EFFECT OF EQUAL CHANNEL ANGULAR PRESSING ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF A356 ALLOY

M.S. Salleh, N.N.M. Ishak, S.H.Yahaya, Sivaraos and A. Abdullah

Fakulti Kejuruteraan Pembuatan,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya,
76100 Durian Tunggal, Melaka, Malaysia.

Corresponding Author's Email: shukor@utem.edu.my

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ABSTRACT: This work investigated the effect of equal channel angular pressing (ECAP) on the microstructure and mechanical properties of non-dendritic A356 alloy. This alloy was casted by cooling slope casting in order to produce a globular microstructure feedstock for ECAP process. After that, ECAP process was performed using 120° of die angle via route A for 2 passes at room temperature. The microstructure of the processed alloys was observed under an optical microscope (OM) and scanning electron microscope (SEM) whereas the mechanical properties of the alloy were validated using Vickers hardness test and tensile test. Microstructure observation showed that after 2 passes, the grain size was obviously refined to 35 μm from 75 μm in the as-cast sample. The mechanical properties of the alloy were ultimately improved in ECAP sample. The hardness of the ECAP sample increased as high as 77.6 HV as compared to the as-cast alloy which was 42.3 HV. The ultimate tensile strength also increased from 105 MPa to 237 MPa after 2 passes deformation. It was also discovered that the distribution of α-Al and eutectic phases were more homogeneous at the ECAP sample than using non-dendritic structure feedstock.

KEYWORDS: *Equal Channel Angular Pressing; Aluminium Alloys; Mechanical Properties*

1.0 INTRODUCTION

For more than four decades ago, equal channel angular pressing (ECAP) has been known as one of popular severe plastic deformation techniques [1]. This process focuses on refining the grain size of the material, thus enhancing its mechanical properties [2-3]. There are several techniques for refining a grain size; constrained groove pressing (CGP), accumulative roll bonding (ARB), accumulative back extrusion (ABE), tubular channel angular pressing (TCAP) and high pressure torsion (HPT) [4-8]. Generally, this process started by pressing the subjected material through a die consist of two channels intersected at certain angles. Because of higher shear stain imposed on the material throughout the ECAP process, the microstructure of the material was altered hence improving its mechanical properties [9].

ECAP process is a promising technique of grain refinement which is often used for aluminium alloys and steel. Chegini et al. [10] has performed a study on the effect of ECAP on Al- 7075 alloys. They found after four passes of ECAP via route B_c, the grain sizes were reduced from 40 μm to 0.5 μm whereas the microstructure of the billet are essentially equiaxed and the distribution of phases becomes homogeneous [10]. Other than that, the literature also stated that the grain size of the Al- Cu alloy is obviously decreased from 261 μm of an undeformed material to 177 μm after 2 ECAP passes and the size is reduced to 55 μm as the number of passes increase up to 9 [11].

Various industries in automotive and manufacturing widely utilize aluminium alloy due to its fluidity and mechanical strength. Moreover, due to its light weight properties, the alloy is used in engine block production as it helps to reduce the fuel consumption [12]. Al- Si alloy can be categorized in three categories which is hypoeutectic alloy (less than 11% Si), hypereutectic (11% - 13% Si) and eutectic alloy (more than 13% Si) [13-14]. Even though it is widely used in various industries, it also has a limitation such as low ductility. Hence, many attempts have been done to enhance its elongation to fracture the aluminium alloys.

Previous studies lack of information regarding the ECAP process that uses a non-dendritic billet. There is a huge opportunity to explore the potential of using non-denritic billet to be used in ECAP processing as it can improve the mechanical properties of the alloys. Therefore, in this study, a cooling slope casting was used to get the non-dendritic microstructure for ECAP process. In cooling slope casting, the metal alloy was melted at low superheat temperature and poured onto the incline plate and then solidified alloy were collected in the mould. After that, ECAP process was used to deform the billet in the mould. The produced samples underwent microstructural and mechanical analysis in order to evaluate their strength and hardness.

