3D FEM simulation on Deformation and Strain analysis for grain refinement of Mg Alloy passed through ECAP

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Abstract. Equal Channel Angular Pressing (ECAP) is a cutting-edge Severe Plastic Deformation (SPD) process for grain refining of materials up to ultra-fine or nanostructured standards, resulting in superior mechanical properties. To consider the effect of each processing parameter on the end results, computer simulation is one of the better alternatives to real ECAP deformation. The alloys used in this study are AZ61 magnesium alloy, which is a difficult material to work with in automotive applications. The ECAP process is subjected to 3D FEM simulation using ANSYS software in order to better understand the process/die design parameters. 90° channel angles and corner angles 20° i.e the best combination suggested by experimental studies were used in the simulation. For a single ECAP pass, the ECAP phase was simulated. Extrusion load, established stresses, effective strain, and temperature variation on the processed material were all noted in the results. The minimum channel angle produces the highest temperature profile on the material, developing maximum stress and strain at the deformation zone, according to the observed results. Furthermore, the results obtained using such computational techniques show that the shear strain decreases as the channel and corner angle increase.

Keywords- Severe Plastic Deformation, Equal Channel Angular Pressing, AZ61 magnesium Alloy, ANSYS, Element method simulation

1. Introduction

Nowadays, the manufacturing industry needs products that are high in strength, have a broad tolerance range, and are affordable to consumers. Magnesium is widely used and has a large scope of applications. For example, AZ61 magnesium is used in the automotive industry because it is a lightweight material with a high load capacity [1]. The ECAP technique is one of the most well-known methods for meeting the needs of the industry in today's world. It is a technique in which a material is subjected to high stress, resulting in a positive strain in the material. That strain is what helps to improve the properties and create
an ultra-fine microstructure [2]. Equal channel angular pressing is the safest technique for extreme plastic deformation in ductile metals. In a number of ways, equivalent channel angular pressing has been found to be superior to other techniques [3]. The key benefit of ECAP is that the material's cross-sectional area remains unchanged. Figure 1 depicts the ECAP basic sketch. The two angles visible in the above figure are angle of channel (Φ) and angle of corner, which are two significant ECAP parameters. The angle of channel, which ranges from 90˚ to 135˚ is the angle at which two die channels converge. Corner angle, on the other hand, is the outer arc angle at the point of intersection, which can range from 0˚ to 30˚ degrees [4]. The software simulation technique was discovered to be an effective method for saving time, energy, and material while determining the impact of each processing parameter on material behaviour. For investigating the ECAP operation, the finite element method of software simulation is a well-simplified method. More specifically, by changing the formation of die gas corner and geometry of mould, the material strain hardening rate was investigated. The impact of angle of channel variations, angle of corner, strain intensity, and friction force that existed between channel and billet has been visualized using parametric studies. According to the available research, the strain softening behaviour must be used to accelerate the strain localization in various regions. Furthermore, in most cases FEM studies does not include convergence analysis for depicting the results in their models, and automated re-meshing functions have been used in some cases to achieve stable simulation results. However, in the most recent research available, there is only a small amount of work for the simulation of ECAP on AZ61 magnesium Alloy. This research is performed on a AZ61 magnesium alloy for various channel angles and corner angles in order to evaluate the strain rate deformation and total deformation that occurs after a plunger enforces a load. [5-7]

Figure 1. Setup for analysis for grain refinement of Mg-Alloy with angle of channel as Φ and angle of corner as Ψ

2. Material and Methods
AZ61 magnesium Alloy have a lot of promise in research and development because of their wide variety of applications in the machining and automotive industries. As magnesium is alloyed with aluminium, it has a higher strength and ductility. Mg proves to be the best source for overcoming iron adulteration. Table 1 and Table 2 showing the AZ61 magnesium Alloy composition and properties of material without ECAP [8].
Table 1 Composition of Material used (in %)

| Composition of Material used (in %) |
|------------------------------------|
| Mg | Al | Zn | Mn | Fe | Si | Cu | Ni |
| 93.1 | 5.95 | 0.64 | 0.26 | 0.005 | 0.009 | 0.0008 | 0.007 |

Table 2 Properties of material without ECAP

| Properties                              | METRICS (MPa) |
|-----------------------------------------|---------------|
| Tensile strength                         | 310           |
| Yield strength for value of strain as 0.200% | 230           |
| Compressive yield strength 0.2% offset   | 130           |
| Ultimate bearing stress                  | 470           |
| Bearing yield stress                     | 285           |
| Shear strength                           | 140           |

