Experimental and Numerical Investigation of Groove Pressed UFG Pure Aluminum

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Abstract: Fabrication of ultrafine grained materials by imposing severe plastic deformation for improvement of mechanical and physical properties of metals has been the focus of many researches over the past few years. In this process, a sheet is subjected to repetitive shear deformation conditions by utilizing asymmetrically grooved and flat dies through alternate pressing. In this study, a 2mm thick commercial pure aluminum sheet was subjected to repetitive pressing up to four passes. Mechanical properties including, hardness and tensity were obtained. Results show that, although increasing the number of passes causes higher strength magnitude, the strength's slope decreases. After validation of finite element modeling, strain distribution and uniformity behavior of the grooved plate were investigated using plain strain and plain stress conditions. Results show that strain in the surface and near the teeth of the die is lower than other areas.

Keywords: Aluminum, Constrained Groove Pressing, Severe Plastic Deformation, Ultrafine-grained Material.

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1 INTRODUCTION

Many methods for production of ultrafine grained materials by imposing severe plastic deformation such as equal channel angular pressing (ECAP), high pressure torsion (HPT), accumulative roll bonding (ARB), twist extrusion (TE), equal channel angular rolling (ECAR) and friction stir processing (FSP) have been recently introduced. However, the following techniques are impractical for fabrication of plate-shaped ultrafine grained materials [1]. ARB, repetitive corrugation and straightening (RCS), constrained groove rolling (CGR) and constrained groove pressing (CGP) processes are designed to make plate-shaped ultrafine grained materials. If a perfect bonding is not achieved between the plates during ARB, the existence of the bonding interface may decrease the mechanical properties of ARB processed materials. ARB has strict requirements for the surface condition of the rolled plates and the atmosphere during the roll-bonding process [2]. RCS process introduces some elongation to the specimen causing strain inhomogeneity in the sheets. Also, in this process no attempt occurs to maintain the specimen size. In the CGR process, deformation is applied by rolling mechanism which may create additional tensile strain in the specimen due to bending strain condition, leading to crack nucleation and growth [3]. CGP is a practical process to impose nearly uniform strain to specimen by asymmetrical grooved and flat dies. Schematic of the CGP is presented in Fig. 1. A plate-shaped workpiece is located between a pair of asymmetrically grooved dies that are tightly constrained [4]. As the dies press the workpiece, the inclined regions of the workpiece (single hatched regions in Fig. 1(b)) are subjected to shear deformation under the plane-strain deformation condition ($\varepsilon_{eff} = 0.58$), while the flat regions (unhatched regions in Fig. 1(b)) remain unchanged. A pair of flat dies imposes a second pressing on the grooved workpiece (Fig. 1(c)) in which the deformed regions are subjected to the reverse shear deformation ($\varepsilon_{eff} = 1.16$) while the un-deformed regions remain unchanged [4].

The workpiece is then rotated 180° (Fig. 1(d)), allowing the un-deformed regions to be deformed by further pressings by the asymmetrically grooved dies. The successive pressings by grooved dies (Fig. 1(e)) and flat dies (Fig. 1(f)) result in a nearly even distribution of plastic strain ($\varepsilon_{eff} = 1.16$) throughout the workpiece and one pass of CGP accomplished. By repeating the CGP process, a large amount of plastic strain can be accumulated in the workpiece without changing its initial dimensions [4].

After the first pressing pass the process can be continued through two approaches. In the first approach named single-orientation pressing, the inclined regions of the plate; after every pass, remain parallel to the previous pass. In the other approach (cross-orientation pressing), the inclined regions of the plate after every pass are perpendicular to the previous pass. In other words after every pass the plate is rotated 90° around the vertical axis.

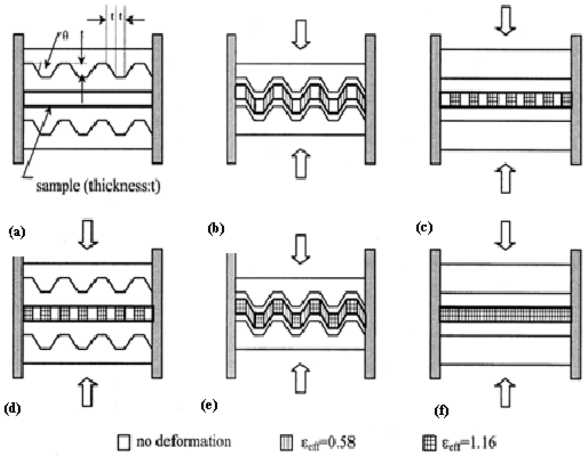

Fig. 1 Schematic of the sequences of the CGP [4]

The second approach has some advantages such as higher grain refinement rate and lower crack propensity due to more even distribution of bending and stretching locations where the materials are subjected to the most severe loading condition and thus prone to cracking [5]. The present study is led by the latter approach. In order to investigate strain distribution in CGPed plates after four pressing steps FEM simulation has been accomplished.

2 EXPERIMENTAL PROCEDURE

In the present study pure aluminum commercial plates with dimensions of 88mm×88mm×2mm were pressed up to four passes using cross-orientation pressing approach.

