ASEAN Engineering Journal

Full Paper

AN ANALYSIS OF THE EVOLUTION IN THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF ALUMINUM ALLOY FOLLOWING THE ECAP PROCESS

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Article history
Received
30 July 2024
Received in revised form
18 April 2025
Accepted
23 April 2025
Published online
30 November 2025

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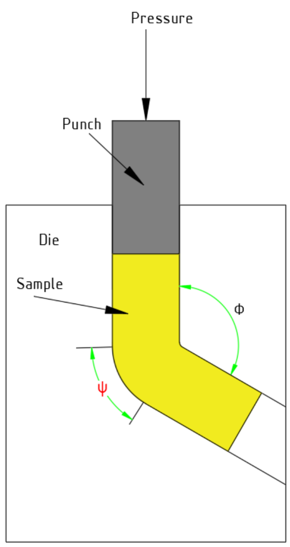
Graphical abstract



Abstract

An analysis of the changes in the microstructure and mechanical properties of Aluminum Alloy 6016 after the ECAP process is presented in this study. It involves designing an easy-to-use die set and having it manufactured for the ECAP procedure. After heating and nitrogen permeation to achieve the required hardness and strength, the A6016 Aluminum extrusion experiment was conducted. The extruded product was tested for hardness, tensile strength, and microstructure to examine the effect of the processing on the microstructure and mechanical properties of the aluminum alloy. Experimental results show that the die can only press each billet for a maximum of 2 times and cracks on the 3rd pass. The hardness of the billet increased from 36.5 HB (as-received sample) to 67.4 HB and reached 78.8 HB after the first and second pass, respectively. The tensile strength of aluminum also increased significantly; particularly, the maximum tensile stress rose from 50 bar from the initial billet to 65 bar and 70 bar after the first and second pass, correspondingly. The microstructure of the part also changed considerably. From the initial spherical shape structure, the grains were elongated in the pressing direction after the first pressing; and in the second pressing, some grains continued to be elongated further while some others were broken into smaller grains. The overall results show that after only 2 presses through the ECAP channel, aluminum 6016 has significantly improved its microstructure and mechanical properties.

Keywords: Mechanical, Microstructure, ECAP, Hardness, Aluminum alloy

1.0 INTRODUCTION

A metalworking process called severe plastic deformation (SPD) uses high pressure to produce materials with incredibly fine grains and greatly improved mechanical qualities [1-3]. A broad variety of techniques are used to treat severe plastic deformation (SPD), but some of the most popular ones are equal channel angular pressing (ECAP), high pressure torsion (HPT), accumulative roll bonding (ARB), and repetitive corrugation and straightening (RCS), surface mechanical attrition treatment (SMAT), cyclic close die forging (CCDF), reciprocating extrusion-compression (REC), etc. [4-5].

The process of Equal Channel Angular Pressing (ECAP) involves pressing a metal workpiece through a die that has two equal-sized channels that intersect at a particular angle. The material undergoes severe shear strain during this process, which improves its mechanical qualities and forms ultrafine grains without affecting the cross-sectional area of the workpiece [6, 7].

Some advantages of ECAP include: UFG materials made by ECAP frequently have better ductility and strength than their coarse-grained counterparts; it can be applied to a wide range of metals and alloys; and the process itself does not call for a lot of expensive or complicated machinery [6-8]. However, it has some disadvantages, including the possibility of flaws, limited billet size, and slow and time-consuming process [9-10].

Bhandari [11] designed an ECAP die for processing Aluminum alloy using computer simulations. A moderate and even strain on the material was achieved, gaps were reduced, and material flow was balanced in the ideal design. The alloy's microstructure was effectively improved by the ECAP process, increasing its tensile strength and hardness.

Awasthi [12] investigated the effects of equal channel angular pressing (ECAP) on the microstructure of Aluminum alloy at various processing temperatures using a combination of simulations and experiments. The ductile behavior of the material led to a decrease in stress with higher temperatures, as demonstrated by the well match between the simulation and experimental results. The material's altered structure following ECAP processing was validated by a microstructural analysis.

Naik [13] examined the effects of a channel's angle during the metal pressing process on the characteristics of magnesium alloy. The results revealed that parameters like hardness, strength, and corrosion resistance are greatly impacted by channel angle. With a particular channel angle and processing path, they were able to achieve the highest increase in ductility (76%) of any group.

