

FE Simulation Investigation of Magnesium Alloy by Equal Channel Angular Processing

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Abstract: Magnesium alloy is one of the structure metals of great potential. The hcp structure makes its plasticity is poor at room temperature, which severely limits the development of magnesium alloy. Magnesium alloy plastic problem can be resolved through grain refinement method, and equal channel angular processing is one of the more effective methods of grain refinement. In this paper, two-dimensional dynamic simulation of equal channel angular processing for magnesium alloy were done with the finite element software. The deformation of magnesium alloy was analyzed when die angle and die corner angle were different. The results show that: in the main deformation zone, when die angles were different, the sample deformation in the horizontal direction is very uniform. But in the sample longitudinally direction, the greater the die angle, the more uniform the sample deformation. Die corner angle has no significant effect on the uniformity of the longitudinally deformation of the sample, but it affects the size of the dead zone and sample warpage.

Keywords: magnesium alloy; FEM; ECAP; die angle, die corner angle

1 Introduction

Magnesium alloys as the 21st century green engineering metal structural materials have the characteristics of low density, high specific strength and specific stiffness, damping performance is good, mechanical processing convenience and easy recycling etc with density and specific strength, stiffness, damping performance machining convenient and easy recycling. These advantages make it widely used in automotive, 3C aerospace and other fields[1,2]. However, magnesium and magnesium alloys are HCP structure[3], when

the deformation temperature is below 225°C, plastic deformation is limited to the basal plane {0001} <1120> slip and pyramidal plane {1012} <1011> twinning, as shown in Figure 1. Its plasticity at room temperature is very low, which severely limits the magnesium and magnesium alloy applications [4].

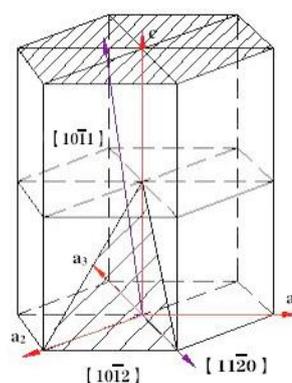


Fig.1 HCP structure of magnesium alloy

To realize the value of magnesium and magnesium alloys, we must firstly solve the plastic problem. From the Hall-Petch formula (1) it can be known that grain refinement can improve the strength and ductility of the material:

$$\sigma_s = \sigma_0 + kd^{-0.5} \quad (1)$$

Where σ_s is yield strength, σ_0 is the yield limit of monocrystal, k is a constant and d is the grain size. Under normal circumstances, the material slip system number determines the value of Taylor coefficient. There is a positive relationship between the value of k and Taylor coefficients. magnesium and magnesium alloys Taylor coefficient is larger due to the hcp structure relative to the face-centered cubic and body centered cubic, so its k is larger, and

the potential through grain refinement method to improve the magnesium alloy plastic of is much greater than the iron alloy, aluminum alloy, etc. [5,6]. The reason why the grain finer material is high strength and hardness than the coarse grains of the material is mainly because of the relatively large area of grain boundaries of fine material [7].

Equal channel angular processing is developed by Segal [8] and is one of the most effective methods to improve one of the plastic material currently [9,10]. Many studies have proved the equal channel angular extrusion can significantly refine the material grain. Yao and Zhao et al [11] found the organization of the ultra-low carbon steel sample after 4 passes was refined significantly and the average grain size is reduced to 0.3 μm . Jiang and Da [12] extruded two kinds of Al-Mg-Mn alloy having similar composition but with and without Zr addition at 350°C and the crystal grains of 1-2 μm were obtained after six times. Xu and Qin et al [13] found the grain size of AZ31 magnesium alloy with four times reduced from 8.3 μm to 2.5 μm . ECAP die is shown in Figure 2. Two channels of equal cross-sectional area intersected at a certain angle. One angle is die angle Φ , another is die corner angle Ψ . In Equal channel angular pressing process, the sample moves downward the punch pressure P. when it is through the die corner, the sample will produce the nearly ideal shear deformation. Since the deformation process does not change the cross-sectional shape and area of the material, so the total strain can be accumulated from repeated extrusion. Under ideal conditions, the size of the shear strain after one pass by the formula (2) [14,15] determined by:

$$\gamma = 2 \cot\left(\frac{\phi + \varphi}{2}\right) + \varphi \operatorname{cosec}\left(\frac{\phi + \varphi}{2}\right) \quad (2)$$

In addition, the total equivalent strain after N passes can be represented by the formula (3) :

$$\bar{\varepsilon} = \frac{N}{\sqrt{3}} \left[2 \cot\left(\frac{\psi}{2} + \frac{\phi}{2}\right) + \psi \operatorname{cosec}\left(\frac{\psi}{2} + \frac{\phi}{2}\right) \right] \quad (3)$$

Only if one assumptions are met which is no friction, the formula (3) are only established [16]. Wu and Baker [17] have been verified the formula (3) through experimental study and have proved its rationality. Iwshashi and Horita [18] found that by finite element simulation when $\Phi = 90^\circ$, $\Psi = 0^\circ$, dead zone

is easily be produced, and when $\Phi = 90^\circ$, $\Psi = 20^\circ$, the dead zone can be minimized.

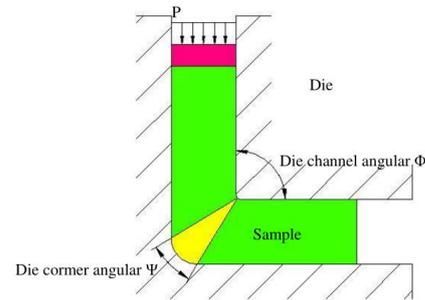


Fig.2 Schematic representation of ECAP

In this paper, dynamic simulation of AZ31 magnesium alloy channel angular processing was done through the finite element software Deform-2D. The deformation under different process parameters were simulated, and the changes of field quantities in the process of magnesium alloy AZ31 ECAP deformation were analyzed.

