EXPERIMENTAL AND COMPUTATIONAL SIMULATION OF PRODUCING ULTRA-FINE GRAIN STRUCTURE PROCESSED BY CGP

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ABSTRACT

In this research the constrained groove pressing (CGP) process as a severe plastic deformation (SPD) method was applied on commercially pure aluminum plates. According to the principle of CGP, a material is subjected to repetitive shear deformation by utilizing asymmetrically grooved dies and flat dies which are constrained by a channel. Each complete groove pressing pass consists of four pressing operation steps. Considering the geometry of the die, in each complete pass, a large amount of strain is induced into the specimen. In the present research the effects of the deformation passes on the mechanical properties of the specimens were tested by micro hardness tests. In addition, in order to investigate the material flow along the grooves in the CGP process, the finite element simulations were carried for one of the process. Our approach involves computational simulation of the entire synthesis process for the optimization. Results show that the flow stress of the material and its hardness are affected by the number of passes. Post process of the finite element analysis showed that the real state of the CGP process is a combination of plane stress and plane strain conditions.

Keywords: Aluminum, CGP, Finite Element Analysis, Mechanical Properties, UFG

I. INTRODUCTION

Structural changes in materials subjected to SPD and their effect on properties have been investigated for more than two decades. In the last ten years, our knowledge of the governing phenomena has been largely extended. However, the SPD-processed metals have ultra-fine grained structures that cannot be obtained through conventional thermo-mechanical processes. As a result, the SPD metals exhibit unique and excellent properties such as high strength, compared with the conventional materials having a coarse grain size of over several tens of micrometers. Since SPD was demonstrated as an effective approach to produce UFG metals, extensive research has been carried out to develop SPD techniques and to establish processing parameters and routes for fabricating UFG metals and alloys with enhanced properties. ECAP [3-9, 21-22] and ARB [3-6] are the SPD techniques that were first used to produce nanostructured metals and alloys possessing sub micrometer or even nano-sized grains. There were many researches were carried out to trim down the drawbacks of the earlier ECAP and ARB processes by changing routes and die angles. Theses ECAP and ARB techniques directs the evolution of other SPD technique like HPT [10]. This nonstop work on researching SPD techniques has a recent development of a number of other SPD processes like HPT [12,14], TW [13], MDF [15] and RCS [16-17]. Over the past decade, new methods such as constrained groove pressing (CGP) [9] and constrained groove rolling (CGR) [10] have been investigated. These two new methods have been capable of producing plate-shaped ultrafine-grained materials. CGP as a severe plastic deformation was initially proposed by Shin et al. [9]. Based on the principle of CGP, a material is subjected to repetitive shear deformation under plastic strain deformation conditions by utilizing asymmetrically grooved dies and flat dies through alternate pressing [11,12]. In this field a number of numerical investigations have also been made. Park et al. investigated the GP process by use of FEM. In another research, Yoon et al. studied the plastic deformation and the strain localization in this process by means of 2D finite element simulation. They neglected the plastic deformation along the groove direction [13]. Present scenario, SPD techniques are emerging from the domain of laboratory-scale research into commercial production of various ultra-fine-grained materials. It is only the matter of time to unearth new and superior SPD technique.

In this present study the mechanical behavior of, the commercially pure aluminum sheets under the annealed conditions were selected to investigate the mechanical properties of the deformed material. The hardness and the flow stress were studied as a function of the number of passes. For analytical purposes, the plastic deformation behavior of the specimen during the first groove pressing step was also simulated using the Finite Element method.

II. GRAIN REFINEMENT

At room temperature, the yield stress of metallic materials increases with the decreasing grain size. This is known as the Hall-Petch relationship. One of the possible techniques, used to obtain small grains in metals, consist in applying a large level of plastic strain to a course-grain precursor. A simultaneous accumulation of localized dislocations and increase in the lattice misorientation are responsible for crystal subdivision and subsequently developed submicroscopic grains. However, some researches reveal that, particularly in pure metals, there exists a limit below which reducing the grain size further results in shifting in the deformation mechanism into a different yet unknown mechanism of plastic flow.

Strain hardening, which is defined as a change in flow stress with strain, is caused by the interaction of dislocations with each other and other defects. The traditional picture of plastic deformation behavior and its mechanical response (i.e. hardness increase due to work hardening) seem to be no longer valid while reducing grain size far into submicron scale. For example, in nanocrystalline Cu, deformation behavior falls into two patterns. Using molecular dynamic simulations, there has been found [4] that, if the crystal size is small enough (in Cu it is for the grain size from 5 nm to 50 nm), grain boundary sliding starts to dominate the deformation behavior. This result was recently confirmed in nanocrystalline Ni experimentally [14]. It was found that electrodeposited nanocrystalline Ni, subjected to plastic strain, did not build up a residual dislocation network.

