An Investigation of the Equal Channel Angular Pressing Process on the Hardness of Heat-Treated Al-7075 Alloy

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ABSTRACT

Equal-Channel Angular Pressing (ECAP) is among the most applicable severe plastic deformation processes used to fabricate ultrafine-grained materials with superior mechanical properties. In this study, Al-7075 alloy that has undergone heat treatment was processed with ECAP. The samples generated a variety of microstructures. ECAP has been carried out in a mold with 120° channel angle at room temperature. The findings demonstrate that after processing, brittle coarse silicon particles were successfully broken down to smaller sizes in Aluminum-rich matrix. Corrosion resistance and hardness tests improved following T6 and T5 heat treatments, with the former being preferred because of a complete change in the morphology of the silicon particles compared to the latter. Following three passes on the route Bc and 4 passes on route A, hardness was increased with ECAP processing from 60.66 Hv to 1133.47 Hv and 124.91 Hv and alloy's corrosion resistance evaluation improved from 0.04240 to 0.00173 and 0.00149 mmy-1. In the present study, the ECAP processing of Al-7075 alloy utilizing both techniques increased both hardness and strength.

Keywords-ECAP; hardness; heat-treated Al-alloy

I. INTRODUCTION

Equal-Channel Angular Pressing (ECAP) is one of the most significant methods for material processing and includes significant plastic deformation. ECAP's primary objective, dissimilar to drawing, rolling, and extrusion, is to accumulate material deformation with no reduction in the workpiece's cross-section. Due to the straightforward shear method, a bulk material's grain structure is refined uniformly [1]. The grain structure is extremely fine due to the multiple pressings. Materials with ultra-fine grains generally have grains with sizes between a few hundred and several thousand nanometers. This is an area of transition between metals with nanostructures and coarse-grained materials, in which the grain boundaries are crucial to plastic deformation. Due to the initial ECAP passes, an effective grain refining occurs in a series of steps, including homogenous dislocation distribution, development of elongated sub-cells, elongated sub-grains, and their subsequent dissolution into equiaxed units [2]. Si, Al, and Mg make up the Al A356 alloy, which possesses good qualities, including great casting characteristics, corrosion resistance in atmospheric environment, and good fluidity. The alloy has been extensively used for replacing steel components in machinery, defense, and aerospace industries, especially in the automobile sector. Al-Si alloy's electrochemical and mechanical characteristics are significantly affected by the distribution and shape of Si particles [3]. Due to their low density, high strength, and superior resistance to corrosion, AI alloys are widely employed in structural, industrial, and transportation applications. Al-Zn-Mg and Al-Zn-Mg-Cu alloys from 7th series, which are heat treatable, have recently being utilized as primary materials in the marine, automotive, and aerospace industries. The high strength/density ratio and strong thermal conductivity of Al-based materials makes examining their tribological behavior appealing.

The tribological characteristics of Al alone are poor, however various Al alloys may have acceptable wear resistance due to the dispersion regarding hard second phase particles in relatively soft matrix [4, 5]. By using 662 precipitation-hardening procedures, applied heat treatment modifies silicon particles and increases the strength related to Al alloys due to solubility changes of the alloying elements in the matrix with temperature. Because of their small grain sizes, ultra-fine materials exhibit exceptional performance and have several unusual chemical, mechanical, and physical properties [6]. A procedure called Severe Plastic Deformation (SPD) is utilized to create ultrafine-grained (UFG) materials. ECAP is considered the most appropriate approach for SPD [7]. In the ECAP method, the sample is simply sheared by pressing through a die that has 2 equal-cross-section channels that meet at angle Φ with the corner curvature angle. According to some experts, route Bc is the most efficient way to produce UFG material, while other researchers contend that route A is more efficient. According to several studies, grain refining could increase the corrosion resistance of many alloys [8, 9]. It has been hypothesized that grain refinement increased alloys' mechanical properties but decreased their corrosion resistance. Additionally, certain researchers discovered that Al-Mg and pure Mg alloys' corrosion resistance was reduced by grain refinement using ECAP, while a Hall-Petch-like relation for grain size that depends on the rate of corrosion has been suggested. The impact of heat treatment on the corrosion resistance and hardness of A-356 alloy has been improved by the ECAP processing. In [10], heat treatment was carried out using T6 and T5, and ECAP processing was carried out with route Bc [10]. Because of the shear strain accumulation, ECAP reaches unusually high strain by enabling an endless number of pressing passes. This high imposed shear strain leads to grain refinement, hence enhancing mechanical characteristics. Through specimen rotation about its longitudinal axis after every pass in the ECAP, numerous processing routes could be utilized, introducing various slip systems and significant grain refinement [11]. The effects of the ECAP technique on the hardness of heat-treated Al-7075 alloy were investigated in [12-14]. Optimizing conditions enhances the material's performance, whether through mechanical strength or print quality. Authors in [15] highlight the importance of precise processing in achieving desirable outcomes in material fabrication.

