

# THE EFFECT OF EQUAL CHANNEL ANGULAR PRESSING (ECAP) ON THE MICROSTRUCTURE AND HARDNESS OF A356 ALUMINIUM ALLOY

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**ABSTRACT:** Equal channel angular pressing (ECAP) is one of popular techniques of severe plastic deformation (SPD), a process of producing an ultra-fine grained (UFG) microstructure. This work focused on the microstructural analysis and mechanical properties of A356 aluminium alloy after processing by ECAP. Cooling slope casting and conventional casting techniques were used to produce feed materials for ECAP process. ECAP process was carried out at room temperature by route A for one pass. The microstructure observation was carried out before and after ECAP under optical microscope as well as its hardness. It is found that the microstructure distribution of ECAPed sample in combination with cooling slope casting was more homogeneous compared to the microstructure of ECAPed sample in combination with as-cast. The results also showed an obvious reduction of grain size after the alloy was pressed using ECAP process with average grain size of 58 $\mu$ m for cooling slope ECAPed and 96 $\mu$ m for as-cast ECAPed. The hardness of the alloy increased after ECAP process with an increment about 33.6% for conventional casting and 21.2% increment for cooling slope casting sample.

**KEYWORDS:** *Aluminium Alloy; Equal Channel Angular Pressing (ECAP); Severe Plastic Deformation (SPD); Cooling Slope Casting*

## 1.0 INTRODUCTION

Severe plastic deformation (SPD) is a technique commonly used for generating ultra-fine grained material, thus, improve the mechanical properties of the materials [1-2]. Ultra-fine grained materials refer to

a grain size in the range of 100-1000 nm while grain size less than 100 nm were categorized as nano-grained microstructure [3]. There are numerous SPD techniques that have been developed and the most popular and attractive technique is equal channel angular pressing (ECAP) [4]. The other SPD process includes high pressure torsion (HPT), accumulative roll bonding (ARB), tubular channel angular pressing (TCAP), constrained groove pressing (CGP) and accumulative back extrusion (ABE) [5-9].

ECAP processing has been introduced over more than four decades ago by Segal et al. [10] at the physical Technical Institute Academy of Science of Buelorussia, Minsk. During ECAP process, a billet is pressed through a die consists of two channel intersecting at certain angles. A high shear strain is imposed during the process which could lead to the alteration on its microstructure, hence, enhancing the mechanical properties [11]. Previously, there are many materials that have undergone ECAP process effectively, including aluminium alloy, magnesium alloy and various types of steels. The study mostly focused on the microstructure evolution and mechanical properties after ECAP. Abd El Aal and Sadawy [12] have conducted a study on the effect of ECAP number of passes on the microstructure evolution, mechanical properties and corrosion behaviour of pure aluminium. They found that after 10 passes of ECAP, the grain size has been reduced to  $0.3\mu\text{m}$  while the microhardness increased up to  $60.8 \pm 0.05$  HV.

Aluminium alloy is widely used in various industries mainly in automotive and manufacturing due to its fluidity and mechanical strength. Its light weight properties become the main reason for it to be used in engine block production as it helps to reduce the fuel consumption [13]. However, aluminium alloy has a limitation due to low ductility and toughness, thus, in recent years, many attempts were carried out to enhance the properties of this alloy. Feed materials of as-cast aluminium alloy with dendritic  $\alpha$ -Al are used in ECAP. Instead of using as-cast aluminium alloy, cooling slope casting is introduced as another technique to produce fine and globular microstructure in obtaining homogeneous microstructure after ECAP process. In this research, A356 aluminium alloy is used to produce feed materials for ECAP processing through conventional casting and cooling slope casting.

Cooling slope casting (CS) is a simple semisolid casting process that requires simple equipment at lower running cost. In this casting technique, the melt is poured on the inclined cooling slope plate downward into a vertical mould and solidified in the mould [14]. The

sample cast by cooling slope gives non-dendritic microstructure as the dendrite arm is fragmented due to the shearing effect which occurs on the inclined slope plate [15]. This cooling slope casting is widely used to produce feedstock materials for semi-solid metal processing and it can also be used as feedstock materials for ECAP processing.

The main focus of this work was to produce feedstock for ECAP using cooling slope casting. The primary objective of this work was to investigate the evolution of the microstructure of A356 aluminium alloy after cooling slope casting in combination with ECAP processing. The hardness of the as-cast sample and cooling slope casting sample before and after ECAP were also studied.