Taking into account the recent literature announcements on deformation behavior, one can split polycrystalline metals into the following grain size regimes. For sizes greater than1000nm, traditional mechanisms determine deformation (coarse-grained polycrystalline metals). In the range from 1000 nm down to 30 nm, disordered grain boundaries begin to dominate the mechanical behavior (ultrafine-grained polycrystalline metals). This transition becomes much more evident below100 nm. At smaller scales, the atomic sliding at grain boundaries increases, leading to virtually no further work hardening of the plastically deformed metal. The introduced classes of metals have been shown in Fig. 1, revealing the type of mechanical response and characteristics of dislocation activity. The supposed grain size, dg, for the change in the deformation mechanism, was indicated with a number of tick marks.

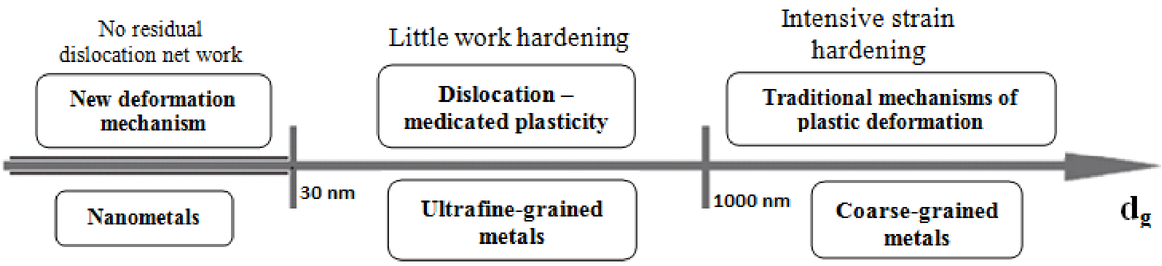


Fig.1 Classification of Polycrystalline Metals According To the Grain Size

Data shown in Fig. 1 have one important implication for grain refinement in metals via plastic strain. Plastic working remains efficient in terms of producing small grain sizes only in the range down to 30 nm for most metals and their alloys. Concluding further, one can state that, employing metal forming, it is possible to fabricate only so called ultra-fine grained (UFG) metals, not even touching desirable nanometals. However, new findings on the mechanism of plastic flow of nanometals could shed more light and open the gate for metal forming also in this range. For now, the nanometals' territory has been restricted to new synthesis-based methods of materials fabrication.

There are a lot of peculiarities affecting the grain refinement obtained by severe plastic deformation. Alloys are more responsive to intensive straining than pure metals, which results in finer grains. This effect, however, requires the application of larger strain. The rate of grain refinement can be increased by the presence of coarse second-phase particles [6,7]. UFG metals exhibit exceptionally high strength and reduced, but reasonable ductility. As stated in Fig. 1, they cannot go through strain hardening and are prone to flow localization during forming. However, by choosing appropriate parameters of the grain refinement process, it is possible to remove or delay the plastic instabilities. Usually researches aiming at grain refinement do not take into consideration the influence of strain rate. Dislocations [16] generated under static conditions of deformation run through small grains without virtually any disturbance in their movement. Dislocations move with a constant rate which depends only on the mechanical properties of metal. So performing high speed working is the only way to increase probability of collisions between dislocations and achieving a higher rate of strain hardening [9].The process parameter interactions should be studied further and the traditional picture of the metal forming technology should be revised in the light of latest findings on grain refinement. It is worth emphasizing that all metallic materials respond to severe straining in basically the same way. Technically, nanostructure can be achieved locally by a number of processes.

Grain refinement by severe plastic deformation implies the creation of new high angle grain boundaries. The creation of high angle boundaries is a result of grain subdivision mechanisms. Various SPD processes such as ECAP, ARB, HPT, HE, TW and RCS are well investigated for producing ultra grained metals. These investigations shows metals produced by these processes have very small average grain size of less than 1µm, with grain boundaries of mostly high angle mis-orientation. In the optical microstructure of metals over 5 passes of the ECAP processes shows the strong filamentary microstructure development with an increased number of passes. In aluminum and aluminum alloys submicron grain sizes can be developed by using ECAP processes. Here the ECAP processed metals shows good agreement with the standard Hall-Petch relationship i.es, microstructure refinement and mechanical properties improvement. [3-5].

Dynamic strain aging achieved on Al 6061 alloy processed through ECAP having parallel channels resulted in the formation of nanodimensional particles. In the longitudinal section of the material, the grains are somewhat elongated along the direction of the shearing strain and in the transverse section, equiaxed grains were predominated. This causes the material leads to UFG structure containing grain boundaries with a predominantly high angle misorientations. Because of these changes considerably higher strength and better plasticity was achieved as compared to material after a standard strengthening treatment. Materials having low Stacking Fault Energy (SFE) such as Al and Cu can be easily downed to nanometer scale [7, 8].

