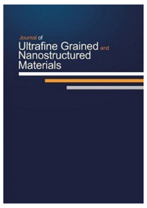

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Grain Refinement Efficiency of Multi-Axial Incremental Forging and Shearing: A Crystal Plasticity Analysis

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ABSTRACT

Severe plastic deformation is a technical method to produce functional material with special properties such as high strength and specific physical properties. Selection of an efficient severe plastic deformation for grain refinement is a challenging field of study and using a modeling technique to predict the refinement efficiency has gained a lot of attentions. A comparative study was carried out on the grain refinement ability of two severe plastic deformation techniques. Accordingly, beta-tin samples were processed for almost the same strain level by the equal channel angular extrusion (ECAE) and the newly developed multi-axial incremental forging and shearing (MAIFS). Optical microscope and tensile tests were used to investigate the microstructure and mechanical properties. It was found that the MAIFS process is more efficient in grain refinement than ECAE by help of crystal plasticity analysis and experimental observation. This was ascribed to the more activated slip systems in MAIFS than ECAE and activation of secondary modes of deformation in MAIFS. The conclusion was supported by the finer grains that was observed in the sample processed by MAIFS and compared with grain size of the sample processed by ECAE. Finally, these observations were related to materials flow for beta-Tin during tensile test.

Keywords: *Crystal Plasticity; Grain Refinement; Severe Plastic Deformation; Texture; VPSC.*

1. Introduction

Nowadays, severe plastic deformation (SPD) processes become popular due to their ability to produce materials with special mechanical and physical properties [1]. SPD is referred to the processes in which large strains are imposed on the material while at the same time, in most cases, restrain the sample shape change. The most dominant effect of these processes is the refinement of the material's microstructure toward fine and ultra-fined grain structures [2]. This microstructure refinement dominantly determines all mechanical and physical behavior of the processed material. Introduction of the SPD processes could be mentioned as one of the most revolutionary steps in study of ultra-fined structured materials because of its effectiveness on the microstructure refining of bulk materials and its ease of implementation compared to other counterpart processes. However, more studies in this field are still vital to understand the mechanisms behind microstructural evolution. This understanding helps to determine the best material, process and controlling parameters to increase grain refinement efficiency [3].

Equal channel angular extrusion (ECAE) is one of the earliest methods introduced by Segal [4] for SPD and bulk grain refinement. From then on, a lot of studies have been conducted to reveal more about microstructural evolution mechanisms in this process and to connect evolved microstructure to observed mechanical and physical properties [5]. Grain refinement phenomenon in ECAE has been extensively studied experimentally and theoretically, especially for Face Centered Cubic (FCC) materials. It has been also modeled to understand the related mechanisms. Several review papers have been dedicated to this issue in the literature [2][6][7]. It is not clearly obvious what related mechanisms are responsible for grain refinement. Several modeling and experimental investigations were dedicated to give an answer to the problem of how different strain passes in different ECAE routes caused different grain refinement efficiency. Furukawa et al. [8] suggested that the efficiency of grain refinement is the highest for route B of the die angle of 90° based on characteristics of macroscopic shear deformation of a cubic element in ECAE. While this conclusion was in good agreement with experimental results for high purity aluminum [9], their model predictions were not in accordance with the experimental ECAE of aluminum alloys using die angle [10]. Some theories such as the intersection of shear planes [9][11] also show the same deficiency in explanation of optimum route for. Gholinia et al. [10] could explain the reverse grain refinement efficiencies for; however, they couldn't explain grain refinement efficiency for. The controversies among these theories were solved by Zhu and Lowe [12]. They incorporated crystallographic structure in their modeling and therefore they could explain the optimum route for grain refinement for different die angles. However; as argued by Saiyi Li [13], they assumed that {1 1 1} planes of grains should be aligned between the macroscopic shear direction and grain elongation direction. This assumption was in contrary to experimental observation [14-16]. Saiyi Li [13]used this idea to model grain refining efficiency based on crystal plasticity analysis and he could explain grain refining efficiency for strain path variations based on the number of favorable activated slip systems.