## 2.0 EXPERIMENTAL PROCEDURE

The type of alloy used in this work was aluminium alloy A356. Table 1 shows the composition of the aluminium alloy. Feedstock material for ECAP process was produced using conventional casting and cooling slope casting. The samples were then undergoing mechanical testing and microstructural analysis.

The cooling slope inclined plate made of stainless steel with of 90 mm width, marked at 200 mm, 300 mm, and 400 mm slope length while the angle of the slope was fixed to 60°. Aluminium alloy was melted in a furnace at temperature above 700°C then it was cooled into its desired pouring temperature. The temperature of the melt was measured using K- type thermocouple. Figure 1(a) shows the apparatus for cooling slope casting experiment. It was noted that the surface of slope plate was coated with boron nitride to avoid adhesion between the melt and the plate. Water was allowed to circulate underneath the cooling slope plate to cool the plate while the melt flowed on the plate. For conventional casting, the melt was poured directly into the mould.

Table 1: Chemical composition of A356

Cu	Mg	Si	Fe	Mn	Ni	Pb	Zn	Sn	Ti	Al
0.2	0.2-0.6	6.5-7.5	0.5	0.3	0.1	0.1	0.1	0.05	0.2	BAL

Samples of aluminium alloy were machined into cylindrical type of 15 mm diameter and 80 mm length. The ECAP experiment was carried out at room temperature for one pass using a split die with channel angle of 120° following route A. It was noted that in route A, the sample was pressed without any rotation, route BC where the sample was rotated by 90° in the same direction between passes, route BA was where the

sample was rotated by 90° in an alternate direction between passes while in route C, the sample was rotated by 180° between passes [16]. Figure 1(b) shows the ECAP mould used in this experiment. Lubricant molybdenum disulphide (MoS<sub>2</sub>) was used to reduce friction between billets and mould.

The morphology of ECAPed and cast samples were then examined under optical microscope (OM). The samples were ground using silicon carbide abrasive paper with grit size from 240 until 1200 and polished with 3 µm - 1 µm diamond compound. The samples were then etched using Keller's reagent for 3 - 10 seconds. Image analysis were done by calculating the grain size (GS) and shape factor (SF) of α-Al phase in the sample with the help of Image-J software. Shape factor and grain size were determined using Equations (1) and (2), respectively [17].

$$SF = \frac{4\pi A}{P^2} \quad (1)$$

$$GS = \sqrt{\frac{4A}{\pi}} \quad (2)$$

Where A is the area and P is the perimeter of the primary solid phase. A shape factor must be close to 1 to reach its optimum condition. While for grain size, smaller grain size would exhibit best result.

For hardness testing, the test was carried out using Vickers hardness tester by imposing a 1kgf load for 10s. The samples were prepared by grinding through SiC paper (240 - 1200 grit) followed by polishing and etching. At least 10 measurements were taken for each sample and the average hardness value was calculated.

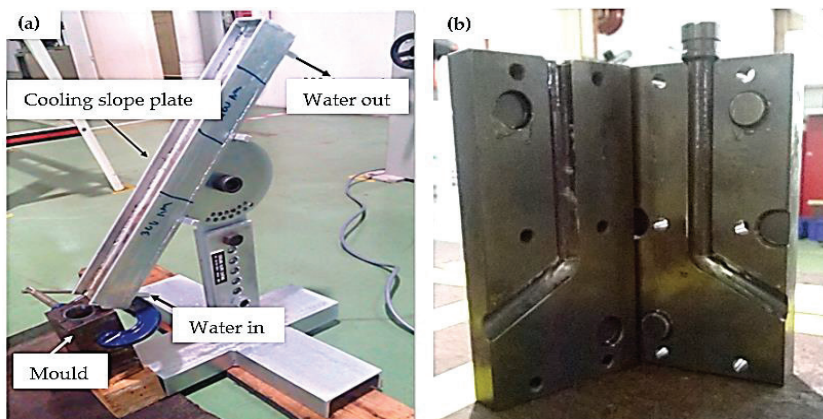


Figure 1: (a) Cooling slope casting apparatus and (b) ECAP mould

### 3.0 RESULTS AND DISCUSSION

#### 3.1 Cooling Slope Casting

Figure 2(a) shows the micrographs of aluminium alloy sample after being processed by conventional casting and Figure 2(b) shows cooling slope casting of A356 aluminium alloy. From these figures, the bright phase refers to primary  $\alpha$ -Al phase while the dark region surrounding the  $\alpha$ -Al phase is eutectic phase. The morphology of  $\alpha$ -Al primary phase found in as-cast sample is almost dendritic and it is altered into a non-dendritic structure when it is casted using cooling slope. During cooling slope casting process, the dendritic arm is fragmented and altered to become a nearly globular microstructure due to the shearing effect on the CS plate [18].