In ARB processed materials it was noted that the evolution of microstructure and increase in mis-orientation of boundaries were much faster than those when using conventional rolling. HPT is another implementation of the SPD on metals and it can be successfully applied to refine microstructure in metals, alloys and recently in composites and semiconductors. HPT can refine the final grain size 100nm or less, but the drawback of this technique is the samples processed are invariably small in size and this effective grain refinement technique used so far in laboratory experimentation [9, 10].

III. CGP DEVELOPMENTS

Constrained groove pressing (CGP) is a processing method, in which a metal is subjected to an intense Plastic deformation through repeated dominant shearing and pressing (flattening) of plate.In2001, Zhu et al. described an SPD method based on the repetitive corrugating and straightening (RCS) which is more known now as CGP [1–3].

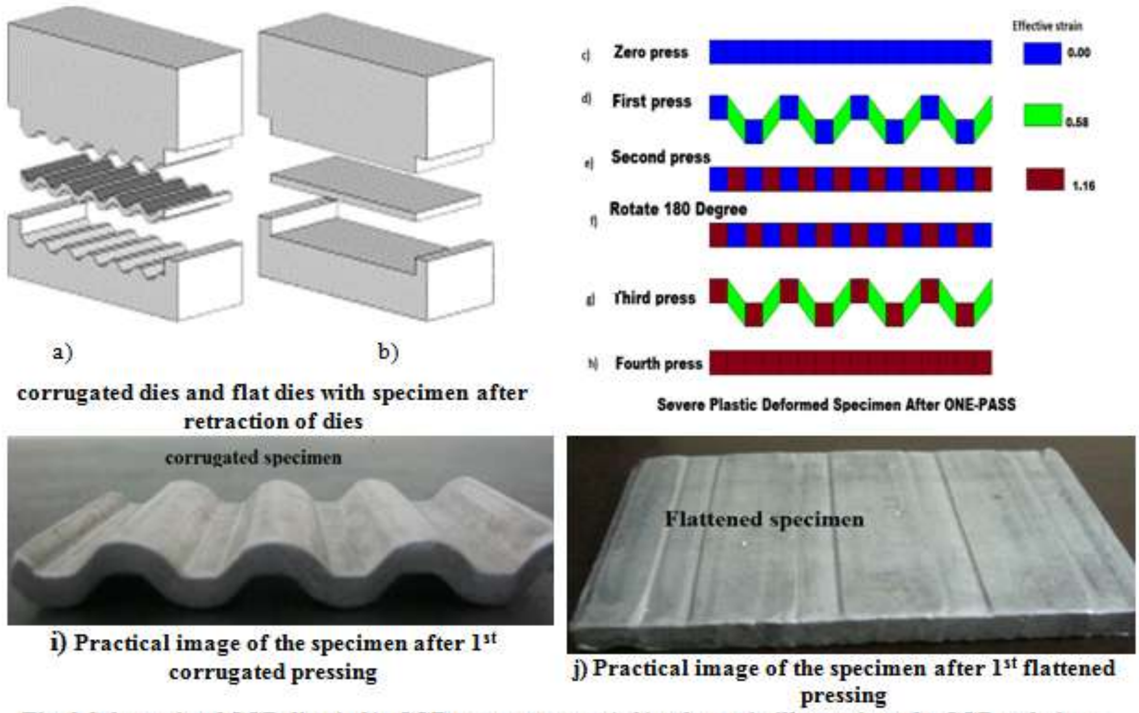


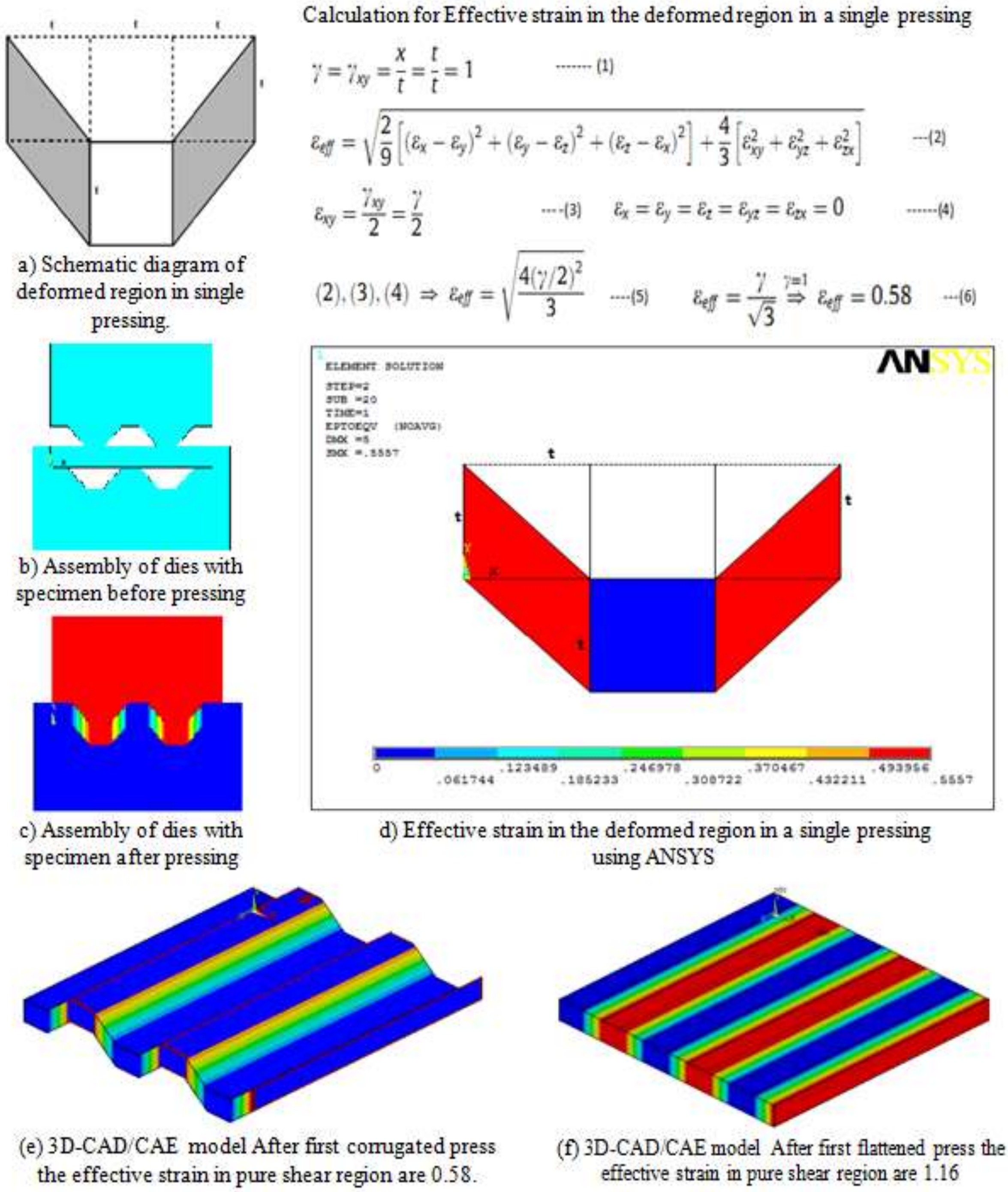
Fig. 2 Schematic of CGP dies (a-b), CGP process stages (c-h) schematic illustration of a CGP technique, and practically processed Al sheets (i-j)

This method comprises bending of a straight plate with corrugated tools and then restoring the straight shape of the plate with flat tools. The repetition of the process is required to obtain a large strain and desired structural changes. It has been shown that ultrafine grained structure can be introduced into metals and alloys via severe plastic deformation. Using CGP method, the coarse grains in pure metals and alloys were successfully refined to the grain size of tens to a few hundreds of nanometers. The submicron grain materials showed very high strength compared to materials with micrometer grain structures. The drawback of ultrafine grained structure materials is their elongation to fracture. Because of low strain hardening in submicron grain structure, the elongation is then dramatically decreased [7–9].Unlike the widely used ECAP process for structure refinement, the CGP process has the advantage that severe plastic deformation can be applied to metal in sheet or plate form[10].The groove pressing is carried out so that the dimension of the gap between the upper die and lower die is the same as the sample thickness and therefore the inclined region of the sample is subjected to theoretically pure shear deformation under plane strain deformation condition. If dies are designed with the groove flank angle (θ) of 45◦, a single pressing yields a shear strain of about 1 in the deformed region. This is equivalent to an effective true strain of 0.58.By repeating this process; a very large amount of plastic strain can be accumulated in the sample without changing its initial dimensions very substantially. The method has been found to have the potential to produce ultrafine structure in plate shape materials. This investigation is an attempt to refine rather coarse grain structure of commercial purity aluminum using CGP technique. The effectiveness of two steps successive groove and flat pressing (corrugation process) was examined with the aim to study the effect of pressing condition on the mechanical behavior of aluminum. The evolution processes of finegrained structure, grain boundary formation and mechanical characteristics developed due to straining process were investigated.