As it was indicated before, in order to give a good and acceptable explanation for grain refinement in SPD processes, it is important to apply crystal plasticity concepts in the investigations. This paper is going to compare the grain refining efficiency of ECAE with newly developed severe plastic deformation, Multi-axial Incremental Forging and Shearing (MAIFS) [17][18], based on the idea of the activation of slip systems. A brief description of MAIFS and ECAE processes is brought in Figure 1. As it is presented by Figure 1,

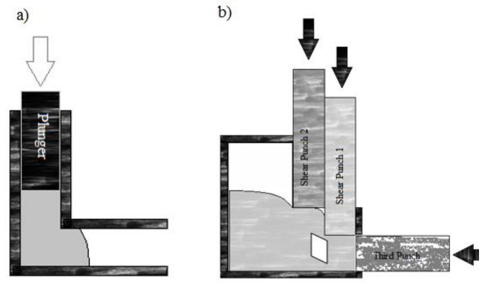

Fig. 1- a) The ECAE process. A plunger extrude material through the L-shape channel and b) The MAIFS process. The material is back extruded by first and second punch to the final channel and final product is produced by the third punch in a non-equal angular pressing fashion.

the material is back extruded by first and second punch to the final channel and the final product is produced by a third punch by non-equal angular pressing. Theoretically, this process imposes two approximate simple shear deformations on the material where the shear planes are perpendicular to each other. One simple shear deformation can be assumed between two shear punches as shown in the Figure 1 and the other simple shear deformation occurs during final angular extrusion by the third punch. Material which subjects to such complex deformation history has the opportunity for grain refinement during the process.

In this paper, after comparing the resulted mechanical behavior and microstructural features of Beta-Tin subjected to both processes, the experimental results will be discussed and analyzed by help of crystal plasticity.

2. Experimental Procedure

To compare grain refining efficiency in ECAE and MAIFS, two processes were conducted on the beta-tin samples with similar deformation conditions. Beta-tin samples were separately processed by one pass of MAIFS and two passes of ECAE route A, in order to ensure the same level of imposed strain on the samples. The processed samples geometries are shown in Figure 2.

After MAIFS and ECAE processing of samples, they were carefully cut in x-y mid-plane sections, grounded, and polished at the presence of cold water stream to keep samples cold and wash the debris to prevent scratching of the surface. The samples

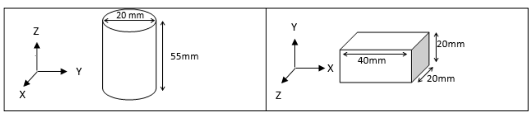

Fig. 2- The geometries of the processed samples by ECAE (left) and MAIFS (right)

were then etched by 2 ml HCl, 5 ml HNO3, 93 ml methanol solution [19] to reveal the microstructure for the analysis of optical microscopy.

To further investigate the impact of two processing methods on material's behavior, tensile tests were carried out. Figure 3 shows the schematic presentation of tensile specimen that was cut from the mid-plane of samples. Due to the plane strain nature of the deformation in the both processes, all the tensile samples are prepared in shear plane of the deformation along the deformation path.

3. Crystal Plasticity Modeling

To interpret the experimental observation and evolutions of different microstructures in the samples, crystal plasticity analysis was utilized. One essential part of crystal plasticity modeling is the calculation of actual deformation history.

In this work, deformation history for samples subjected to MAIFS process were calculated with the help of scribed grid on specimen in course of the deformation in equal time increments for each steps of MAIFS deformation. Initial and final state of specimen is shown in Figure 4 (because no analytical formulation has been put forward yet for the MAIFS process). The detail of calculation process can be found in another research paper [17].

