



Microstructure and mechanical properties of the annealed 6060 aluminium alloy processed by ECAP method

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ABSTRACT

Purpose: The main goal of this paper is to present the investigation results of microstructural evolution and mechanical properties changes in commercial EN AW 6060 aluminium alloy after intensive plastic deformation, obtained by equal channel angular pressing (ECAP) techniques in an annealed state.

Design/methodology/approach: Annealing heat treatment was used to remove various types of internal stress in a commercially available alloy in order to increase workability of the material. The evolution of its properties and material behaviour was evaluated after 2,4,6, and 8 passes of the ECAP process.

Findings: It was found that the mechanical properties and microstructure during intensive plastic deformation, such as that during the ECAP process, were changed. Plastic deformation refined grains in the aluminium alloy and increased its mechanical properties.

Research limitations/implications: The presented study shows results of the investigated material in an annealed state.

Practical implications: The applied processing route allows development of materials characterized by high strength and ultrafine grain microstructure compared to un-deformed annealed aluminium alloy.

Originality/value: The work presents data about the influence of intensive plastic deformation on the microstructure and mechanical properties of 6060 aluminium alloy after annealing.

Keywords: Aluminium alloy; Heat treatment; Equal channel angular pressing; Microstructure; Microhardness; Tensile test

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PROPERTIES

1. Introduction

Severe plastic deformation (SPD) is an interesting method for modifying the microstructure of a material since it allows production of ultrafine grained (UFG) materials [1-3]. In recent years, many SPD methods have been developed to improve mechanical properties without degrading ductility for pure metals and their alloys. SPD techniques such as equal channel angular pressing (ECAP), high pressure torsion (HPT), and accumulative roll bonding (ARB) are already well established for obtaining ultrafine grained materials [3-7]. The ECAP method is an especially attractive technique for several reasons: the process depends on die types (shape and angle of channels) and its method is relatively simple; the process can be used for the pressing of large samples with potential to manufacture materials with large area in structural applications and can be used on almost every type of material [7-15]. ECAP consists of repetitive punching of a billet through two of the same cross-sectional channels intersecting at an angle ϕ . Generally, the channel angle is equal to 90° or 120° . The channels of the dies are circular or square – the same as the cross sections of billets. The general principle of the ECAP method is: the tool (die) is a block with channels with identical cross-sections. A sample has the same cross-section shape as its channels. The stamp goes into the same channel as the sample, then forces it through the second channel. Under these conditions, the sample moves as a rigid body and deformation is achieved by simple shear in a thin layer at the crossing plane of the channels. When the stamp is stopped, it is retreated and the sample has been uniformly deformed [1-4, 14-20]. The main goal of this paper is to present the investigation results of microstructural evolution and mechanical property changes in commercial EN AW 6060 aluminium alloy after intensive plastic deformation, obtained by equal channel angular pressing (ECAP) techniques in an annealed state.

2. Experimental methods and procedure

In this experiment, 10 mm diameter rods of commercially available EN- AW 6060 aluminum alloy

were used. Their mean alloy chemical composition (in wt. %) according to the PN-EN 573-3 standard- are given in Table 1. The aluminum alloy rods were cut into cylindrical specimens 10 mm in diameter and lengths of 40 mm.

Thermal processing of the alloy was carried out in a laboratory furnace at 400°C and held for 1 hour, then cooled to room temperature. Annealed samples were pressed through an ECAP die with a channel angle of 120° . Between the channels of the ECAP die, the inner contact angle and the outer corner angle were 120° and 45° , respectively. The 6060 aluminum alloy was successfully processed by ECAP 2,4,6 and 8 times, of which two cycles of the process are shown in Figure 1. The process was performed in a vertical hydraulic press at room temperature and a lithium grease with MoS_2 and graphite used as a lubricant. During rotation and extrusion, the orientations of the geometrical characteristics, such as the specified planes and directions in the sample, were transformed. In this case, route A was used. After ECAP, the samples were cut and machined into cylindrical samples with 5 mm cross-sections of working area and a gauge length of 10mm for tensile testing. Tensile tests were carried out using a Zwick Z20 tensile test machine at room temperature. Another set of samples, which underwent repeated ECAP cycles, were cut into a small pieces in directions parallel to the cross and longitudinal sections of the processing axis and were then mounted in a resin. Afterward, the surfaces of the mounted samples were mechanically ground and polished using diamond suspension. For the subsequent microscopic characterization samples, an aqueous solution of iron (III) chloride (5%) with 20 drops of hydrofluoric acid (30%) was added. Metallographic analysis was carried out by bright field optical microscopy. From select samples, a thin film was prepared to observe subgrains evolution. Samples were cut into thin slices then ground and a 3 mm diameter disk was cut. Next, the samples were electrochemically polished. This process was necessary to prepare the appropriate thin films for Transmission Electron Microscopy (TEM) analysis. The microhardness of the prepared samples was measured on a Future-Tech FM-700 hardness tester with a load of 1N and loading time of 15s. The indenter used was pyramidal in shape and, was composed of diamond. To obtain the average value, at least 20 points were measured for each sample.

