Abstract

Background/Objectives: Pressed and sintered Al1100 powder is subjected to Equal Channel Angular Pressing (ECAP) process to study densification and deformation behaviour under different initial relative density and shear friction conditions. Methods/Statistical Analysis: Commercially pure Aluminium (Al 1100) powder containing 99% Al, 0.05–0.2% Cu, 0.05% Mn, remainder of Si, Fe and Zn is processed through normal powder metallurgy route followed by ECAP process. Finite Element Analysis through simulations are carried out using DEFORM 2D software for different initial relative densities of 0.700, 0.750 and 0.800 under three friction coefficients of 0.05, 0.075 and 0.15. Effective stresses, strains and loads are plotted. Findings: Full densification is achieved near the inner corner of the die channel compared to the outer corner at the end of the process. Uniform densification (relative almost greater than 0.980) is achieved in the middle portion of the specimen. As the friction is increased load required also increases. Formation of dead zone near the inner corner of the die channel reduces as the initial relative density is increased from 0.700 to 0.800. With higher initial relative density, complete densification occurs in the lower friction conditions like close to 0.05 shear friction coefficient. Effective stress is higher in the plane of intersection of the die channels where the actual deformation occurs. With the increase in initial relative density, effective strain also increases along the length of the specimen whose value is higher near the top portion of the die channel as compared to the bottom portion. Application/Improvements: ECAP eliminates residual porosity. Ultra fine grained structures are produced, even finer (better mechanical properties) than that by ECAP of cast products. Best suited for aerospace, defence and biomedical applications.

Keywords: Aluminium, Densification, ECAP, Powder Metallurgy, Simulation

1. Introduction

Segal et al.¹ did a pioneering work to impose large plastic strains on metals thus developing one of the popular Severe Plastic Deformation (SPD) processes called Equal Channel Angular Pressing (ECAP). ECAP is at present the most developed SPD processing technique for wrought metals to produce Ultra-Fine Grained (UFG) materials without changing the cross-section of the deformed specimen. In this method a large amount of simple shear deformation can be produced in a material by pressing through two intersecting channels having identical cross sections¹⁻³. Deformation occurs in a plane at the intersection of the two channels¹.

With this process, microstructure control of wrought materials is difficult along with limited improvement in the properties of these materials. For example, the minimum grain size that can be achieved in aluminium alloys produced by casting is about 10 µm¹. In case of pressed and sintered products, the presence of voids or porosity is

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one of the major factors causing reduction in mechanical properties of Powder Metallurgy (P/M) products. High intense plastic shear involved in the ECAP process on P/M processed specimen would result in high densification of the final product and grain refinement. The simulation of compacted and sintered porous Al–1100 is done in DEFORM 2D software, with material assumption that the porous materials are treated the same as the compressible rigid visco-plastic materials. As part of the simulation the material density (relative density) is calculated and updated in each step.

The limiting strain rate and flow stress are specified for the fully dense state. The material density is specified at each element. This model in DEFORM 2D software is acceptable for compacted, sintered powders no less than 70% fully dense. In this work initial relative densities range from only 0.700, 0.750 and 0.800 the modelling is accurate and closely represents consolidation and densification during forging (ECAP).

In the modelling, no special yield function model is used apart from the inbuilt porous material processing routine of DEFORM 2D software, as so far no universally accepted yield function for porous plasticity has been devised for initial relative densities less than 0.9. Gurson model is acceptable for initial relative densities greater than 0.9. Moreover, this work includes the initial relative densities of 0.7, 0.75 and 0.8 only, so the simulation is quite accurate.

2. Numerical Modelling

2.1 Assumptions
- Plane strain deformation.
- Isothermal at a constant temperature of 20°C with heat generated due to friction and deformation was neglected.
- The billet material was considered isotropic and homogeneous.
- Uniform initial relative density throughout the specimen.

2.2 Simulation Control
Newton-Raphson Iteration method was used with the maximum iterations per step as 200. The Von Mises flow rule was applied by the software. The convergence error limit for velocity and force were limited to 0.001 mm/s and 0.01 N respectively. Solution step with equal die displacement of 0.4 mm.

