Optimization of Die Parameters in Annular Channel Angular Extrusion Based on Strain Distribution Uniformity

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Abstract. In this paper, a recently developed backward extrusion method enforcing severe plastic deformation is modified for processing cup-shaped part with homogeneity strain. Variation of channel angles (Φ) and corner angles (Ψ) have been employed to obtain a better strain distribution. The performance is analyzed using finite element modeling Deform 3D commercially available software. To verify the simulation results, the experiment was carried out for AZ80 magnesium alloy. The present work investigates effective strain distribution behavior, analyzed by several strain regions during the forming process. Furthermore, the influence of different channel and corner angles on the strain distribution uniformity of the wall in the formed part is especially evaluated. The best strain homogeneity is obtained with Φ=75° and Ψ=60°. Particularly worth mentioning is that the strain uniformity achieved by this novel method is better than that obtained in the conventional backward extrusion. While the smaller corner angle (Ψ) can develop gradient effective strain distribution, adversely affecting the strain homogeneity.

Keywords: Annual channel angular extrusion; Finite element analysis; Effective strain distribution; Strain homogeneity.

1. Introduction
Magnesium alloy is currently the lightest metal structural material and has been applied for many years in aerospace, automotive, electronics and other industries1,2. The considerable potential application in magnesium alloys can be further enhanced by the advanced mechanical properties using severe plastic deformation (SPD) processing3. SPD techniques can produce ultra-fine grain(UFG) of materials, resulting in strengthening based on the Hall-Petch relation-ship4. Over several decades of development, the application of SPD technology has gradually become widespread. Equal-channel angular pressing (ECAP) is the most commonly used SPD techniques, since it's capable of producing homogeneous fine-grained microstructures in bulk materials with large dimensions, which makes it a better candidate for structural applications5.

Nowadays, the extrusion process, especially the backward extrusion (BE) method performs well in terms of material saving and high surface quality, has become one of the most promising manufacturing processes6. Even so, different strain distribution through the extruded part and the larger extrusion load limit the development of BE method. Furthermore, inhomogeneous mechanical properties and microstructures restrict the application of products as load-bearing components. V. Shatemashhadi et
al\textsuperscript{7}. Proposed a novel method for the backward extrusion, and a lower punch pressure as well as a higher effective strain was obtained compared to those in the conventional backward extrusion. Moreover, the strain distribution of the wall in the extruded part was uniform, resulting in homogeneous microstructure and mechanical properties. This method is entitled "annular channel angular extrusion" in this article for it is similar to ECAP in deformation of the shaft section but with the annular channel. S.H. Hosseini et al\textsuperscript{8}. modified deformation zone geometry by elimination of mandrel’s fillet and adding particular slope, as well as analyzed the strain uniformity and evolution of microstructure in pure aluminum by FE and experimental methods, respectively. B. Manafi et al.\textsuperscript{9}. Introduced hydrostatic in the annular channel angular extrusion. Although the extrusion load was further reduced, the sealing of the mold was extremely high. S.H. Hosseini et al\textsuperscript{10}. taken into account the minimum relative extrusion pressure and obtained optimum billet radius of annular channel angular extrusion by the upper bound approach. In the ECAP, channel angle $\Phi$ is usually considered to be 90 degree, but other angles such as 60 or 75 degrees are also used\textsuperscript{11}. Acute channel angles ($\Phi<90^\circ$) in ECAP can achieve a better effective strain within minimum number of passes, resulting in ultra-fine grain(UFG) and high fraction of high angle grain boundaries, which enhance mechanical and superplastic properties\textsuperscript{12}. A.V. Nagasekhar et al\textsuperscript{12}. studied deformation behavior and strain distribution for various channel angles of $\Phi=60^\circ$, $75^\circ$ and $90^\circ$. F. Djavanroodi et al\textsuperscript{13}. found that strain distribution was more homogeneous in the acute channel ECAP than in 90°. Kazuko Furuno et al\textsuperscript{14}.studied microstructural development during the ECAP using 60° die. The grain sizes obtained by using the 60° channel angle were smaller than that achieved using a conventional 90° die, resulting in strengthening of both pure aluminum and an Al-1%Mg-0.2%Sc alloy. Nevertheless, requirements for deformation and punch pressure for processing were more stringent in the above studies\textsuperscript{12-14}.The corner angle also plays an important role in the uniformity of the effective strain distribution and the elimination of the corner gap\textsuperscript{15-17}. Since the annular channel angular extrusion is similar to ECAP, the introduction of acute channel angle ($\Phi<90^\circ$) and different corner angles in the new method may result in a more uniform effective strain distribution or even more homogeneous microstructure.