Table 1.

Chemical composition of EN- AW 6060 alloy

| Element concentration in wt., % | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Al |
|---------------------------------|---------|---------|-----|-----|----------|------|------|-----|------|
| | 0.3-0.6 | 0.1-0.3 | 0.1 | 0.1 | 0.35-0.6 | 0.05 | 0.15 | 0.1 | Rest |

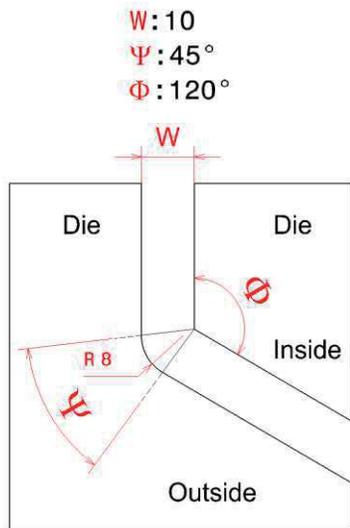


Fig. 1. Schematic of Equal Channel Angular Pressing, die having a channel angle of 120° used in the experiment

3. Results

3.1. Structure and mechanical properties

The grain structure of un-deformed annealed 6060 aluminium alloy (A0) is presented in Figure 2. Micrographs of sample A0 were taken to compare microstructural grain changes after sequential passes. The average grain sizes in A0 are in the range of 50-200µm, as shown in Figure 3.

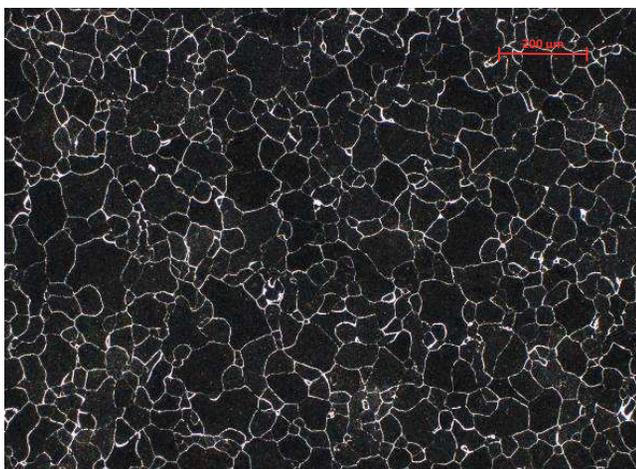


Fig. 2. Microstructure of examined material in the initial annealed state. Light Microscopy, magnification 50x

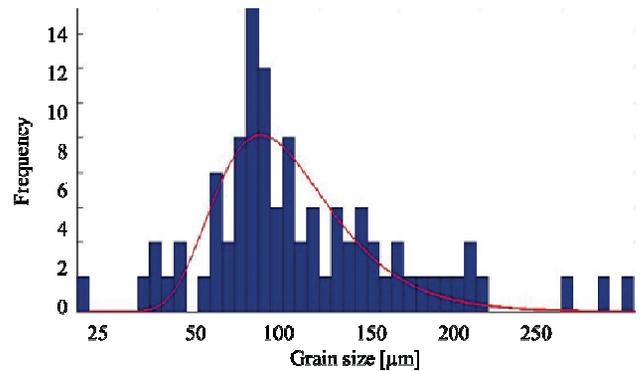


Fig. 3. Histogram of grain size distribution of the A0 sample in the initial annealed state

The average ratio between width and elongation of processed samples changed as shown in Figure 4.

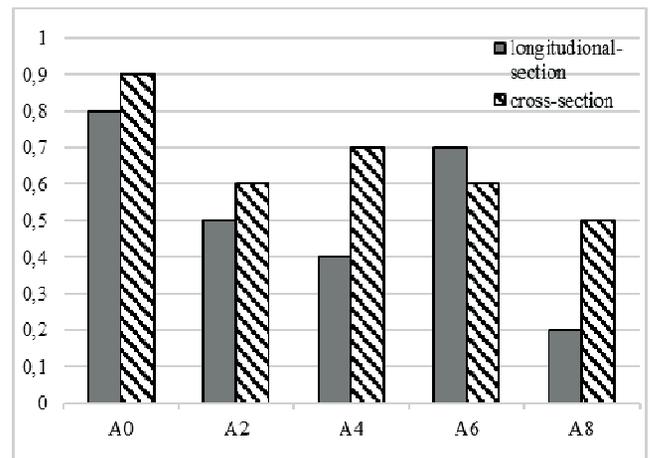


Fig. 4. Anisotropy of grain size induced by SPD process in the longitudinal and transvers section after 2, 4, 6, 8 ECAP passes