2 Finite element model

The finite element software Deform-2D software is a set of process simulation system based on finite element for the analysis of metal forming and related industry forming process and heat treatment processes. During the simulation, the sample is magnesium alloy square sample AZ31 of size 12 × 12 × 60mm. Deform software material library has no the specific parameters of AZ31 magnesium alloy, so it is needed to determine the flow stress of AZ31 magnesium alloy relations, that is equation (4):

$$\bar{\sigma} = c \bar{\varepsilon}^n \dot{\bar{\varepsilon}}^m + y \quad (4)$$

Where c and y are constants, $c = 205$, $y = 0$. The strain index $n = 0.044$, the strain rate exponent $m = 0.144$. During equal channel angular processing, the geometry of the mold doesn't change, so the die is set to a rigid body during the simulation process, the sample is a deformable body, so it is set as a rigid plastic body. The meshing number is 8000, and the node number is 8241. The die parameters include die channel angle Φ and die corner angle Ψ . Theoretically, die channel angle Φ

and die corner angle Ψ are in the range of 0° to 180° , but the actual die corner angle Ψ is preferably in the range of from 0° to 90° , the die channel angle Φ is preferably in the range of 90° to 150° . The specific parameters are shown in Table 1. In the finite element simulation process, the magnitude of the die corner angle is mainly decided by the radius of the outer arc of the die. The relationship of die corner angle, the die outer arc radius and of the width of the die channel can be deduced from Figure 3 [19]:

$$\tan\left(\frac{\varphi}{2}\right) = \frac{EF}{AE} = \frac{EF}{AD - DE} = \frac{\frac{R \cdot \sin\left(\frac{\phi}{2}\right)}{\tan\left(\frac{\phi}{2}\right)}}{\left(\frac{L}{\sin\left(\frac{\phi}{2}\right)}\right) - \frac{R \cdot \sin\left(\frac{\phi}{2}\right)}{\tan^2\left(\frac{\phi}{2}\right)}}$$

$$\Rightarrow \varphi = 2 \tan^{-1}\left[\frac{R \cos\left(\frac{\phi}{2}\right) \sin\left(\frac{\phi}{2}\right)}{L - R \cos^2\left(\frac{\phi}{2}\right)}\right] \quad (5)$$

When die channel angle $\Phi=90^\circ$,

$$\varphi = 2 \tan^{-1}\left[\frac{R}{2L - R}\right] \quad (6)$$

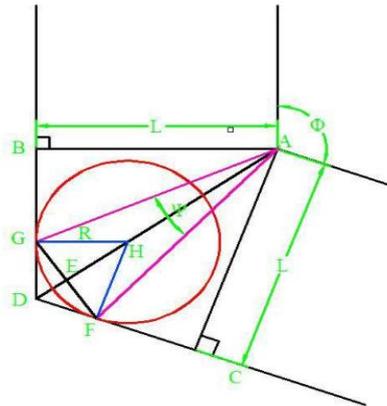


Fig.3 The relationship between the die corner angle, the die outer arc radius and of the width of the die.

Table 1 The parameters for the simulations of the square-section channel of ECAP process

| Material | AZ31magnesium alloy | | | |
|---------------------------------|---------------------|-----|-----|-----|
| Temperature($^\circ\text{C}$) | 250 | | | |
| Punch Speed(mm/s) | 8 | | | |
| Die Displacement(mm) | 0.6 | | | |
| Friction Factor | 0.15 | | | |
| Die channel angle($^\circ$) | 90 | 100 | 110 | 120 |
| Die corner angle($^\circ$) | 15 | 26 | 37 | 52 |

When die channel angle was 90° and the value of the die corner angle were 15° , 26° , 37° and 52° respectively, it is brought into the equation (6) and the corresponding radius R can be calculated, they respectively were 2.79mm, 4.5mm, 6mm and 7.87mm.

In order to analyze the uniformity of the deformation of the sample, Figure 4 gives 3 section: top surface, middle surface and bottom surface. On each section 13 nodes are chosen respectively. The field quantities of these sections and nodes were analyzed.

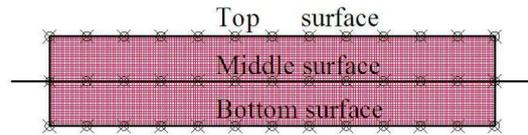


Fig.4 Sections and nodes selected to observe deformation

3 Results and Analysis

3.1 Effect of die channel angle

Fig.5 Effective strain of nodes on three sections at different die channel angle: (a) $\Phi=90^\circ$ (b) $\Phi=100^\circ$ (c) $\Phi=110^\circ$ (d) $\Phi=120^\circ$

Table 1 shows each parameter value, the selected value of die channel angles are 90° , 100° , 110° and 120° . The die corner angle is 37° and the inner arc radius r is 2mm in the same time. Figure 5 shows the equivalent strain curve of different nodes on the three sections in this case. The horizontal axis of the curve represents distance of each node from the sample left side surface and the vertical axis represents the equivalent strain of each node. As can be seen from the figure the sample after deformed can be divided into three parts, namely the head deformation zone, the main deformation zone and tail deformation zone, which is consistent with the study of Xu[20] et al. The head deformation zone: This is the first extrusion part, which is 50-60mm part in the figure. The deformation of this part is very uneven, equivalent strain distribution gradient is bigger. The main deformation zone: This section takes up about 2/3 of sample along the length direction, which is 10-50mm part. In the horizontal direction, the equivalent strain distribution is uniform. But in the direction of perpendicular to the horizontal direction of

sample, the deformation is not uniform. The tail deformation zone: that is in the deformation stage, which is in the part of the 0-10mm. This part deformation is not complete. if realized extrusion continuously of the sample, there is no tail deformation, and therefore this part can be negligible. It can also be seen from the figure, as die channel angle increases, the upper, equivalent strain gap of middle and lower three section gets smaller, that is, the greater the die channel angle, the more uniform deformation of the sample.

3.2 Effect of die corner angle

Fig.6 Effective strain of nodes on three sections at different die corner angle: (a) $\Psi=15^\circ$ (b) $\Psi=26^\circ$ (c) $\Psi=37^\circ$ (d) $\Psi=52^\circ$

Figure 6 represents the equivalent strain curve of different nodes on the three sections when the die corner angle are respectively 15° , 26° , 37° and 52° whit the die channel angle of 90° . It can be seen from the figure, the impact of the die corner angle on the sample equivalent strain is small, and has no obviously effect on the uniformity of the deformation geometry. But this does not mean that die corner angle does not affect the magnesium alloy ECAP deformation. Figure 7 presents the deformation of the sample and the grid during simulation when the die corner angle are respectively 15° , 26° , 37° and 52° whit the die channel angle of 90° . The four selected die corner angle could not avoid the formation of the dead zone. The dead zone is the gap between the sample and the die which forms when the sample is through the die corner. The dead zone area increases with increase of the die corner angle. So in order to produce a smaller dead zone in ECAP process, it is necessary to select a smaller die corner angle. The cell of sample part no extruded is rectangular, and when the sample was through the die corner, the cell deformed the rectangle was elongated, such as nodes p4, p5, and p6 is shown, when the sample is through the die corner, it was subjected to the shearing force. When die corner angles are different, warpage phenomenon of the sample tail occurs in different degrees, in other words, p1 p2 p3 is not kept horizontal. The larger the die corner angle, the greater the angle between the

p1p2p3 and the horizontal direction, the warpage phenomenon of the sample is also more serious. when the die corner angle are 37° and 52° , a small gap also formed between the die and the top and bottom surfaces of the sample, which may result in slightly reduced the size of the sample in the longitudinal direction after the extrusion.