An asymmetric channel extrusion die structure is proposed. The extrusion channel is designed into three parts: the extrusion section, the back compression section and the shaping section. Asymmetric steps are set to increase the shear strain. By designing the back pressure structure, the three-direction stress state of metal at the hatch is improved, reduced strain gradient between the upper part of the cabin section and the wall. So that it obtains a more uniform equivalent plastic strain and avoids the occurrence of forming defects.

2. Principle of the Annular Channel Angular Extrusion

As shown in Figure 1, in the annular channel angular extrusion, the mold comprises three major pieces, which are punch, mandrel, and die. Xue Yong et al\textsuperscript{18}. Studied three different mold structures, Figure 2, namely hemispherical channels, half conical channel and conical channel. Higher effective strain value along with lower SD and Max Damage often means better forming results. Figure 3 shows the results of the research, the effective strain value, SD value and Max damage of the half conical channel are intermediate levels of the three structures. Thus, half conical channel was introduced into this paper. The billet had been placed in the mandrel and pressed by a punch, and then extruded along the gap between the mandrel and die. The extruded part was gradually formed after through two corners. In order to obtain a higher shear strain, the two corners of the mandrel adopt a relatively small transition fillet.\textsuperscript{8} After the extrusion, the extruded part could be taken out with the mandrel.
3. The Corner Design of the Mandrel and the Die

The extruded magnesium alloy cup-shaped part has an outer diameter of 200mm and a wall thickness of 16mm. Therefore, as seen in Figure 4, the width of the corner passage was set to 16mm. As with the half conical channel mentioned above, we introduced a step at the bottom of the mandrel, where h and α were set as variable as shown in Table 1. It can be seen from the Figure 5 that the effective strain value, SD value, and Max Damage in the structure 2 (2mm×45°) are intermediate levels of the three structures. Step with h=2mm and α=45° was applied to the following research. After the billet flowed into the bottom region, the subsequent deformation in the shaft section was similar to the ECAP. Acute channel angles (Φ<90°) in ECAP can achieve a better effective strain as well as homogeneous strain distribution. Consequently, we referred to the parameters of the ECAP to set the channel angle (Φ) and the corner angle (Ψ). In order to study the influence of different Φ and Ψ on the uniformity of strain distribution, channel angles (Φ) are 60°, 75° and 90°, respectively. When the channel angle (Φ) is less than 60°, defects such as fold and fracture are likely to occur in the corner. Corner angles (Ψ) are 30°, 60° and
90°, respectively. Corner angle (Ψ) below 30° is generally less than 5mm, which may cause the corner gap.

Figure 4. The corner design diagram of the annular channel angular extrusion.

Figure 5. Effective strain value, SD value and Max Damage of different steps in the mandrel.

Table 1. The parameters of the step.

| h (mm) | 1  | 2  | 3  |
|--------|----|----|----|
| α(°)   | 45 | 45 | 60 |

4. The FEM and Experimental Methods

The DEFORM 3D-v11 software was used for FE simulation. The type of simulation was Lagrangian incremental, as well as the direct iteration method was selected. In this study, the employed material was the AZ80 magnesium alloy. The material model was defined as elastic–plastic. The billet was established by simple geometry in DEFORM. Table 2 shows the parameters of the simulation. All the mold parts were defined as rigid bodies, and drawn by introducing the simple 2D section rotation. Set the punch down speed to 1mm/s. The friction between the workpiece and the matrix was shear friction, and the friction coefficient was 0.3, which frequently used in the hot forming with lubrication.