2.0 EXPERIMENTAL PROCEDURES

In this study, A356 aluminium alloy was used and its chemical composition is displayed in Table 1. Figure 1 illustrates the heat flow versus temperature curves and the liquid fraction for A356 alloy. The DSC analysis was used to determine the pouring temperature of the aluminium alloy.

Table 1: Chemical composition of A356 aluminium alloy

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

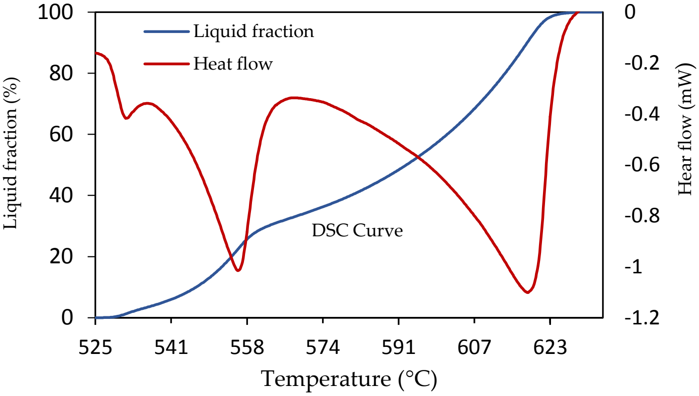

Figure 1: DSC curve

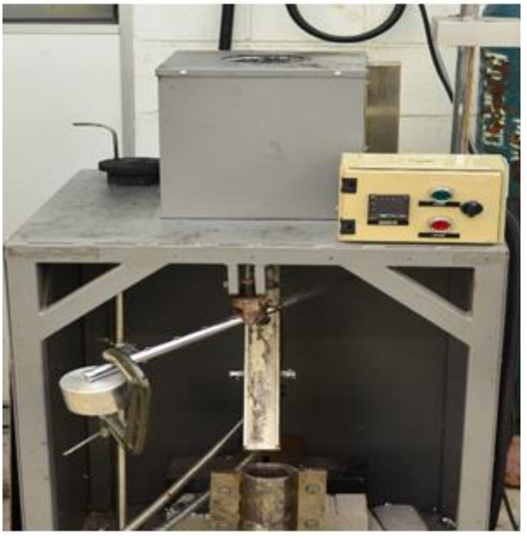

Figure 2: Cooling slope casting experiment apparatus

In order to obtain a non-dendritic feedstock for equal channel angular pressing (ECAP) process, cooling slope (CS) casting process was selected. The process began by placing a small pieces of A356 alloy in the furnace and superheated up to 700°C. The molten alloy was cooled to the designated pouring temperature prior to pouring it on the incline CS plate made of stainless steel with 90 mm width at various pouring temperature and cooling slope length. The tilt angle of the cooling slope as shown in Figure 2, was kept constant at 60° to reduce adhesion of the solidified alloy. The incline plate surface was coated with a thin layer of boron nitride to prevent the adhesion between molten alloy and the plate surface. A water was allowed to flow underneath the plate to increase the nucleation rate of α-Al particles to avoid an unnecessary growth of dendritic microstructure. In terms of as- cast (permanent mould casting), the aluminium alloy was heated to 700 °C and directly poured into the mould. The billet obtained by these casting process was then ground with silicon carbide paper (240 – 1200 grit). After that, diamond compound (3 - 1 μm) was used to polish the sample. Keller's reagent was then used by immersing the sample for 7 seconds before examining it under an optical microscope.

Optical micrographs of the samples were examined under Carl Zeiss optical microscope (OM). Image- J software was used to estimate the area and perimeter of α-Al phase in each sample in order to calculate the grain size (GS) with formula of $4\pi A/ P^2$ and shape factor (SF), $(4A/\pi)^{1/2}$. A is the area and P is the perimeter of the α-Al phase. The best shape factor which should be near to 1 and the smallest globule size of α-Al were selected to undergo the ECAP process.