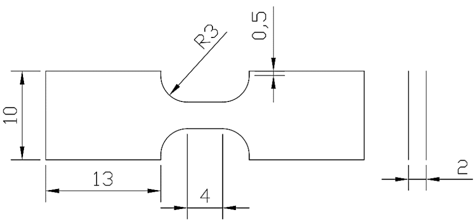

Fig. 3- Schematic presentation of tensile specimen (all dimensions are in mm).

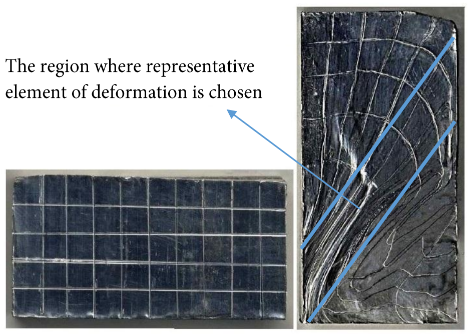

Fig. 4- Scribed grid in undeformed state (left) and deformed state (right).

The deformation history can be calculated based on continuum mechanics theories for every time step using velocity gradient [20]:

$$L_{ij} = \frac{\partial v_i}{\partial x_j} \quad (1)$$

Where is velocity and is coordinate for every material point. To approximate this equation, differences can be used in place of differentiations. This would lead to equation (2) that is more convenient in essence of numerical calculation and present experimental methodology:

$$L_{ij} \cong \frac{\Delta v_i}{\Delta x_j} \quad (2)$$

This equation leads to a two dimensional velocity gradient tensor in our case (plane strain). This tensor is illustrated by equation (3):

$$[L_{ij}] = \begin{pmatrix} L_{xx} & L_{xy} \\ L_{yx} & L_{yy} \end{pmatrix} = \begin{pmatrix} \frac{\Delta v_x}{\Delta x} & \frac{\Delta v_x}{\Delta y} \\ \frac{\Delta v_y}{\Delta x} & \frac{\Delta v_y}{\Delta y} \end{pmatrix} \quad (3)$$

For ECAE, the deformation was analytically modeled by using velocity gradient tensor [21]:

$$L = \frac{\dot{\gamma}}{2}\begin{bmatrix} 1 & -1 & 0 \\ 1 & -1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (4)$$

Where $\dot{\gamma}$ is engineering shear rate. The symmetric part of these velocity gradient tensor, named deformation rate tensor D_{ij} may be used to calculate the instantaneous strain rate in every time increment. Equation (5) presents this tensor. Equation (6) also can be employed to calculate the effective strain rate in every time step.

$$[D_{ij}] = \frac{1}{2}\left([L_{ij}] + [L_{ij}]^T\right) = \begin{pmatrix} L_{xx} & \frac{1}{2}(L_{xy} + L_{yx}) \\ \frac{1}{2}(L_{xy} + L_{yx}) & L_{yy} \end{pmatrix} \quad (5)$$

$$\dot{\varepsilon}_{eff} = \frac{2}{3}\sqrt{\frac{3}{2}\left(D_{xx}^2 + D_{yy}^2\right) + 3D_{xy}^2} \quad (6)$$

In equation (6) it is assumed that. This assumption is reasonable because of incremental nature of the methodology. The deformation histories presented by eqs. (3) and (4) could be used directly as an input for visco-plastic self-consistent (VPSC) method [22]. Initial random texture with 500 grain orientations were used to model texture evolution. Grain Fragmentation and grain co-rotation schemes [3] were used to capture grain refinement effects on texture evolution. The secant interaction type was used to model grain interaction with homogenous medium. Tetragonal single crystal with Voce hardening type was used. However, no self or latent hardening behavior was assumed. This assumption is reasonable since the aim of this paper is to compare the two processes and as far as the same material behavior is used for the two processes, the results are reliable for the purpose of the comparison. Single crystal data are summarized in Table 1.