Fig.7 The deformation of the sample at different die corner angles: (a) $\Psi=15^\circ$ (b) $\Psi=26^\circ$ (c) $\Psi=37^\circ$ (d) $\Psi=52^\circ$

4 Conclusions

The effects of the die channel angle and the die corner angle on sample deformation uniformity have been researched and analyzed by the two-dimensional finite element simulation of magnesium alloy ECAP process, and the following conclusions can be obtained:

- (1) The sample can be divided into three parts: the head deformation zone, the main deformation zone and the tail deformation zone according to its deformation after the extrusion.
- (2) In the main deformation zone, the die channel angle has little effect on the uniformity of the sample deformation in longitudinal direction, the greater the die channel angle, the more uniform the specimen deformation in longitudinal direction.
- (3) The die corner angle has no significant effect on the uniformity of the sample deformation in longitudinal direction, The equivalent strain in horizontal direction does not significantly change when the die corner angles are different.
- (4) The die corner angles have a certain impact on the size of the dead zone and sample warpage. Dead zone area and the degree of warpage of the sample increase with the die corner angle increase, when the die corner angle are 37° and 52° , a small gap also form between the die and the top and bottom surfaces of the sample

5 Declaration

Acknowledgements

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Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors' contributions

The author's contributions are as follows: Shubo Xu was in charge of the whole trial; Sen Zhang and Shubo Xu wrote the manuscript; Peng Liu, Cainian Jing, Guocheng Ren assisted with sampling and laboratory analyses.

Competing interests

The authors declare no competing financial interests.

Consent for publication

Consent to publish

Ethics approval and consent to participate

Not applicable

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References

- [1] M Dwain, A Magers. Global review of Magnesium parts in automobiles[J]. *Light Metal Age*, 1996, 54(9/10): 60-63.
- [2] A Luo, M O Pekguleryuz. Review cast Magnesium alloys for elevated temperature application[J]. *Journal of Materials Science*, 1994, 29(20):

5259-5271.

- [3] S K Guan, L H Wu, P Wang. Hot forgeability and die-forging forming of semi-continuously cast AZ70 magnesium alloy[J]. *Materials Science and Engineering a*, 2009, 499(1/2): 187-191.
- [4] L Y Wang, G S Huang, Y G Fan, et al. Grain refinement of wrought AZ31magnesium alloy[J]. *The Chinese Journal of Nonferrous Metals*, 2003,13(3):594-598.
- [5] Q Wang, Z M Zhang, B H Zhang,et al. Development in strengthening and toughening magnesium alloys by deformation [J].*Materials Science*,2006,2:431-433.
- [6] H J Hu, D F Zhang, M B Yang, et al. Grain refinement in AZ31 Magnesium alloy rod fabricated by extrusion-shearing sever plastic deformation process[J]. *Transactions of Nonferrous Metals Society of China*, 2011, 11: 243-249.
- [7] Y H Chung, J W Park, K H Lee. An analysis of accumulated deformation in the equal Channel angular rolling(ECAR) process[J]. *Mater Inter*, 2006, 12(4): 289-293.
- [8] V M Segal, V I Rezn, E A Drotyshevskij, et al. Plastic working of metals by simple shear[J]. *Russian Metallurgy*, 1981, 19(1): 99-104.
- [9] V M Segal. Materials processing by simple shear[J]. *Science and Engineering: a*, 1995, 197(2): 147-164.
- [10] D Song, A B Ma, J H Jiang, et al. Corrosion behaviour of bulk ultra-fine grained AZ91D Magnesium alloy fabricated by equal-channel angular pressing[J]. *Corrosion Science*, 2011, 53(1): 362-373.
- [11] X C Yao, X C Zhao, X G Wang, et al. Effects of Equal Channel Angular Pressing on Microstructure and Properties of ultra-low Carbon Steel [J]. *Materials for Mechanical Engineering* ,2005,29(11):46-48.
- [12] L N Jiang, M J Da. Influence of Zr addition on the microstructure evolution and thermal stability of Al-Mg-Mn alloy processed by ECAP at elevated temperature[J]. *Materials Science and Engineering a*, 2007, 452: 552-557.
- [13] S B Xu, Z Qin, T Liu, et al. Effect of severe plastic deformation on microstructure and mechanical properties of bulk AZ31 Magnesium alloy[J]. *Trans. Nonferrous Met. Soc. China*, 2012, 22: 61-67.
- [14] I Balasundar, R M Sudhakara, T Raghu. Equal Channel angular pressing die to extrude a variety of materials[J]. *Materials and Design*, 2009, 30: 1050-1059.
- [15] F Djavanroodi, M Ebrahimi. Effect of die Channel angle, friction and back pressure in the equal Channel angular pressing using 3D finite element simulation[J]. *Materials Science and Engineering a*, 2010, 527: 1230-1235.
- [16] Y Iwahashi, J T Wang, Z Horita, et al. Principle of equal-channel angular pressing for the processing of ultra-fine grained materials[J]. *Scripta Metar*, 1996, 35(2): 143-146.
- [17] Y Wu, I Baker. An experimental study of equal Channel angular extrusion[J]. *Scripta Metarialia*, 1997, 37(4): 437-442.
- [18] Y Iwahashi, Z H Orita, M Nemoto, et al. An

investigation of microstructural evolution during equal-channel angular pressing[J]. *ACTA Mater*, 1997, 45(11): 4733-4741.

- [18] F Djavanroodi, B Omranpour, M Ebrahimi, et al. Designing of ECAP parameters based on strain distribution uniformity[J]. *Progress in Natural Science: Materials International*, 2012, 22(5): 452-460.
- [20] S B Xu, G Q Zhao, Y G Luan, et al. Numerical studies on processing routes and deformation mechanism of multi-pass equal Channel angular pressing processes[J]. *Journal of Materials Processing Technology*, 2006, 176: 251-259.