The goal of the current study is to comprehend the way the material's microstructure and mechanical characteristics change after being treated with ECAP, which is known to increase the material's strength. Age and other heat treatment variables are investigated to determine how they affect hardness in conjunction with ECAP processing, and how they improve the hardness and general performance of Al-7075 alloy. Higher levels of temperatures than those utilized in other works are considered.

II. EXPERIMENTAL WORK

Workpiece: As the primary ECAP material, Al-7075 alloy was used in the studies. Table I displays the Al-7075 alloy's chemical composition. The extruded rods have been annealed for one hour at 415 °C before ECAP, and after that, they were cooled in furnace. Al7075 rods were bent to cylindrical shapes of 140 mm in height and 20 mm in diameter, which were after that sent through an ECAP die with outer curvature angle of Ψ = 20^o and a channel angle of Φ = 120^o. Figure 1 illustrates the schematic of the ECAP die. With the use of processing route BC (a 90^o clockwise rotation around the sample axis between every pass), all billets were pressed up to four times at the temperature of the room with pressing speed of ~ 0.50 mm/s. Figure 2 shows the ECAP die with the four heating elements, the billet pressed from the top, and the exit channel towards the reader.

TABLE I. CHEMICAL COMPOSITION OF THE Al 7075 ALLOY

Ti	Cr	Zn	Cu	Mg
0.02	0.21	5.7	1.50	2.65
Mn	Fe	Si	Al	
0.04	0.09	0.07	Base	

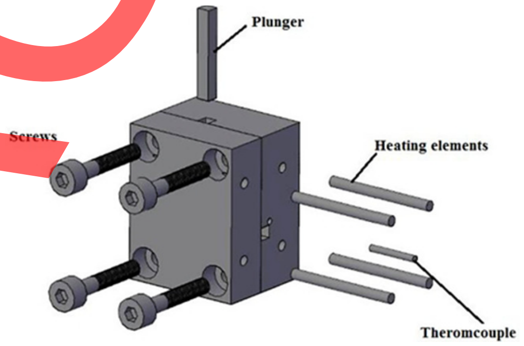


Fig. 1. Schematic illustration of the ECAP die.

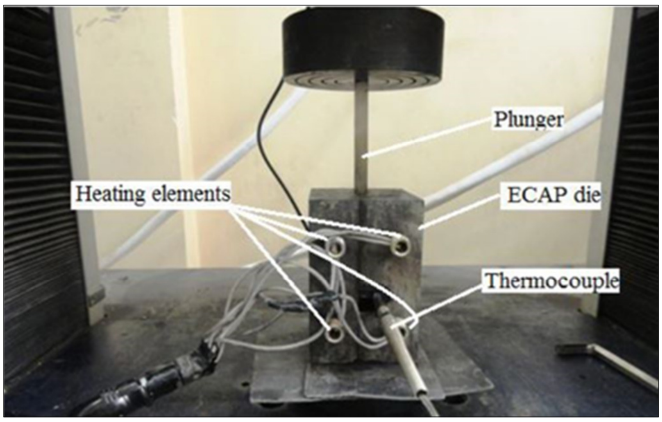


Fig. 2. ECAP die with the four heating elements.

The samples were prepared for T6 and T5 heat treatments using a tube furnace fixed on the machine as shown in Figure 3.