Despite significant research into ECAP, there is still a gap in the data regarding the outcomes of severe plastic deformation of Aluminum alloys using this method. In this study, a detailed investigation of a process involving the design and fabrication of a simple die for the ECAP process and the experimental extrusion of 6016 aluminum alloy is presented. After extrusion, the product was tested for hardness, strength, and microstructure to assess the impact of this processing method on the microstructure and mechanical properties of the material.

2.0 METHODOLOGY

The ECAP method changes the grain size of the experimental material, resulting in extremely large forces in the die [14-16]. Furthermore, to achieve effective extrusion, multiple passes are required to achieve uniformity and optimal size. Therefore, a robust, high-strength, durable, wear-resistant, easy-to-manufacture, and cost-effective die set is essential. The most critical design requirements for the die are [14-18]:

- Ability to withstand very high pressures without cracking or excessive deformation that compromises the design dimensions.
- High wear resistance due to significant frictional forces.
- High surface hardness but overall softness to prevent die damage.
- Multiple-use capability due to the need for numerous extrusion passes to achieve desired results.

The extrusion punch must meet the following requirements:

- High hardness to transmit a large compressive force to the billet.
- High allowable compressive stress to withstand a large, centered compressive force.
- Ensure stable operation over a large number of extrusion cycles without cracking or bending which would damage the die.

Based on the above technical requirements, the aluminum profile extrusion die in this study is made of SKD61 steel with the following composition: C (0.32-0.42%), Si (0.8-1.2%), Mn 0.5%, Cr (4.5-5.5%), Mo (1-1.5%), V (0.8-1.2%).

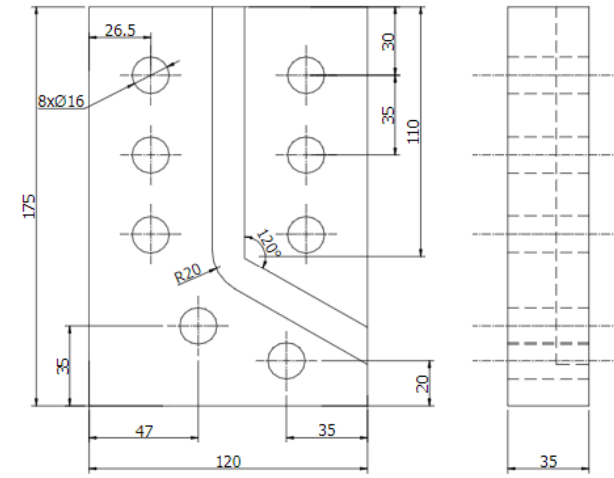
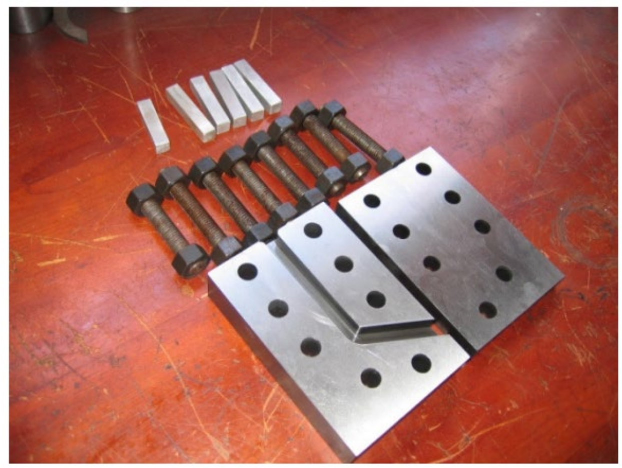


Figure 1 Design drawing of the die



a)

(b)

Figure 2 Die and billet set for ECAP pressing experiment: (a) Before assembling the die, (b) After assembling the die

Figure 3 ECAP experiment on 100 Ton hydraulic press

The die groove is manufactured with the dimensions of 14.02x14.02 mm. The die set is heat treated after fabrication. To improve wear resistance, the die is nitrided to achieve a surface hardness of 62-65HRC. The required nitriding layer thickness is 100 to 200 µm. The extrusion punch is designed with the dimensions of 14x14x110 mm and is made of HSS steel with a hardness of 63-65 HRC. The initial aluminum billet is machined to a size of 14x14x70 mm and polished to reduce friction. Figures 1 and 2 show the die design drawing and the die set and aluminum billet prepared for the ECAP experimental process, respectively.

The experiment was conducted on a 100-ton hydraulic press with a pressing speed of 0.2 mm/s (Figure 3). BP Turbine Low X46 lubricant, which can withstand temperatures up to 300^{o}C, was used to minimize friction between the workpiece and the die.

