Finite Element Modeling and Mechanical Properties of Aluminum Proceed by Equal Channel Angular Pressing Process

F. Al-Mufadi, F. Djavanroodi

***Abstract*—During the last decade ultrafine grained (UFG) and nano-structured (NS) materials have experienced a rapid development. In this research work finite element analysis has been carried out to investigate the plastic strain distribution in equal channel angular process (ECAP). The magnitudes of Standard deviation (S. D.) and inhomogeneity index (C_i) were compared for different ECAP passes. Verification of a three-dimensional finite element model was performed with experimental tests. Finally the mechanical property including impact energy of ultrafine grained pure commercially pure Aluminum produced by severe plastic deformation method has been examined. For this aim, equal channel angular pressing die with the channel angle, outer corner angle and channel diameter of 90°, 20° and 20mm had been designed and manufactured. Commercial pure Aluminum billets were ECAPed up to four passes by route B_C at the ambient temperature. The results indicated that there is a great improvement at the hardness measurement, yield strength and ultimate tensile strength after ECAP process. It is found that the magnitudes of HV reach 67HV from 21HV after the final stage of process. Also, about 330% and 285% enhancement at the YS and UTS values have been obtained after the fourth pass as compared to the as-received conditions, respectively. On the other hand, the elongation to failure and impact energy have been reduced by 23% and 50% after imposing four passes of ECAP process, respectively.

***Keywords*—**SPD, ECAP, FEM, Pure Al, Mechanical properties.

I. Introduction

MECHANICAL properties enhancement for metals and alloys are for practical and industrial applications. One method of achieving the desired mechanical properties this severe plastic deformation. The most important feature of this method is the ability for producing ultrafine grained (UFG) and even nano-structured (NS) materials. The NS grain size scales is referred to as being between 100 to 1000 nm [1].

There are number of SPD technique for fabrication of UFG or NS, among these techniques, equal channel angular pressing is an especially attractive processing technique for several reasons; large billet size production, relatively simple procedure, reasonable homogeneity and sufficiently high strain and finally potential to be scaled up for use in commercial metal processing procedures [2], [3].

Finite element methods (FEM) have been widely used for the purpose of investigating the global and local deformation behavior with various die parameters. A number of FEM based analyses for classical ECAP die, especially for one pressing pass, have been reported in literature [4]-[9]. Nagasekhar et al. [4] conducted finite element simulations to investigate the effect of channel angle in equal channel angular extrusion/ pressing (ECAE/ ECAP). It was found that the deformation behavior is more complicated for acute angles and is relatively smooth for obtuse angles. The effective strain homogeneity was greater for a right angled extrusion as compared with the others. Djavanroodi and Ebrahimi [6] investigated the effect of die channel angle, friction and back pressure in ECAP. Their finite element simulations showed that decrease in the die channel angel or increase in the coefficient of friction led to increased levels of strain accompanied by increased homogeneity of strain distribution. Also higher punch pressures were required to increase the levels of strain. They also studied the effect of die parameters and material parameter on effective strain distributions in ECAP process. Their results showed that die channel angle greatly influences the magnitude of effective strain whereas channel displacement affected the homogeneity of effective strain [5]-[8]. Rezaee and Ahmadian [9] modeled the mechanical behavior of ultra-fine grained aluminum. The model simulated multiple compressions in a die channel. A dislocation based model was used to predict the yield strength and grain size of AA 1100 aluminum alloy. Their results proved good agreement between the experimental and numerical findings.

There has been number of experimental investigation on effect of ECAP process on mechanical behavior of aluminum [10]-[15]. Roven et al. [10] conducted tests for mechanical properties of a wide range of aluminum alloys. Equal Channel Angular Pressing (ECAP) was used to produce Severe Plastic Deformation (SPD) in AlMg, AlMn, AlMgSi and AlMgSc alloys. They showed that the mechanical properties of age hardened aluminum alloys improved with SPD, whereas the other alloys did not show significant improvement over conventional processing techniques. Kim et al. [11] studied microstructure evolution for AA 1050 by ECAE using a 90° die and a 120° die. It was found that the ECAE process was effective in producing Ultra-Fine Grain materials. The initial grain size of 160 μm was reduced to 4 μm by the 90° die and 12 μm by the 120° die. Fu et al. [12] conducted an extensive study of grain refinement of Al 6061 due to ECAE processing. They showed that the best grain refinement is still at ultra-fine level and the finest grain size obtained was 0.71 μm. Their