Biographical notes

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Appendix

Figure and table captions list

Fig.1 HCP structure of magnesium alloy .

Fig.2 Schematic representation of ECAP .

Fig.3 The relationship between the die corner angle, the die outer arc radius and of the width of the die .

Fig.4 Sections and nodes selected to observe deformation .

Fig.5 Effective strain of nodes on three sections at different die channel angle: (a) $\Phi=90^\circ$ (b) $\Phi=100^\circ$ (c) $\Phi=110^\circ$ (d) $\Phi=120^\circ$.

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Table 1 The parameters for the simulations of the square-section channel of ECAP process

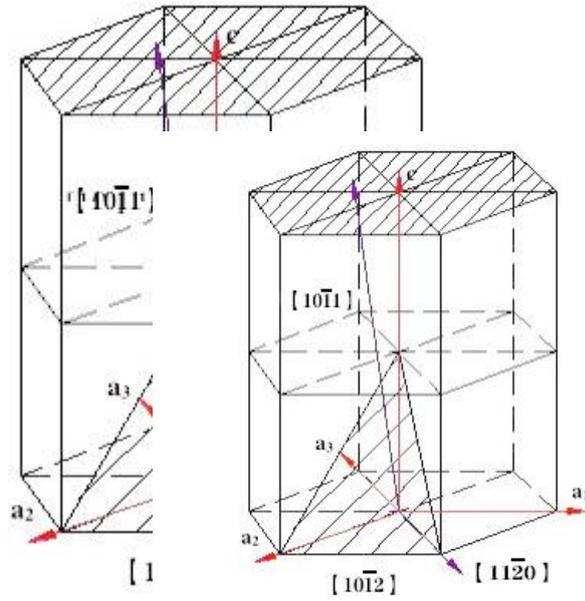


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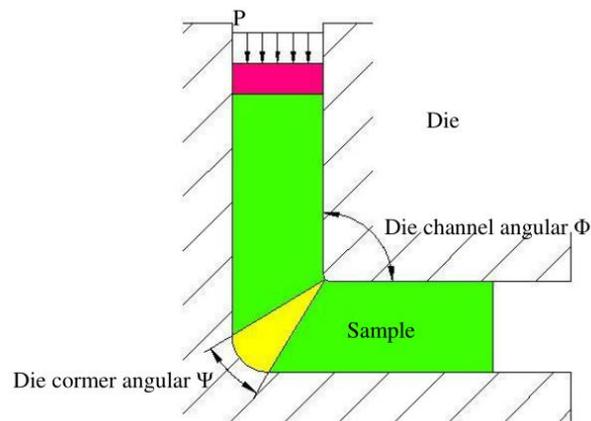


Fig.2 Schematic representation of ECAP

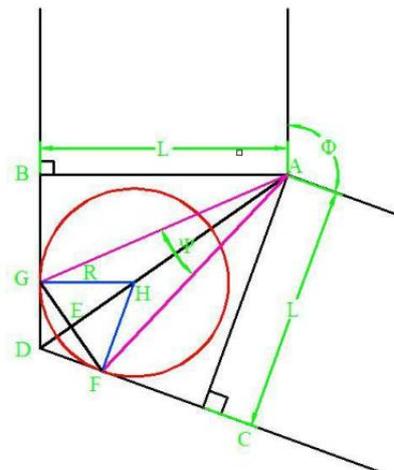


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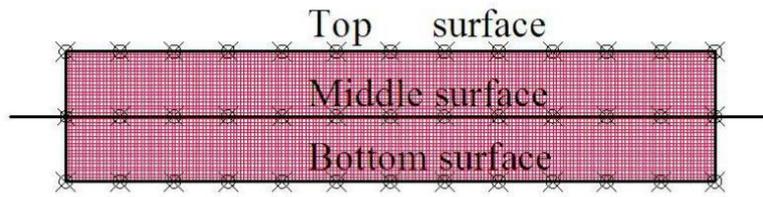


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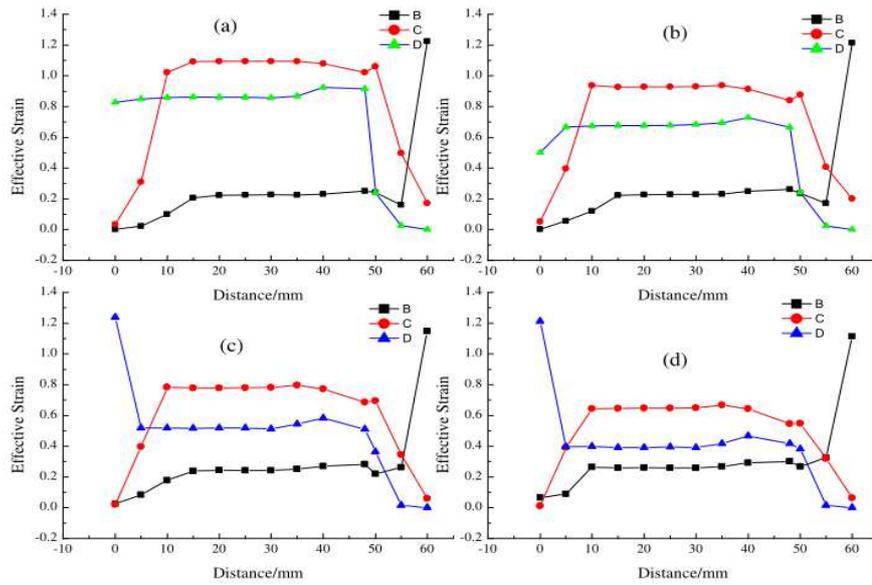