3.0 RESULTS AND DISCUSSION

Figure 4 shows the detailed part being compressed in the die. Figure 5 shows the detailed part being successfully compressed out of the die. Figure 6a shows the aluminum blank after being pressed 1 time, and Figure 6b shows the aluminum blank product after the second press (after the first compression, the size is machined and then compressed again). The die cracked during the third compression, so for this die design, the compression force in the third compression increased significantly and exceeded the die's strength.

After the pressing experiment, the hardness and tensile strength of the parts were tested [19, 20]. Figure 7a shows the hardness of the aluminum parts before and after processing. The results reveal that after one pressing, the hardness of the part increases by about 1.8 times, after the second pressing, it increases by 1.2 times compared to the first pressing, and is 2.2 times compared to the original blank. This proves that the ECAP pressing process significantly increases the hardness of aluminum, and the change in hardness compared to the previous pressing decreases significantly with further pressing [7, 9, 11].

Figure 4 An Aluminum billet inside the die cavity in the ECAP pressing method

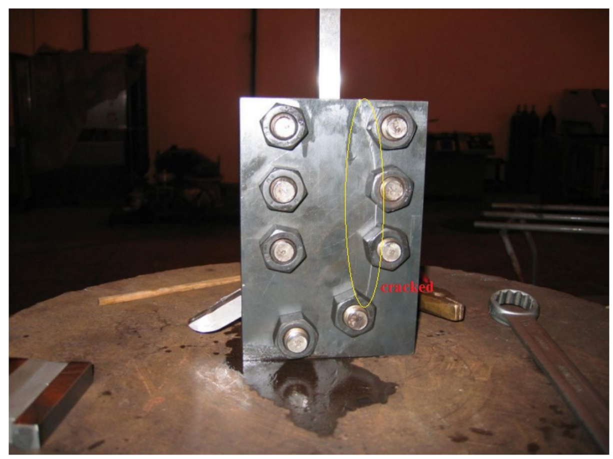


Figure 5 An Aluminum billet being pressed out of the die cavity

(a) (b)

Figure 6 Aluminum billets after ECAP pressing: (a) Through 1 pass, (b) Through 2 passes

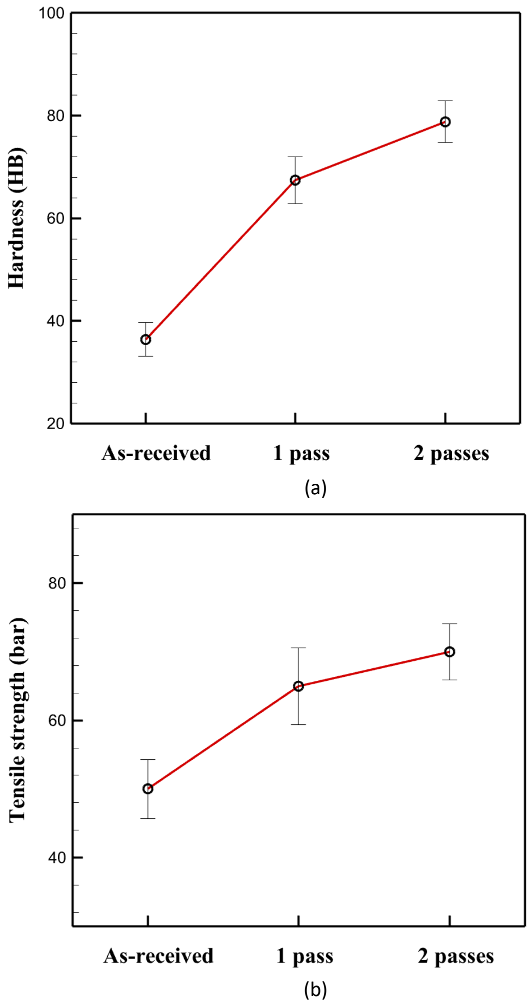


Figure 7 The evolution in mechanical properties of Aluminum alloy: (a) Hardness, (b) Tensile strength

To check the tensile strength, the part after extrusion was machined according to the tensile standard [20]. Figure 7b shows that the tensile strength of the part increases from 50 bar to 65 bar after one extrusion and reaches 70 bar after two extrusions. To examine the microstructure of aluminum before and after deformation, this study uses a metallographic microscope. The samples were cut transversely and polished. The samples were then etched with a solution composed of 1%HF + 2.5%HNO_3 + 1.5%HCL + 95%$H_2$0. Figure 8 presents the microstructure of aluminum before and after deformation. Figure 8a shows that the grain structure on the original blank is spherical and has an average size of 6.5 µm. However, after one extrusion, the material grains are elongated and have an average size of 5x15 µm. The microstructure of the second extrusion shows that the structure of the material has changed compared to the first extrusion; e.g. some grains continue to elongate and some grains that have elongated in pass 1 are broken into smaller ones [12, 16].