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results elucidated that there was not further refinement after 8 passes up to 16 passes. They further found that there was no nano structure evolution in Al 6061 even after 16 passes. Puertas et al. [13] demonstrated the viability of using mechanical parts for industrial consumption using the ECAE/ECAP process. They used AA 1050 aluminum alloy for the manufacturing of Francis turbine blades. They reported a 25% increase in hardness values for the nano structured part processed by ECAE as compared to the parts made by conventional means. Sheri et al. [14] combined the ECAP process with ageing treatments of Al 7075 alloy. They found that three or four passes led to ultra-fine grained material of size less than 500 nm. Also dynamic ageing at 393 K led to optimum mechanical properties. Baig et al. [15] conducted an extensive study of the response of AA 6082 alloy over varying strain rates and temperatures. ECAPed samples were tested over a temperature range of 294 to 473 K and strain rates ranging from 10^{-4} to $10^{3}s^{-1}$. The billets were solution heat treated and over aged. ECAP was performed over 4 to 6 passes. The resulting specimens showed significant increase in yield strength as well as hardness. The experimental results also showed good agreement with constitutive model using Johnson Cook's formulation.

In this research, ECAP die with the channel angle of 90°, outer corner angle of 20° and channel diameter of 20mm has been designed and manufactured. Then, commercial pure aluminum has been pressed up to four passes by route B_C. Finite element analysis has been carried out to study the strain distribution on the samples during ECAP process. Finally, the effect of the process has been investigated on the mechanical properties of deformed samples. Hardness measurement, tensile strength and impact test have been utilized to evaluate mechanical properties of the specimens after ECAP process.

II. Experimental Procedure

ECAP die set up was designed and manufactured from three steel blocks shown in Fig. 1 where, a photo of the die and the press can be seen. The die angles are: $\Psi = 20^{\circ}$ and $\Phi = 90^{\circ}$. The die material is H13 tool steel heat treated to hardness Rockwell C (HRC) of about 45. The flashing along the longitudinal axis of the billet caused by ECAP operation were removed using a lath machine. Water coolants were used to reduce the heat induced during the process, since the temperature may cause the changes in the microstructure of the specimen. Four passes of ECAP process using route B_C were performed. Aluminum billets from extruded rod were cut with the nominal dimensions of 20mm × 140mm. The experimental condition of the ECAP process, Lubricant MoS_2, Ram speed (V) 2mm/sec, ECAPed temperature at Room temperature (25 ± 3°C), Die channel angle 90°, Outer corner angle 20°, Channel diameter 20mm, and Route B_C. Prior to operation, the pressing tool components and billets were lubricated in order to minimize friction during process. The aluminum billets were ECAPed at room temperature, because of the excellent ductility of materials with a punch speed of about 2mm/s.

Microhardness measurements of the samples before and after ECAP process using the Vickers scale were recorded. Vickers (HV) measurements were conducted using a Buehler Micromet II microhardness tester on the transverse, and the longitudinal planes. A load of 500g and a dwell time of 15s were used. The tensile specimens dimensions used for testing were Length=100mm and width = 12mm. The samples were cut using a wire Electrical Discharge Machining. Two tensile tests were conducted for each ECAP passes and the average values were taken for discussions. Tension test was performed at room temperature using servo-hydraulic MTS testing machine Fig. 2.

True stress σ and true strain (ε) were calculated from their corresponding engineering strain (e) and engineering stress S values. Charpy impact tests were performed according to ASTM E23. The samples dimensions were 55mm×10mm×2mm; see Fig. 3. The long axis of the impact sample is parallel to the pressing direction. A 45° groove was machined on the longitudinal plane in the middle of the sample with a depth of 2mm and a radius of 0.25mm at the root. The tests were performed on an impact tester with maximum impact energy of 450J and an accuracy of ±1J, See Fig. 3. Each impact experiment was also repeated on three subsequent samples.

Fig. 1 ECAP die set-up used in this research

Fig. 2 Commercial pure aluminum sample during tensile test

Fig. 3 Impact test machine using in this research

III. Numerical Analysis

Finite element simulations were carried by using Simufact forming software. The sample model has the same geometry with the experimental work. The true stress-true strain relationship were determined by fitting the data to the equation $\bar{\sigma} = C\,\bar{\varepsilon}^n$, where $\bar{\sigma}$ is the effective von-misses stress, $\bar{\varepsilon}$ is the effective plastic strain, C is the strength coefficient (C=52MPa) and n is strain hardening exponent (n=0.14), respectively (tensile tests were performed to determine c and n according to ASTM B557M (2006) for pure Al). The number of elements after solid mesh generation was 14714 and automatic re-meshing was used to accommodate large deformation during all of the analyses. The die, punch and back punch were assumed to be rigid so that there is no deformation. The punch speed was equal to 1mm.s^{-1} and all of the simulations were performed at the ambient temperature see Fig. 4.