A Pressing sequence schematic illustration of a CGP process is presented in Fig. 2(a-h). At first, a set of asymmetrically grooved dies tightly constrained by groove is prepared. As groove pressing is carried out such that a gap between the upper die and the lower die is same with the sample thickness, the inclined region of the sample (light green shaded area in Fig. 2(d) is subjected to pure shear deformation under plane strain deformation condition. However, no deformation is induced in the flat region (blue shaded area in Fig. 2(d). For the present die design with the groove angle (θ) of 45°, a single pressing yields a shear strain of 1 at deformed region. This is equivalent to an effective strain, €eff of 0.58. The second pressing is performed with a set of flat dies (Fig. 2(b)). By flat pressing under the constrained condition, the previous deformed region is subjected to the reverse shear deformation while the previous unreformed region remains unreformed. The cumulative strain, €eff in the deformed region following the second pressing becomes 1.16 (grey shaded area in Fig. 2(e). After the second pressing, the sample is rotated by 180° (Fig. 2(f)). This allows the undeformed region to be deformed by further pressings due to the asymmetry of the grooved die. Then, the successive pressings with a grooved die (Fig. 2(g)) and a flat die (Fig. 2(h)) result in a homogeneous effective strain of 1.16 throughout the sample. By repeating a CGP process, very large amount of plastic strain can be accumulated in the sample without changing its initial dimensions and, resultantly, an ultra fine grained structure can be obtained. From Fig.2(c,d,e,f,h) are showing flattened CGP specimen , Fig. 2(d and g) are showing corrugated the CGP specimen and Fig. 2(c, d, f, g,h) shows one complete deformation of the plate conducted ,which is equivalent to two pressing and two straitening steps is known as one pass.Fig.2(i and j) shows the Practical image of corrugated and flattened specimen.

3.1 Experimental Procedures

Commercial purity aluminum was supplied in the form of cold-rolled 10 mm thick plate. Prior to CGP pressing, the plate was annealed at the temperature of 250^{0}C for 1.5 h in order to obtain the recrystallized structure. In the present study, a plate of aluminum with dimensions of 80 × 50 × 5mm was pressed with the CGP technique.



a) Schematic diagram of deformed region in single pressing.

b) Assembly of dies with specimen before pressing

c) Assembly of dies with specimen after pressing

d) Effective strain in the deformed region in a single pressing using ANSYS

(e) 3D-CAD/CAE model After first corrugated press the effective strain in pure shear region are 0.58.

(f) 3D-CAD/CAE model After first flattened press the effective strain in pure shear region are 1.16

Fig.3 (a-f) the scheme of the deformed region in the groove pressed sample with effective strain calculations and 2D&3D -simulation using ANSYS.

In this experiments each process is consists four stages. (1) Flat sheet become corrugated which is results in a 0.58 strain in deformed section (Fig.2(d)). (2) A pair of flat dies flatten the corrugated sheet imposing an extra 0.58 strain to the previously deformed section (Fig.2 (d-e)) it is worth to note that in this stage the sheet has two different sections; (a) Unstrained section with zero strain.(b) shear strained section with 1.16 strain. (3) the flat sheet is rotated 180^0 around the axis perpendicular to the plane of the sheet and then the stage (1) is repeated. (4) Corrugated sheet is flattened at the end of the 4^{th} pressing the sheet under goes uniform strain magnitude of 1.16 and one pass of CGP accomplished. By repeating the CGP process, a large amount of plastic strain can be accumulated in the work piece without changing its initial dimensions.Referring to fig.3 (a) and Equation (1)-(6),it can be observed that the applied effective strain in the deformed areas in single pressing is equal to 0.58. In this paper to get clear picture of the constrained groove pressing and showing the effective strain calculation through 2D&3D -simulation using ANSYS as shown in the fig.3 (b-f).

3.2 Finite Element Simulation Procedure

In order to investigate the strain distribution in the CGP process after four pressing steps, the finite element technique was accomplished. To investigate the plastic deformation and strain localization behavior of the CGP process, the Elasto-plastic FEM technique was adopted. The simulations were investigated after one full pass using the commercial finite element code ABAQUS/Explicit. The simulation was considered under 2D plane strain condition. Stress–strain curve of the aluminum which was used in the simulations is shown in Fig .4. The kind of mesh used in the simulation is CPE4 elements for the 2D plane strain conditions. The coefficient of friction in the work piece die interface was selected as 0.1, which is within a typical (0.05–0.1) range in the cold forming of metals.

There have been a couple of previous investigations addressing the numerical analysis of the deformation behavior in CGP process [12, 13, 14, 20]. Park and his colleagues simulated the CGP process using FEM, but did not discuss strain and stress distributions in detail. In the present study, the plastic deformation behavior of the specimen during groove pressing was simulated for one full pass using the commercial Elasto-plastic finite element analysis code ABAQUS/Explicit [21]**.** An isothermal two-dimensional plane-strain problem was considered, since deformation along the normal direction is negligible. The number of initial four node iso-parametric plane-strain elements is 497 and nodes 576. This number of elements was found to be sufficient to show the local deformation of the strain rate insensitive materials. The specimen with dimensions of 80 mm in length and 5mm in thickness was considered for simulations (width is unity along the plane normal direction in plane-strain condition). The specimen was modeled with CPE4 mesh and dies were modeled with analytical rigid lines. Pure aluminum material properties were used in all FE simulations.

