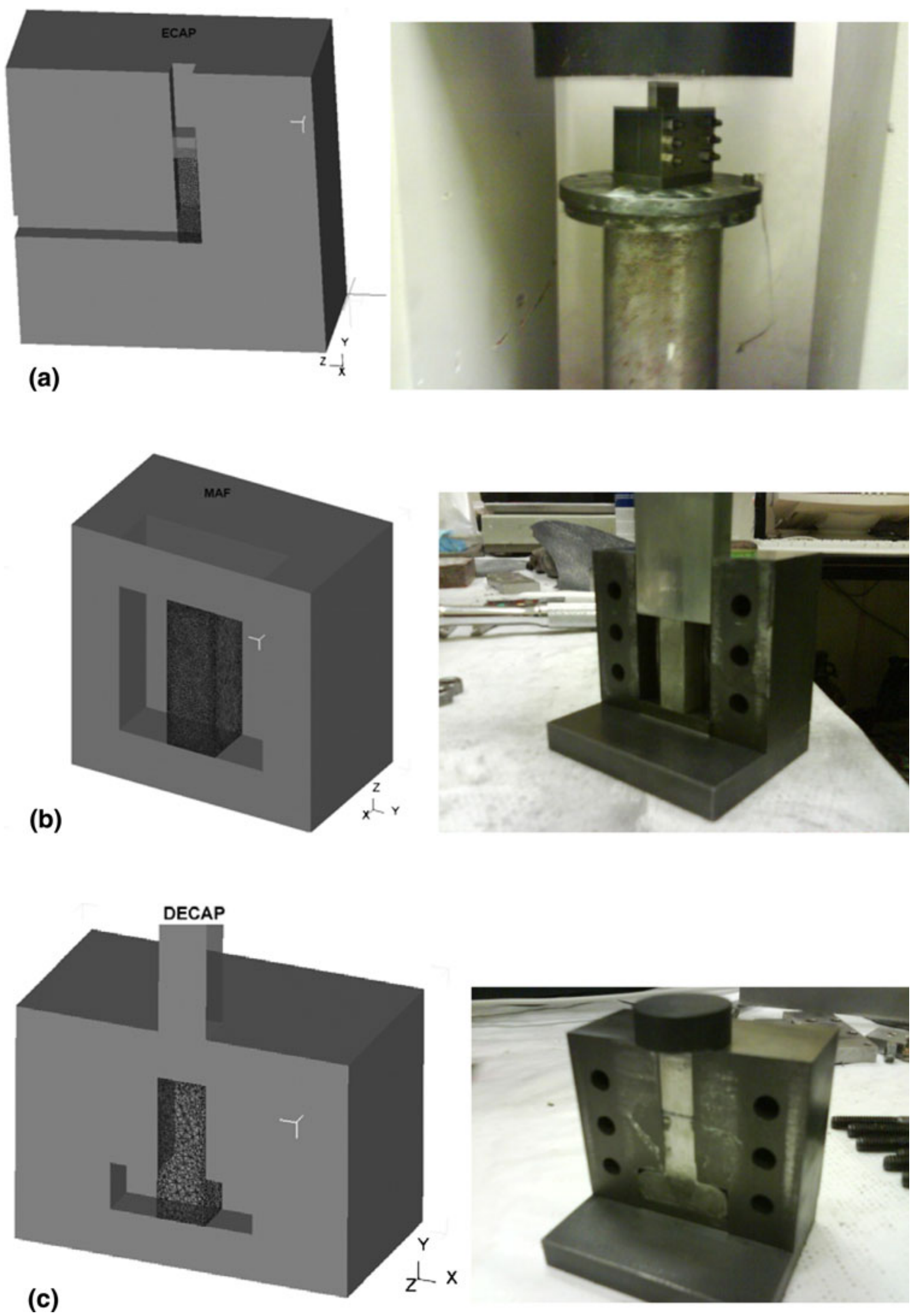

Fig. 1 Experimental dies and the workpiece mesh utilized for the SPD processes simulation; (a) ECAP, (b) MAF, and (c) DECAP. Sample size ($W \times H \times$ L) = 10 × 10 × 30 mm

obtain the conditions that promotes an improvement in the grain refinement to produce a bulk fine-grained Al6060 alloy.

