Simulation of the Microstructural Evolution of AA6061 in Equal Channel Angular Pressing Using Monte Carlo Method

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1- Introduction

Recrystallization takes place due to energy storage from homogeneous deformation. Non-uniform strain field in a deformed sample due to sample geometry and inhomogeneous deformation leads to non-uniform grain size distribution. A great number of modelling studies have been carried out to simulate the equal channel angular pressing (ECAP) of aluminum alloys and annealing process of deformed alloy samples. However, very few studies in the literature have focused on modeling the microstructure evolution of ECAPed aluminum alloy sample during annealing. This work has been undertaken to simulate the annealing kinetics of ECAPed AA6061 using Mont-Carlo method to predict the grain size distribution after annealing. It is noted that the predicted strain distribution in the ECAPed aluminum alloy sample under various conditions was used as input data for the annealing kinetics model.

2- Numerical Model

The stress-strain distribution in the ECAPed AA6061 sample was predicted by 3D FEM using ABAQUS software. The output of the FEM model was then used in the Mont-Carlo model to simulate the microstructure evolution during annealing of the ECAPed aluminum alloy. The stored energy in the cross section of the ECAPed sample was calculated according to Eq. 1.

$$H = \frac{2\gamma}{D} \quad (1)$$

where D is the sub-grain size and γ the energy per unit area of the sub-grain boundary which is assumed to be 0.5 J/m^2 in this study. The sub-grain size is estimated based on Eq. 2.

$$D(m) = \left(3.5 + \frac{1.7}{\bar{\varepsilon}}\right) \times 10^{-7} \quad (2)$$

A 2D Mont-Carlo method was adopted to simulate the annealing kinetics. A domain with 100×100 grids was chosen in which a random number was allocated to each node in the domain named as $S_i \in <1,48>$ representing the orientation of the site in a grain.

Those sites encircled by other sites of the same orientation were then considered as grain inner area. The grain boundary is mapped in the neighboring sites that have different point of reference. The microstructure evolution in the model is considered as the re-orientation of each randomly selected site to the new random orientation of one of its nearest neighbors that is tracked by investigating the lattice site energy changes namely the grain boundary energy and stored energy.

3- Results and Discussion

Strain variations in the ECAped sample pressed in a die with die angle of 90° in the AB line direction is shown in Fig. 1. Strain decreases from A to B along the line AB which is due to flow velocity difference in the sample cross section which is in agreement with the work done by Iwahashi. The two pass strain–displacement graph of ECAP (at both die angles of 90° and 120°) were introduced as input data into the Mont-Carlo model to simulate recrystallization kinetics and the grain refinement process.

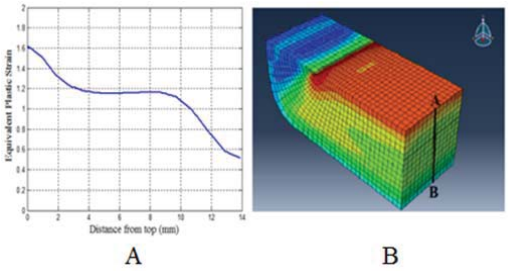

Fig. 1 Strain distribution in AB direction of ECAPed sample

The microstructural evolution of the sample ECAPed in the die with 90° die angle and annealed at 623°C is shown in Fig. 2-a to 2-d. The annealed grains begin to grow separately in the initial stages and then recrystallized grain coalescence happens in the intermediate stage of heating. After recrystallization is complete, grain growth takes place at a relatively low rate. It should be mentioned that the deformed grains were surrounded by recrystallized grains during the annealing process. This is called entrapment of grains. Fig. 3 illustrates the final microstructure in the ECAPed samples

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obtained during annealing process. The final grain size achieved for dies with an angle of 90° and 120° are 2.74 and 4.92 μm, respectively. However, the nucleus density approaches zero at the final downward zones in the 120° die due to low strains. Variations of grain size at different zones along AB for ECAPed samples through dies with angles of 90° and 120°are presented in Fig. 4.

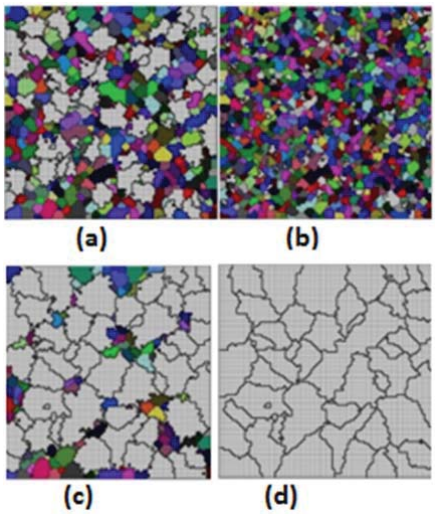

Fig. 2 Microstructural evolution of pressed sample at 623°C

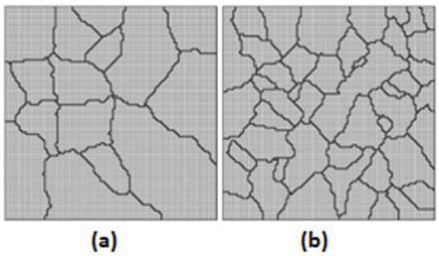

Fig. 3 Final grain size achieved with a die angle of (a) 90°; (b) 120°

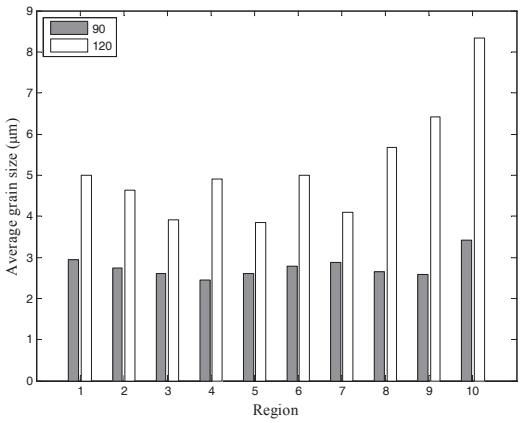

Fig. 4 Grain size distribution within different zones for ECAPed samples through dies with angles of 90° and 120°

4- Conclusions

The finite element method and Monte Carlo model have been used to simulate the annealing of inhomogeneously ECAPed AA6061 aluminum alloy. Based on the predicted results, the following conclusions can be made:

1. Inhomogeneity of the grain size in the recrystallized sample is reduced by increasing the annealing time.
2. The final grain size achieved for dies with an angle of 90° and 120° are 2.74 and 4.92 μm respectively.
3. The nucleus density approaches zero at the final downward zones in the 120° die due to low strain.