In this investigation, a commercial as-cast AZ80(Mg-8wt.%Al-0.5wt.%Zn) alloy was employed. The billet with 90mm in diameter and 360mm in length was preheated at 300°C for 3h to enhance its deformability and reduce the risk of cracking. The extrusion was then conducted at 4-THP-630 hydraulic press with a punch speed of 1 mm/s. Finally a cup-shaped part was produced with 200mm in diameter and 160mm in height(Figure 6). Specimens for OM analysis were prepared by the conventional mechanical polishing and etching using a solution of oxalic acid(0.35g), glacial acetic acid(2ml), and distilled water(60ml). Image-Pro Plus (IPP) software was utilized to analyze the grain size of the cross section through OM maps.
Figure 6. The extruded cup-shaped part.
Table 2. The parameters of the simulations.

| Simulation parameters | Values  |
|-----------------------|---------|
| Elastic modulus(GPa)   | 45.0    |
| Poisson’s ratio        | 0.350   |
| Height of billet(mm)   | 360.0   |
| Diameter of billet(mm) | 90.00   |
| Mesh number of billet(1/4) | 32000 |
| Minimum mesh edge length(mm) | 2.150 |
| Friction coefficient   | 0.300   |
| Extrusion temperature(℃) | 380.0   |

5. Result and Discussion

5.1. Distribution of Strain

Figure 7 displayed a typical velocity distribution and strain grid cloud of the cup-shaped part which was extruded in the mold of \( \Phi = 60^\circ, \Psi = 30^\circ \). In the left zone of Figure 7 was deformation of the flow grid, and the other side presented the distribution of the overall strain. As shown in Figure 7, the velocity at bottom progressively decreased from the inside to the outside in the radial direction, and the lowest speed was obtained at the corner. The velocity at the wall was uniform, which means that the part was well formed. The change of flow grid and geometry during the extrusion process is of great significance for understanding the deformation behavior of the material during the extrusion. It can be seen from the flow grid diagram in Figure 7(a) that the part was roughly divided into the micro-deformation zone (I), the first shear zone (II), the bottom weak shear zone (III), the corner shear zone (IV) and the wall (V). The micro-deformation zone I was formed in the upsetting phase, subjected to smaller deformation, and the mesh was hardly deformation. The transverse grid of the first shear zone II was offset from the horizontal grid by an angle which was related to the corner of the mandrel. The grid shape changed from a rectangle to a parallelogram, which represented a significant shear deformation. The mesh of the zone III at the bottom had a large distortion, but the mesh was less affected at a portion farther from the step. After the billet entered the corner shearing zone IV, the mesh progressively gathered in the corner zone. The bending angle of each line was different, which eventually led to further refinement and elongation of the grid in the wall (V). It can be observed from Figure 7(a) that the grid of the wall is greatly refined, and the wall is mainly made of highly refined and elongated parallel mesh. In the grid cloud diagram in Figure 7, it can be seen that the wall presents a large range of fine meshes, which means that the large triangular mesh became a large number of fine and evenly distributed triangular meshes.
The distribution of the overall strain was shown in Figure 7(b). The strain distribution was basically the same as the five areas described above. The strain from the outer wall to the inner wall was gradually reduced. This was significantly different from the higher strain value in the inner wall of the traditional backward extrusion.

Figure 7. The velocity and strain distribution ($\Phi=60^\circ$, $\Psi=30^\circ$): (a) deformation of the flow grid (b) distribution of the overall strain.

5.2. Average Effective Strain of Extruded Part

Figure 8 that when the corner angle $\Psi$ is constant, the average effective strain decreases with increasing channel angle $\Phi$, which basically decreases linearly. This is the same trend as strain change of ECAP. The smaller channel angle $\Phi$ significantly increased the average effective strain, and the maximum average strain value of 3.82 was obtained at $\Phi=60^\circ$ and $\Psi=30^\circ$, which is about 2.5 times that of the conventional back extrusion.

The average effective strain decreases as the corner angle $\Psi$ increases. Compared with $\Psi=60^\circ$ or $90^\circ$, the corner angle $\Psi=30^\circ$ dramatically improves the average effective strain. As the channel angle increases, the influence of the corner angle $\Psi$ on the average effective strain is gradually reduced. When the channel angle $\Phi$ is $60^\circ$, the average effective strain decreases with increasing the corner angle $\Psi$, which is 13% and 4%, respectively, 11% and 3% for $\Phi=75^\circ$, as well as 7% and 2% for $\Phi=90^\circ$.

Figure 8. Average effective strain of extruded part.

