Modeling and Production of High Strength Al Strips by Equal Channel Multi Angular Pressing Method

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ABSTRACT

Equal channel multi angular pressing (ECMAP) process is an efficient method to enhance the productivity of ultra-fine grained (UFG) materials by increasing process continuity and as a result decreasing the process required time. Comparing repetitive ECAP method, in the same period, the number of passes can be done by ECMAP. In this article, ECMAP of AL strips in two typical annealed and as received conditions were studied, and route C was selected as multi pressing route. Values of equivalent plastic strain (PEEQ) and micro-hardness in the cross section of ECMAPed strips were obtained both by FE simulations and practical tests, correspondingly. These values were also used for obtainingtheinhomogeneity of produced ECMAPed strips. Furthermore, mechanical property for both as received and annealed strips before and after pressing was studied experimentally. Also, load-displacement curve during the ECMAP process was obtained by finite element method (FEM). For FEM results validation, PEEQwas calculated by the analytical method, too. Results show that there is good conformity between FE, analytical, and practical results.

1. Introduction

Bulk materials with ultra-fine grain (UFG) size are known as a new generation of materials with unique mechanical and physical properties. In this regard,one of the processingmethods of UFG materials isto exert severeplasticdeformation. ECAP is the most popular procedure of the SPD methods. So, for increasing the efficiency of ECAP in strip type materials, we recommended ECMAP with high potential in declining the process required time and reducing elaborate works.

Previous works on ECAP usually done on the samples with circular or square cross sections and strip type pieces with rectangular cross section, hardly discussed [1, 2]. Because of some technical limitations, researchers usually focused on one pass mold and tested one pass ECAP or multi pass ECAP with the subjected die. So, few articles published about ECMAP [3-10]. Nakashima et al. [3], Kim [4] and Jung et al. [5] developed ECMAP of samples with square cross section. Recently, Faraji et al. suggested two passes [6, 7] and three passes [8-10] mold as multi pass tubular channel angular pressing (TCAP) for producing nanostructured tubes and there is not precise study on ECMAP of strip type products.

So, in this article, ECMAP of AL strips in two typical annealed and as received conditions is studied, and route C was selected as multi pressing route. Values of PEEQ and micro-hardness in the cross section of

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ECMAPed strips are obtained both by FE simulations and practical tests, correspondingly. These values are also used for obtaining the inhomogeneity of produced ECMAPed strips. Furthermore, mechanical property for both as received and annealed strips before and after pressing, is studied experimentally. Also, load-displacement curve during the ECMAP process is obtained by FEM. For FEM results validation, PEEQ is calculated by the analytical method, too.

2. Finite element and experimental procedure

Numerical simulations were done by Abaqus/Explicit commercial FE code. In the strip type sample, there is not any strain along thickness direction so, plane strain model was used. The element type is 4-node bilinear plane strain quadrilateral, reduced integration, hourglass control (CPE4R). To apply large strains during simulation, the adaptive mesh was used by considering Arbitrary Lagrangian Eulerian (ALE) method. In the ALE formulation, the FE mesh is neither attached to the material nor fixed in the space. Moreover, the concentration of the mesh in a particular region and the mesh distortion are controlled by the procedure. Therefore, it is possible to manage the path-dependent behavior of the material and the free surface conditions, while maintaining the mesh suitability by using the ALE formulation [11]. Penalty method and Columb friction condition considered between contacting surfaces and friction coefficient taken to be 0.1[5, 12]. Die and punch were taken as rigid analytical bodies.

Die Geometrical parameters are depicted in Figure 1. The geometry of designated die revealed that three equal channel angular pressing occur on each element of ECMAPed strips.

After the quantometric test, the Al1050 composition was obtained, and the results are listed in Table 1 and after the tensile test, mechanical properties of Al strips were attained and listed in Table 2. Strip samples of 20×60 mm were cut from a sheet of 3mm thickness. The die was manufactured from CK60 steel and hardened to reach 60 RC hardness. For better force control and easier splitting die halves, the outer surface was preferred to be in the shape of truncated cone. For accurate assembling of the die parts, 6 grinded pins were positioned in the farthest places on die halves (Figure 1). The geometrical parameters, e.g. Φ_2 (channel angels), $\psi_1$and ψ_2 (corner angles) were taken to be 150, 15 and 30 degrees, respectively.

Table 1. Composition of Al1050 strips.

