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Enhancement of Mechanical Properties for Al-Mg-Si Alloy Using Equal Channel Angular Pressing

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***Abstract*—**Equal channel angular pressing (ECAP) of commercial Al-Mg-Si alloy was conducted using two strain rates. The ECAP processing was conducted at room temperature and at 250°C. Route A was adopted up to a total number of four passes in the present work. Structural evolution of the aluminum alloy discs was investigated before and after ECAP processing using optical microscopy (OM). Following ECAP, simple compression tests and Vicker's hardness were performed. OM micrographs showed that, the average grain size of the as-received Al-Mg-Si disc tends to be larger than the size of the ECAP processed discs. Moreover, significant difference in the grain morphologies of the as-received and processed discs was observed. Intensity of deformation was observed via the alignment of the Al-Mg-Si consolidated particles (grains) in the direction of shear, which increased with increasing the number of passes via ECAP. Increasing the number of passes up to 4 resulted in increasing the grains aspect ratio up to ~5. It was found that the pressing temperature has a significant influence on the microstructure, Hv-values, and compressive strength of the processed discs. Hardness measurements demonstrated that 1-pass resulted in increase of Hv-value by 42% compared to that of the as-received alloy. 4-passes of ECAP processing resulted in additional increase in the Hv-value. A similar trend was observed for the yield and compressive strength. Experimental data of the Hv-values demonstrated that there is a lack of any significant dependence on the processing strain rate.

***Keywords*—**Al-Mg-Si alloy, Equal channel angular pressing, Grain refinement, Severe plastic deformation.

I. INTRODUCTION

GRAIN size can be seen as a key microstructural factor affecting nearly all aspects of the physical and mechanical behavior of polycrystalline metals [1]. Bulk ultrafine-grained (UFG, < 1µm) and nanocrystalline (NC, < 100 nm) materials have attracted considerable attention thanks to the potential achieving unusual mechanical properties as well as improving strength-to-weight ratio [2]. Among the various techniques used for producing UFG and NC-structured materials, severe plastic deformation (SPD) techniques have been successfully applied to a large number of metallic alloys to achieve ultrafine-grained structures with unique properties [3], [4].

High strength and superplastic properties are commonly achieved in light alloys, as a result of the refinement of coarse-grained structures down to the nanoscale. Among light alloys, the AA6XXX alloys based on the Al-Mg-Si system are widely used because they show a good combination of formability, plasticity, corrosion resistance, capacity for crucial shape forming along with their ease for joining, high strength-to-weight ratio, extrude-ability, and an excellent response to surface finishing operations [5], [6]. These properties have become increasingly focused for versatile applications of Al-Mg-Si alloys such as design of armor structures, rocket, missile casing, light-weight defense vehicle, cars, car body outer panels, and marine structures [7]-[9]. To further improve their mechanical properties, several studies tried to reduce the grain size by SPD using equal channel angular pressing (ECAP) [10]-[12]. The fact that the material cross section is unchanged during pressing is significantly a main advantage achieved in ECAP, which tells that the material could be pressed repeatedly to reach a high total strain. Furthermore, ECAP has a major industrial significance because bulk materials could be processed using this technique [13].

Different studies described the fundamental process of metal flow during ECAP [14]. The principle of process description is illustrated schematically in Fig. 1, where a die is designed to contain a channel that is bent through an immediate angle of 90◦. A sample is machined to fit in into the channel, which is then pressed through the die using a plunger [15].

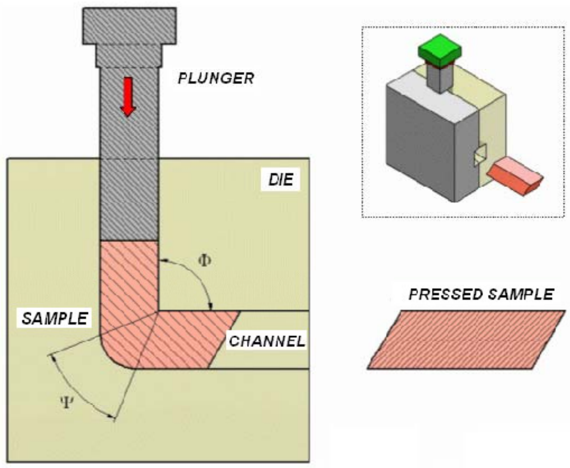

Fig. 1 Schematic illustrations of the ECAP die [17]