For the ECAP process, the cylindrical billet of cast sample was machined (80 mm x Ø 15 mm) and then annealed at 440 °C. After that, the sample was pressed through a die with a channel angle of 120° and curvature angle of 30° using route A (the sample is pressed without any rotation) for 2 passes. The experiment was performed using 150-ton hydraulic press and the billet samples were lubricated with molybdenum disulphide (MoS_2) to reduce the friction between the billet and mould. The morphology of ECAP samples were examined under an optical microscope and for the hardness testing, the test was carried out using Vickers hardness tester with a load of 1 kgf for 10 seconds. All the samples were ground and polished before conducting the test. In the hardness test, 10 measurements were taken for each sample and the average value of hardness was calculated. Tensile test was carried out using universal testing machine (UTM) with 100 kN load. The specimens for tensile test were machined parallel to the pressing direction with a gauge length of 10 mm with 2.5 mm diameter in accordance to ASTM E8M standard.

3.0 RESULTS AND DISCUSSION

3.1 Cooling Slope Technique

The microstructure of the as-cast A356 ingot shown in Figure 3(a), exhibited a dendritic structure whereas the cooling slope casting ingot revealed a near globular structure as shown in Figure 3(b). It was clearly seen from Figures 3(a) and 3(b) that the primary α-Al phases were at the bright region whereas the darker phase that surrounded the primary α-Al represented eutectic phase. The transformation of dendritic α-Al of as-cast to a non- dendritic during cooling slope casting was due to the shearing effect during the process [13]. The fragmentation of α–Al was due to the existence of shearing force on the plate and it also acted as a nucleating agent to form the non dendritic structure [15]. The formation of nuclei was because of the contact between molten alloy and the CS plate due to the applied shear stress from the gravitational force [16].

In terms of cooling slope casting experiment, the optimum parameter that was suitable to be used in the production of feedstock for ECAP process was a billet that was produced with a pouring temperature of 625 °C and with a slope length of 200 mm. The shape factor obtained at this parameter was ¬0.82 which was close to 1 and it turned out to be the best shape factor whereas the grain size showed the smallest size of 75.7μm.

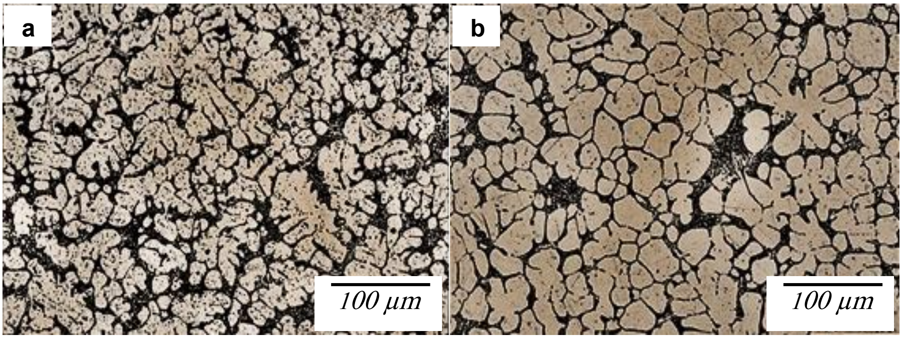

Figure 3: Microstructure of (a) as-cast sample and (b) cooling slope casting pour at 625 °C with length 300 mm

3.2 Annealing

Figures 4 (a) and (b) display an optical micrographs of the as-cast and cooling slope casting A356 after annealing process at 440 °C. Annealing process was performed to reduce the strength and hardness of the cast sample before using it as a feedstock for ECAP process. Figures 4(a) and 4(b) show that both as-cast and cooling slope casting sample after annealing process contain large grain, involving primary α-Al phase, bounded by eutectic constituents, consisting of fine and irregular shape of Si particles. The α-Al became coarser and the Si particle was seen seated between the α-Al. The grain size of the α-Al in Figure 3(b) was 30 μm and increased to 40.5 μm in Figure 4(b) after the annealing process.