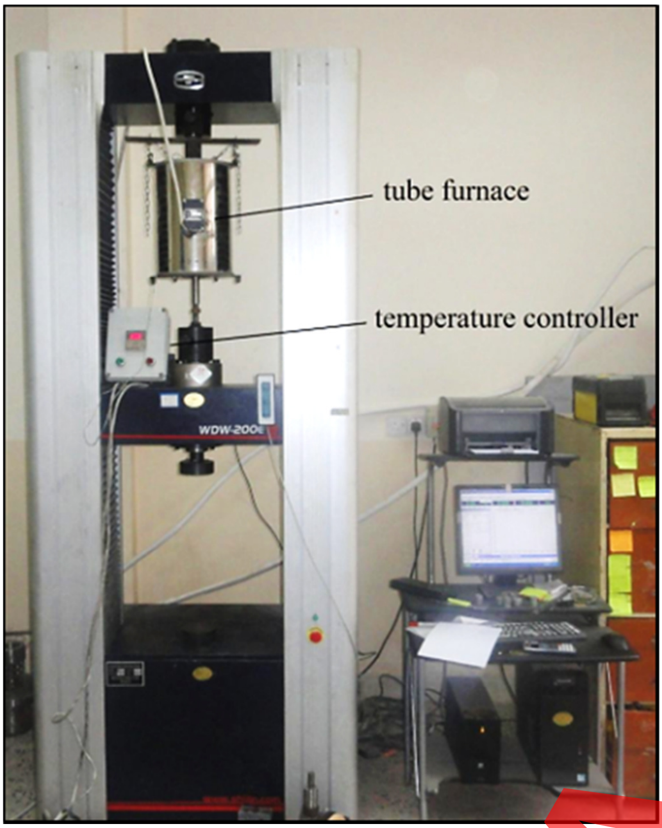


Fig. 3. Mechanical testing system after modifying the machine to fit a tube furnace.

The T5 heat treatment was completed at 160 ^{o}C for 5 hr, whereas the T6 composition heat treatment was completed at 535 ^{o}C for 8 hr, succeeded by water quench. The samples were aged for 3 hr at 180 ^{o}C. Both as-cast and heat-treated samples were ECAP processed at ambient temperature utilizing cycle A in which the specimen was fixed through all passes and cycle Bc in which the samples were rotated by 90^{o} around a linear axis between passes in the die as shown in Figure 4. Optical microscopy, SEM, and EDX were utilized to analyze the micro-structure characteristics of the SPD processed Al 7075. Each sample was taken from rounded rod normal to the movement of the pass and and were grounded with consecutive grades with silicon carbide abrasive sheets from P-180 to P-2000. The samples were polished further with the use of diamond suspension down to 1 μm to achieve a mirror-like quality. In addition to recording the SEM images, elemental mapping was carried out with the use of EDX.

III. RESULTS AND DISCUSSION

A. *Micro-Structure of Al 7075 Pre/Post Heat Treatment*

The SEM image of the as cast Al (6.7%) Si-alloy with magnification factor of 150x and SEM Hv of 15 KV is shown in Figure 5(a), which displays a common hypo-eutectic solid structures, with majority dendritic α-Al, i.e. the white phase being encircled with an eutectoid mix (black phase). The morphology of the eutectoid silicon debris is coarse flake. Because of the low temperature of the heat treatment during the T5, the flake morphology of the silicon particles changed into a coarse acicular and generally spherical form, as shown in Figure 5(b). Following T6 heat treatment, the morphology related to the eutectic Si particles altered. Throughout solution heat treatments, the flack silicon particles break down to smaller portions and eventually spheroidize, as seen in Figure 5(c). Because of the altered morphology of the Si particles, T6 heat treatment enhanced alloy more compared to the T5 heat treatment.

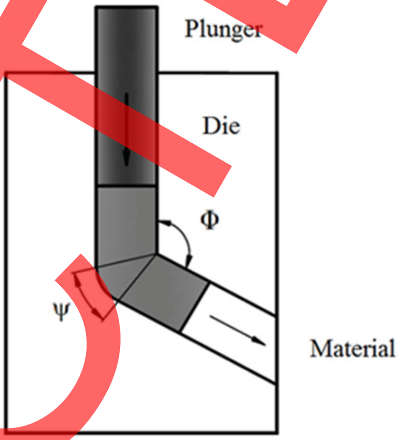


Fig. 4. The internal channel and the two angles of the die.