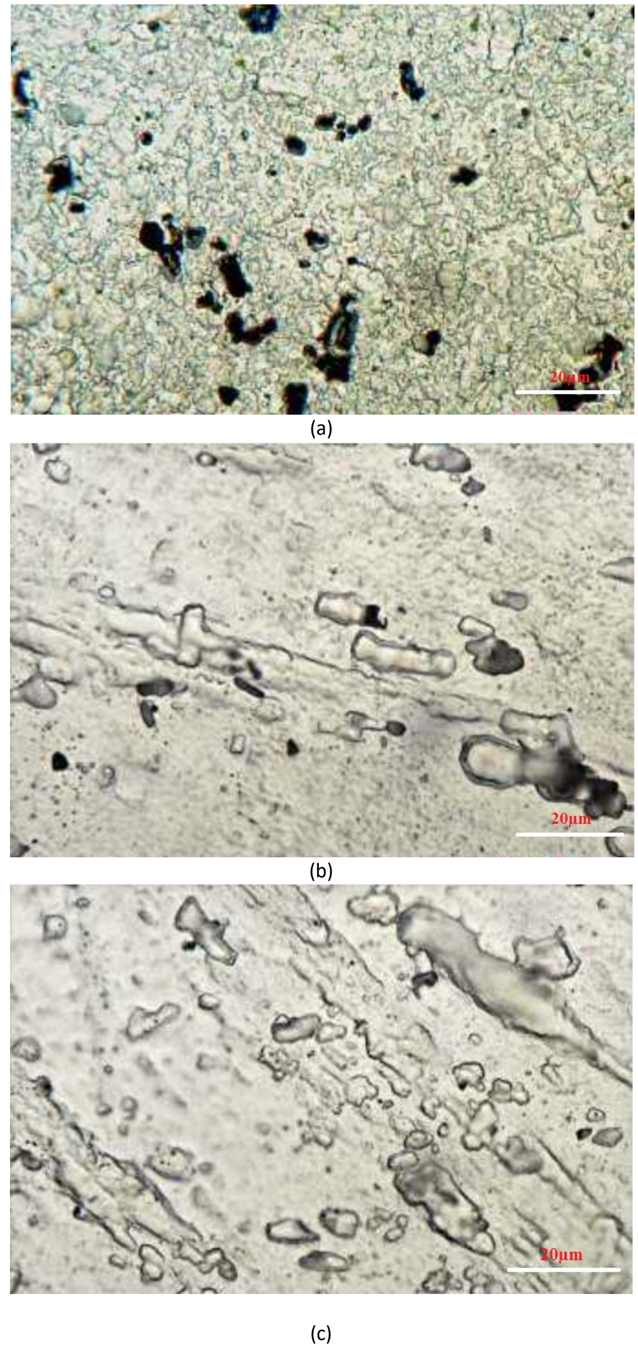


Figure 8 Microstructure of aluminum alloy: (a) As-received, (b) Through 1-pass pressing, (c) Through 2 passes

4.0 CONCLUSION

This paper presents an experimental study on the hardness, strength, and microstructure of Aluminum alloy A6016. The results show that a simple die design made of SKD61 steel and heat-treated and nitrogen-permeated can be used for up to two passes. The results show that after extrusion, the hardness of the material increases by 1.8 times and 2.2 times compared to the original sample, for the first and second passes, correspondingly. The maximum tensile strength of the tensile sample also increases from 50 bar to 65 bar and 70 bar, for the first and second passes, respectively. The microstructure of the Aluminum part after processing also changes significantly, from a spherical shape in the original part to the elongated shape in one direction after the first extrusion, and then to a reduced shape in the second. At the same time, after the second time, some grains coinciding with the extrusion direction continue to be elongated while the grains in the other extrusion direction are broken down into smaller grains. With this simple die design, only a maximum of two extrusions can be performed for each part. Therefore, the author group has designed an improved die and is conducting experiments to increase the number of extrusions for each part and to process the grain size to below 200 nm.

Acknowledgement

We acknowledge Ho Chi Minh City University of Technology (HCMUT), VNU-HCM for supporting this study.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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