Grain size measurements were carried out in two dimensions in cross sectional (CS) and longitudinal sections (LS) as shown in Figure 4. The aspect ratio was calculated for each sample in proportion to the length and width of a selected grain (at least 20 grains were measured). The straight lines (of width and lengths) had to intersect at right angles. The ratio of grain size, in the case of un-deformed samples, was relatively high due to previous recrystallization annealing. Relaxed grains formed into a nearly oval shape. To specify a wide range of grain sizes in an un-deformed condition, a histogram was made and is shown in Figure 3. After 2 passes (A2), grains decreased in width in both CS and LS (their sizes were ~40 to ~50 µm, respectively) and length in CS (~75 µm), but as

expected, in LS the length increased, which on average equalled 170 μm .

Grain size decreases and elongation tendency were also observed in samples after 4 passes (A4). In the group that had 6 ECAP passes (A6), this trend changed. Microstructure evolution of the plastically deformed samples is shown in Figure 5. To understand the grain size and mechanical property changes, samples were processed into a thin film for TEM analysis. The TEM micrographs of subgrain structure are shown in Figure 6. Thin films were prepared for sample A6- after 6 passes.

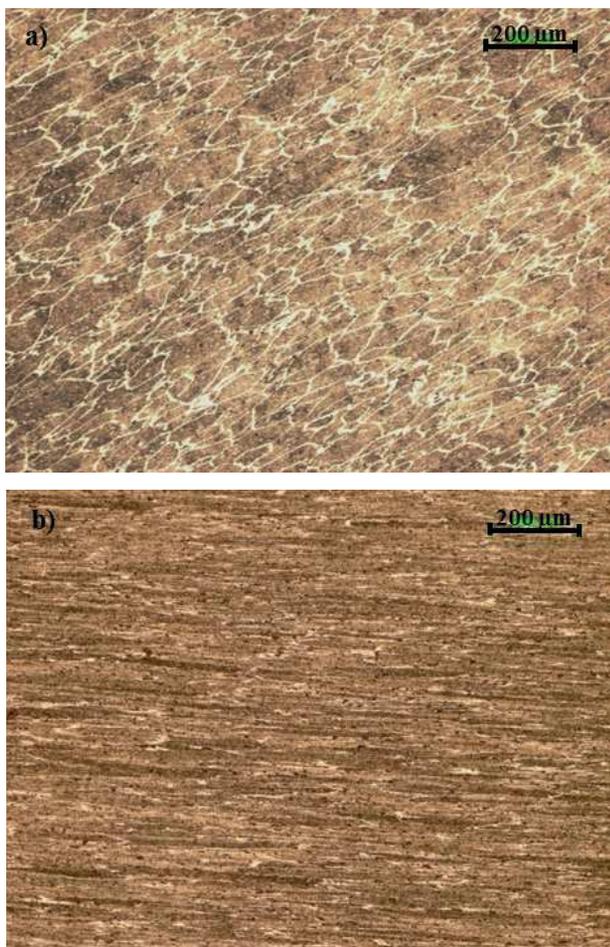


Fig 5. Microstructure of the longitudinal section of the investigated samples after 2 passes a) and after 8 passes b) Light Microscopy, magnification 50x

The intensive plastic deformation during extrusion has a large impact on the microstructure and texture of processed materials. Relatively large stacking-fault energy in aluminium alloys impeded changes to the dissociation into partial dislocation. The dislocation climb is limited in cold

forming (which for Al alloys is below 70°C). During macroscopic observation of the A8 sample, cracks were noticed as they appeared on the surface. The occurrence of cracks might have been the result of the hardening effect due to previous steps (in passes 6 and 7). As is shown in Table 2, the highest increase of the hardness value was after initial passes. The hardness value increased up to the A6 sample and then decreased slightly.