Fig. 2 Designed grooved die (right), flat die (left)

Table 1 Chemical composition of used Al

Al	Si	Fe	Cu
Base	0.189	0.397	0.106
Mn	**Mg**	**Cr**	**Ni**
0.0379	0.0142	0.0028	0.0073
Zn	**Ti**	**Be**	**Pb**
0.0282	0.0093	0.00003	0.002
Sb	**Sn**	**V**	**Zr**
0.0012	0.0038	0.0173	0.001

The chemical composition of the CGPed aluminum is shown in table 1. Designed grooved die is shown in Fig. 2 (right), and designed flat die is shown in Fig. 2 (left).

As it is shown a container is used to constrain the specimen in the die. Before pressing, the plate of Al was annealed at 773 K for 2 h. The whole pressing operation was carried out using a 250 ton hydraulic pressing machine at room temperature.

Hardness measurements were carried out along the central line of the transverse cross-section using a Vickers bulk hardness tester with a 1 kg load for 15 s. The mean hardness values were obtained, through calculating an average of 8 measurements. Tensile testing was carried out on a specimen with dimensions depicted in Fig. 3, using a 50 KN tensile testing machine at a cross head speed of 0.1 mm/s.

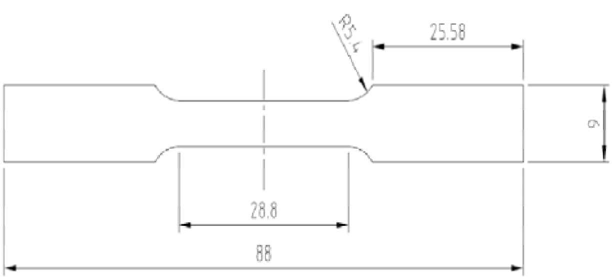

Fig. 3 Dimensions of tensile test specimen (mm)

3 SIMULATION PROCEDURE

In order to investigate the strain distribution in the CGP process after four pressing steps, the finite element technique was accomplished. The simulations were investigated after one full pass using the commercial finite element code ABAQUS/Explicit. The simulation was considered under 2D plane strain and plane stress conditions. 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 and CPS4 elements for the 2D plane strain and plane stress conditions, respectively. The mesh number used in the simulation is 8800.

The coefficient of friction in the workpiece–die interface was selected as 0.1, which is within a typical (0.05–0.1) range in the cold forming of metals [6].

4 RESULTS AND DISCUSSION

4.1. Mechanical properties

In order to monitor the effect of constrained groove pressing on the hardening behavior and mechanical homogeneity of CGPed specimens, the hardness was measured. The as-receive sample had a mean hardness value of 28 HV, which increased rapidly to 41.5 HV after the first pass ($\varepsilon_{eff} = 1.16$) as a result of strain hardening.

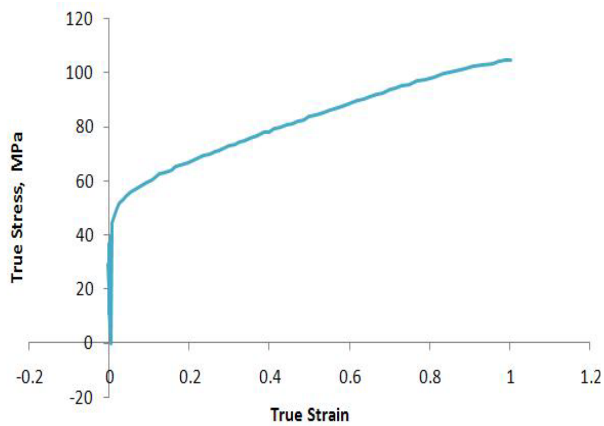

Fig. 4 Stress-strain curve used in the simulation

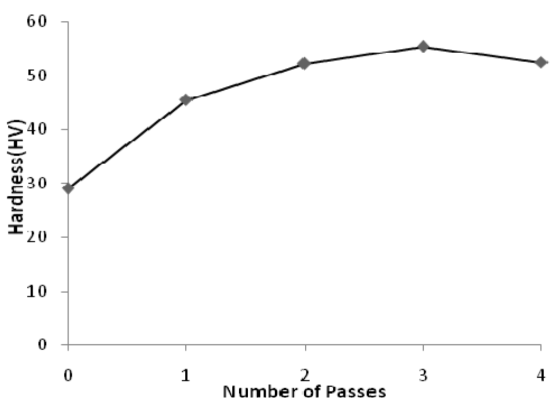

Fig. 5 Mean of Vickers hardness variations with number of passes

After the second ($\varepsilon_{eff} = 2.32$) and the third ($\varepsilon_{eff} = 3.48$) passes the hardness value increased slightly and then decreased to 47 HV after the fourth pass ($\varepsilon_{eff} = 4.64$) (Fig. 5). The decrease in hardness in subsequent groove pressing step may be due to strain softening after imposing 3.48 strain.

The hardness measured along the central line of the transverse cross-section did not vary significantly (Fig. 6) which confirms that the deformation is homogenous along this direction.