3.3 ECAP Process

In ECAP, the billet was pressed through a split die consisted of two channels intersecting at certain angles. After two passes of ECAP process, the grain size of α-Al phases were refined. Figure 5 shows the microstructure of the alloy after subjected to the ECAP through route A. The average grain size of the ECAP sample after 2 passes was reduced about 2 times with respect to the undeformed sample from 75.7 μm to 35.3 μm respectively. The microstructure of cooling slope casting sample in combination with ECAP showed the most homogeneous distribution of primary α-Al phase and eutectic constituents compared to the as- cast sample combined with ECAP. Finer and homogeneous distribution of α-Al and eutectic phases found in microstructure of cooling slope casting combined with ECAP were anticipated that would enhance the mechanical properties of the material. Moreover, it was also discovered that the Si particles became finer than the as-cast and cooling slope casting sample and well distributed. The chances of microstructure and the grain refinement were due to the shear strain imposed on the sample during the process.

Figures 6 (a), (b) and (c) illustrate the SEM images of as-cast after one ECAP pass and cooling slope sample after first and second ECAP passes respectively. It was observed that the phases were homogeneously distributed in the sample as the number of passes increased from 1 to 2 passes. Figure 7 shows the SEM-EDX elemental mapping of as-cast sample after 1 pass of ECAP. Some of the elements such as Al, Cu, Mg and Fe distributed homeogenously in the sample but the Si particles were intensified at the certain region at the dendrite of α-Al. Figure 8 shows a different pattern of elemental distribution as the alloys had undergone cooling slope casting process. All of the elements such as Al, Cu, Si, Mg and Fe were distributed homogenously in the alloys. This was due to the effect of cooling slope casting which broke up the dendrite structure of the alloy. The cooling slope casting samples (Figure 9) which underwent 2 passes of ECAP showed a better refinement in terms of structure as well as elemental distribution. The Si distribution in this sample showed improvement and was distributed homogenously around the Al gobules. Evidently, 2 passes of ECAP were able to refine the Al globules, leading to mechanical properties of the alloy improvement.

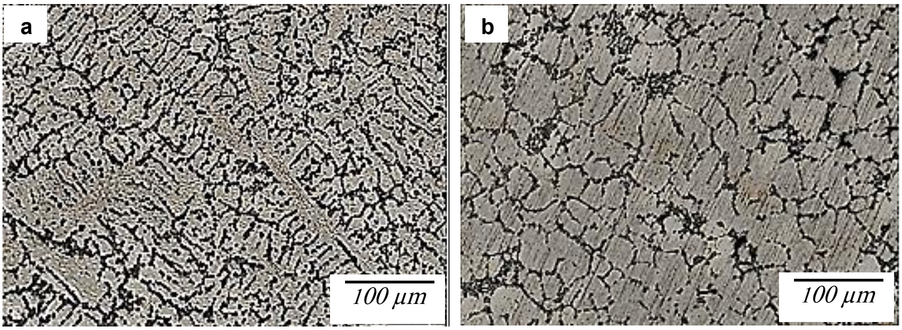

Figure 4: Microstructure of (a) as-cast sample and (b) cooling slope casting sample after annealing

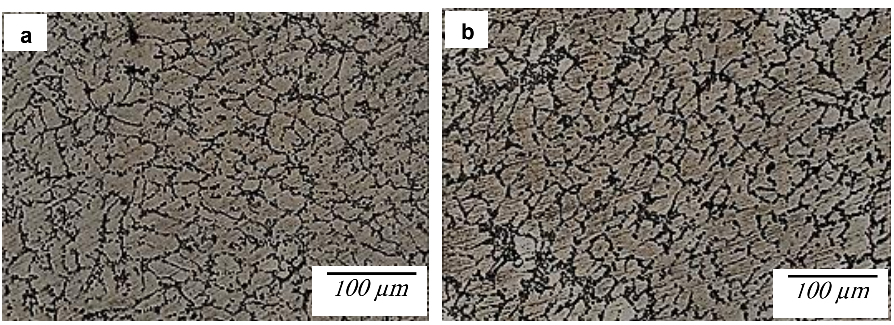

Figure 5: Microstructure of (a) cooling slope casting after 1 ECAP passes and (b) cooling slope casting after 2 ECAP passes