The strain imposed on the sample in each passage through the die is dependent primarily upon the angle between the two parts of the channel, Φ (90◦ as shown in Fig. 1), and also to a minor extent the angle of curvature, Ψ, representing the outer

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arc of curvature where the two channels intersect. Generally, ECAP is conducted using a die having a channel angle of *Φ*=90◦ to achieve optimum results [15]. A well acknowledged method to estimate the magnitude of total strain [16]. The accumulated strain ε_{eq} by passage through ECAP die is given by:

$$\varepsilon_{EQ} = \frac{N}{\sqrt{3}}\left[2cot\left\{\left(\frac{\phi}{2}\right)+\left(\frac{\psi}{2}\right)\right\} + \psi cosec\left\{\left(\frac{\phi}{2}\right)+\left(\frac{\psi}{2}\right)\right\}\right] \quad (1)$$

where N is the nature of separate passages through the die.

UFG and NC-structured materials have a number of unusual properties still requiring deeper investigations to be fully understood. As a result, the present study aims to examine some activities within this area that are currently in progress among research. Results on Al alloys deformed by ECAP will be presented giving particular emphasis on the properties achieved by refining the materials to the ultrafine grain scale.

II. Experimental Procedures

Hot rolled rods of commercial Al-Mg-Si alloy are used in this study. The chemical composition of the as-material is given in Table I. The rods are machined to billets with dimensions of 14 mm in diameter and 70 mm in length.

TABLE I
Chemical Composition of Al-Mg-Si alloy

Element	Si	Fe	Cu	Mg	Sn	Sb	Zn	Al
wt.%	0.366	0.129	< 0.024	≈ 0.377	< 0.024	> 0.331	< 0.323	BAL.

The ECAP die and plunger were designed taking into consideration the high pressure inside the deformation zone. They were manufactured from three assembled high strength steel parts (W320 heat treated to HRC of about 55). The die angles were set at: Ψ = 6° and φ =90◦. In the present work, Route A (the sample is pressed without rotation) was adopted up to a total number of four passes (corresponding to an equivalent strain of εeq ~ 4.24 according to (1)). The billets were lubricated using graphite-based lubricant and pressed into the ECAP die at a cross head speed of 6 and 60 mm/min using 500 KN universal testing machines. The ECAP process was conducted first at room temperature then at 250°C.

The experimental results explored the effects of ECAP processing temperature, processing cross head speed, and number of passes through the ECAP die on the mechanical properties. Fig. 2 shows the billets images before and after ECAP processing. The shape and dimensions of billet was changed after ECAP procession, where mechanical properties, microstructures, and further investigation are done on the obtained billet.

In order to provide clear description of the ECAP condition, this investigation used three digits designation. The first digit indicates the ECAP processing temperature (R for room temperature and H for 250°C), the second digit indicates the cross head speed (1 and 2 for cross-head speed of 0.1 and 1 mm/sec, respectively), and the third digit indicates the number of ECAP passes.

Following ECAP, simple compression tests were performed using a material testing system (MTS-810) with a constant speed of 5 mm/min. Compression specimens having 14 mm in gauge length were cut parallel to the longitudinal axis of the ECA-pressed billets. The deformed specimen showed very little barreling (less than 2%). For optical microscopy imaging, the samples obtained after ECAP were then sliced perpendicularly to the longitudinal axis with a thickness of ~ 5 mm. The samples were polished to a mirror-like finish. Microstructural evolution of the disks before and after ECAP was characterized by a Leica Eclipse MA 100 optical microscopy. Hardness measurements were also conducted on the polished surfaces using digital metallic Vicker's hardness tester (TH 721) before and after ECAP. Testing was carried out on the surfaces under applied load of 10 N and a dwell time of 15 sec for each separate measurement and a reported value of the average of 5 readings is recorded.