2. Simulation Method

In this study, isothermal FEM simulations of the ECAP, MAF, and DECAP processes were carried out using the commercial finite element code DEFORM 3D™ (Version 6.01) (Ref 23), considering a three-dimensional model. According to experimental (Ref 24) and theoretical (Ref 25) analyses, the isothermal condition can be fulfilled at low pressing speeds. Heat generated due to deformation and friction was neglected. Figure 1 shows the initial mesh systems used in the workpiece of the simulations and the experimental dies. The workpiece in simulations was modeled with 11867 nodes and 53291 elements using tetrahedral elements. This number of elements was found to be sufficient to express local deformation of the strain rate insensitive workpieces through calculations adjusting the number of elements in DEFORM 3D™. In order to accommodate large strains and to take into account the occurrence of flow localization preventing further calculation during the simulation an automatic remeshing scheme was used for all simulations. It is assumed that the hardening behavior is isotropic and independent of strain rate. As the strength and rigidity of the steel die are high when compared to aluminum, the die was modeled as a rigid surface. The ECAP and DECAP nondeformable channel has a 90° angle and a zero mating radius, the cross-sectional area for the entrance channel was of 10×10 mm (see Fig. 1). The top surface of the workpiece was in contact with the punch, resulting in the movement of the workpiece. Previous simulations to evaluate the influence of pressing speeds in ECAP, MAF, and DECAP were investigated, for this purpose workpieces of Al6060 alloy were simulated at room temperature using pressing speeds of 0.24, 2.4, and 24 mm/s and together with the compressive tests results showed that the strain rate has no significant influence on the flow curves stress-strain, due to all simulations were carried out only at a constant punch speed of 2.4 mm/s. Table 1 presents the material parameters considered in the simulations. The coefficients of friction between the die and the workpiece were considered in three levels, 0, 0.5, and 0.1.

3. Experimental Procedure

Compressive tests were performed and the flow curves were used in the simulation. Figure 2 presents the flow curve of the material used in this study a commercial alloy Al6060 after a homogenization heat treatment. The dies considered for the experimental analysis were made of D2 steel. For the ECAP, MAF, and DECAP simulations and experimental analysis workpieces were machined into rectangle shapes with starting dimensions of $10 \times 10 \times 30$ mm; the samples were extruded and forged with loading direction as shown in Fig. 1. Prior to each extrusion pass, the channels were cleaned and coated with lubricant (graphite + oil). A ram speed of 20 mm/min at room temperature was used to carried out the experimental extrusion and forging. The effective strain (Von-Mises strain) achieved in each pass of extrusion and forging was about 1.2 in. agreement with values reported (Ref 6, 10). The microstructural analysis was performed in a TEM-Jeol 2010 in sections parallel to the extrusion axis. Disks with a diameter of 3 mm were punched out from small slides thinned mechanically of deformed Al6060. The disks were thinned by an electropolishing method.

Table 1 Material parameters* used in the simulation (23)

Mechanical behavior of 6060 alloy	Compressive Tests (flow curve)
Temperature (isothermal)	293 K
Young's modulus	68947 MPa
Poisson's ratio	0.3

* Flow curves (Fig. 2) considered as input in the simulation for obtain other mechanical properties.

4. Results and Discussion

The influence of the SPD (ECAP, MAF, and DECAP) processes on distribution of the strain, friction on material flow, forging, and extrusion pressure required for grain refinement in Al6060 alloy is discussed based on the results obtained from the mathematical simulation and experimental results. Figure 3 shows FEM predictions of the effective strain distribution during ECAP (a), MAF (b), and DECAP (c) after one pass and $\mu = 0.05$. The following observations are made from Fig. 3: (i) large corner gap occurring in strain hardening materials due to differences in stress and flow velocity between inside and outside regions, (ii) less sheared bottom zone due to a round corner angle or the corner gap, (iii) transient regions at the end of the samples appeared, and (iv) average strain in the middle steady region that presents the theoretical value of 1.2. The shear angle in the central region of ECAP deformed sample is 45° (see Fig. 3a), which is comparable to theoretical values (Ref 10). The FEM results show that the shear angle and the average strain values are slightly higher than the theoretical values; these could be attributed to the sheared zone in the bottom region due to the corner gap formation and the friction