IV. RESULTS AND DISCUSSIONS

4.1 Micro Hardness

The mean value of hardness as a function of the number of passes for the transverse and perpendicular cross section of the samples is shown in Fig.5. The initial annealed sample had an average hardness of 29 VHN.While after 20 groove pressing (€eff =5.22) it rises to about 55 VHN. Fig.5 shows the hardness variation across the length of the perpendicular cross section of the specimen for each pass. In order to monitor the effect of CGP on the hardening behavior and mechanical homogeneity of the CGPed specimens, the hardness was measured. The receive samples had a mean hardness value of 29 VHN, which increased rapidly to42 VHN after the first pass (€eff=2.32) as a result of strain hardening. After the second (€eff = 2.32), third (€eff = 3.48) passes and after fourth (€eff = 4.64) pass the hardness value increased slightly and then decreased to 49VHN after fifth pass

(€eff = 5.22) . the hardness measured along the center line of the transverse cross section did not vary significatintly,which confirms that the deformation is homogenous along this direction.

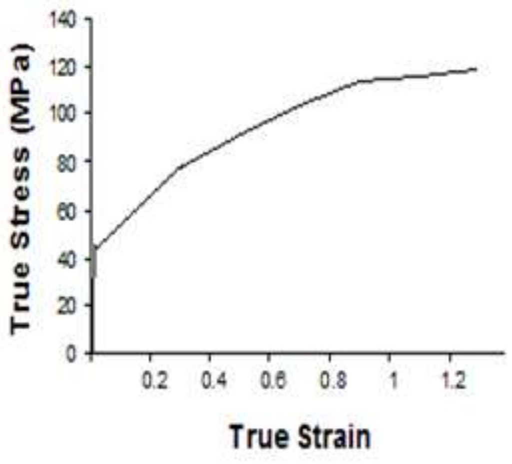


Fig.4. the stress-strain curve of the commercial pure Al used in the Finite element simulations

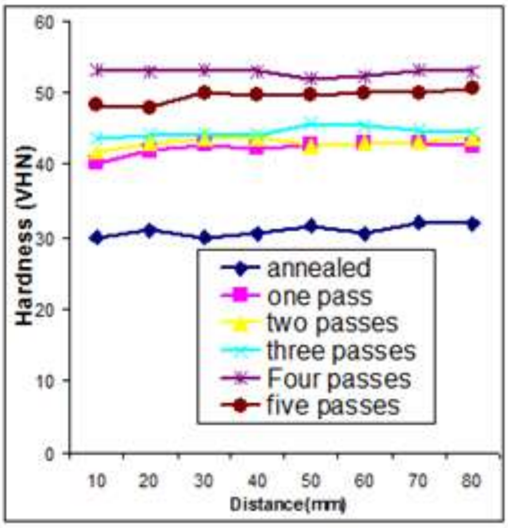


Fig.5. the Vickers hardness variations across the length of the perpendicular cross-section of the specimen for each pass.

5.2 Simulation Results

The distribution of the equivalent plastic strain (PEEQ) in different pressing steps of CGP process in plain strain condition is presented in Fig.6(a-b) (Result of plain stress condition is very similar to plain strain).Variation of PEEQ in the center line of the work piece after the fourth pressing step (one full pass) is presented in Fig 6. The distribution of strain is not uniform and is lower in the surface and interface areas between shear and flat areas (areas near the teeth of the die).

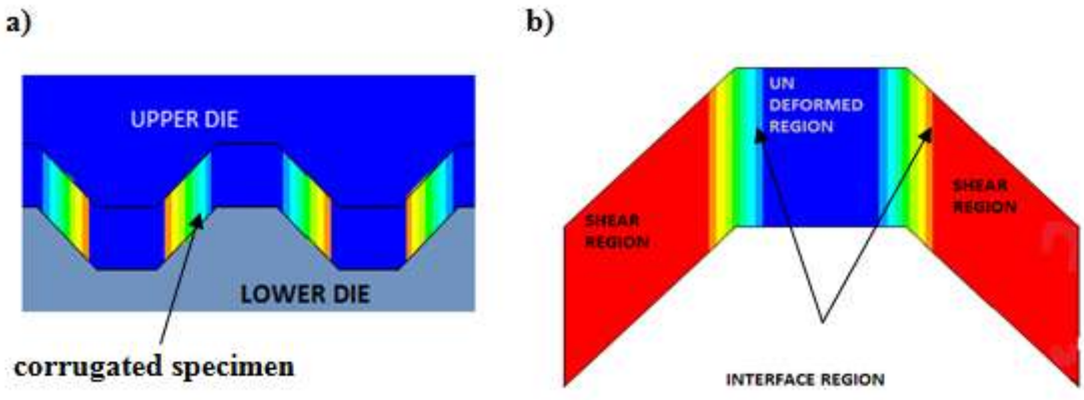


Fig. 6 (A-B) Schematic of Groove Pressing Showing Different Deformation Regions in the Specimen