(a) (b)

Fig. 2 Snap shots for sample (a) before and (b) after ECAP processing

III. Results and Discussion

A. Microstructure Observations

The microstructure of the as-received samples of Al-Mg-Si alloy is shown in Fig. 3. It revealed the formation of almost equiaxed grains with average grain size of 65µm with well-defined grain boundaries in the vicinity of the sample center. Figs. 4 and 5 show the typical micrographs taken from the central portion of the disc post ECAP processing via 1-up to-4 passes of route A at a processing temperature of 250 °C, and 1 pass at room temperature at a strain rate of 1.4 x10^{-3} and 1.4x 10^{-2} s^{-1}, respectively. Influence of the deformation amount on the shape and size of the grains developed during deformation is clearly depicted in the images displayed. It is clear that increasing the amount of induced strain from 1-to-4 pass resulted in severe elongation of the structure in the shear direction of the ECAP processes as shown in Figs. 4 and 5 (a)-(e)) compared to Fig. 3.

Inspection of these microstructures revealed important observations which were consistent for all processing conditions. Grain was revealed via optical microscopy (OM) as shown in Figs. 4 and 5. In order to explain the influence of ECAP processing on the mechanical properties of the processed alloy, the following structural features will be discussed.

The average grain size of the as-received Al-Mg-Si disc tends to be larger than the size of the ECAP processed discs (achieved in the first three passes) due to the fact that original grains breakup into bands of sub grains. These sub boundaries subsequently evolve with further pressings into high angle grain boundaries [16]. The average size of the equiaxed grains, which dominated the microstructure before ECAP processing, is determined in the first pass through the die by the width of the subgrain arrays measured perpendicular to their longer axes [15]. Moreover, significant differences in the grain morphologies of the as-received and processed discs were observed. The angle of orientation of the sheared grains of each condition should reflect the amount of straining that the structure went through, which represented the losses in energy in terms of rigid body rotation and densification of the structure. Intensity of deformation was observed via alignment of the Al-Mg-Si consolidated particles (grains) in the direction of shear, which increased with increasing the number of passes via ECAP as shown in Figs. 4 (c), (d) and 5 (c), (d) compared to Figs. 4 (a), and 5 (a) for the ECAP samples, processed at strain rate of 1.4 $x10^{-3}$ and 1.4x 10^{-2} s^{-1}, respectively.

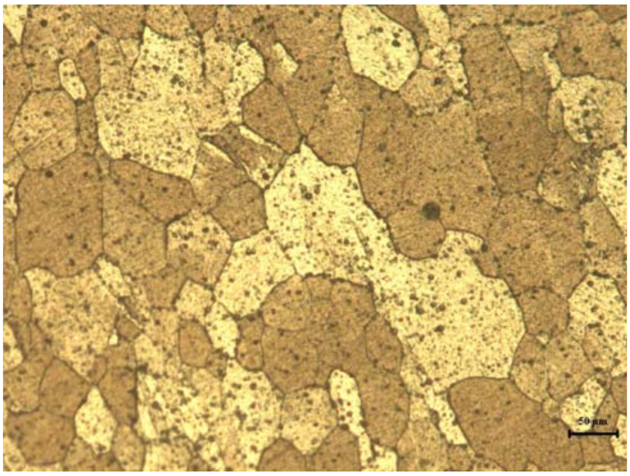
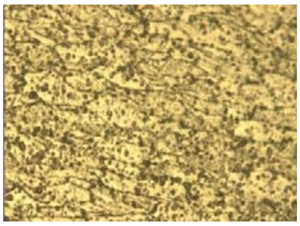
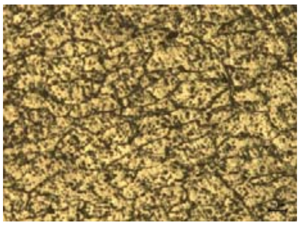


Fig. 3 OM micrographs of as-received Al-Mg-Si alloy

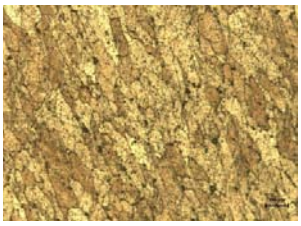
During the ECAP process, SPD was realized by accumulated plastic deformation, which increased obviously with the increase of extrusion pass [18]. This finding can be seen in Figs. 4 and 5, where the elongated grains are inclined to the horizontal X-direction over a range of angles from 20° to 60° as the number of ECAP passes increased from 1-up to-4 passes for the tow condition of strain rates (Fig. 4). A similar trend was observed for the discs processed at a strain rate of 1.4x 10^{-2} s^{-1} (Fig. 5). It showed that total introduced deformation of ε_{eq} ~ 4.24 (which corresponds to processing through 4 passes) wasn't enough for the formation of a uniform equiaxed UFG structure (Figs. 4 and 5).