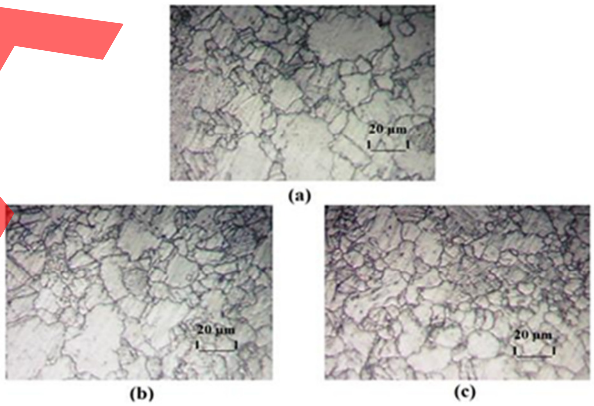
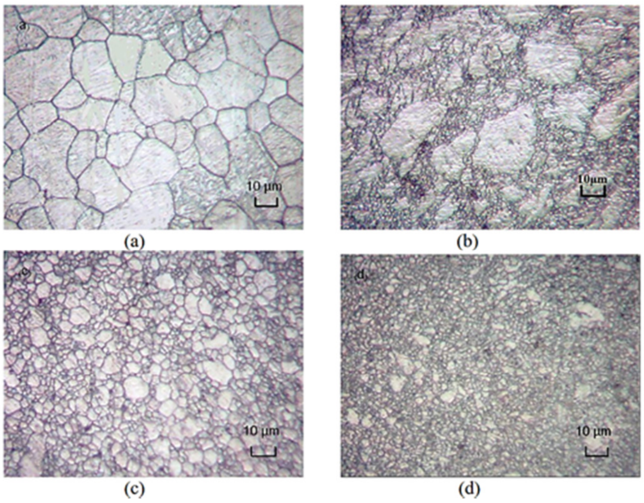


Fig. 5. Micro-structure of the Al-alloy 7075, (a) as cast, (b) T5-heat treatment, (c) T6- heat treatment..

B. *Micro-Structure of ECAP Processed Samples*

The micro-structure of the ECAP processed as-cast samples following two passes on the route Bc after T5 and T6, respectively, is depicted in Figures 6(a)-(b). The microstructure after T6 and T5 heat treatment showed uneven shape and certain solid Al particles were still adhering to one another and the separation process was not finished. The grain refinement takes place throughout the first pass due to the higher dislocation rate, which caused coarse grains to break into numerous finer grains with some larger grains nearby. Figure 6 shows that the mass loss was reduced considerably after 2 passes of the ECAP process and increased with increasing applied load of the wear test. This reduction in the wear mass loss after the ECAP process can be attributed to the grain refinement and the increase in the strength according to the Hall–Petch relationship which increases corrosion resistance. Figures 6(c)-(d) depict the microstructure of the as-cast ECAP processed samples following two passes on the route A at T5 and T6, respectively.



(a) (b)

(c) (d)

Fig. 6. Micro-structure of the ECAP as cast samples by two strokes, (a) T5 heat treatment (Bc cycle), (c) T6 heat treatment (A cycle).

The shear bands that are created at the start of route A quickly subdivide the coarse alloy grains. Following two passes, it is evident that the micro-structure is made up from longitudinal grains with certain grains becoming highly expanded, with grain borders generally tending to be at a 45° angle. The eutectoid state doesn't spread evenly throughout the substrate, and the microstructure is fairly unhomogeneous. At T6, the eutectic phase is finer in both methods. The typical Si particle and grain size is shown in Table II. The microstructure elucidates that the grain size refinement is clear after the first three passes, as shown in Figure 7.