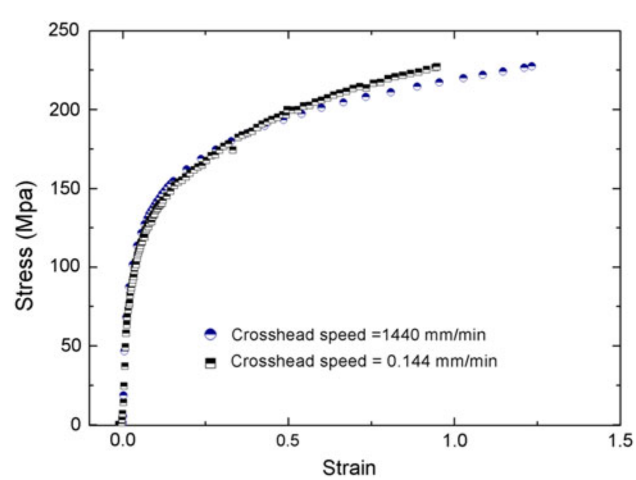

Fig. 2 Stress-strain curves of Al6060 at solutionized and homogenized heat treatment conditions

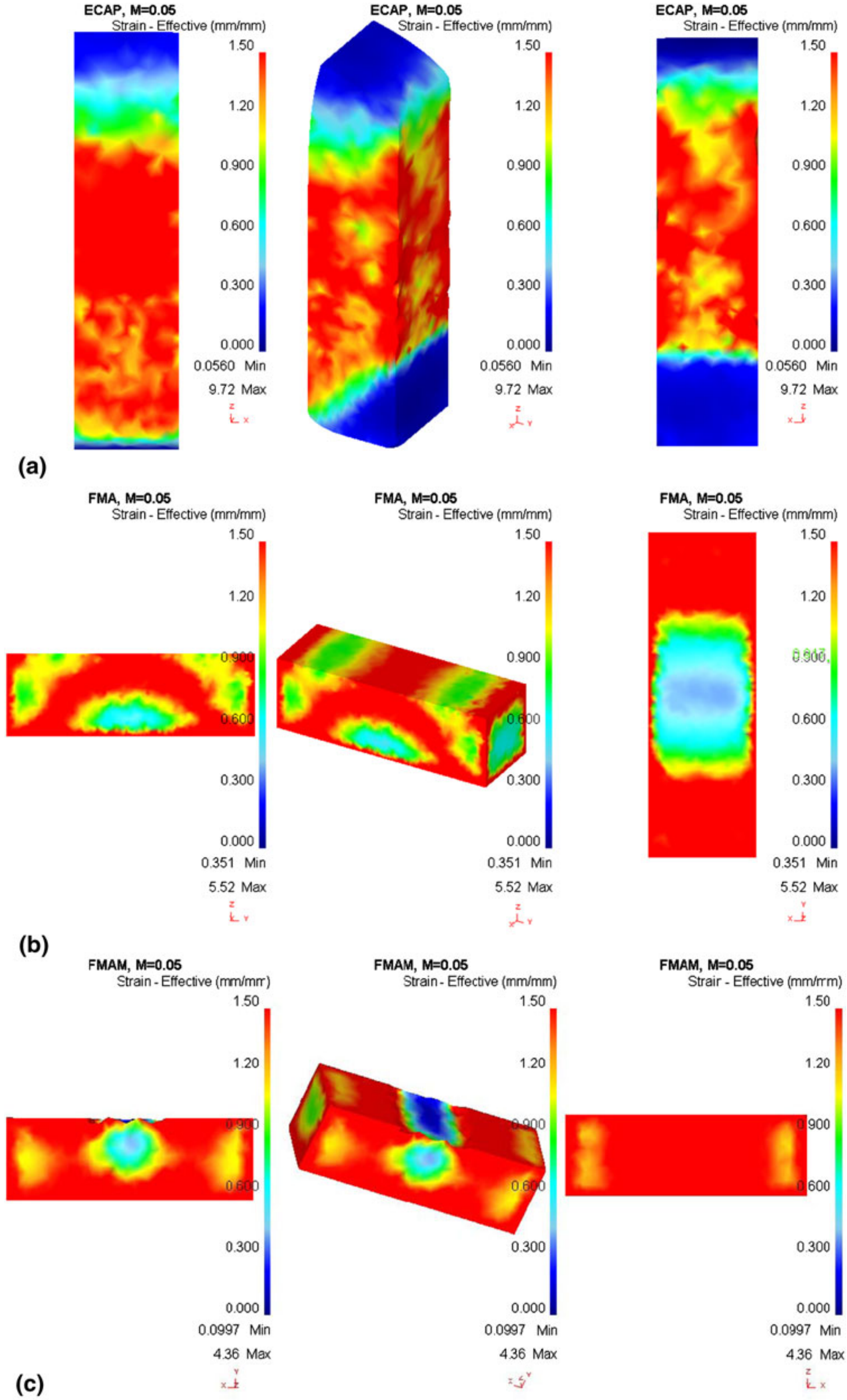

Fig. 3 FEM predictions of the effective strain distribution during ECAP (a), MAF (b), and DECAP (c) after one pass and a friction coefficient of 0.05