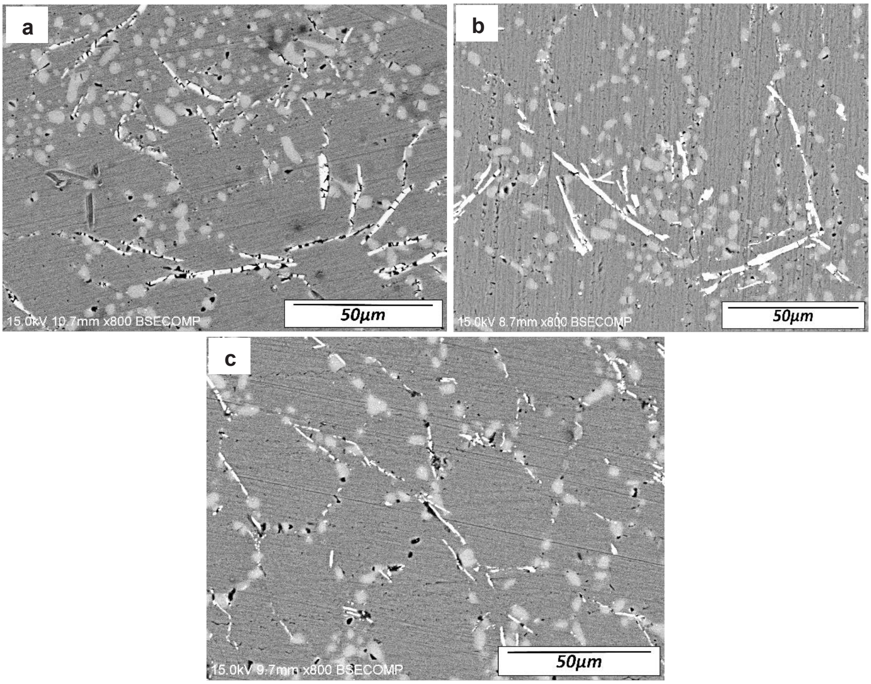

Figure 6: SEM image of (a) as- cast after 1 ECAP pass, (b) cooling slope casting after 1 ECAP pass and (c) cooling slope casting after 2 ECAP passes

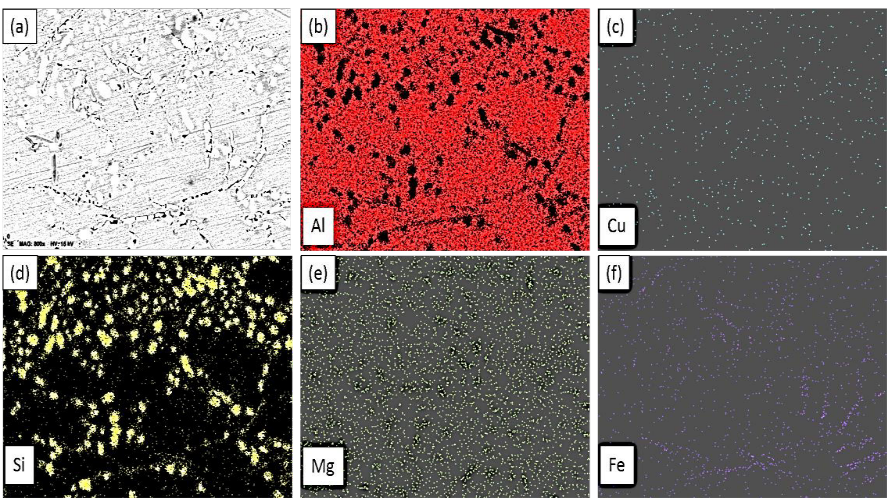

Figure 7: SEM- EDX elemental mapping of as- cast after 1 pass of ECAP: (a) SEM image, (b) Al, (c) Cu, (d) Si, (e) Mg and (f) Fe