TABLE II. MEAN GRAIN SIZE VALUES AND Si PARTICLE SIZE

Pass number and route	Silicon particle size (µm)	Grain size (µm)
0 pass	4.22	170.51
0 pass-T5	3.25	163.00
0 passes-T6	2.46	116.00
2 passes Bc	2.54	125.13
2 passes Bc-T5	2.30	78.00
2 passes Bc-T6	1.63	64.61
2 passes A	2.68	105.10
2 passes A-T5	1.987	77.20
2 passes A-T6	1.74	62.85
3 passes Bc-T6	1.33	48.49
4 passes A-T6	0.761	40.40

According to Figure 8(a), increasing the strain using route on the T6 sample on route Bc enhances the solid's shape to the point where it fills the solid cavities after a minimum of three passes. Both as-cast T5 and T6 samples after route Bc's third and fourth passes revealed surface cracks along the sample. Figure 8(b) shows the sample after 4 ECAP passes after T6 heat treatment. It demonstrates that by increasing the level of strain through route A, grain refinement occurs within the elongated shape, grain width reduces, deformation bands develop within the grains, the micro-structure had better uniformity of the expanded Al phase's surrounding the eutectoid combination.

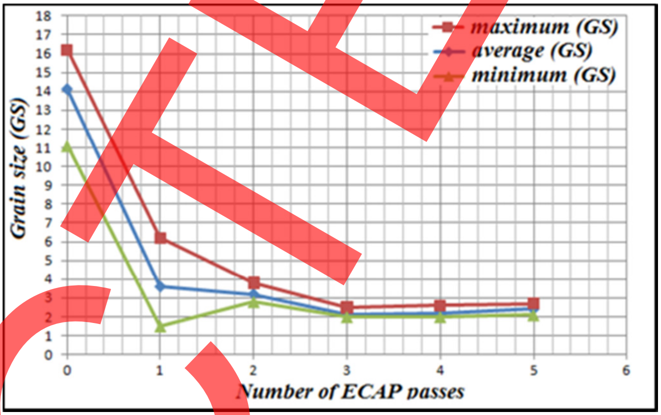


Fig. 7. Grain size refinement after the ECAP process.

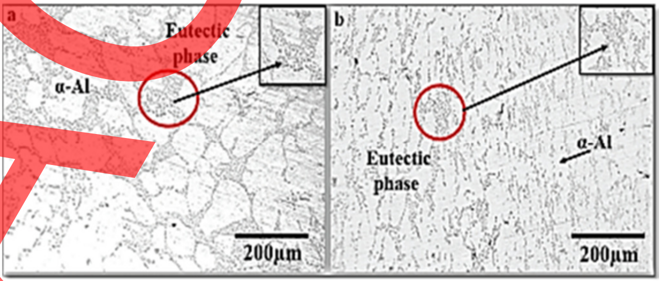


Fig. 8. Micro-structure of the ECAP (T6) as casted specimen: (a) with three strokes on cycle Bc, (b) with four strokes on cycle A.

Following the ECAP procedure, the AL-7075 alloy's microstructure showed two significant effects: the eutectic mixture phase and primary α-Al phase changes. The initial Al dendrites were surrounded by Si particles with a big, brittle flack morphology in the as-cast structure, which had the usual dendritic form of α-Al. Regarding the T6 sample, after three passes, the α-Al phase underwent substantial plastic deformation in the Bc route, changing to an almost spherical shape. Rather than the rheocast process, the application of ECAPP via route Bc resulted in the globularization of the microstructure of α-Al. While applying more passes along route A, the α-Al phase took on a longitudinal and fibrous shape.

Table II displays the grain size and mean silicon particle size of the treated samples. Following T6, the eutectiod Silicon debries were spheroidized and evenly dispersed on the grain's borders. The mean size of the eutectic as cast Si debries decreased from 4.22 µm to 3.25 µm and 2.46 µm with T5 and T6, because to the narrowing and brake failure processes throughout the T6. After four passes along route A, the ECAP (T6) reduced the large Silicon debries into tiny pieces that were equiaxed, with a mean approximate size of size 0.76 µm. Due to the high dislocation density, the as-cast alloy's grain size decreased after the ECAP (T6) from 170.5 µm to 40.4 µm with four strokes. As a result of the continuous shearing on 3 crystallographic planes in route Bc, the sub grain's borders evolved very quickly to highly anglular grain 's borders, whereas in the cycle (A), continuously shear occurs only on 2 planes of crystallography. Table II shows that the eutectic Silicon size of grain is less with the cycle Bc than with A. ECAP processing of the extruded material resulted in somewhat finer grains compared to heat treatment processing. Following T6, Al 7075 alloy could be processed using three passes of route Bcp.