effect. The main difference in strain development is in the bottom regions. The deformation characteristics of the central section of the sample are different than the outer; the strain values remain almost without change along pressing direction. Hence, more homogeneous strain and microstructure can be achieved in the MAF and DECAP processes with the reduction

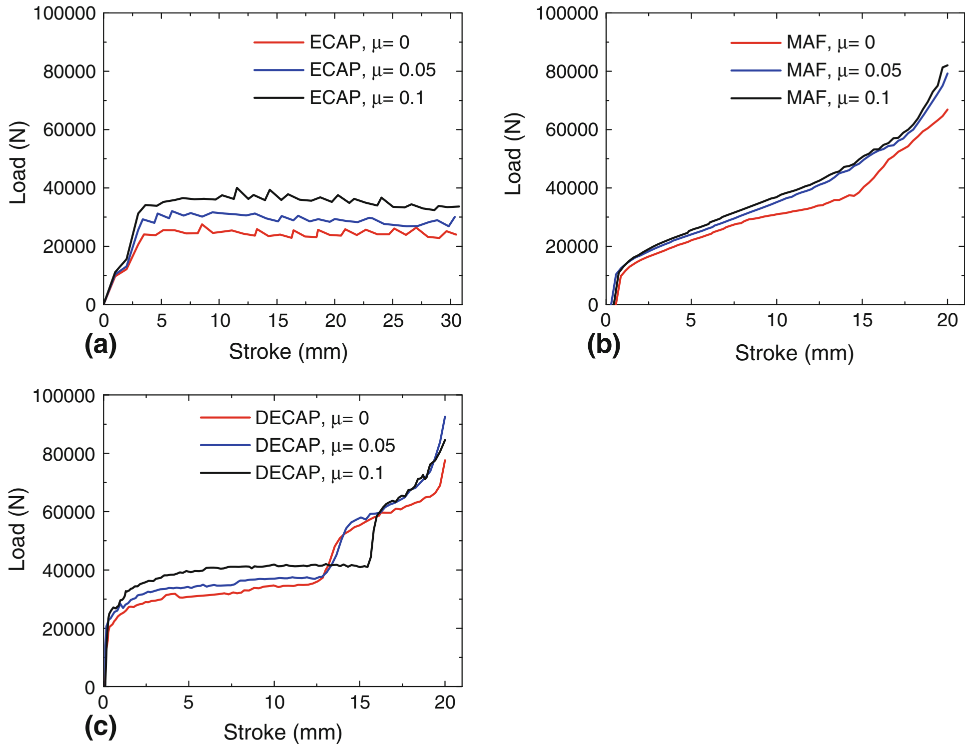

Fig. 4 Load versus stroke curves as a function of the friction coefficient for the ECAP, MAF, and DECAP processes