This result is supported by Aziz et al. [19] where they focused on the mechanism of nucleation and fragmentation in the primary phase in obtaining a near spheroidal microstructure. According to Aziz et al. [19], there are four stages of microstructural evolution where it starts with dendritic growth and when it starts to flow down the CS plate, then the dendritic arm is fragmented becoming rosette followed by ripened rosette and finally become globular at the end of the slope plate. Figure 3 shows the microstructure evolution of A319 on CS plate. Figure 3(a) shows a dendritic growth obtained at the impact zone, Figure 3(b) rosette microstructure found in top zone area, Figure 3(c) ripened rosette microstructure at middle zone and Figure 3(d) shows the nearly globular microstructure at the end of the slope plate.

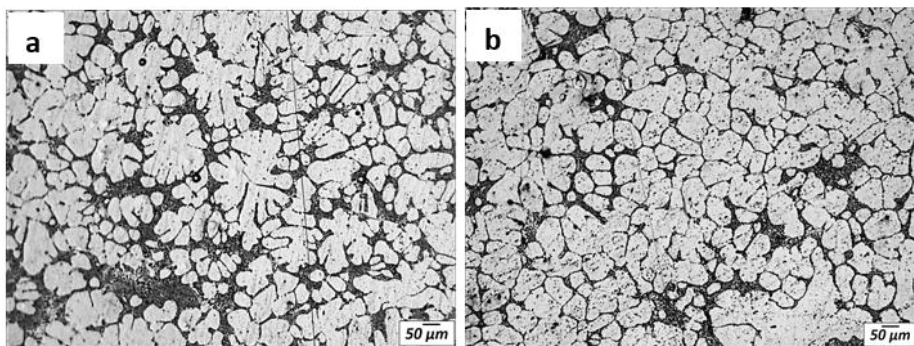


Figure 2: (a) Microstructure of as-cast A356 and (b) Microstructure of CS of A356



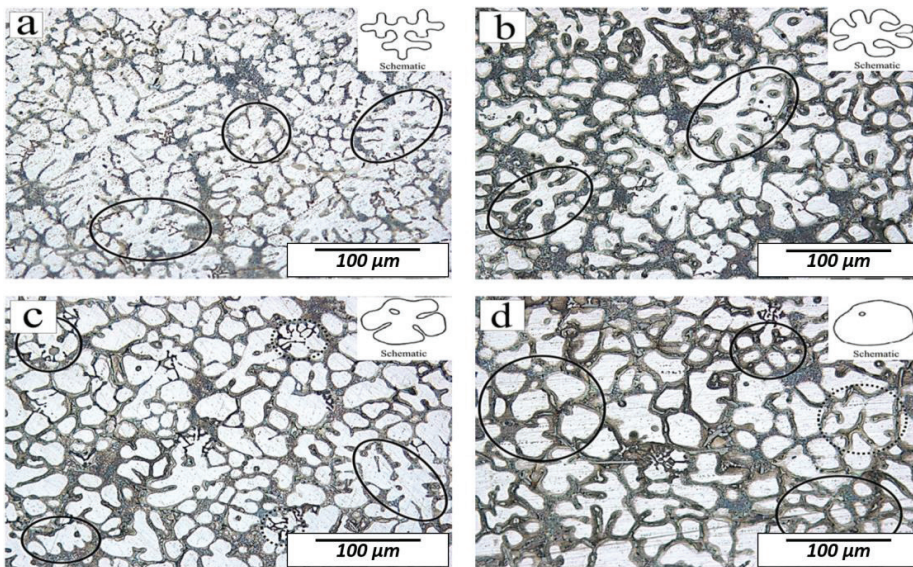


Figure 3: Four stage of microstructure evolution of A319 on CS plate  
 (a) dendritic growth stage, (b) rosette, (c) ripened rosette, and  
 (d) nearly globular [19]