IV. Results and Discussions

A. Validation of Simulation Analysis

The pressing force is an important factor in metal forming operation. Many factors will affect the result of the experiment; the accuracy of the sensors, the friction, the punch speed, the material property and so on. Moreover, the applied material properties and the simplification of the physical model will affect the simulated results. If the punch force in the simulation meets well with that in the experiment at the same punch position, the parameters used in the simulation are considered as the optimum. After one pass, the pressing pressure magnitudes obtained by the experimental work and the simulation results are 67MPa and 61MPa respectively. This represents a 9% discrepancy between the experimental and the numerical results, which for all practical purposes is acceptable.

B. The Effective Strain Distribution and Plastic Stress

As mentioned before, one of the major challenges in this process is obtaining a homogeneous material, and since strain is a major contributor, studying the strain behavior is very important. Effective strain distribution has been studied by two parameters; one is inhomogeneity index (C_i) and the other is inhomogeneity factor (IF) or coefficient of standard deviation (S.D.). These parameters are defined as follows [8]:

$$C_i = \frac{\varepsilon_{\max} - \varepsilon_{\min}}{\varepsilon_{ave}} \quad (1)$$

$$IF = \frac{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\varepsilon_i - \varepsilon_{ave}\right)^2}}{\varepsilon_{ave}}$$

$$S..D. = \sqrt{\frac{\sum_{i=1}^{n}\left(\varepsilon_i - \varepsilon_{avg}\right)^2}{n}} \quad (2)$$

where; ε_{ave}, ε_{max} and $\varepsilon_{min,}$ are the average, maximum, minimum effective strain, respectively. Also, ε_i is effective strain in each element and n is number of data. Lower value for IF or C_i means that better strain distribution uniformity for ECAPed sample. Equation (2) takes the strain value of all defined specimen elements in to account, therefore it is believed that the IF parameter is a more convenient for examining the level of strain distribution uniformity within the work-piece. Effective plastic strain, Ci and IF values of commercial pure Aluminum after ECAP process up to four passes are given in Table I and shown in Fig. 4. As indicated in Table I, the pass increased the maximum plastic strain at the final pass to 5.173, and the minimum plastic strain from 4.071. Also Fig. 5 shows the minimum, maximum and average of effective plastic strain of commercial pure Aluminum after ECAP process up to four passes. Comparison of inhomogeneity index (Ci) and inhomogeneity factor (IF) or coefficient of standard deviation (S.D.) are made in Fig. 6. The comparison of effective plastic stress on different cross section and surface for commercial pure Aluminum after first pass of ECAP process are shown in Fig. 7.

TABLE I
Effective Plastic Strain (EPS) of Commercial Pure Aluminum after ECAP Process up to Four Pass

Number of Pass	Min. E.P.S.	Max E.P.S.	Range E.P.S.	Average E.P.S.	C_i	IF or S.D.
Pass#1	0.669	2.478	1.809	1.324	1.366	0.494
Pass#2	1.482	3.035	1.553	2.078	0.747	0.428
Pass#3	2.674	4.462	1.788	3.495	0.512	0.445
Pass#4	4.071	5.173	1.102	4.655	0.237	0.265

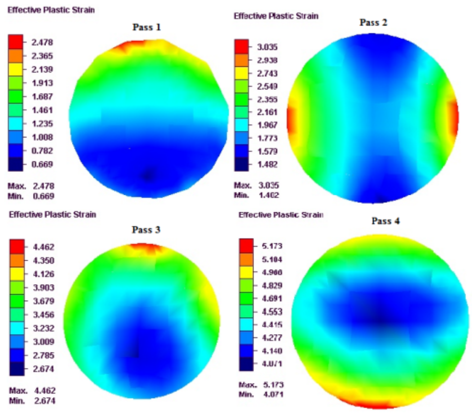

Fig. 4 Cross section of effective plastic strain of commercial pure aluminum after ECAP process up to four passes

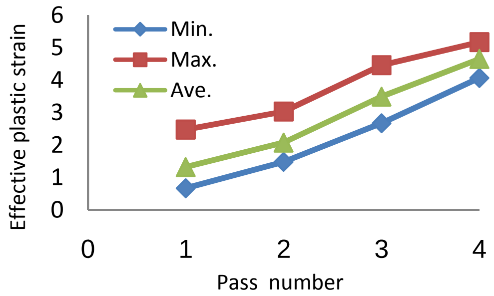

Fig. 5 The min, max and average of effective plastic strain of commercial pure Aluminum after ECAP process up to four passes