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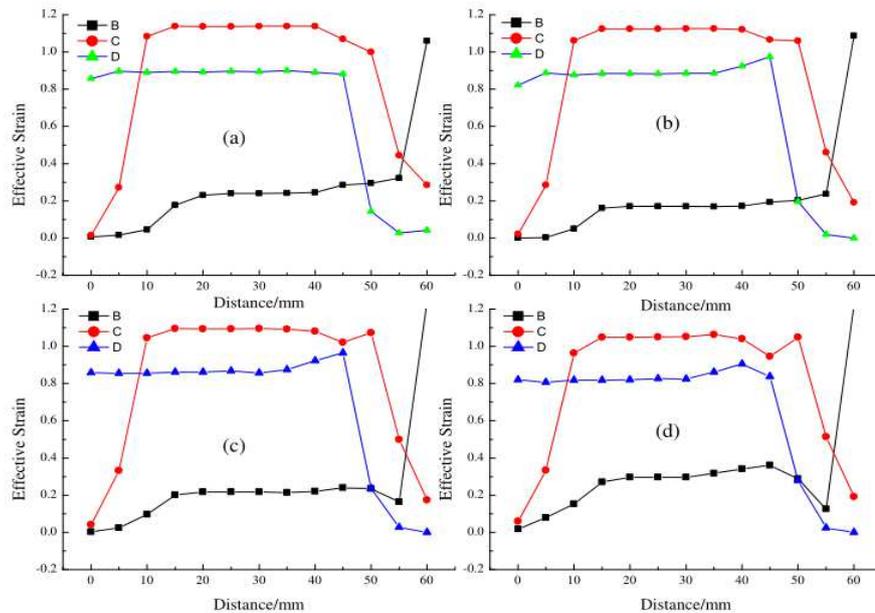


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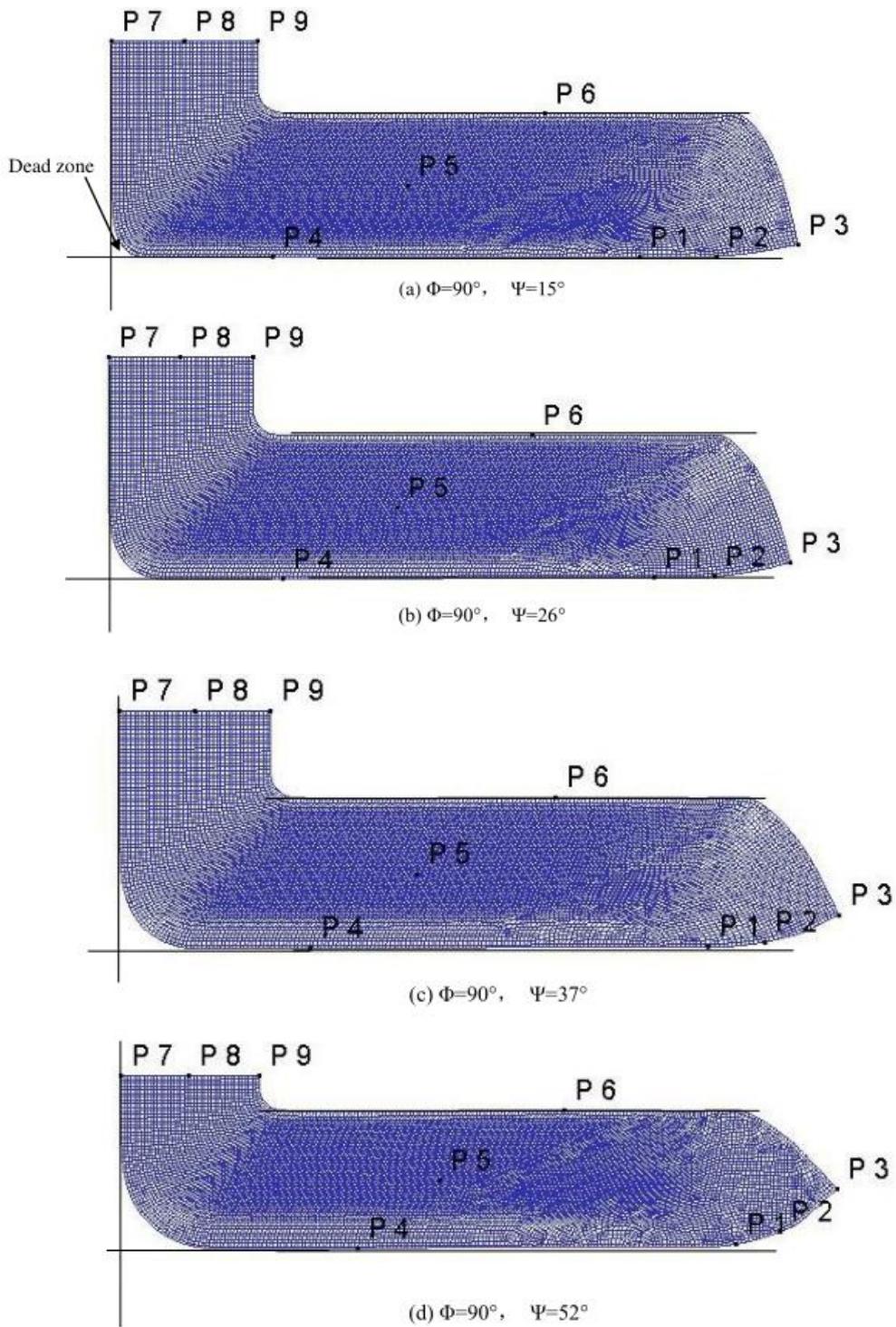


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| Material | AZ31magnesium alloy | | | |
|----------------------|---------------------|-----|-----|-----|
| Temperature(°C) | 250 | | | |
| Punch Speed(mm/s) | 8 | | | |
| Die Displacement(mm) | 0.6 | | | |
| Friction Factor | 0.15 | | | |
| Die channel angle(°) | 90 | 100 | 110 | 120 |
| Die corner angle(°) | 15 | 26 | 37 | 52 |