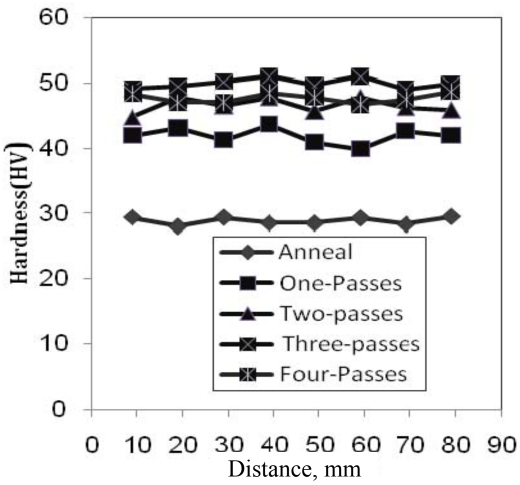

Fig. 6 The Vickers hardness profile along the transverse direction of the CGPed samples

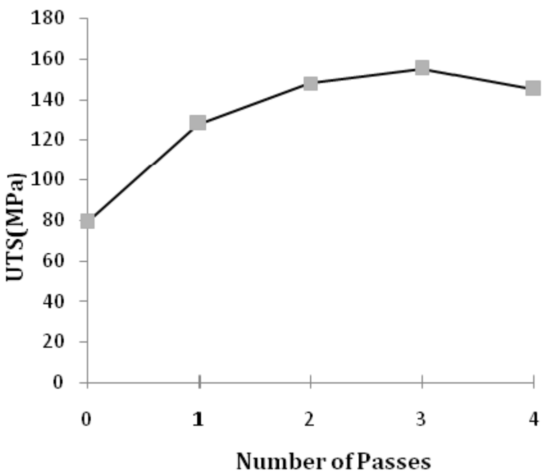

Fig. 7 Ultimate tensile strength against number of passes

The ultimate tensile strengths (UTS) of the CGPed specimens are shown in Fig. 7. The ultimate tensile strength of annealed sample is 79 MPa. It increased to 155MPa after three passes and then decreased slightly to 146 MPa. The decrease in UTS in the fourth pass may be due to creation of crack on the surface of the workpiece. The mechanical properties thus indicate improvement by CGP which is due to strain hardening and grain refinement.

4.2. 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. 8. (result of plain stress condition is very similar to plain strain).

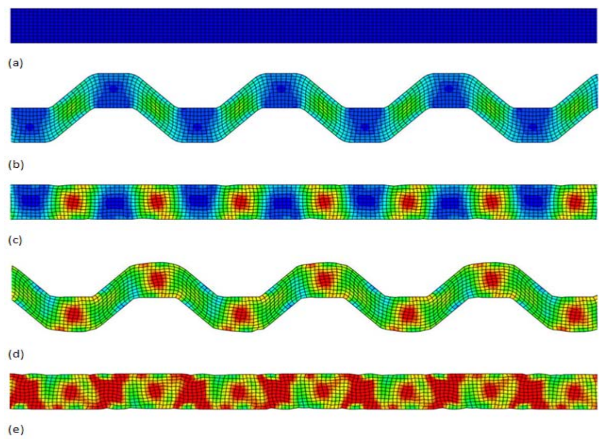

Fig. 8 Equivalent plastic strain contours in different pressing steps (a) Initial (b) After first pressing step (c) After second pressing step (d) After third pressing step and (e) After fourth pressing step

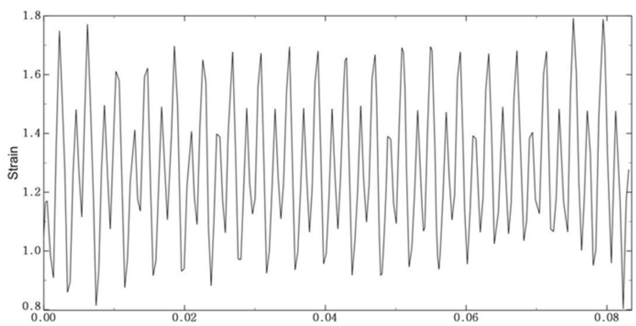

Fig. 9 Variation of PEEQ in the center line of the workpiece after the fourth pressing step

The equivalent plastic strain was imposed at the inclined areas at the first and third pressing steps, and the magnitude was doubled at the second and the fourth pressing steps. Maximum PEEQ in the inclined shear area after the first pressing step is 0.83 which is greater than the theoretical value (0.58) due to presence of tension in addition to shear in this area (not pure shear). Variation of PEEQ in the center line of the workpiece after the fourth pressing step (one full pass) is presented in Fig. 9. 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).

5 CONCLUSION

In this study the commercial CGPed pure Al was investigated. Samples were pressed up to four passes and strain of 4.48 imposed at the fourth pass. Hardness and ultimate tensile strength increased in the first three passes and then decreased slightly at the fourth pass. The increase in the first pressing pass has a higher rate. The results of 2D plain stain 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 workpiece and is lower in the areas near the surface and the teeth of the grooved die.

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