Simulation 3D FEM is used to investigate the variation in the extrusion load, and also amount of effective stress and strain of AZ61 magnesium alloy developed by ECAP method of simulation. The benefits and merits of using this specific method, namely software simulation, can be attributed as study of the changes and characteristics on experimental test material, and the outcomes can be predicted or visualized on the actual process [8-10]. One of the most prominent disadvantage of this kind of technique is that one single simulation is insufficient for the large size billets, so some method for large billets is needed to be created. The ANSYS Workbench programme was used to run 3D FEM simulations on rigid visco-plastic materials [6]. The APDL Known as ANSYS Parametric Design Language solver was used to perform static structural analysis. During process of severe plastic deformation the conclusion of ductile, fracture damage was incorporated by the means of ANSYS WORKBENCH device. For the purpose of depicting the boundary conditions during the simulation, input was considered from the tensile test data, displacement control medium and free extending length on Y axis with one end free and other fixed. With a quadrilateral/triangular element shape and a 1 mm element dimension, a hex-dominant method was used to mesh. Finally, from ANSYS WORKBENCH 18 analysis, Von-Mises stress, principal stresses, equivalent plastic strain, and results concluded from the strain simulation technique were extracted for further theoretical and numerical modelling [11-12].

3. Result and Discussion

Incorporating true stress-strain gained from experimental setup with the Hollomon's flow law, the uniform deformation regions were identified. Table 3 summarizes the (K) i.e. coefficient of strength and (n) i.e. exponent of strain hardening values for every ECAP passes. The 0.2 offset yield force, ultimate tensile strength, elongation, and modulus of elasticity were all evaluated using experimental tensile test results. The Poisson's ratios of each ECAP pass were estimated using ANSYS WORKBENCH 18.0 and a trial and error approach with reverse simulation analysis [13]. One pass of
technique of ECAP with inconstancy of design of die parameters is proceeded using ANSYS computer simulation.

3.1 Analysis of the Extrusion load
The impacts of various angles such as channel angle and corner angle on extruder load is depicted using a single pass ECAP modelling using FEM-based simulation software. Figure 2 illustrates the simulation effects in terms of an extruder force vs. time graph for the optimal channel and corner angle values [14-15]. The increase in load during the initial process indicates that the billet has reached the die channel's corner, and the load has stabilized since reaching its full value. For the purposes of this study, Fig 2 shows that the maximum load for a die with a channel angle of 90 and a corner angle of 20 is approximately 861.83 KN. Similar results have also been documented by Liu el. The maximum load is reached as the material moves through the Deformation region, according to their brass ECAP simulation analysis.

![Graph between extrusion force (in N) vs. Time (in sec)](image)

**3.2 Deformation analysis**
Two-stage deformations were considered in this paper: The uniform deformation stage was defined as the damage nucleation site, including the GTN parameter ranges (nucleation strain and the corresponding nucleation void volume fraction); The non-uniform deformation stage, which includes the second stage GTN impact parameter ranges, was defined as the non-uniform deformation stage. [16-17]

3.2.1 Total Deformation By passing the material piece through the bent ECAP channel and using FEM-based simulation tools, the complete deformation of Mg alloy is investigated. During the extrusion process, the Successful total deformation of a Mg alloy billet is shown in Fig 3(a). The curve representing the variance of this deformation over time is shown in Fig 3(b). The bent zone of the channel or the corner area of the channel, known as the main deformation zone, is where the Mg alloy experiences the most deformation. The maximum deformation measured is 0.021m, while the minimum deformation measured is 0.009m. The scale is from 0.009m to 0.021m.
3.3 Stress analysis

The maximum stress in the billet during the extrusion phase is shown in Fig. 4(a). The highest stress is observed in the channel's corner area, which is also known as the key deformation zone. The overall stress is reduced and the stress distribution is widened when an outer radius is present. [nine] The added inner radius reduces the overall stress and further spreads the stress distribution. On all simulation scenarios, the overall stress that exists on a 105° channel angle is slightly higher than on a 90° channel angle on every corner radius. Furthermore, for channel angles greater than 120°, the stress is significantly reduced.

3.3.1 Equivalent Stress

Fig. 4(a) illustrates the Effective Equivalent Stress distribution in billet during extrusion process and Fig 4(b) illustrates the Equivalent stress vs Time curve during simulation in the billet during the period of extrusion. The key deformation zone is located inside the channel's corner area, which has the highest stress. The maximum value of effective equivalent stress can be shown to range from nearly zero to 14.4 GPa. Similar patterns in stress growth have been established by Niu et al. In their numerical simulation of ECAP processing, they discovered that the highest stress generation occurs at Deformation [18].
Figure 4. (a) Setup for calculation of Equivalent stress (b) Variation of Equivalent Stress (in Pa) with Time (in sec)

3.3.2 Maximum principal stress Simulations of ECAP plastic deformation in the AZ61 magnesium alloy and the resulting overall principal stress distribution ranges. The maximum value of the effective principal stress is 152.43 GPa at the corner or bent region of the channel. This very high value increase the strength of the Mg alloy billet thus making the worth of ECAP method. Maximum Principal Stress is concentrated to a region known as main deformation zone. However the minimum value is -4.331.