Figures

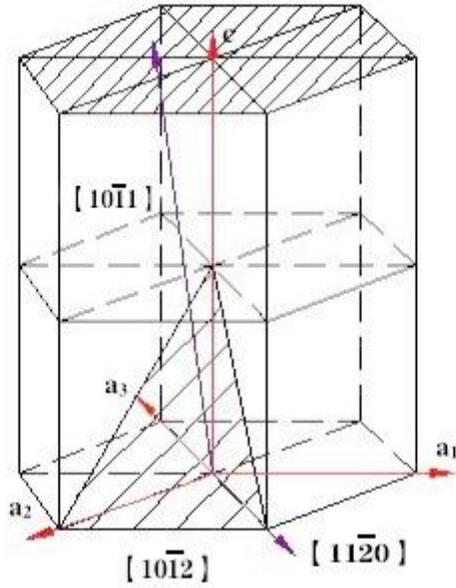


Figure 1

HCP structure of magnesium alloy

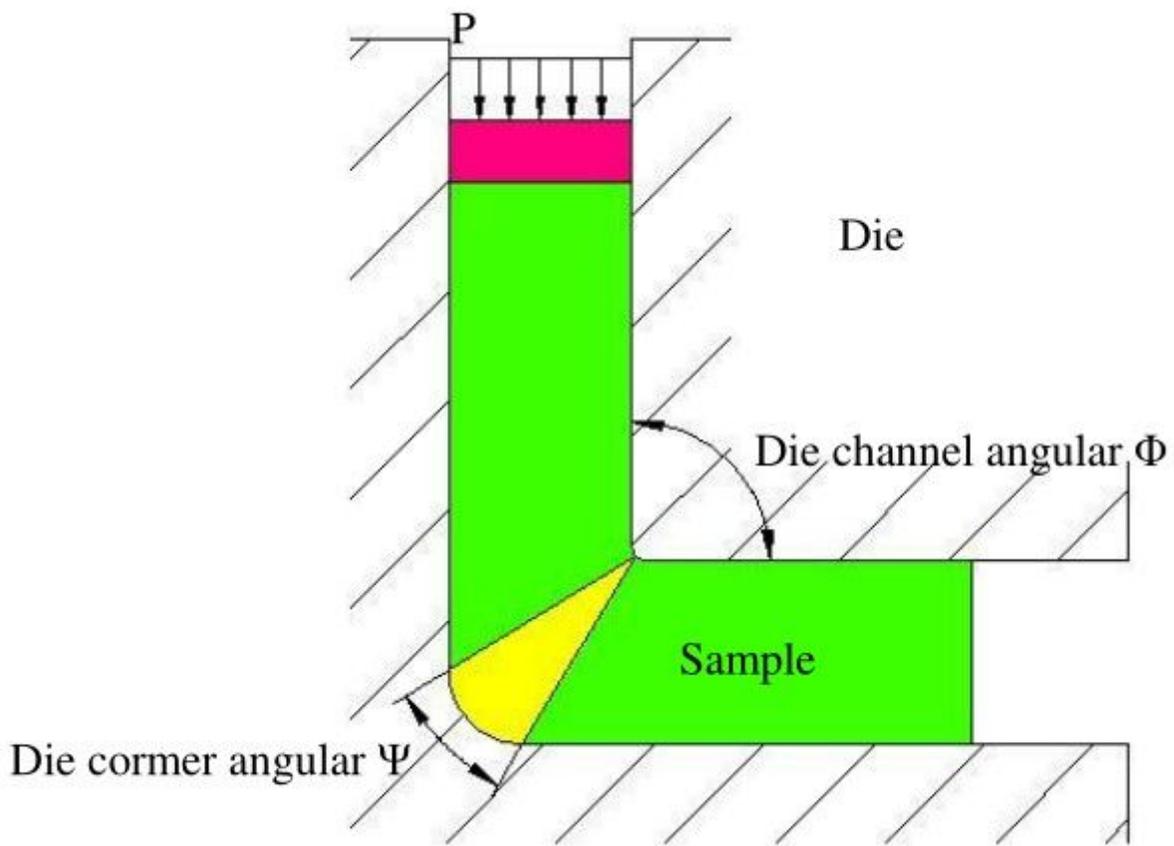


Figure 2

Schematic representation of ECAP

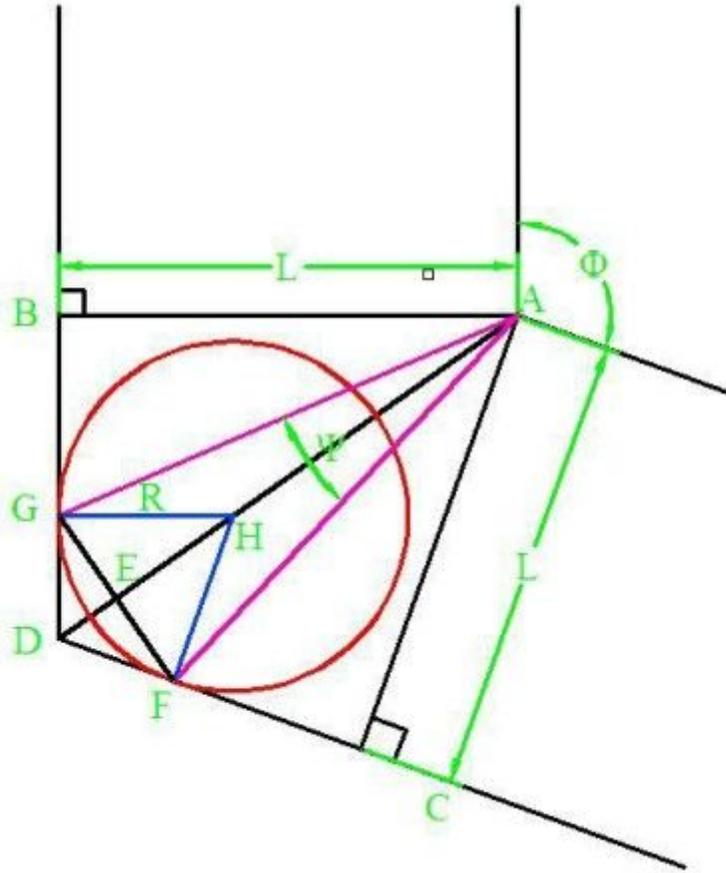


Figure 3

The relationship between the die corner angle, the die outer arc radius and of the width of the die.