### 3.2 ECAP processing

After one pass of ECAP process using a mould with channel angle of  $120^\circ$ , it was observed that the grain size of  $\alpha$ -Al particles were refined. Figure 4 displays the microstructure of as-cast aluminium alloy and cooling slope casting aluminium alloy after one ECAP pass process respectively. After ECAP, it showed that the grains had been successfully sheared as the dendritic structure existed in as-cast sample were fragmented, becoming non-dendritic structure. From the figures, it was observed that the grain of primary  $\alpha$ -Al phase had been refined as the sample was subjected to ECAP process. The changes of microstructure and reduction of the grain size were due to high shear strain imposed on the sample during ECAP which also helped to enhance its mechanical properties. It is also observed that the grain of  $\alpha$ -Al phase for cooling slope cast sample were elongated after ECAP process. This finding is supported by Mishra et al. [20]. It concluded that there were 5 stages of grain refinement which often occur in the ECAP process. Firstly, homogeneous dislocation distribution of the primary particle, followed by elongation of sub-cell then elongation of sub-grain. The next stage is breaking of sub-grains into equiaxed grain and lastly is equiaxed ultrafine structure [20].

Based on the comparison between as-cast ECAPed and cooling slope ECAPed in Figure 4, it was clearly shown that the  $\alpha$ -Al phase and eutectic phase in cooling slope ECAPed sample were distributed homogeneously compared to the as-cast ECAPed sample after one ECAP pass. This result showed that by using cooling slope casting to produce a feedstock material for ECAP processing may lead to a finer and homogeneous distribution of  $\alpha$ -Al and eutectic phase and it is estimated to improve its mechanical properties of the material [21].

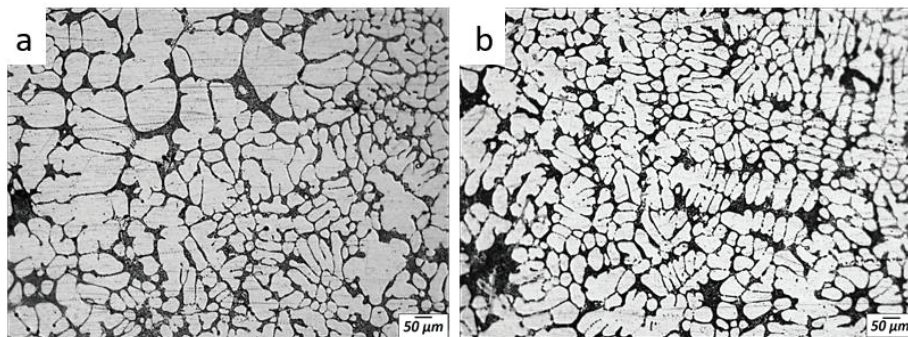


Figure 4: (a) As-cast ECAPed A356 and (b) CS ECAPed A356

### 3.3 Microstructural analysis

The image analysis of each sample was done using Image-J software to find area and perimeter of the particles in order to calculate its shape factor and average grain size. Figure 5 displays the average grain size of  $\alpha$ -Al particles and its shape factor at different condition of processing. As-cast sample exhibited the lowest shape factor with value of 0.5123 and larger average grain size of 110.4 $\mu$ m as there are many dendrite structures found in as-cast sample as shown in Figure 4. The shape factor is a dimensionless quantities used in image analysis to describe the shape of particle where this work focused on spherical shape. Shape factor near to 1 showed the best result in obtaining spherical microstructure. Based on the result, a sample with cooling slope showed the highest shape factor of 0.82. The average grain size of a sample with cooling slope was reduced to 75.37 $\mu$ m from 110.463 $\mu$ m of as-cast sample. It was proven that the  $\alpha$ -Al particles of the sample with CS become globular as the dendrite arms are fragmented due to shearing force on the CS plate [18]. On the other hand, it was also observed that the average grain size of  $\alpha$ -Al particles of cast samples were refined after ECAP process. As-cast sample in combination with ECAP has an average size of 96.3 $\mu$ m from 110.463 $\mu$ m in as-cast sample. Moreover, the cooling slope sample after being processed by ECAP

showed an improvement in terms of the grain size. The grain size was reduced from  $75.37\mu\text{m}$  to  $58.25\mu\text{m}$  with a reduction of approximately 22.7%. It was proven that cooling slope ECAPed gave finer grain size as compared to as-cast ECAPed.