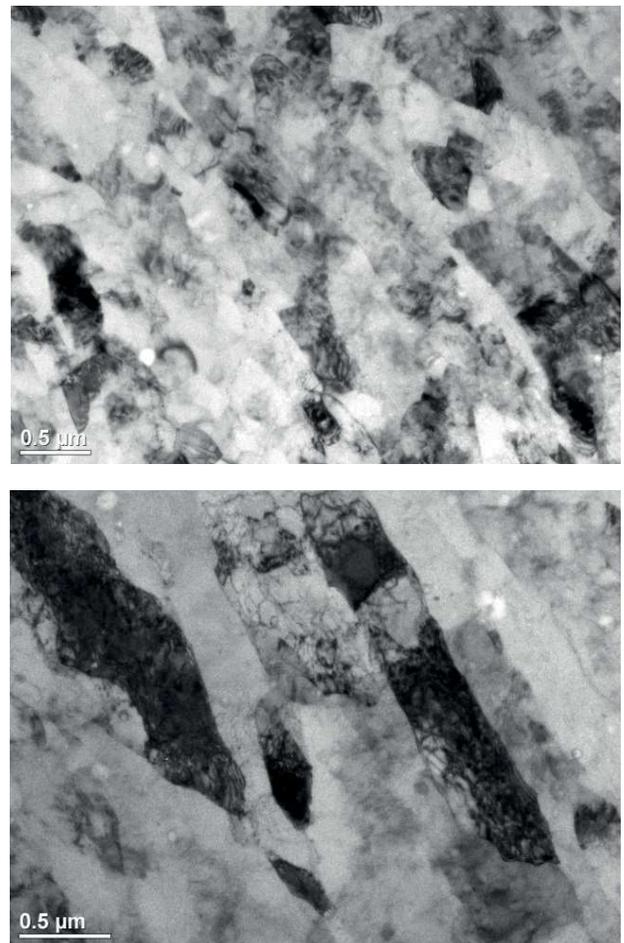


Fig. 6. TEM micrographs showing typical subgrain microstructure created by severe plastic deformation process after 6 ECAP passes

The strength of the 6060 aluminium alloy is significantly higher than before, showing that it is possible strengthen material by ECAP following precipitation hardening. The largest increase in yield stress observed after initial passes showed a decrease in work hardening capability of deformed materials. Ductility was significantly reduced after the first passes and was almost independent of the materials state.

Table 2.
Average microhardness value for tested samples

| Type of sample | Average microhardnes, HV0.1 | Standard deviation | Ultimate tensile strength, Rm, MPa |
|----------------|-----------------------------|--------------------|------------------------------------|
| A0 | 42.2 | 1.34 | ~175 |
| A2 | 64 | 2.14 | 190.35 |
| A4 | 66 | 1.00 | 207.76 |
| A6 | 71 | 1.27 | 233.78 |
| A8 | 68 | 1.11 | 251.54 |

According to norm EN 754-2, tensile strength of pre-annealing 6060 aluminium alloy in T6 state equal to 190 MPa. After heat treatment, this value was observed to decrease. In Figure 7, tensile behaviour of material following ECAP is shown.

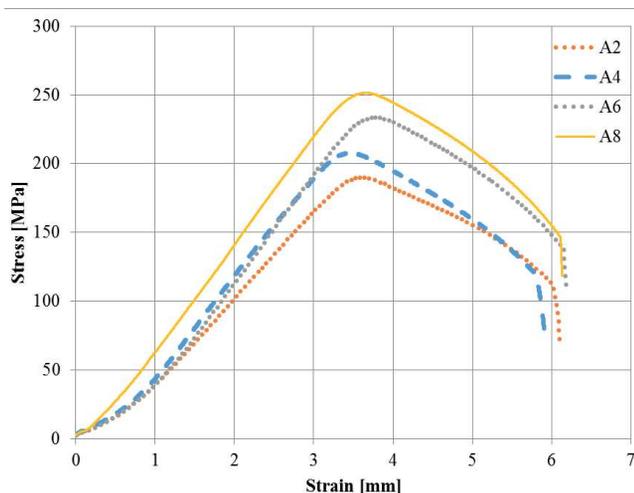


Fig. 7. Tensile testing results of ECAP processed aluminium alloy after different numbers of pressing

As shown in the diagram, the samples characterized by the best fracture stress values were A6 and A8. The tensile strength of the processed samples increased more than 60 MPa, wherein strain changed nearly the same amount in each case.

4. Conclusions

One of the most widely used severe plastic deformation (SPD) processing methods is equal channel angular pressing (ECAP). This method creates a homogenous microstructure of a processed alloy, and the whole process of grain refinement can be finely controlled.

In this research experiment, route A was used, specifically for the route grain size evolution shown in Figure 4, which reveals the importance of rotations between each of the passes.

The most significant microhardness and tensile changes were well observed after initial passes, however the best results were observed after 6 and 8 passes.

The largest grain size reduction in width and the largest elongation were observed after the first two passes. The most notable result was the smallest grain with a width of ~22 μm which was obtained after 8 ECAP passes.

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