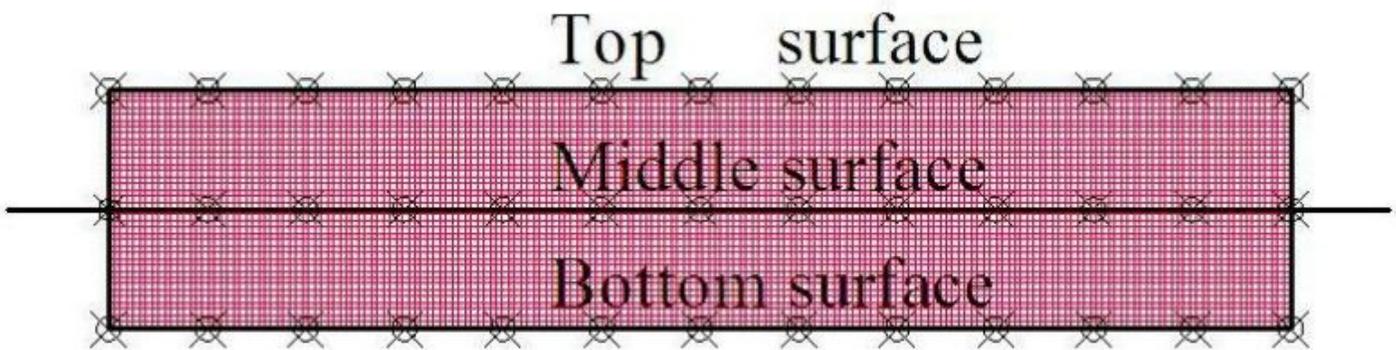


Figure 4

Sections and nodes selected to observe deformation

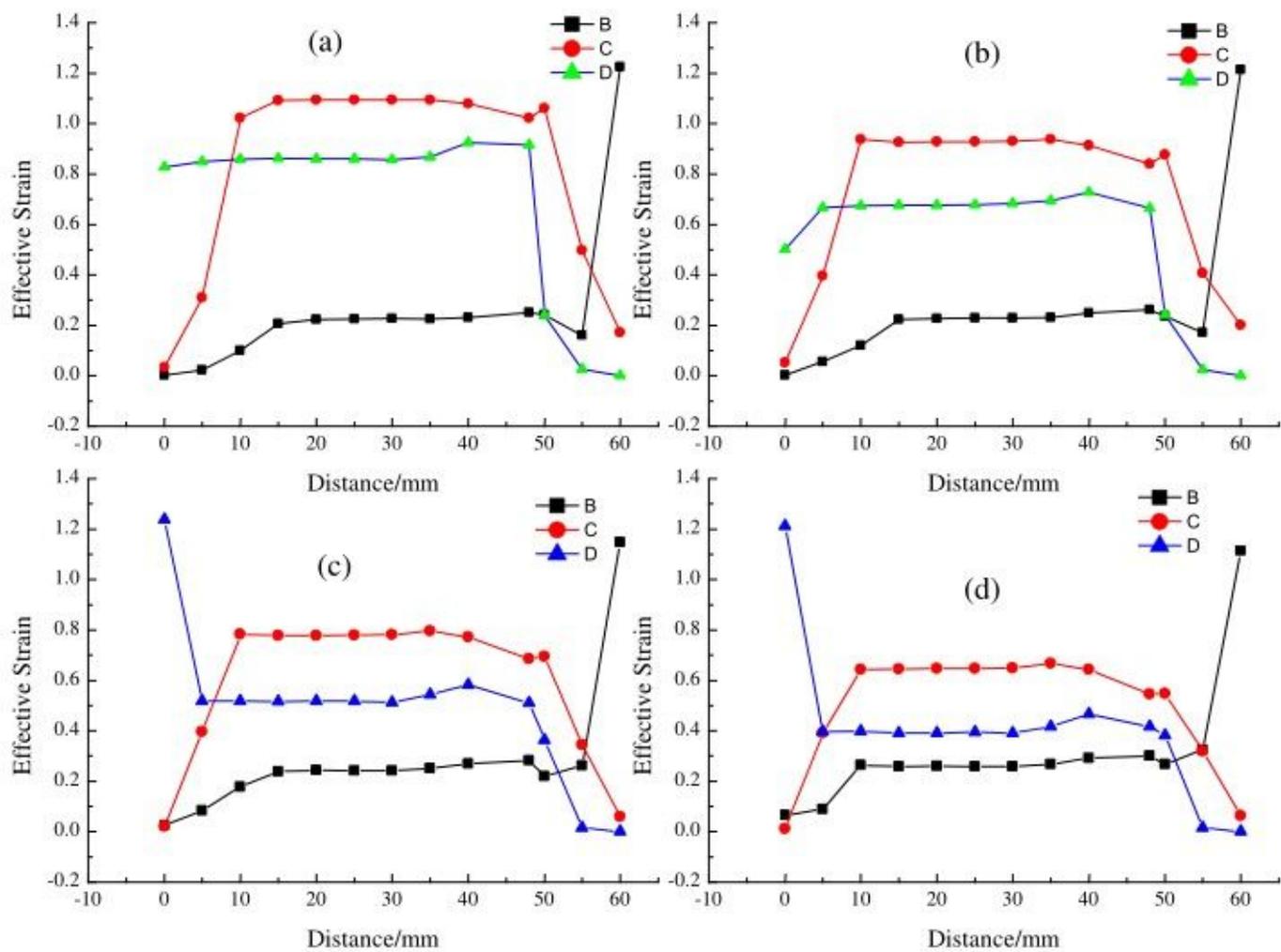


Figure 5

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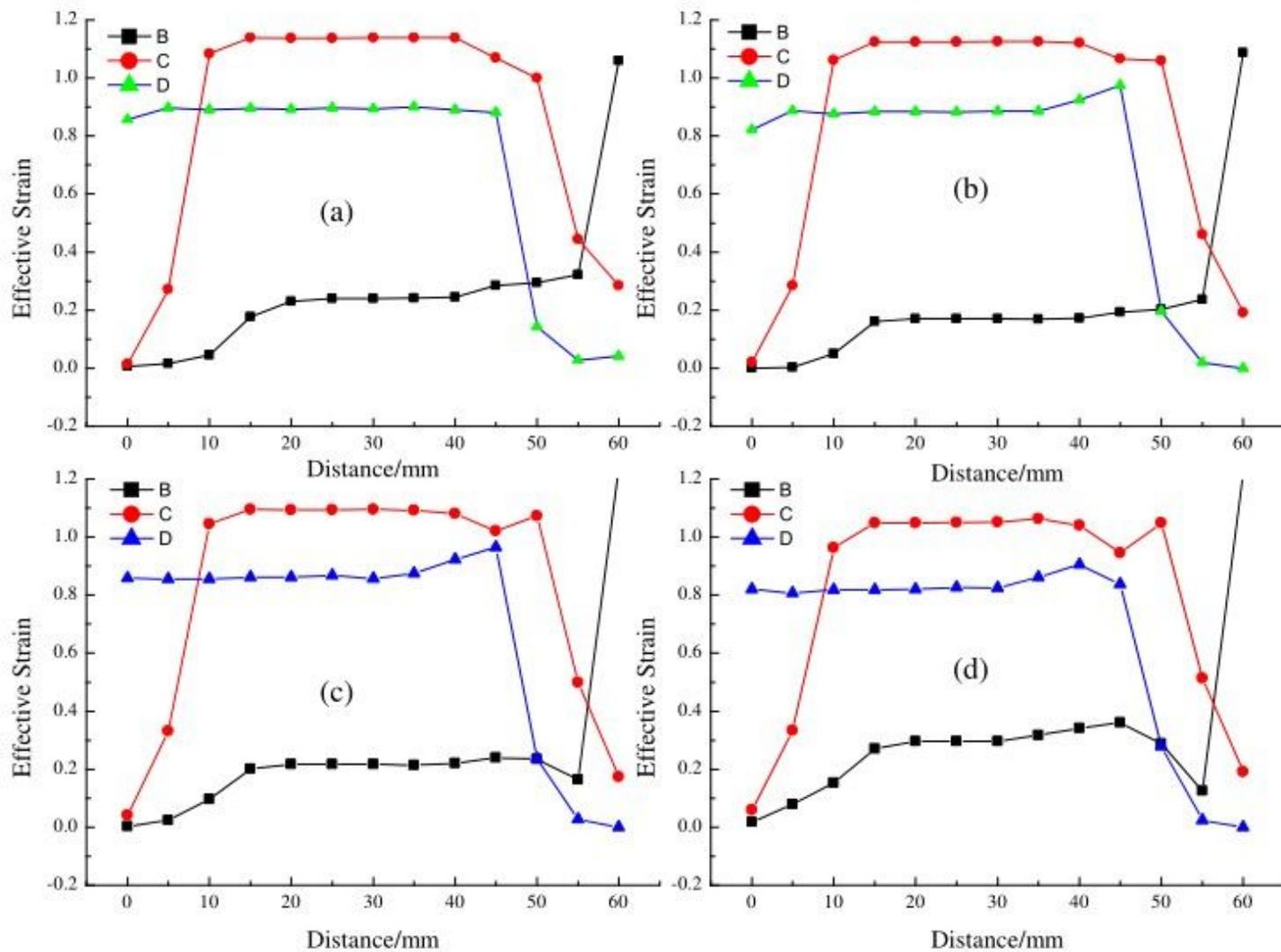


Figure 6