(a)

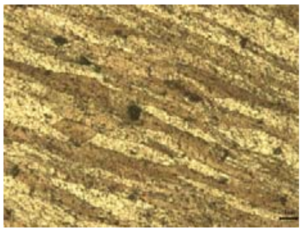


(b)



(c)

(d)



(e)

Fig. 4 OM micrographs of Al-Mg-Si alloy after ECAP processing at strain rate of $1.4x10^{-3}$ s^{-1} at (a)-(d) 250 °C and (e) room temperature through (a), (e) 1, (b) 2, (c) 3, (d) 4 passes

Due to the SPD induced with increasing the number of passes, the as-received equiaxed grains were heavily elongated in different directions following the orientation of slip planes as shown in Figs. 4 (c), (d) and 5 (c), (d). Even within the same grain, several orientations of the subgrains revealed deformation on more than one slip plane of the aluminum alloy indicative of multiple slip, which was manifested in Figs. 4 (d) and 5 (d) which agrees with the theoretical shearing pattern that developed when processing a polycrystalline materials via ECAP [15]. This could provide an indication of the evolution of substructure of medium-to-high angle boundaries which matches with [19]. Further investigation with SEM and TEM is necessary to validate this observation.

Increasing the number of passes up to 4 resulted in a slight increase in the grains aspect ratio (L/W) from ~4.5 (Fig. 4 (a)) up to ~5 (Fig. 4 (d)) which is in accordance with [20]. A similar trend was observed for the discs processed at the higher strain rate (Figs. 5 (a)-(d)).

Increasing the strain rate induced higher degree of strain hardening on the structure, which was manifested by slight excess elongation (higher aspect ratio) of the sheared grains compared to the ECAP processed disc at the lower strain rate deformed at the same processing conditions as shown in Figs. 5 (a)-(e) compared to Figs. 4 (a)-(e). These results demonstrated that the strain rate has no significant influence on the equilibrium structure formed by ECAP; however, since recovery occurs more easily when pressing at the slower speeds, these lower strain rates produced more equilibrated microstructures [14]. Moreover, increasing the strain rate resulted in increasing the intensity of shear lines as shown in Fig. 5 (d) (at strain rate of 1.4x 10-2 s-1) compared to the ECAP disc processed at the same number of passes at lower strain rate (1.4x 10^{-3} s^{-1}) as shown in Fig. 5 (d).

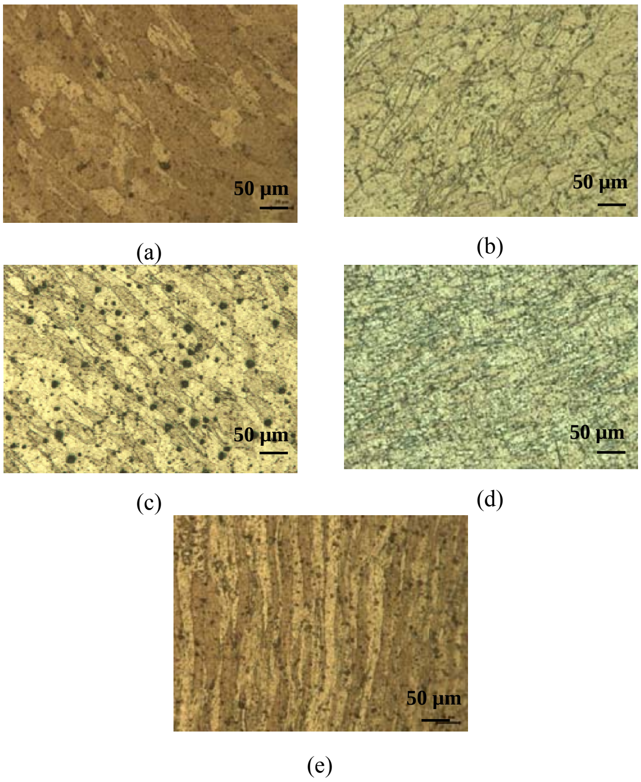


Fig. 5 OM micrographs of Al-Mg-Si alloy after ECAP processing at strain rate of 1.4x10^{-2} s^{-1} at (a)-(d) 250°C and (e) room temperature through (a), (e) 1, (b) 2, (c) 3, (d) 4 passes

