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Mechanical and microstructural characterization of 6061 aluminum alloy strips severely deformed by Dissimilar Channel Angular Pressing

Evren Tan[b,*], *Alp Aykut Kibar*[a], *C. Hakan Gür*[b]

[a]*The Scientific and Technological Research Council of Turkey, 06100, Ankara, Turkey*
[b]*Middle East Technical University, Metallurgical and Materials Eng. Dept., 06531, Ankara, Turkey*

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ABSTRACT

Dissimilar Channel Angular Pressing (DCAP) is a severe plastic deformation technique to improve the mechanical properties of flat products by producing ultrafine grains. In this study, the changes in the microstructure and mechanical properties of 6061 Al-alloy strips deformed by various numbers of DCAP passes were investigated. Some DCAPed samples were also held at 200 °C and 350 °C to investigate the effect of post-annealing. Mechanical properties were determined by hardness and tension tests; and microstructural changes were investigated by TEM analysis. Up to a critical level of plastic strain, remarkable improvements have been observed in the strength and hardness of the severely deformed strips; and the improvements have been explained by variations in grain size, dislocation structure, and formation of subgrains.

1. Introduction

Grain size refinement brings many advantages to mechanical properties of the polycrystalline materials. However, conventional metal working techniques are not sufficient for obtaining submicron grain sizes due to their insufficient straining capacity and inability of producing substructures with high angle misorientations [1]. Consequently, various severe plastic deformation (SPD) techniques have been developed to overcome these problems and to produce ultra fine grained (UFG) materials that have average grain size less than 1 μm.

One of the most studied techniques is the Equal Channel Angular Pressing (ECAP), of which the dominant mechanism is simple shear that was firstly introduced by Segal et al. [2]. Although it is possible to produce UFG structure by multi-passages of bulk materials through an ECAP die without changing the material geometry, it is not a continuous process and not suited for deformation of sheet products. To overcome these difficulties, Continuous Confined Strip Shearing and Equal Channel Angular Rolling were developed by Lee et al. [3]. In a similar process, called Dissimilar Channel Angular Pressing (DCAP), a metal strip or sheet is fed through the feeding rolls into the inlet channel which has a slightly thinner cross-section than the material thickness in order to prevent the material to escape from the roll gap. The material passes through the forming zone where the inlet and the outlet channels intersect at a specific angle [3], and it flows into the outlet channel which has the original thickness of the sheet allowing the sheet metal to retain its initial thickness and leaves the DCAP die with its original shape. Maintaining the original shape has many advantages over conventional cold rolling process, especially when the post strengthening of the thin products is considered.

* *Corresponding author*. Tel.: +90 312 2105916; fax: +90 312 2102518.
E-mail addresses: etan@metu.edu.tr (E. Tan), alpaykut@gmail.com (A.A. Kibar), chgur@metu.edu.tr (C.H. Gür).

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The deformation behavior of DCAP can be characterized predominantly as shear deformation with minor tension and compression modes which can be assumed as insignificant [4]. The shear deformation leads to the equivalent true strain. The strain imposed to the material can be calculated by Eq. (1) modified by Lee et al. [3] based on the original formula for ECAP method [2].

$$\varepsilon = \frac{2N}{\sqrt{3}} K^2 \cot\frac{\phi}{2} \quad (1)$$

In this equation, K is the thickness ratio of the inlet/outlet channels, N is the number of passes, and ϕ is the die channel angle.

Severe plastic deformation processes differ from conventional cold working techniques in terms of microstructure evolution related to subgrain formation, evolution of the cells, types of boundaries, nucleation and growth processes and dislocation behavior. Grain refinement is simply represented as the formation of dislocation cell structures and subgrain boundaries with low misorientation in the early stages; and with further deformation, transformation of subgrain boundaries into high angle grain boundaries leading to ultra fine grains. Valiev et al. [5] explain this transformation as the conversion of cellular structure to a granular one and occurring of partial annihilation of dislocations of different signs at the cell boundaries. Besides, the grain boundary character may change depending upon the process type and route, such as high-angle and low-angle, equilibrium or non-equilibrium, special or random, and also formation of segregations along the grain boundaries [6].