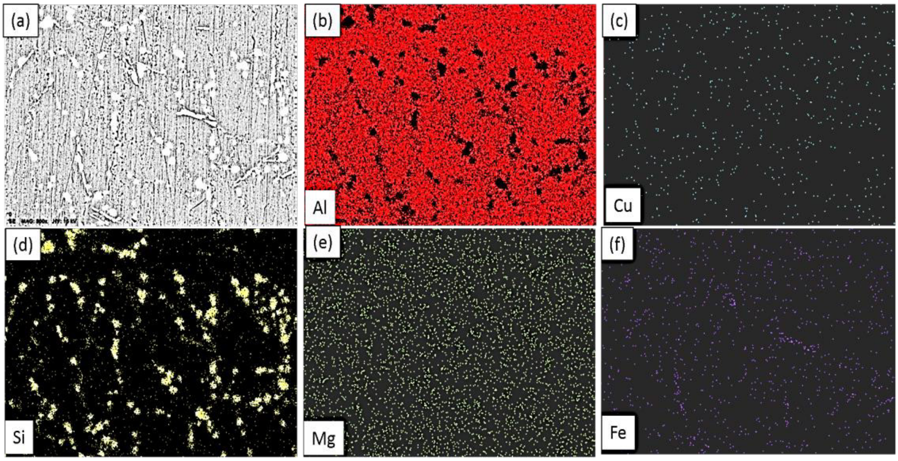

Figure 8: SEM- EDX elemental mapping of cooling slope casting after 1 pass of ECAP: (a) SEM image, (b) Al, (c) Cu, (d) Si, (e) Mg and (f) Fe

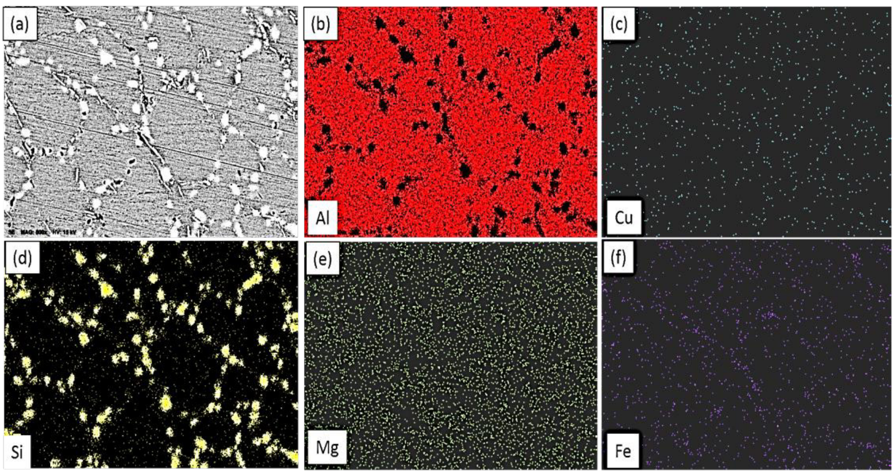

Figure 9: SEM- EDX elemental mapping of cooling slope casting after 2 passes of ECAP: (a) SEM image, (b) Al, (c) Cu, (d) Si, (e) Mg and (f) Fe

3.4 Mechanical Properties

Figure 10 shows the hardness of the alloy before and after one and two ECAP passes via route A of conventional casting and cooling slope casting sample respectively. The hardness had improved significantly after it was subjected to ECAP process. The enhancement of hardness value was related to the microstructure features where the smaller of the grain size resulted in the higher of the hardness value. It was also revealed that the hardness value of as-cast increased about 83% after being processed by ECAP from 42.4 HV to 77.6 HV respectively. Three factors were related to the hardness improvement; Si fragmentation, dislocation density increment and grain refinement caused by the high strain induced during the ECAP process [16]. Nevertheless, different type of casting gave different value of hardness where cooling slope casting exhibited higher hardness than as- cast sample. Besides , the distribution of the α- Al phase and Si particles were also contributing to the main reasons of the hardness improvement [17]. As discussed in previous section, the primary α-Al phase and Si particle were distributed homogeneously in the microstructure of cooling slope casting sample with two ECAP passes. As predicted, the Vickers hardness for this sample exhibited the highest hardness compared to others with the value of 84.3 HV.