2.3 Boundary Conditions
- Displacement and Rotation in the X and Y directions for all the nodes in the die were arrested.
- Punch was given a displacement in the -Y direction.

3. Results and Discussion
3.1 Densification Behaviour
Figure 2 shows densification behaviour of the Al specimen for various shear friction coefficients of 0, 0.05, 0.075 and 0.15. At the end of process, comparatively full densification is achieved near the inner corner than near the outer corner of the die due to a sharp turn in the die channel thereafter. As the coefficient of friction increases, with other parameters as constant, the corner gap (gap between outer corner and the billet) is reduced due to increase in densification.

Moreover, the densification is increasing along the bottom of the specimen as the friction coefficient is increasing. In Figure 2 due to high friction comparatively, along the top and bottom of the die channel the relative density of the specimen is higher compared to the middle portion which is not in contact with top and bottom die channel. The front region called as transient region, where relative densities vary, reduces with increased friction. Since from the beginning of the process itself the material at the front region starts to get densified more with die contact. Uniform densification is achieved in the middle portion of the specimen.

Figure 3 shows the load in N for the displacement in mm of the punch for various friction coefficients. In the beginning the billet fills the entire die and densification...
starts, so the load requirements gradually increase for all four cases as shown. As is evident from the figure, the load requirement is higher if friction is higher.

Interesting observation made is, once reaching the peak load at about halfway through the exit die channel, in case of no friction condition, the load continues to increase due to densification whereas in case of $\mu = 0.15$ though the load required to continue the deformation is higher than the previous case but it decreases with increase in displacement.

In the curves that represent $\mu = 0.05$ and $\mu = 0.075$, the load requirement is similar as explained earlier until the peak load is reached then the load required is reduced. It then increases in the final stage through the die channel. This is explained by the decreasing corner gap and formation of high density region at the outer corner near the bottom as in Figure 2.

Occurrence of a kink in the load stroke curve (small reduction) in the load required in $\mu = 0$, $\mu = 0.05$ and $\mu = 0.075$, but not in $\mu = 0.15$ curve suggests that there is a slight elastic recovery taking place which reduces the load requirements. As friction increases the elastic recovery becomes insignificant and densification occurs faster so load curve does not have a kink rather reduces gradually with displacement.

Figure 4 shows the densification behaviour of the specimen having initial relative density = 0.750 for different shear friction coefficients 0, 0.05, 0.075, 0.15. Full densification occurs in the central portion of the specimen almost similar to the previous case (Figure 1). The difference being, in Figure 2 wherein full densification occurs both near the outer and inner corners of the die channel compared to inner die channel as in Figure 1.

Another important observation made is the overall increase in the final relative density in each element at the end of the process compared to relative density = 0.700 case. This can be seen by comparing the colour charts of two Figures 2 and 4. This observation translates to overall increase in the densification of the specimen if the friction increases.

From the Figure 5 which shows the load in N for the displacement in mm plotted for various values of $\mu$, as explained earlier initially the load increases gradually for all the cases. But for curves of $\mu = 0.05$, $\mu = 0.075$ after

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**Figure 2.** Final relative density distribution of the specimen with initial relative density = 0.700 before ECAP process.

**Figure 3.** Load-stroke curves for initial relative density = 0.700.

**Figure 4.** Final relative density distribution of the specimen with initial relative density = 0.750 before ECAP process.
reaching peak load the load requirement decreases then remains approximately constant contrary to what was observed from Figure 3.

In the curve corresponding to $\mu = 0.15$ there is a slight increase in the load required just after halfway through the die channel which happens due to reduction in the corner gap and beginning of dead zone formation due to densification.

Figure 6 shows the final deformed specimen having initial relative density = 0.800 for various friction coefficients. Even here full densification occurs in the specimen similar to previous cases. In this case, complete densification occurs in the outer corner of the die channel in lower friction case itself comparing Figure 6 with Figure 4.