C. Hardness

The impacts of T5 and T6 heat treatments, along with the ECAP processes using routes A and Bc, on Al 7075 alloy hardness are shown in Figure 9. The morphology changes of the Silicon particles from the particles of the coarse flakes, which badly impact the mechanical characteristics, to the acicular Silicon particles after T5 heat treatment, is responsible for the improvement of the Al 7075 alloy following heat treatment. After T6 heat treatment, the eutectic Si was observed to spheroidize, which increased the samples' hardness. In essence, the spheriodization of Silicon particles following T6 heat treatment and the precipitation regarding Mg_2Si particles throughout the aging phase serve to boost the final tensile strength and hardness. This is evident by the fact that the average hardness value rises with the number of passes. The main α-Al tends to sheroidize through the Bc cycle, where the expanded form was dominating through the A cycle, besides the silicon parts got fractured due to the increasing in the specimens hardness following the second ECAP pass.

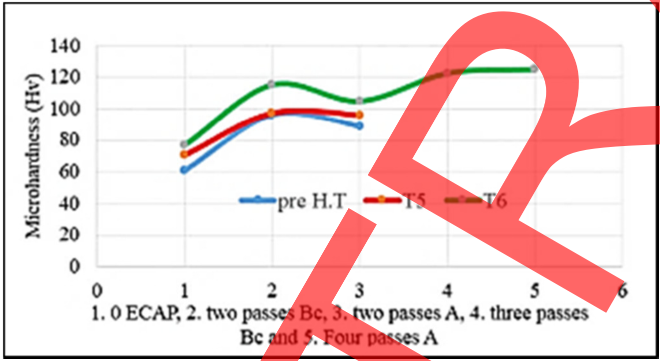


Fig. 9. Micro-hardness of the ECAPed heat treated ECAPed A-356 alloy.

Micro-structure remained inhomogeneous and the occurrence of dendritic forms diminished. Additionally, it was noted that applying deformation causes brittle and hard eutectic Silicon formations to break, and that as deformation increases, the mean free space of these particles decreases. Since the strength and the mean free space of particles are inversely related, raising the pass number raises the hardness values of the samples. Due to the fragmentation related to the eutectic Silicon particles, grain size reduction, and the aging process, both samples became harder after 3 ECAP route Bc passes and 4 ECAP route A passes. The primary α-Al phase and even distribution of Silicon particles in ECAPed route A are crucial in increasing the hardness of the ECAPed materials.

IV. CONCLUSSION

After examining the electro-chemical characteristics and hardness regarding heat-treated ECAPed A-356 using A and Bc cycles and varying pass numbers in 3.5 wt.% NaCl solution, it was found that improvements in the mechanical and electrochemical properties of the alloy Al 7075 are greatly influenced by the shape of the Si formations. Both routes A and Bc could be used to reduce the grain size and Si particle size with the use of the ECAP method, although route A is better suited for Al 7075 than route Bc. Because of the altered Si formation shape and the precipitation regarding Mg_2Si particles during aging, which increases the hardness of the Al 7075 alloy, heat treatment T6 is preferable over T5.

ECAP passes, and subsequent micro-structural evolution as well as Silicon particle fragmentation with re-distribution at the boundaries of the grain, are of high importance in reducing the rate of corrosion and increasing polarization resistance due to the decreased cathode to anode (Ac/Aa) area ratio in micro-galvanic effect. Eutectoid Silicon parts became more uniformly dispersed and less in size than seen in previous works. As a result, the regional distribution results were improved to greater layer stability by reducing the cathode to anode area ratio. The ECAP method improves the dispersion of the eutectic mixture throughout the material, resulting in the ultra-fine-grained bulk materials with enhanced hardness and corrosion resistance.

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