4. Results and Discussion

Figure 5 shows optical microstructures of material processed in two processes. These pictures represent that in MAIFS, the grain refinement is more severe than in ECAE. Figure 5 also shows that the grain distribution in MAIFS is more uniform and monotonous compared to ECAE. Microstructure in ECAE has a bimodal grain size that shows the occurrence of incomplete dynamic recrystallization while a full equiaxed grains are evolved in sample processed by one pass of MAIFS.

Figure 6 compares flow curves of samples cut from work pieces processed by ECAE and MAIFS. The flow curves show constant hardening after yielding until the onset of necking. This type of hardening suggests that multi mechanisms of restoration phenomena such as dynamic recrystallization are responsible for the observed flattening of flow curve during the tensile testing. Actually, the curve shapes show the possibility of grain boundary sliding which was reported during creep indentation experiment for this alloy [23]. This statement may be supported by the fine grain sizes produced by the imposed severe plastic deformation, high temperature and moderate strain rate on the tin alloy during experiments.

By examination of tensile curves in Figure 6, it could be easily understood that the material processed by ECAE has higher flow stress compared to the material processed by MAIFS. This behavior could be readily explained by finer grain sizes in MAIFS product compared to ECAE product considering that grain boundary sliding could be the main mechanism of deformation in the tensile tests.

The strain analysis of MAIFS [17] and ECAE [11] show that two passes of ECAE impose higher strain compared to one pass of MAIFS (equivalent strain in ECAE is 2.3 [11]while it is approximately 1.5 after one pass of MAIFS). This statement rises a big question in mind that how MAIFS could produce a finer and more homogenous grain sizes compared to ECAE. To answer this question, the crystal plasticity analysis based on VPSC algorithm was used in this study.

To understand how microstructural features and mechanical properties evolve after deformation, it is essential to investigate the texture evolution. Figure 7 shows evolving of texture during MAIFS and ECAE processes after the first pass. Although, the deformation history and shape of deformed grid in Figure 4 indicates that in MAIFS process, some components of simple shear exist; however, the texture evolution in Figure 7 shows that in the MAIFS process texture components other than simple shear are also activated. This deviation from simple shear is due to the high value of compression and tension components that naturally exist in MAIFS process.

In MAIFS pole figure, big rotation in simple shear component in comparison to ECAE process could be seen. The maximum intensity of texture in

Table 1- Beta Tin single crystal mechanical properties [24].

Slip System	Slip plane and slip direction		Critical resolved shear stress (MPa)
1	{1 1 0}	<-1 1 1>	0.13
2	{1 1 0}	<0 0 1>	0.13
3	{1 0 0}	<0 1 0>	0.15
4	{1 1 0}	<-1 1 0>	0.16
5	{1 2 1}	<-1 0 1>	0.17

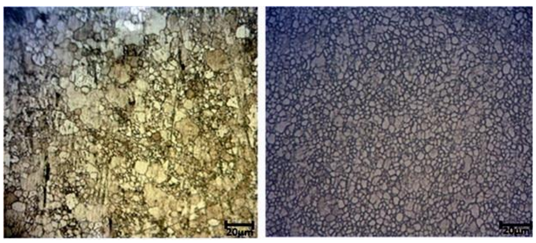

Fig. 5- Optical microstructure after two passes of ECAE (left) and one pass of MAIFS (right).

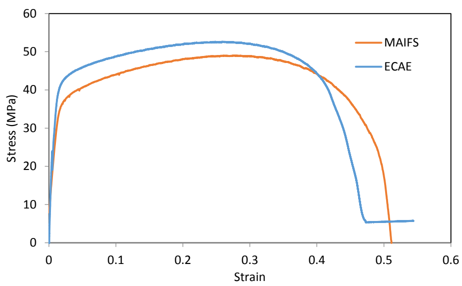

Fig. 6- Flow curves of samples processed by ECAE and MAIFS.