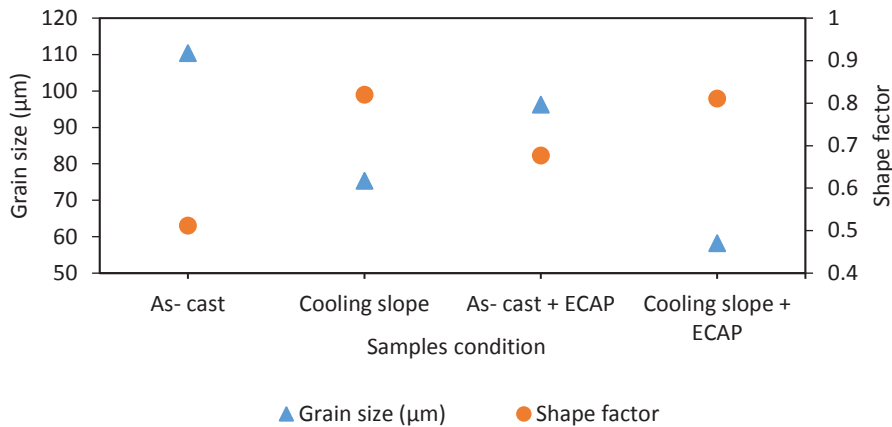


Figure 5: Grain size and shape factor of A356 aluminium alloy at different condition

### 3.4 Hardness

The hardness of each sample was done using Vickers hardness. Figure 6 shows the hardness value of each sample before and after ECAP process for as-cast and cooling slope casting sample. It showed that the hardness value of cooling slope casting was higher than as-cast sample with value of  $84.5 \pm 7.6 \text{ HV}$  and  $74.5 \pm 4.2 \text{ HV}$  respectively. Moreover, the trend in Figure 6 shows that the hardness of A356 increased after being processed by ECAP. Hardness value of as-cast sample was  $74.5 \pm 4.2 \text{ HV}$  and increased up to  $99.5 \pm 9 \text{ HV}$  for as-cast ECAPed. Cooling slope ECAPed showed the highest hardness value of  $102.4 \pm 8 \text{ HV}$  with 21.2 % increment from cooling slope casting hardness. Homogenous distribution of primary  $\alpha\text{-Al}$  phase in the cooling slope sample was one of the main factors that influenced the high hardness value. The hardness value was related to the shape factor and average grain size where the higher the shape factor gave higher hardness as the hardness value was directly proportional to the shape factor. Highest hardness value was obtained by the cooling slope ECAPed due to the reduction of grain size and the porosities in the sample.



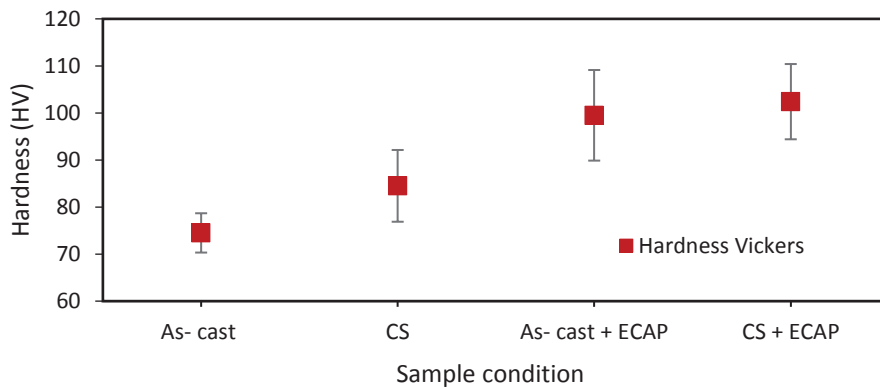


Figure 6: Vickers hardness of A356 aluminium alloy before and after ECAP process

#### 4.0 CONCLUSIONS

In this study, cooling slope casting technique is performed in order to produce feed materials for ECAP processing. It is found that the dendritic structure that normally exists in as-cast sample is altered into a finer and globular microstructure after cooling slope casting. After ECAP process, it is observed that the microstructure for both as-cast and cooling slope casting are refined into smaller grain size. However, the homogeneous distribution of  $\alpha$ -Al and eutectic phase is obtained by cooling slope ECAPed only whereas as-cast ECAPed shows an inhomogeneous distribution of phases. The hardness of ECAPed sample is higher than as-cast and cooling slope sample as the grain size is refined after ECAP which leads to the reduction of porosities. It can be concluded that the cooling slope ECAPed sample exhibits better mechanical properties in terms of its hardness and gives finer and homogeneous distribution of  $\alpha$ -Al and eutectic phase.

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