Si	Fe	Cu	Mn	Mg	Zn	Ti
0.10154	0.25277	0.00672	0.04187	0.01537	0.02269	0.04327
Cr	Ni	Pb	Sn	V	Sb	Al
0.00120	0.00406	0.00828	0.00001	0.01198	0.00967	99.4999

Table 2. Mechanical properties of Al1050 strips.

Parameter	Value
Young’s modulus (E)	69GPa
Poisson’s ration (ν)	0.33
Density (ρ)	2700 kg/m^3
Thickness (t)	3mm

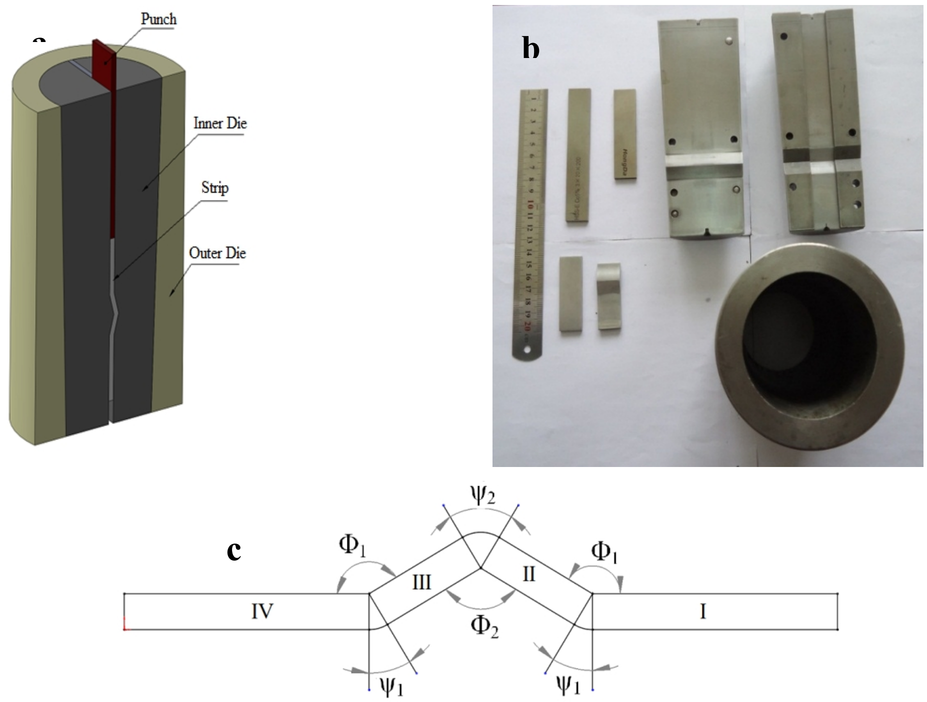

Fig 1. (a) Schematic of ECMAP, (b) Experimental setup and (c) Process parameters.

For the ECMAPed strips, microhardness measurements were done on seven points in the cross section starting from the top surface to the bottom.

3. Results and discussion

The deformed shape of the as received strip is illustrated in Figure 2. It is obvious that except for the front and end part, three separate regions exist due to the first, second and third channel. Because of different deformation history the front and end part of the strip are not similar. It is inferred from Figure 2 that for each pass of ECMAP, PEEQ will be ~ 0.64. Also, at the end of the process the strain is almost steady along the thickness of the work-piece. The amount of PEEQ is high at the middle of the strip and decreases toward the outer surfaces. So, PEEQ is at its minimum on both top and bottom surfaces and maximum on the center of the strip.

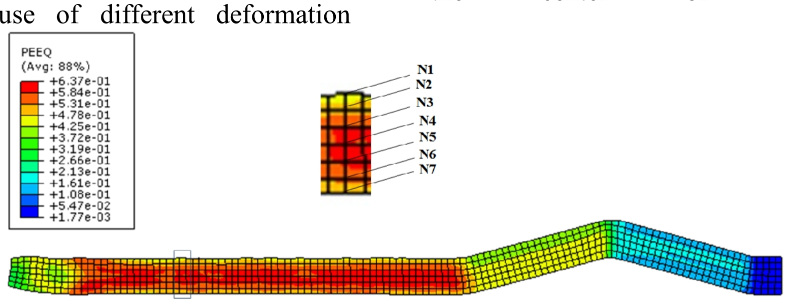

Fig2. PEEQ contour of the as recieved sample.