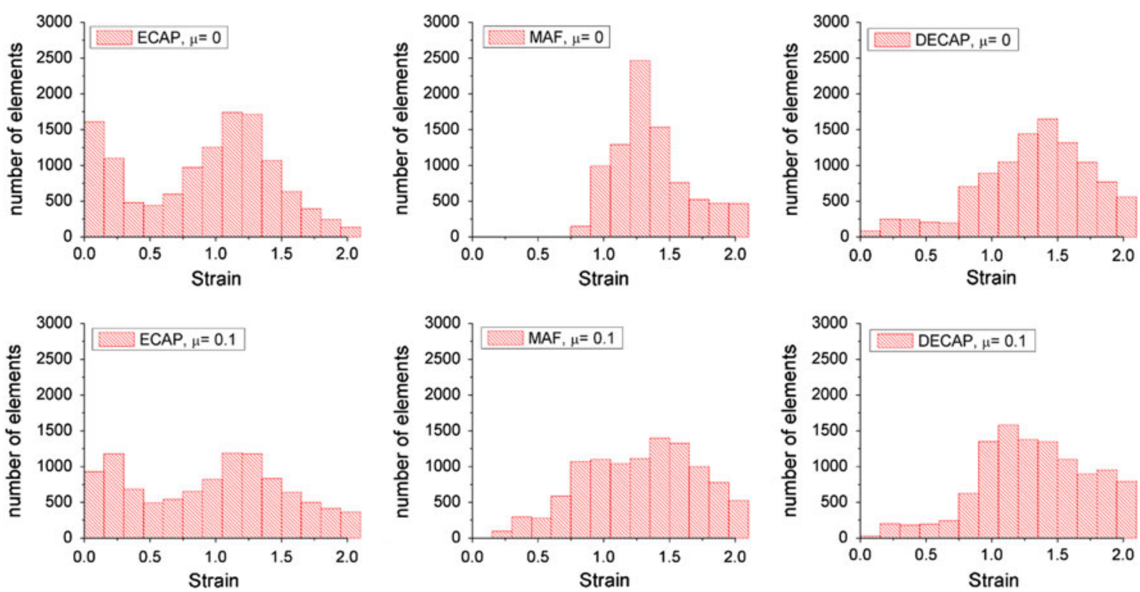

Fig. 5 Strain distribution curves as a function of the coefficient of friction

of the coefficient of friction. Likewise, the minimum (ε_{min}) and the maximum (ε_{max}) effective strain values are (0.9, 1.2), (1.3, 1.4), and (1.4, 1.5) after the first pass in ECAP, MAF, and DECAP, respectively. The results of the simulation in ECAP reveal that the deformation in the central steady region is uniform and at the end region is inhomogeneous when compared with MAF and DECAP in which the deformation in the central steady region is localized. The friction has an important role on material flow for all the SPD processes studied. The analysis of material element deformation histories along flow lines reveals that ECAP could be a combination of shearing and stretching (i.e., tension and/or compression). Also the friction and dies geometry affect the strain distribution.

4.1 Material Flow

Figure 4 shows the load-displacement curves for different values of coefficient of friction utilized in ECAP, MAF, and DECAP processes. From this figure, it is possible to observe that the load increases with the friction (0-0.1), and the highest

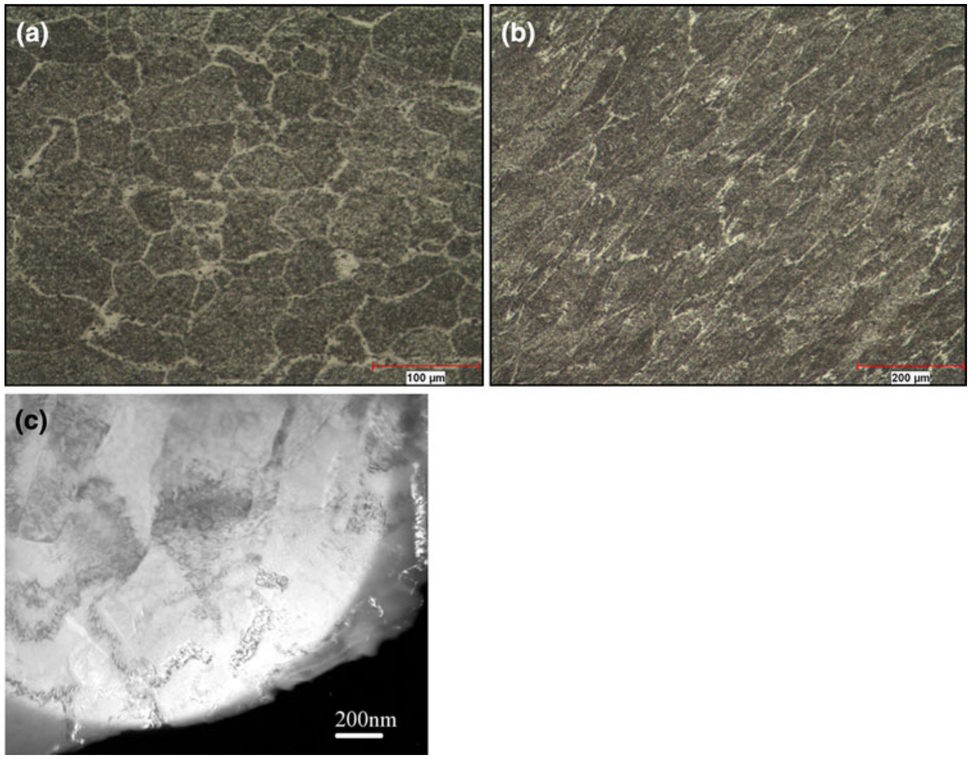

Fig. 6 Al6060 microstructures, (a) at solutionized and homogenized heat treatment conditions, (b) one pass with DECAP and (c) after 2-pass with DECAP at room temperature