Effective strain of nodes on three sections at different die corner angle: (a) $\Psi=15^\circ$ (b) $\Psi=26^\circ$ (c) $\Psi=37^\circ$ (d) $\Psi=52^\circ$

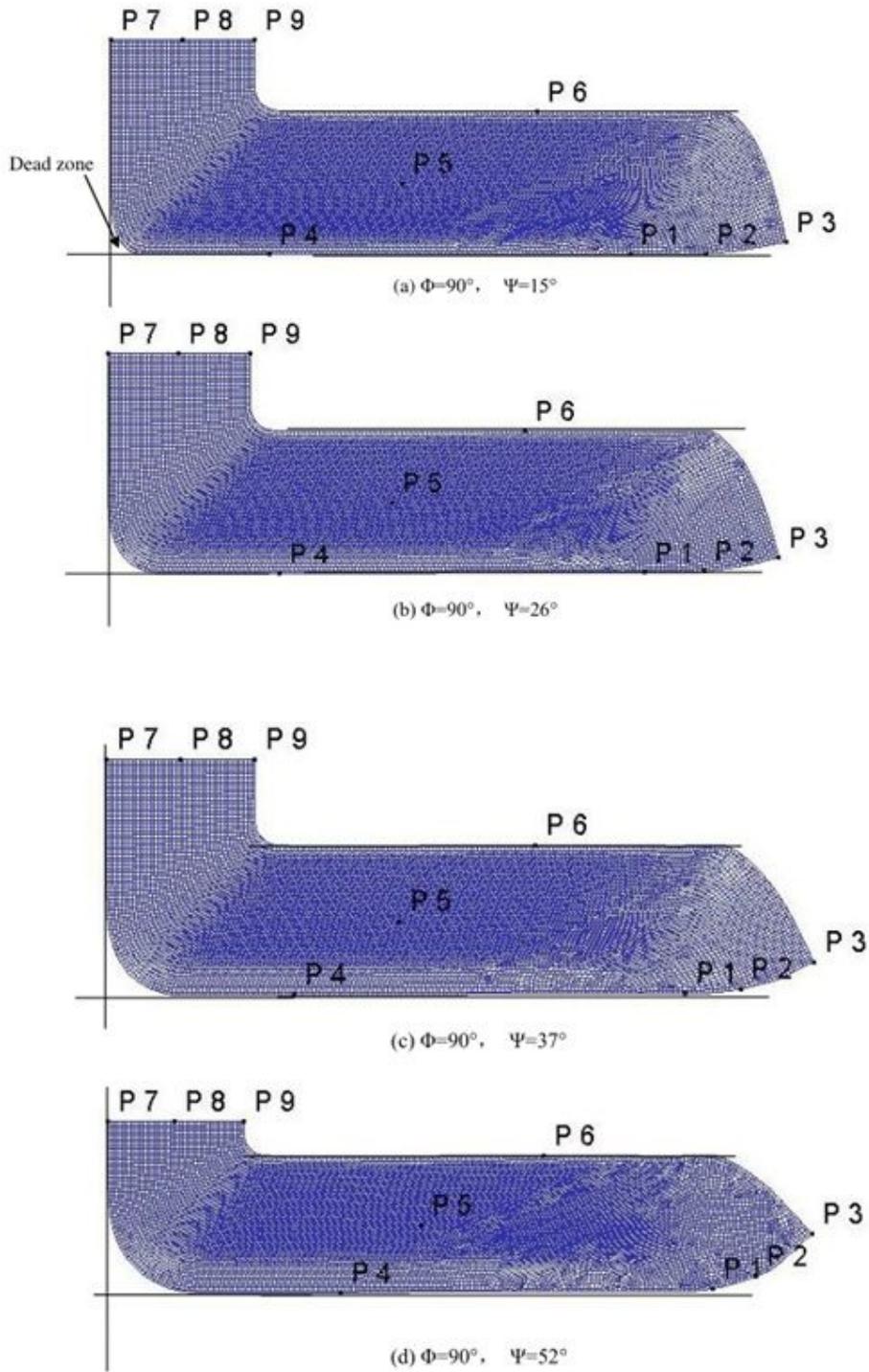


Figure 7

The deformation of the sample at different die corner angles: (a) $\Psi=15^\circ$ (b) $\Psi=26^\circ$ (c) $\Psi=37^\circ$ (d) $\Psi=52^\circ$