Figure 3 shows the values of PEEQ in the cross section of the as received sample. The values obtained by FEM on seven points are located in equal distance from each other. It is clear that the values of PEEQ are higher in the middle part of the sample and descend toward the outer surfaces of strips.

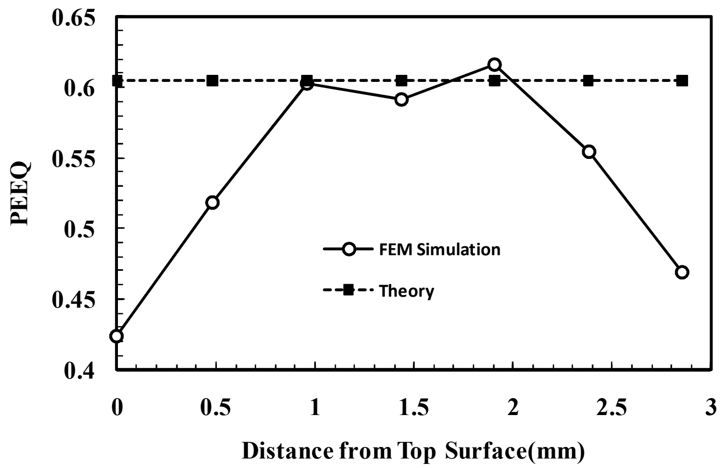

Fig3. PEEQ of the as recieved sample.

For validation of FEM results, the amount of PEEQ was achieved from analytical method, too [13]. Because of not considering the effects of friction and material properties, analytical methods give constant lines. For the geometry used in this study, Eq. (1) was employed.

$$\bar{\varepsilon}_T = \sum_{i=1}^{3}\left[\frac{2\cot(\phi_i/2+\psi_i/2)+\psi_i \operatorname{cosec}(\phi_i/2+\psi_i/2)}{\sqrt{3}}\right] \quad (1)$$

The parameters Φ_1, Φ_2, $\psi_1$and ψ_2 were taken to be 165°, 150°, 15° and 30°, respectively. Figure 3 depicts the analytical result for PEEQ.

For further legalization of FEM results, microhardness measurements were done on three strips after ECMAP. Hardness measurements were done on seven points in cross section starting from the top surface to bottom for all pieces and for each point the average amount was considered (Figure 4). It is concluded that for both types of ECMAPed samples, the hardness values near the top and bottom surfaces are minimum. Furthermore, the hardness values increase toward the middle part of strips. The hardness values of annealed strips are reasonably lower than the as received strips, and the hardness values of ECAPed strips are higher than the as received strips. Compared with the annealed strip, the rise of hardness in the as received strip is more than ECMAPed samples.

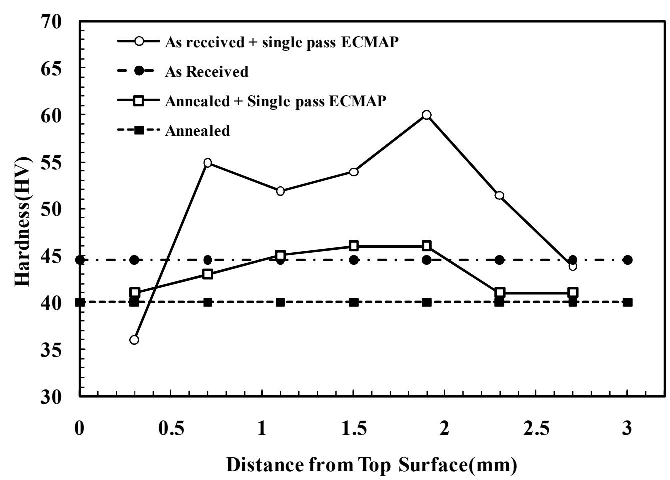

Fig 4. Hardness values from cross section of the sample.

The comparison between Figure 3 and Figure 4 revealed that the trend of microhardness and PEEQ curves is similar. Also, Figure 3 illustrates that the FEM results for PEEQ have good correspondence with analytical results. Both declared results demonstrate that FEM simulation is acceptable enough and simulation results agree well with experimental outcomes. For more validation of FEM simulation, load-displacement curves were extracted by both FEM and experiments that will be discussed later.