It would be proper to conclude that increasing the initial relative density would help in complete densification more favourably in lower friction conditions itself. Here, the overall increase in the relative density of the specimen is higher compared to the previous case which in turn shows upward trend compared with the first case.

In the Figure 7 showing load-stroke curves the trend of the curves is very similar to that observed in the case of initial relative density = 0.750. In case of $\mu = 0.15$ curve towards the end of the deformation, the load decreases quite gradually but as in Figure 5 for $\mu = 0.15$ curve there is a sudden drop. This can be explained by the difference in the densification along the length of the specimen having different initial relative densities.

In this case again after reaching the peak load nearly at the middle of the deformation for curves of $\mu = 0, 0.05, 0.075$, the load requirements remains approximately the same but for $\mu = 0.15$ curve the load required decreases with increase in the displacement.

Figure 8 explains that when the coefficient of friction increases peak load increases. The peak load increases with increase in initial relative density. This increase is predominant when the coefficient of friction is higher.

The slope of the curves indicates that peak load does not vary much when the value of $\mu$ varies from 0.05 to 0.075. This implies that for small increase in friction the (in the middle region) variation in the peak load is low. For initial relative densities 0.700 and 0.750, the variation in the peak load requirements is almost overlapping. Also from $\mu = 0$ to 0.05, the increase is quite significant whereas from $\mu = 0.075$ to 0.15 there is a predominant increase in the peak load.
3.2 Effective Stress and Effective Strain Profile

The above Figure 9 is included for no friction case i.e. $\mu=0$ for various initial relative densities. From the Figure 9, the effective stress is more near the plane of intersection of the two die channels which is where the actual shear deformation of the specimen happens. This zone of shear deformation goes down towards the bottom channel with increase in relative density as shown.

Due to lower initial relative densities in the first two cases there is a small region near the inner die corner where the effective stress is less than that in the shear zone. This observation is not made when the initial relative density is 0.800. Along the length of the pressed sample, the effective stress has uniform value as shown in the Figure 9.

![Figure 9](image_url1) 
**Figure 9.** Effective stress profile at just before the completion of the deformation process.

![Figure 8](image_url2) 
**Figure 8.** Variation of Peak load with Coefficient of friction for various Initial relative densities ($d$).

![Figure 10](image_url3) 
**Figure 10.** Effective strain profile at just before the completion of the deformation process.

| MATERIAL | PROPERTY/TYPe | DIMENSION/VALUE |
|----------|---------------|----------------|
| BILLET   | POROUS Al-1100|                |
|          | HEIGHT        | 50 mm          |
|          | WIDTH         | 10 mm          |
|          | INITIAL RELATIVE DENSITY | 0.700, 0.750, 0.800 |
|          | SHEAR FRICTION COEFFICIENT | 0.05, 0.075, 0.15 |
|          | MESH ELEMENTS | 1000           |
|          | AVERAGE STRAIN RATE | 1 s$^{-1}$   |
| DIES     | RIGID         |                |
| TOP DIE  | FILLET RADIUS | 2 mm           |
|          | CHANNEL ANGLE | 90°            |
| PUNCH    | RIGID         |                |
|          | SPEED OF TRAVEL | 1 mm/s       |
Finite element modelling of the ECAP process was done for porous Al 1100 in DEFORM 2D software. Simulations were carried out for various friction coefficients and initial relative densities of the specimen.

Densification and deformation behaviour were shown with load-stroke curves for various initial relative densities and density profile of the specimen in fully deformed state. With this peak load assessment can be made for various initial relative densities.

With increase in friction, the corner gap is reduced due to increase in densification as well as load requirement is high. With increase in initial relative density, even at lower friction coefficient complete densification can be achieved.

As the coefficient of friction increases the peak load increases, which in turn increases with increase in initial relative density. Smaller the increase in friction coefficient, smaller the increase in peak load requirement.

Effective stress and strain profiles were included which shows the regions of the specimen subjected to high stress and strains and their variation along the length of the specimen.

5. References

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