Formation of ultra fine structure with high misorientations by DCAP has been reported in several studies [3,4,7]. Equivalent strain level is a very important parameter when the microstructural properties are considered. Different microstructural characteristics were observed at different levels of strains related with the number of DCAP passes. Lee et al. [3] mentioned such evolutions in the microstructure of 1050 Al alloy at different accumulative strain levels based on the theory of Chang et al. [8] which proposed a structural evolution sequence of dislocation cells such as poligonized dislocation walls, partially transformed boundaries, and ultrafine grains with increasing strain level.

Changes in the dislocation density, formation of ultra fine grains and reduction in grain size during the DCAP process improves the mechanical properties of the materials. These improvements can be detected by the observations of higher hardness and strength, better fatigue and superplastic properties without reducing the ductility so much as compared to conventional deformation techniques. However, this improvement reaches saturation at a critical strain level, and further plastic straining causes a decrease in hardness and strength [3,9–11]. This behavior can be explained by strain softening due to dynamic recovery and recrystallization processes [11] related to the change of the total dislocation density representing a competition between dislocation generation and annihilation processes [7,9,12]. Hence, the amount of deformation must be strictly controlled to achieve the desired mechanical and microstructural properties.

In this study, 6061 Al-alloy strips, which are used in construction and automotive industry, were deformed by DCAP to improve their mechanical properties. The success of the application was verified by mechanical tests and microstructural investigations via transmission electron microscopy.

2. Experimental Procedures

6061-T6 strips with 120 mm × 300 mm × 2 mm dimensions were annealed at 415 °C for 3 h to have a uniform and fully recrystallized microstructure. Then, using a laboratory scale deformation set-up, DCAP process was applied on the specimens up to 5 passes with a speed of 20 cm/min at room temperature. The thickness of the inlet channel was designed as 1.9 mm to prevent escaping of material from the roll gap. The specimens were fed through the rolls, and taken from the outlet channel with the thickness of 2.0 mm. The channel angle and the outer corner angle of the die are 120° and 0°, respectively. Samples were fed through the rolls with route A (without changing the feeding direction between subsequent passes), and with route C for once (changing the feeding direction by 180° before the second DCAP pass).

The hardness of the upper and lower surfaces was measured via macrohardness with HB 2.5 tip at 15.6 kg while the thin side sections were controlled via microhardness with HV tip at 500 g. Measurements were taken through at least two different profiles along the side thickness (close to the upper surface, from the middle and close to the lower surface) of each specimen to be able to see the change in hardness values at different parts of the specimen. Hardness results of the samples were obtained by taking the average values of at least five different hardness measurements from each specimen.

Tensile specimens were machined parallel to the deformation direction according to ASTM B557M-02a. Tensile tests were performed at room temperature with a machine having a load cell of 30 kN and at a strain rate of 1.0 mm/min.

In order to evaluate the subgrain size and the peak intensity differences, XRD measurements were conducted by using the diffractometer having Cu-Kα target. Scanning was performed in the 2θ range of 0° and 90° with a speed of 2°/min. The subgrain size was roughly calculated by using the Scherrer formula [13].

TEM investigations were conducted by JEOL 2100 (LaB6 filament) operated at 200 kV. Some sets of the deformed samples were annealed at 200 °C and 350 °C for 1 h to observe the post annealing effect, and also to have clear images. The specimens were cut into small strips and thinned from 2 mm to 500 μm by mechanical thinning, and then, punched into 3 mm diameter disks; finally thinned to 200 μm by further grinding. The samples were polished with an electrolyte of 25% nitric acid + 75% methanol solution at about −33 °C with 15–20 V in Struers-Tenupol-5 Double Jet Electropolisher.

3. Results and Discussion

3.1. Mechanical Properties

Fig. 1 shows that the hardness of the samples increased remarkably after the first and second DCAP passes. This is an indication of the increased dislocation density and the