One of the main factors that indicate the higher potential to create more passes is higher homogeneity. With the aim of homogeneity survey and more comparison of FEM with experimental results the inhomogeneity index for hardness and PEEQ results was obtained from Eqs. (2) and (3), respectively [14].

$$H_i = \frac{H_{\max} - H_{\min}}{H_{avg}} \quad (2)$$

$$C_i = \frac{\varepsilon_{\max} - \varepsilon_{\min}}{\varepsilon_{avg}} \quad (3)$$

Where $H_{\max}$, $H_{\min}$ and H_{avg} denote the maximum, minimum, and average of hardness and $\varepsilon_{\max}$, $\varepsilon_{\min}$ and ε_{avg} denote the maximum, minimum, and average of PEEQs in the cross section plane, respectively.

The inhomogeneity indexes for hardness and PEEQ are shown in Table 3. It is evident that in the case of annealed + single pass ECMAP, the SPD process did not change the hardness property that much. The reason is the excess softness in pure aluminum after annealing. However, in the case of as received + single pass ECMAP, the enhancement in hardness is high enough. Moreover, inhomogeneity results are close to simulation results.

Table 3. Inhomogeneity index for PEEQ and Hardness.

PEEQ / Hardness		Inhomogeneity index
PEEQ		0.477
Hardness	As received + Single pass ECMAP	0.357
	Annealed + Single pass ECMAP	0.116

The other important factor in ECMAP is the required load of the process, which could be obtained from FEM. Figure 5 depicts extracted force-displacement curve during the process. It is evident that the trend of the force-displacement curve varies in four different zones. The sharp change of the first zone occurs when strip reaches the end of the first and beginning of the second channel.

Once strip starts moving in the second channel, the hydrostatic force increases noticeably and this occurrence leads to a rise in friction force and subsequently the required pressing force. After the first channel, the identical incidences take place in the second and third channels. It means that when the strip reaches the end of each channel, due to the enhancement of friction force, the required force increases suddenly. It is evident that at the end of the third and beginning of the exit channel, the force-displacement curve reaches the top value due to the maximum hydrostatic and friction force. After this step, due to declining friction surface and consequently the friction force, the force displacement curve reduces smoothly.

For tensile testing inspection four samples were prepared by wire cut machine. First, two samples were cut from the as received and annealed strips. Second, two samples were cut from the strips of the same type after ECMAP.

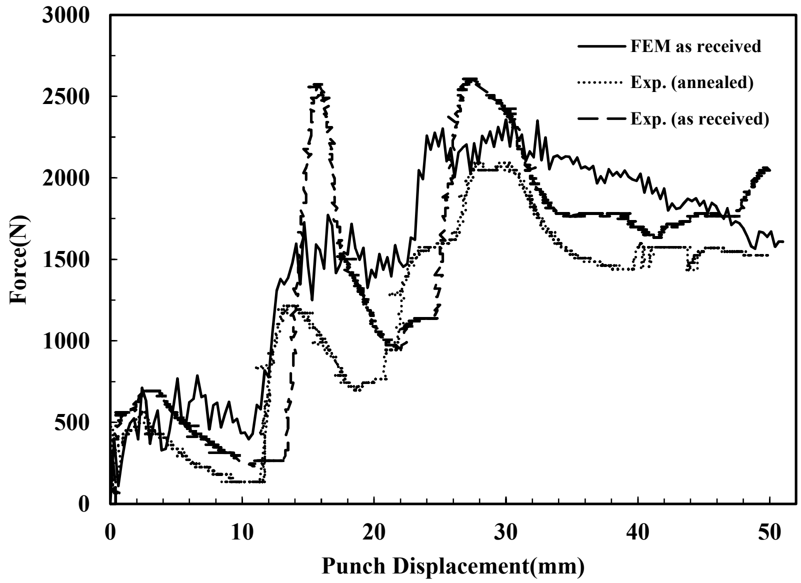

Fig 5. FEM and experimental results for force-displacement curve.

The standard geometry for tensile test is depicted in Figure 6a [15]. Figure 6b illustrates the tested samples and Figure 6c reveals the stress-strain curves obtained from tensile tests. The first comparison between the as received sample and the ECMAPed sample reveals that the latter has more strength but less elongation and that the same occurrence happens for the annealed samples. In the case of the as received strip, the strength of strips increased 27% after the ECMAP process. But in the case of annealed strips, due to excessive softening in the annealing process, strength did not change obviously (15%). It is inferred that initial cold work before annealing produced more strength on the samples than single pass ECMAP. The next comparison is among annealed and as received samples. The stress-strain curves of the annealed samples stand in lower levels in strength and higher level of elongation.