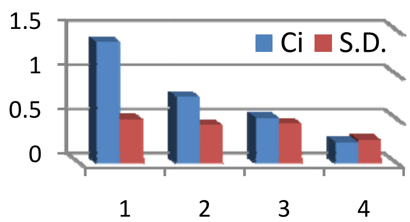

Fig. 6 The magnitudes of Standard deviation (IF or S. D.) and inhomogeneity index (Ci) versus pass numbers

C. Hardness Evaluations

The variations of average Vickers micro hardness (HV) versus the number of ECAP passes up to 4 using route Bc have been listed in Table II. As can be observed, the HV magnitude of pure Al is 21 HV before ECAP process. Applying the ECAP process on the billets leads to 219% enhancements after the fourth pass as compared to the annealed condition. Fig. 8 shows the variation of hardness values with respect to number of ECAP pass, as it can be seen that there is a sharp increase in hardness values after the first pass for the sample. In addition, the rate of increase in hardness magnitude diminishes with the number of passes.

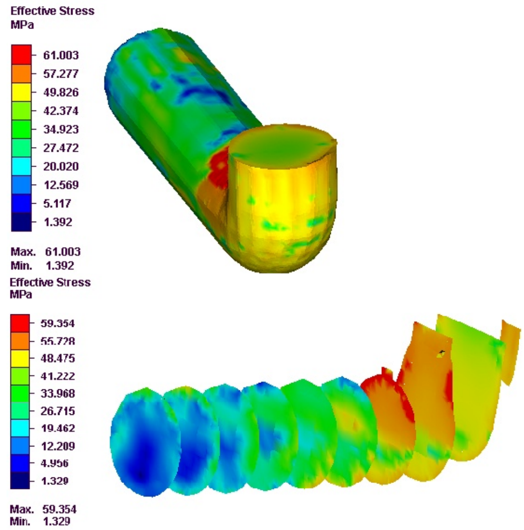

Fig. 7 Multi Cross section and surface of effective plastic stress of commercial pure Al after first pass in ECAP process

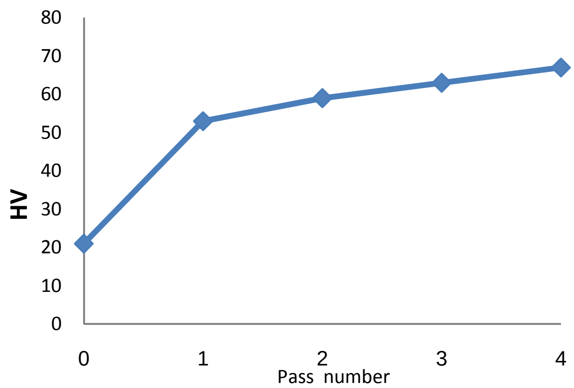

Fig. 8 Trend of hardness changes during ECAP process of commercial pure Al

These increases at the HV magnitudes after the first ECAP pass are considered to be caused by the formation of the ultrafine grained structure and increase in the dislocation density. Furthermore, HV values of the specimen have been slightly increased by adding pass number due to the saturation of the strengthening.

TABLE II
MECHANICAL PROPERTIES OF COMMERCIAL PURE ALUMINUM SAMPLE BEFORE AND AFTER ECAP PROCESS UP TO FOUR PASS

Property	**Pass number**				
	Pass 0	**Pass 1**	**Pass 2**	**Pass 3**	**Pass 4**
σ_{yp} (MPa)	33	92	123	136	142
σ_{UTS} (MPa)	65	120	151	159	165
El(%)	30	17	17	16	16
Hardness (HV)	21	53	59	63	67

D. Tensile Evaluations

Tensile tests were carried out at room temperature on the samples before and after ECAP process up to four passes in a direction parallel to the pressing. Generally, it can be found that the as-received samples have a more ductile behavior when compared with ECAP processed samples and the strengths are increased by the process. Fig. 9 and Table II lists the yield strength, ultimate tensile strength and elongation to failure of commercial pure aluminum before and after ECAP operations up to four passes by route B_C. Yield strength of the as-received pure Aluminum sample is increased by about 180% from 33MPa to 92MPa in the first ECAP pass and increased by about 330% to 142MPa after the fourth pass as seen in Table II. Ultimate tensile strengths show similar behaviors to yield strength but have lower increasing rates. As can be calculated, about 84% & 150% increments have been achieved after the first and fourth passes as compared to the annealed condition, respectively. Finally, it can be concluded that these results are consistent with HV test results in terms of the changes in mechanical behaviors. Similar to hardness results, the reason of this behavior is caused from the decrease in the grain size due to the formation of the ultrafine grained structure and increase in the dislocation density. These results are also consistent with literature results [16]-[18].