Quite the contrary, the pressing temperature has a significant influence on the microstructure of the processed discs. ECAP processing temperature of room temperature resulted in a significant change of the microstructure which can be observed from the large increase in the grains aspect ratio and the orientation angle of the sheared grains to the horizontal X-direction compared to the counterparts processed at 250°C. It was suggested that the faster rates of recovery at the higher temperatures led to an increasing annihilation of dislocations within the grains and a consequent decrease in the numbers of dislocations absorbed into the subgrain walls [14]. The large increase in the aspect ratio of the sheared grains can also reflect the dominant effect of strain softening over strain hardening that is induced by heating during ECAP [21].

B. Mechanical Properties

The most important data deduced from the compression test is the compressive strength, since it reflects the overall mechanical behavior of the Al-Mg-Si discs before and after ECAP processing via different processing parameters. Moreover, the compression test provides an indication of the level of ductility. The results of the compression and the hardness test are summarized in Table II. The as-received Al-Mg-Si sample has yield strength of 150 MPa, ultimate compressive strength of 180 MPa, hardness of 55 HV, and large elongation to failure (23%).

From Table II, it can be seen that there is a sharp increase in Hv-values after the first ECAP pass for the disc processed at a strain rate of 1.4 x10^{-3} s^{-1} (the increase reached 43% compared to that of the as-received alloy). After four passes, the hardness experienced another increase of about 10% compared to that produced by the first pass. A similar behavior was recorded for the disc processed at a strain rate of 1.4 x10^{-2} s^{-1}. 1-pass resulted in the Hv-value increase by 42% compared to that of the as-received alloy. ECAP through 4-passes resulted in additional increase in the Hv-value of about 14% compared to the counterpart processed via one pass. Experimental data of the Hv-values demonstrated that there is a lack of any significant dependence on the processing strain rate. All of these results demonstrate that there is no significant influence of strain rate on the mechanical properties of the ECAP processed discs. The hardness results pointed to a saturation regime, as the increase in hardness diminishes with number of pressings. The increase in hardness values points towards the high dislocation density that is built inside the materials during ECAP, and the evolution of fine subgrain structure within the original grain structure [13].

TABLE II
MECHANICAL PROPERTIES OF AL-MG-SI ALLOY AFTER ECAP PROCESSING VIA DIFFERENT PROCESSING PARAMETERS

Sample conditions	Yield strength	Compressive strength	Vicker's hardness,	Elongation to failure %
H11	212	232	79	13
H12	218	230	79	12
H13	225	234	84	12
H14	225	236	87	10
R11	243	249	110	9
H21	215	237	78	13
H22	215	236	82	13
H23	222	236	85	11
H24	226	239	89	12
R21	240	254	117	10

The ECAP processing temperature had a significant influence on the hardness readings. One pass of ECAP processed at room temperature resulted in the Hv-values increase by 39 and 50% for the samples processed at strain rates of 1.4 x10^{-3} and 1.4x 10^{-2} s^{-1}, respectively, compared to the counterparts processed at 250°C. These obtained results can be attributed to the fact that ECAP processing at room temperature have to be accompanied with high strain hardening; on the other hand, hot ECAP have to be accompanied with strain softening and grain coarsening, which caused a drop in mechanical properties of the processed discs.