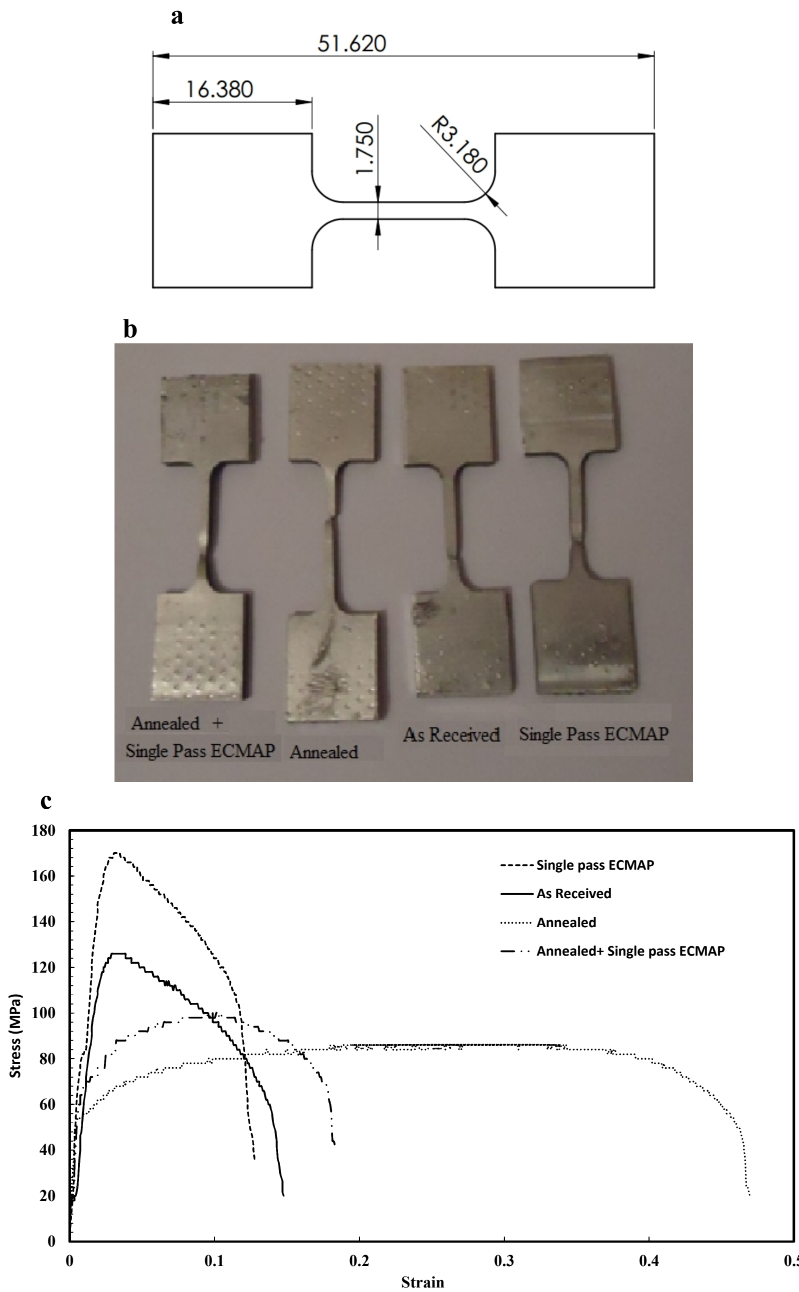

Fig 6. Tensile test: (a) geometry (mm), (b) samples and (c) results

4. Conclusion

ECMAP of AL strips in two different annealed and as received conditions were considered and route C was considered for the production of UFG strips. Values of PEEQ and micro-hardness in the cross section of ECMAPed strips were obtained both by FE simulations and practical tests, respectively and comparison was done between the results. It is inferred that the values of both PEEQ and hardness are higher in the middle part of the sample, and it descends toward the outer surfaces of strips. Moreover, the inhomogeneity index was calculated for both PEEQ and hardness. Also, mechanical properties for both as received and annealed conditions before and after pressing were studied experimentally. Besides, the required force curve during the process was obtained by FEM and experimental works. It is concluded that due to die geometry, the load curve shows three sudden changes. Results show that for the discussed process parameters, there is good conformity between FEM, analytical, and experimental results.

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