5.3. Effective Strain Distribution of the Wall

Some previous authors determined the degree of strain uniformity by comparing several points’ standard deviation. This method has certain limitations and cannot analyze the strain distribution of the extruded
part macroscopically. Therefore, in this paper, the average effective strain and uniformity are analyzed by the overall strain distribution analysis. Figure 9 is the histogram of effective strain distribution in the wall of the extrusion section. Table 3 shows the results of effective strain distribution fitting in the wall of conventional backward extrusion and the annular channel angular extrusion. It can be seen that the strain distribution obtained in the corner angle $\Psi=30^\circ$ is different from that in the $\Psi=60^\circ$ or $90^\circ$. The effective strain distribution of the wall with $\Psi=60^\circ$ or $90^\circ$ exhibit approximate unimodal distribution or negative skewers distribution in some case. Accordingly, Gauss Amp of peak fitting is performed on the data. The fitting formula is equation (1).

$$y = y_0 + A \cdot \exp\left[-(x-x_c)^2 \cdot (2w)^{-2}\right]$$  \hspace{1cm} (1)

Centers ($x_c$) of the peak fitting results were used as the average effective strain of wall, and the uniformity was analyzed by the standard deviation ($w$) and full width at half maximum (FWHM) of the fitting results. The smaller $w$ and FWHM value, the more concentrated the strain distribution is, indicating that the strain uniformity of the wall is better.

**Figure 9.** Wall strain distribution with (a) $\Psi=60^\circ$, $\Psi=90^\circ$ and (b) $\Psi=30^\circ$.

The effective strain distribution at $\Psi=30^\circ$ exhibits a bimodal distribution. The first center $x_{c1}$ and the second center $x_{c2}$ were obtained by double peaks fitting, as well as two standard deviations $w_1$, $w_2$ were simultaneously obtained. The full width at half maximum (FWHM) in this case cannot be compared as a parameter of measuring uniformity to the unimodal distribution. Therefore, the average effective strain and standard deviation of the wall are represented by $x_{ca}=(x_{c1}+x_{c2})/2$ and $w_{a}=(w_1+w_2)/2$, respectively, and then compared with the results of the unimodal distribution.

According to Table 3, when the $\Psi=60^\circ$, the average effective strain ($x_c$) of the wall gradually decreased with the increase of the channel angle $\Phi$, the value of which was 4.31, 3.84, 3.51, respectively. The same trend occurred in $\Psi=90^\circ$, and with the increase of the channel angle $\Phi$, the average effective strain ($x_c$) of the wall was 4.03, 3.63, 3.42, respectively. It is worth noting that the average effective strain value of the wall in the conventional backward extrusion was 1.48, while the annular channel angular extrusion obtained 2.3 to 3 times strain values of the former. By comparing FWHM, it is found that the annular channel angular extrusion obtained a more concentrated effective strain distribution at the wall. The uniformity obtained in the annular channel angular extrusion was more than doubled compared with that of the conventional back extrusion.

When the $\Psi=30^\circ$, the effective strain distribution appears bimodal distribution. In combination with the rule that the effective strain value is gradually reduced from the outer wall to the inner wall, the effective strain is layered on the wall. Figure 10 clearly demonstrated the effective strain stratification of walls at $\Psi=30^\circ$. It can also be seen from Figure 10 that as the channel angle $\Phi$ decrease, the color difference of the corresponding effective strain difference in the wall gradually increase, indicating that the phenomenon of effective strain stratification is becoming more obvious. While the wall extruded by the annular channel angular obtained a higher effective strain, the uniformity of the effective strain distribution begins to decrease and the standard deviation ($w$) rises significantly. It is noteworthy that
the strain distribution uniformity in some cases is not even as good as that in conventional backward extrusion. When $\Phi=60^\circ$ and $\Psi=30^\circ$, the effective strain difference between the inner and outer walls is as high as 3.5, and the effective strain difference corresponding to the peak is still 2.4.

**Table 3.** The results of effective strain distribution fitting in the wall of conventional backward extrusion and the annular channel angular extrusion.