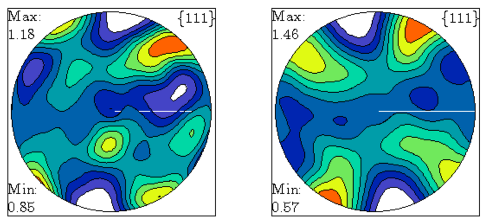

Fig. 7- Simulated texture in MAIS process (left) and simple shear process (right).

MAIFS process is lower than simple shear process texture intensity, despite the larger strain that is imposed in MAIFS process in comparison to one pass of ECAE. Observed behavior in MAIFS process can be related to two different shear deformations that are normal to each other: one between two shear punches and another one for the final non-equal angular pressing. This observation means that grain orientations tend to be more random after one pass of MAIFS compared to simple shear. This randomness of orientations brings this idea to mind that more slip systems are activated in MAIFS process because of more complex deformation history.

In order to understand how slip systems are activated throughout two processes, average slip system activated during one pass of MAIFS and two passes of ECAE was plotted in Figure 8. This figure shows that more slip systems activate in MAIFS process. It also shows descending trend of slip plane activation for ECAE while this trend for MAIFS tends to be ascending by increasing of the imposed strain. This feature indicates that in MAIFS different new slip systems besides previous ones would be activated, while for ECAE, deformation would only proceed with five constant slip systems. More activated new slip systems mean more grain refinement in MAIFS process compared to ECAE according to Li [13]. This shows one of the most important features of MAIFS compared to simple shear-like processes such as ECAE.

The other important features of MAIFS process are shown in Figure 9. In this figure, fractions of each activated mode of deformation are plotted for the two processes. This shows that in MAIFS process compared to ECAE, slip modes other than primary slip systems become activated. Activation of more slip systems also helps more efficiency in grain refinement and rationally explains extra component of texture.

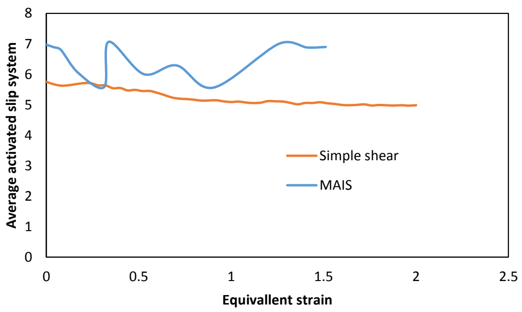

Fig. 8- Average slip system activated in MAIFS and simple shear processes.

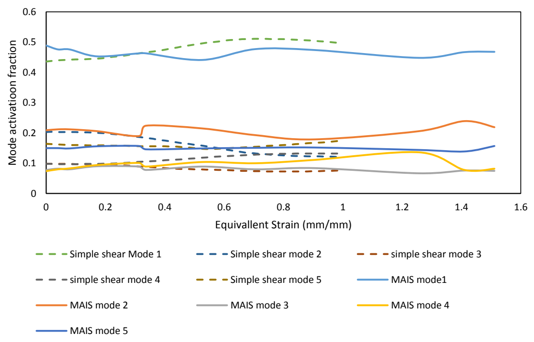

Fig. 9- Fractions of each slip mode activation during MAIS and simple shear.

5. Conclusion

In this study, crystal plasticity analysis was used to explain the microstructural evolution and mechanical properties variations in specimens experimentally processed by two SPD processes of ECAE and MAIFS. The following conclusions can be drawn from this work:

1. Specimen processed by one pass of MAIFS has finer and more homogenous grains compared to specimen processed by two passes of ECAE despite higher strain values imposed by two passes of ECAE and this was explained by activation for slip systems in the MAIFS process based on the crystal plasticity analysis.

2. Tensile tests show that specimen processed by ECAE has higher flow stress in comparison to specimen processed by MAIFS. This observation was explained by finer grain sizes in MAIFS specimen and the deformation based on grain boundary sliding during the tensile test.

3. The Crystal plasticity analysis also shows that more secondary slip systems would be activated in MAIFS and this could lead to more grain refinement in MAIFS compared to ECAE.

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