The specimen was subdivided into three regions according to the deformation modes see Fig.6(b). Shear region, undeformed flat region and interface region between the shear and flat regions. Plastic deformation occurs mainly in the shear region, where the theoretical Von Mises equivalent strain per pressing is 0.58, assuming the deformation mode is simple shear (not pure shear!) and there is no interaction between shear region and flat regions. Fig.6 shows the variation of Von Mises equivalent strain distributions in CGP processed specimen after two cycles. The strain level increased with the number of passes.

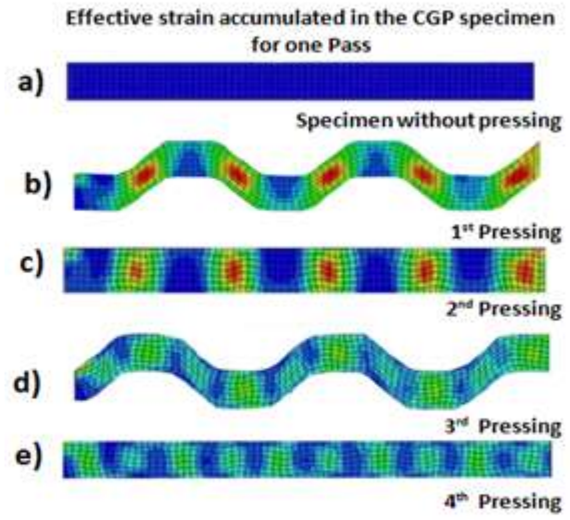


Fig.7 (a-e) Effective strain accumulated in the CGP specimen for one pass

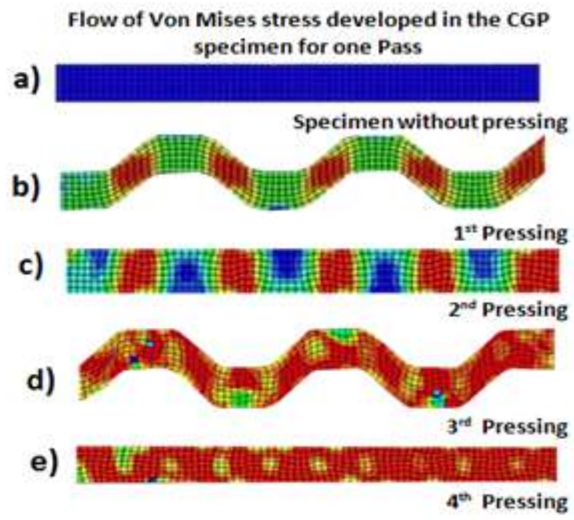


Fig.8 (a-e) Flow of Von Mises stress developed in the CGP specimen for one pass

From Fig .7(a-e), it is observed that the in homogeneity within the specimen was higher as the number of cycles increased. Looking at the first cycle, the Von Mises equivalent strain ε_{eff} values after first pressing and first flattening in the first shear region are $\varepsilon_{eff} = 0.80$ and $\varepsilon_{eff} = 1.66$, respectively, which are larger than theoretical values $\varepsilon_{eff} = 0.58$ and $\varepsilon_{eff} = 1.16$ of the simple shear during the first cycle. This is because of the interaction between the shear region and flat region: more deformation is generated in the shear region in CGP than in the region of simple shear alone. Because of the interaction between the shear region and flat region, the deformation mode in CGP is not simple shear.

The flat regions deform by a negligible amount of deformation during the pressing and flattening steps. During the flattening steps, the flat regions do not deform but the shear regions deform by the same amount of shear strain in the reverse direction. The top die was shifted in the simulation towards RHS(or the specimen rotated about 1800 in the plane of pressing) by the width of the flat regions (that of the shear region 5 mm), between the first flattening and the second pressing steps, in order to impose deformation in the previously undeformed flat regions after first pressing (undeformed regions). It can be found that, the deformation obtained in the first cycle was a little more homogeneous after second flattening than after the first flattening. Even though strain localization was relieved after the second cycle, compared to the first cycle, strain is not as homogeneous as expected. The strain between the maximum and minimum points after the second flattening was smaller than that in the first flattening due to the differences in the relative strength of the flat regions surrounding the shear regions. During the first pressing and flattening steps the relative strength of the flat regions surrounding the shearing region is weak, and deformation diffuses out of the shear region. For the second cycle, the situation of strain localization does not change. The differences in strain between the maximum and minimum points after first flattening and the second flattening are 1.68 and 1.66, respectively. It should be noted that strain distribution after the second flattening is a little more homogeneous than that after the first flattening.