load values are observed in the DECAP process (Fig. 4d). This is due to the continuous increase in the contact between workpiece and die in the exit channel, which leads to a frictional drag. Initially, a corner gap is present for the ECAP case and as the process continues the corner gap is filled completely for high friction conditions but only partially for the low friction conditions. For frictionless condition, the initial corner gap remains unchanged. Also, the plastic deformation zone is wide for frictionless condition and narrow when the friction increases. It can be concluded that the nonhomogeneity decreases with the increase in the friction until the backpressure effect (exerted by frictional drag in the exit channel) is enough to fill the corner gap.

A round inner corner angle (ICA) induces highly inhomogeneous deformation in the sides of the workpiece due to the decreases in the shear deformation components and the increase in the compressive components. For the sharp ICA case ($\Psi_i = 0°$), the deformation shows the typical behavior of strain hardening materials, including corner gap formation due to strain hardening of the workpiece material, transient zones, and relatively uniform shear deformation along the thickness direction due to the balance between the corner gap and the friction effects. Transient regions of the ends of the sample receive only small amounts of strain. In the case of MAF and DECAP, a further increase in friction leads to an diminution in the homogeneity, which could be analyzed in terms of the effective strain distributions showed in Fig. 5.

Figure 6 shows the Al6060 microstructures, (a) at homogenized heat treatment conditions, (b) one pass DECAP and (c) after 2-pass of DECAP at room temperature. Also new small grains were formed after a double DECAP pass deformation (Fig. 6c) with intense double simple shear deformation promoting subgrain formation and evolution. The mean grain size decreased with the increase in the cumulative strain and also new grains were formed after two passes. The initial grain structure disappeared and the microstructure consisted of equiaxed and deformed grains. Although new grains mostly replaced the original grains, some grains were almost free of crystal defects and some were severely distorted, especially near to the grain boundaries. These results indicate that the fine-grained microstructures could be produced by DECAP at room temperature, and the new grains are promoted by the large stored energy and the large dislocation density during the deformation process (see Fig. 6c). It is clear that the changes in grain size during deformation strongly depend on the cumulative strain, and the grains are elongated after the first pass, and refined after two passes, observing a grain size of about 1 µm. Although no strain softening appeared at high strain, the deformation was still able to produce new fined-grains, which suggested that other microstructure evolution mechanism might take place during the deformation. The experimental results suggested that grain subdivision was the mechanism of the structural evolution. The initial deformation led to the formation of dislocation substructures such as cells and dense dislocation walls (DDWs). Subdividing the grains into several blocks, the DDWs are generally called subgrain boundaries. Under repetitive deformation with changing compression axis at the DECAP process, the DDWs were developed in various directions, in this way the initial grains were broken up into several subgrains (Ref 26-28). The width of elongated subgrains was about 0.2-3 µm which demonstrates that fine-grained materials can be produced by DECAP process. The DECAP process is an efficient method for producing a bulk fine-grained material, since the material can be continuously deformed in the T-shaped channel and removed out of the die.

5. Conclusions

A three-dimensional finite element analysis and experimental tests for the ECAP, MAF, and DECAP processes were carried out for one and two passes and different values of coefficient of friction to understand its influence on material flow, extrusion and forging pressure and strain distribution for isotropic strain hardening Al6060 alloy.

The results indicated that the friction has a very important role in all the processes studied. In the ECAP processes as the friction increases, the corner gap decreases due to the material drag effect; also, the average strain increases with friction due to the corner gap. The non-homogeneity in strain distribution decreases with the increase in the friction until the back-pressure effect is sufficient to fill the corner gap; further increase in friction leads to decrease in homogeneity. The round ECAP ICA induces highly inhomogeneous deformation near to the borders of the workpiece. Likewise, the results reveal that the deformation at MAF and DECAP in the central steady region of the samples are nonuniform (localized) and homogeneous at the ends regions. Following from the above, DECAP process is an efficient method to produce bulk fine-grained materials because the materials can be repeatedly deformed in a T-shaped channel and removed out the die directly. The bulk fine-grained Al6060 alloy was successfully produced by DECAP process. The grain size of the samples is near to 3 μm after extruded at room temperature. The grain structure is more equiaxed with the increase in the number of extrusion passes.

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