| Distribution type                  | xc   | w    | FWHM |
|-----------------------------------|------|------|------|
| **Backward Extrusion**            |      |      |      |
| $\Phi=60^\circ$                   | 1.48±0.0 | 0.33±0.0 | 0.78 |
| $\Phi=75^\circ$                   | 4.31±0.0 | 0.19±0.0 | 0.45 |
| $\Phi=90^\circ$                   | 3.84±0.0 | 0.11±0.0 | 0.25 |
| $\Phi=60^\circ$                   | 3.51±0.0 | 0.15±0.0 | 0.34 |
| $\Phi=75^\circ$                   | 4.03±0.0 | 0.12±0.0 | 0.29 |
| $\Phi=90^\circ$                   | 3.63±0.0 | 0.13±0.0 | 0.30 |
| $\Phi=90^\circ$                   | 3.42±0.0 | 0.14±0.0 | 0.34 |
| $\Phi=60^\circ$                   | 3.60±0.0 | 1.63±0.0 |      |
| $\Phi=75^\circ$                   | 5.98±0.0 | 1.46±0.1 |      |
| $\Phi=90^\circ$                   | 3.73±0.0 | 0.63±0.0 |      |
| $\Phi=60^\circ$                   | 4.87±0.0 | 0.73±0.1 |      |
| $\Phi=75^\circ$                   | 3.56±0.0 | 0.59±0.0 |      |
| $\Phi=90^\circ$                   | 4.10±0.0 | 0.28±0.0 |      |
| $\Phi=60^\circ$                   | 2    | 7    |      |
| $\Phi=75^\circ$                   | 6    | 2    |      |
| $\Phi=90^\circ$                   | 2    | 6    |      |

**Figure 10.** Effective strain stratification of wall at $\Psi=30^\circ$. 
Based on the above research, an experiment in which the mold structure was $\Phi=75^\circ$ and $\Psi\approx60^\circ$ was carried out to analyze the grain size and uniformity of the wall in the formed part. As shown Figure 11, the grains in the wall region are refined. The average grain size was about 26 um, as well as the grain size distribution relatively uniform.

![Figure 11. EBSD showing (a) the microstructures and (b) the grain size distribution of the extruded wall in mold with $\Phi=75^\circ$ and $\Psi=60^\circ$.](image)

5.4. Press Load Analysis

The annular channel angular extrusion force versus displacement obtained from FE and experiment($\Phi=75^\circ, \Psi=60^\circ$) has been displayed in Figure 12. Referring to these plots, the process force increases with the punch movement until two shear zone imposed to the billet, showed by region I and III in Figure 12. After passing through region III (maximum load), the pressing pressure decreases with a very slow rate which continuous to the end of the process. It is noted that increase of $\Phi$ or $\Psi$ would lead to the reduction of deformation force. Punch pressure is higher for acute channel angles $\Phi=60^\circ$ and $75^\circ$ than for $\Phi=90^\circ$. Which is similar to the ECAP extrusion load change. The high pressure is also due to the higher strains generated along the outer corner $\Psi$. This is because the larger outer corner $\Psi$ means larger fillet, the billet does not easily accumulate at the corners and can pass through the corners faster, which could reduce the load. Based on obtained calculated and experimental results, the required force to produce the cup using annular channel angular extrusion where $\Phi=75^\circ$, $\Psi=60^\circ$ was equal to 493kN and 574kN, respectively. It can be seen that the experimental force is larger than FE force. This phenomenon may be related to the change of friction state. The simulation results correspond to the experimental results.

![Figure 12. The process force of the annular channel angular extrusion obtained from FE and experiment($\Phi=75^\circ, \Psi=60^\circ$).](image)
6. Conclusion

In this work, the annular channel angular extrusion is modified in channel angles ($\Phi$) and corner angles ($\Psi$), and following conclusions could be made:

(1) The average strain decreases with increasing channel angle $\Phi$, which basically decreases linearly. The maximum average strain value of 3.82 is obtained at $\Phi=60^\circ$ and $\Psi=30^\circ$, which is about 2.5 times that of the conventional back extrusion. The rise of the corner angle can also cause a drop in the effective strain, although not as great as the channel angle has an effect on the effective strain. Moreover, with the increase of the channel angle, the influence of the corner angle $\Psi$ on the average effective strain is gradually reduced.

(2) The annular channel angular extrusion obtained 2.3 to 3 times the average effective strain value of the conventional back extrusion. The uniformity obtained in the annular channel angular extrusion($\Phi=75^\circ, \Psi=60^\circ$) is more than doubled compared with that of the conventional back extrusion.

(3) When the $\Psi=30^\circ$, the effective strain distribution appears bimodal distribution. Although the performance in uniformity is poor, it is expected to provide a reference for the gradient effective strain distribution of the outer wall to the inner wall.

(4) Suggestion: The strain distribution uniformity should be increased at the same time to promote the formation of fine grains and improve the performance.

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