E. Impact Evaluations

For impact testing, samples were cut from longitudinal (pressing) direction. The specimen dimensions are 10mm × 55 mm with a 2mm deep, 45° V notch having a 0.25 mm tip radius at the center of the specimen which is prepared according to the ASTM E23. Fig. 10 shows the impact energy as a function of the number of ECAP passes. It is observed that the impact energy of the annealed samples decreases by adding pass numbers. Impact energy of starting annealed sample is about 39J. After four passes, the impact energy is 30J which is 23% less than that of the un-ECAPed state. The fracture surfaces the samples before and after ECAP process are shown in Fig. 11. The decrease in the impact energy upon ECAP process for pure Al material is related to the microstructure of the as-received and microstructural changes during process. The as-received samples show a typical ductile fracture with high plastic deformation. In contrast, the fracture surface after fourth pass show a fracture with much lower plastic deformation due to the grain refinement and work hardening. This is indicative of the decrease in ductility and creation of large number of voids before necking.

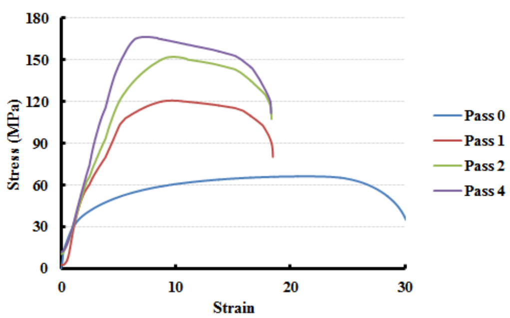

Fig. 9 Trend of mechanical changes during ECAP process of commercial pure Al

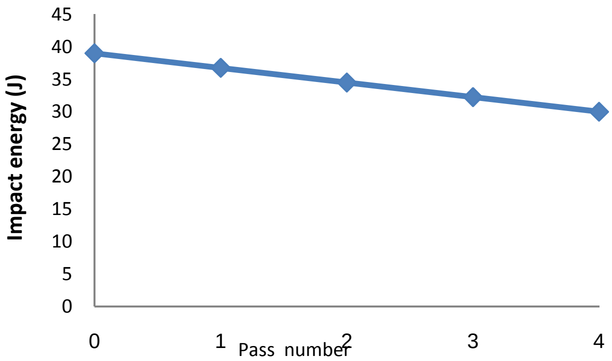

Fig. 10 Trend of impact energy changes during ECAP process of commercial pure Al

Fig. 11 Fracture surfaces of commercial pure Al before and after ECAP process as a function of pass numbers

V. Conclusions

In this work, equal channel angular pressing die set-up with the channel angle of 90°, outer corner angle of 20° and channel diameter of 20mm was designed and manufactured. Then, commercial pure aluminum had been pressed up to four passes by route B_C. Finite element analysis and mechanical tests had been carried out to investigate the effects of ECAP process on the effective plastic strain, tensile properties, hardness measurements and impact energy of specimens. The following conclusions can be drawn.

The ECAP process increased the maximum, minimum and average plastic strain at the final pass to 5.173, 4.071 and 4.655 respectively. It was shown that increasing pass number results in increase of stain homoginity. The inhomogeneity index (C_i) and inhomogeneity factor (IF) or coefficient of standard deviation (S.D.) is reduced by %473 and 86% after forth pass, respectively.

It was concluded that the mechanical properties of ECAPed samples were enhanced. The HV records showed that hardness value have been increased by about 219%, after the fourth ECAP passes as compared to the annealed state. In addition, about 330% enhancements in yield strength have been achieved after the final pass compared with the as-received conditions. Also, it is found that ultimate tensile strength has lower increase than the yield strength. There is about 150% increasing at the UTS value is obtained after the final pass compared with the as-received conditions. Furthermore, it was observed that the highest increase at the mechanical properties is occurred after the first ECAP process. On the other hand, the impact test results indicated that the impact energy decreased by adding pass number. About 23% reductions at the impact energy value have been obtained by imposing four passes of ECAP process as compared to the annealed condition. Finally, experimental values were compared with simulation results and there was a good agreement between them.

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