Figure 5 (a) Setup for calculation of Maximum Principal Stress (b) Variation of Maximum Principal Stress (in Pa) with Time (in sec)

3.3.3 Shear stress Fig 6 (a) illustrates process of finding shear stress in billet during extrusion process .The Maximum value of shear stress is found to be 9182.9 MPa which is as usual at the inner bent region of the channel or inner corner region. However the magnitude of minimum shear stress obtained is also significant and turns out to be -7613.3 MPa by the ANSYS software. Negative sign symbolize that shear stress is on negative side on the axis. Inner bent region is also called as main deformation zone.

Figure 6 (a) Setup for calculation of Shear Stress (b) Variation of Shear stress (in Pa) with Time (in sec)
3.4 Strain analysis

The strain distribution in the billet tends to be highly non-uniform, with significantly different levels of residual strains in different regions. As a result, we used the strained comparative fraction of the sample amount in the total volume versus the strain strength to compare the amounts of cumulative strains in the material after various modes of ECAP. Volume of sample referring to a strained proportional fraction and strain strength coordinate for a given limit.

3.4.1 Maximum Principal Elastic Strain

Fig. 7(a) illustrates the Effective Equivalent Maximum Principal Elastic strain distribution in Mg alloy billet during extrusion process and Fig.7(b) illustrates the Equivalent Maximum Principal Elastic strain vs Time curve during simulation of Mg alloy billet during the period of extrusion. The highest elastic strain occurs inside the corner region of the channel with the value of 0.2972 m/m and is also known as the main deformation zone. The minimum elastic strain can be attributed to be less than 0.033 m/m. It can be observed that the maximum value of effective elastic strain varies from almost 0.033 to 0.2972 m/m.

3.4.2 Shear elastic strain

Fig.8(a) shows the effective shear elastic strain in Mg alloy billet during extrusion process of analysis Fig 8(b) shows the curve for the variation of shear elastic strain which is obtain by the means of ANSYS simulation software. It can be easily seen that maximum value of the shear strain is concentrated to very small region at the bend of the channel. The maximum value of shear strain is limited to 0.5509 m/m and minimum value correspond to -0.4568. We get the negative value of the shear strain where the shear strain is acting in the opposite direction of an axis.

3.4.3 Equivalent total strain

Fig.9(a) illustrates the setup for calculation of effective total strain in a Mg alloy billet during the extrusion process, Fig 9(b) provide the curve for the variation of Total Strain with time. This curve is obtained by the means of simulation software when the analysis is done for Mg alloy. Maximum value of the Total strain can be seen in corner region of the channel known as main deformation zone. 0.362m/m is the maximum value of the total strain produced and minimum value of total strain is approximately equal to zero.
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4. Conclusion

From automotive to aerospace and from industrial to commercial application Mg based alloy can be linked to great use in manufacturing and machining sector. Extreme plastic deformation (SPD) is a useful technique to achieve the desirable properties in a material by going through the grain refinement analysis. These grain refinement analysis can be done by Finite Element Method based Software (FEM), by this means the working condition, mechanical performance, tensile strength of a material can be determined. Therefore to observe these characteristics simulation of the ECAP method of the Magnesium alloy using Ansys software was used. The following conclusion can be drawn from the simulation data:

- Effective Total deformation was studied with the help of simulator. The value of total deformation comes in the range of 0.009m to 0.021m. With 0.021m is the maximum value at the main deformation zone. Also the minimum value is 0.009m
Effective Maximum Principal strain in the Mg alloy billet was simulated and observed. Maximum value during the extrusion of the billet is 0.2972 m/m while the minimum value is nearly zero. The main deformation zone has highest value of the effective principal strain.

Effective Shear elastic strain in the Mg alloy was studied by the means of FEM based analysis software ANSYS. We get the maximum value and minimum value of effective shear elastic strain as 0.5509 m/m and minimum value correspond to -0.4568. Maximum value is found near the main deformation zone.

Effective total strain in the billet ranges from approximately zero at the straight region of the channel to reaching a maximum value of 0.362 m/m at the inner corner region of the channel. These results was observed during analysis of the Mg alloy using ANSYS software.

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