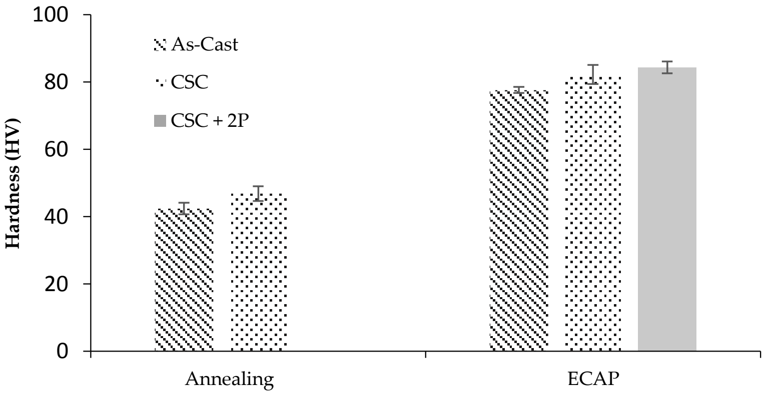

Figure 10: Vickers hardness of as- cast and cooling slope samples after ECAP

Figure 11 shows the results of tensile strength for casting and ECAP processing. Based on the results, the strength of the alloy increased drastically after two passes of ECAP process. The lowest strength was obtained from the as- cast sample with 105.1 MPa value and the highest was attained by CS casting in combination with 2 passes of ECAP with 237.5 MPa value. The improvement of the strength after the first pass of ECAP incresed about 85% because of the presence of dislocation and grain refinement distributed in the sample [18-19]. As discussed previously, the grain size of the sample was reduced significantly after the ECAP process. Moreover, it was observed that the strength increased when the number of passes increased. These results showed a good agreement with a study conducted by El Aal and Sadawy [20] which focused on the microstructure and mechanical properties of aluminium alloy after ECAP process. The study found that the strength of the alloys increased gradually with the increasing ECAP passes.

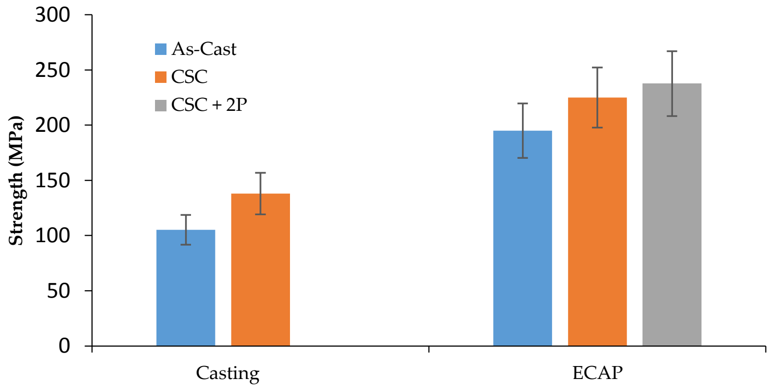

Figure 11: Ultimate tensile strength of as- cast and cooling slope cast samples after ECAP

4.0 CONCLUSION

The cooling slope casting technique is used to produce a non-dendritic feedstock for ECAP. The microstructure of the sample shows a good dispersion of α-Al and eutectic phase becomes more homogeneous. The ECAP samples show a good dispersion of Si particles throughout the samples. In addition, the mechanical properties also show an increasing trend after ECAP. Moreover, by increasing the number of ECAP passes may decrease the grain size, hence, enhancing the mechanical properties.

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