Fig.7(a,b,c,d,e) shows the unreformed specimen , the Deformation of specimen in First corrugated pressing the strain is developed, the Deformation of specimen in First flattened pressing the strain is developed , After 1800 rotation of the first flattened specimen ,the Deformation of specimen in Second corrugated pressing the strain is developed, the Deformation of specimen in Second flattened pressing the strain is developed. Effective strain accumulated in the CGP specimen for one pass (Four pressing) shown in Fig.7 (a-e) Similarly Flow of Von Mises stress developed in the CGP specimen for one pass shown in Fig.8(a-e).

Fig.9 & Fig.10 shows the effective strain distribution in different layers in CGP specimen, i.e Bottom layer, Middle layer and Top layer. From Fig.9 it shows the strain uniformly distribute in the middle layer strain is 1.68 but in top and bottom layer, strain distribution is less in first straightening. From Fig.10 it shows the strain uniformly distribute in the middle layer, strain is about 2.5 but in top and bottom layer strain distribution is less in second straightening process.

Although the average strain level increases, the strain localization intensified with increasing number of CGP cycles, stress need not always follow the same trend, because the stress gradient decreases with strain. It is evident that the stress distribution can be considered as relatively uniform, compared to the strain distribution. The experimental stress values estimated from the hardness are in reasonably good agreement with the simulated results.

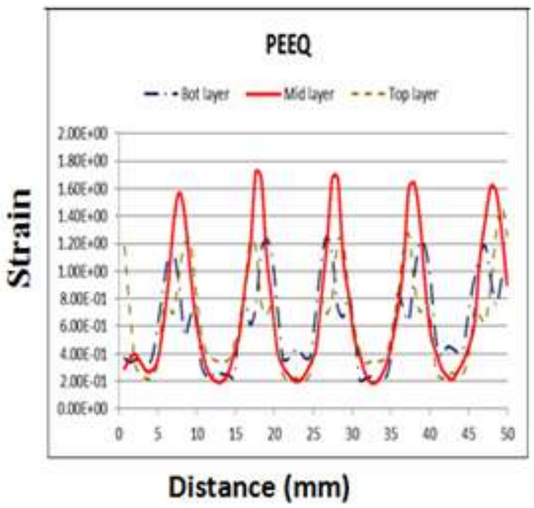


Fig.9 Equivalent Strain after First Straightening

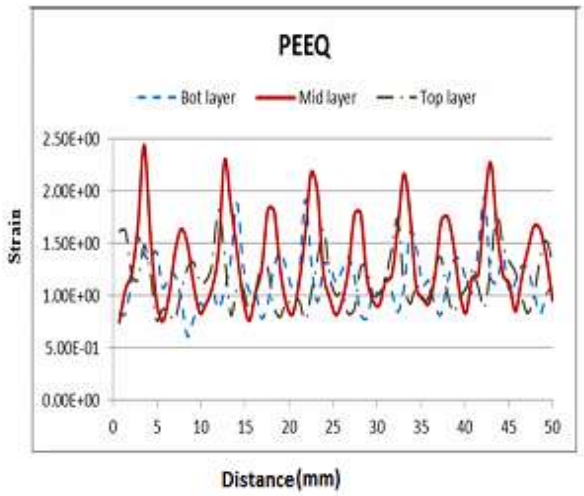


Fig.10 Equivalent Strain after second Straightening

VI. CONCLUSION

- In this study the complete simulation of two corrugation and two straitening process is made using CAD/CAE tools. The commercial pure aluminum CGPed samples were pressed up to five passes.
- From the previous literatures and studies, nanostructured material can be produced by Severe Plastic Deformation (SPD) methods, from these studies it was noted that the CGP method is the most applicable for producing Nanostructured sheet metals.
- The CGP process produces high quality nanostructured materials, where, the quality of surface roughness improves with the increasing number of passes. Also, this process concerned with produce metals and alloys with controlled Nano-sized grains, and free from defects such as porosity, cracks, or other atomic scale defects that are known to compromise properties.

- Hardness increased in the first three passes and then trend decreased slightly at the fourth and fifth pass. Greater refinement of aluminium microstructure and further increase in strengths is expected to occur with larger number of executed passes.
- The hardness measured along the central line of the transverse cross-section did not vary significantly but the non-homogeneity is observed in FEA results. The stress distribution can be considered as relatively uniform, compared to the strain distribution.
- The results of 2D plain strain and plain stress condition showed that PEEQ in the inclined shear region is higher than the theoretical value and after four pressing steps PEEQ is not uniform throughout the work piece and is lower in the areas near the surface and the teeth of the grooved die.

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