From Table II, it is clear that ECAP processing at lower strain rate via 1-pass revealed 41.3 and 28.8% increase in the YS and US, respectively, of Al-Mg-Si processed at 250°C discs, accompanied with 43.5% decrease in the elongation to failure compared to the un-deformed discs. Increasing the number of passes up to 4 revealed 50 and 31% increase in the YS and US respectively of AA6061 discs, the decrease in fracture strain was 56.5% compared to the un-deformed discs. A similar behavior was recorded for the disc processed at the higher strain rate. From Table II, it is clear that the compressive strength and the Hv-values of Al-Mg-Si discs were independent of the strain rate; moreover, the processing number of route has an insignificant influence on the mechanical properties.

ECAP processing at lower strain rate via 1-pass at room temperature revealed an increase of 14.6 and 7.3% increase in the YS and US, respectively, of Al-Mg-Si discs accompanied with 30.7% decrease in the elongation-to-failure compared to the counterparts processed at 250°C. A similar behavior was recorded for the disc processed at the higher strain rate, where 1-pass at room temperature revealed an increase of 11.6 and 7.2% increase in the YS and US, respectively, of Al-Mg-Si discs accompanied with 30% decrease in the elongation-to-failure compared to the counterparts processed at 250°C. All of these results demonstrated that, although it is generally easier to press specimens experimentally at high temperatures, optimum ultrafine-grained microstructures will be attained when the pressing is performed at the lowest possible temperature, where the pressing operation can be reasonably conducted without the introduction of any significant cracking in the billets. By maintaining a low pressing temperature, this ensures the potential for achieving both the smallest possible equilibrium grain size and the highest fraction of high-angle boundaries [14].

The mechanical properties measurements revealed that the Hv-values and the strength of deformed Al-Mg-Si discs were significantly higher than the 1st received ones. Simultaneously, the mechanical properties for the ECAP processed discs at room temperature increased significantly compared to the hot processed discs. The strengthening mechanisms associated with SPD may include solid solution strengthening, strain hardening, and grain refinement strengthening [22]-[24].

The substitution solute atoms of the alloying elements in Al-Mg-Si distort the crystal lattice, hinder dislocation mobility, and hence strengthen the alloy. The amount of strain induced via ECAP resulted in the generation of high density of dislocations [25].

As discussed elsewhere [24]-[26], dislocation strengthening (strain hardening) contributed significantly to the strength and hardness enhancement. ECAP processed discs were subjected to high amount of strain (especially in case of processing at room temperature). The multiplication of dislocations occurred at a faster rate than those annihilated by dynamic recovery (strain softening). The excess dislocations within grains and near grain or subgrain boundaries made dislocation glide more difficult. The dislocation density in the deformed discs increased with ECAP deformation, due to dislocation multiplication or the formation of new dislocations. The net result was that the motion of a dislocation is hindered by the presence of other dislocations, which was consistent with the significant increase of hardness after ECAP processing. As the dislocation density increased, the resistance to dislocation motion by other dislocations became more pronounced. Thus, the imposed stress necessary to deform a metal increased with increasing cold work.

A significant increase of the material hardness and strength post ECAP can be mainly attributed to the formation of the homogeneous UFG microstructure that provided a significant strengthening according to the Hall-Petch law [18].

CONCLUSION

In the current work, ECAP processing of commercial Al-Mg-Si alloy was conducted using two strain rates of 1.4 x10^{-3} and 1.4x 10^{-2} s^{-1} at room temperature and at 250°C. Route A was adopted up to a total number of four passes. The following conclusions can be drawn:

1) A significant difference in the grain morphologies of the as-received and processed discs was observed.
2) Increasing the number of passes up to 4 resulted in increasing the grains aspect ratio up to ~ 5.
3) 1-pass resulted in increase of Hv-value by 42% compared to that of the as-received alloy, whereas 4-passes of ECAP processing resulted in additional increase in the Hv-value.
4) Increasing the number of passes up to 4 at lower strain rate revealed 50 and 31% increase in the YS and US respectively of Al-Mg-Si alloy discs, accompanied with a decrease in fracture strain of 56.5% compared to the un-deformed discs.
5) The mechanical properties showed an insignificant dependence on the processing strain rate.
6) The ECAP processing temperature has a significant influence on the microstructure, Hv-values, and compressive strength of the processed discs.
7) It was proved that total introduced deformation ε_{eq} ~ 4.24 (which correspond to processing through 4 passes) wasn't enough for formation of uniform equiaxed UFG structure.

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