Finite element analysis of the equivalent strain distribution of ZK60 alloy during cyclic extrusion and compression

LIN Jin-bao(林金保)[1*], WANG Qu-dong(王渠东)[2], LIU Man-ping (刘满平)[2], CHEN Yong-jun(陈勇军)[3], Hans J. ROVEN[3]

1. School of Applied Science, Taiyuan University of Science and Technology, Taiyuan 030024, China
2. National Engineering Research Center for Light Alloy Net Forming, Shanghai Jiao Tong University, Shanghai 200240, China
3. Department of Materials Science and Engineering, Norwegian University of Science and Technology, Trondheim 7491, Norway

Abstract: Finite element method (FEM) analysis was used to study the strain homogeneity in the ZK60 Mg alloy during multi-pass cyclic extrusion and compression (CEC). In order to optimize the CEC processing, the effects of process parameters on the distribution of total equivalent plastic strain were investigated. The process parameters include the friction condition, and die geometry. The results show that the strain distributions in the workpiece are inhomogeneous after CEC deformation. The strains of both ends of workpiece are lower than that of center region. The process parameters have significant effects on the strain distribution. Friction between die and workpiece is detrimental to strain homogeneity. In order to improve the strain homogeneity, a big corner radius and a low extrusion angle should be used.

Key words: Cyclic extrusion and compression; Finite element method; Friction; ZK60 magnesium alloy; strain homogeneity

1 Introduction

As one kind of continuous severe plastic deformation (SPD) processing, cyclic extrusion and compression (CEC) seems to be more adaptable for industrial applications. Moreover, it is very suitable for refining grains of not easily deforming metals, such as magnesium alloys, since it imposes three-dimensional compression stresses during processing.

The CEC processing was proposed by Richert[1], and it has been successfully used to produce a variety of metallic materials with ultra-fine grain structures[2-7]. The CEC processing is performed by pushing a workpiece from one cylindrical chamber having the diameter D to another chamber with equal dimensions. The inter-chamber can be considered as an extrusion die having a smaller diameter d, as illustrated in Fig. 1[5]. During the final extrusion pass, the opposite ram was removed in order to release the rod. The equivalent strain ε generated in the workpiece after n-pass CEC processing is given by the following equation[1, 6, 8]:

$$\varepsilon = 2(2n-1)\ln\frac{D}{d} \qquad (1)$$

Since strain affects the microstructure produced in the material, homogeneity of strain across the cross section and longitudinal section of an extruded workpiece is of importance[9]. The stain homogeneity in the ECAE has been widely studied using finite element method (FEM), and finds that the main factor affecting strain homogeneity is the process parameters, which include friction between workpiece and die, die geometry

---

Foundation item: Project (50674067 and 50971087) supported by the National Natural Science Foundation of China; Project (2011-079) supported by Shanxi Scholarship Council of China, Project (20102015) supported by the Doctoral StartupFund of TUST

Corresponding author: LIN Jin-bao; Tel: +86-351-6998205; E-mail: linjinbao@sohu.com

[9-14]. In this paper, FEM was used to investigate the effects of process parameters on the strain homogeneity during CEC processing with a view to providing optimized die geometries and deformation parameters for CEC processing.

2 FEM simulation

The cylindrical die and workpiece can be simplified to an axisymmetric case. Fig. 2 shows the axisymmetric FEM model for the simulation of the CEC processing. In the present study, D is 30 mm, d is 20 mm. The extrusion angle is θ and the corner radius is r. The process parameters used in simulation are listed in Table 1. The effects of process parameters on the strain were investigated after 4-passes CEC.

Isothermal, two-dimensional, axisymmetric plane-strain FEM simulations of the CEC processing have been carried out using the commercial finite element software, MSC.SuperForm. In the simulation, the die and the ram can be approximately considered as rigid bodies since their strength is much higher than the workpiece's. Automatic remeshing was used to accommodate large deformation during the simulations. A self adaptive step length was used as the time step of the calculation. The simulation was performed at 350 °C and was kept under isothermal condition. The friction between the billet and the die was modeled with the Coulomb friction law.

The most important data in FEM simulation is the material rheology[12]. A slight modification of the material parameters maybe has a great influence on the numerical predictions[15]. To obtain results with a high degree of confidence, the material rheology for the studied alloy was defined by compression stress-strain curves, which were measured using a Gleeble 3500 machine at 350 °C, as shown in Fig. 2.

Table 1 Process parameters used in simulation

Parameters	Values
Friction coefficients (μ)	0, 0.1, 0.2, 0.3
Corner radius (r)	0, 45, 60, 90 (°)
Extrusion angle (θ)	1, 1.5, 2 (mm)

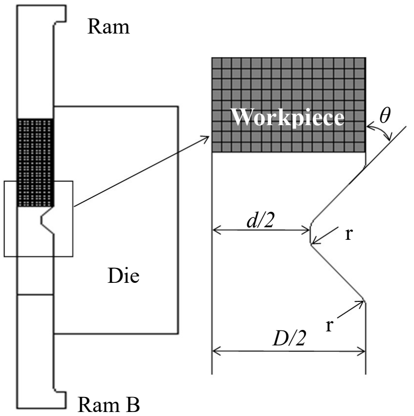


Fig.1 The axisymmetric FEM model for the CEC

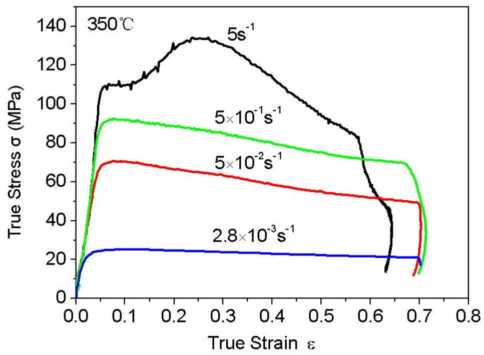


Fig.2 The true stress-strain curves of as-extruded ZK60 alloy at 350 °C

3 Results and discussion

3.1. Effect of friction

Fig. 3 shows the simulated total equivalent plastic strain (TEPS) distribution in the workpiece after 4-passes CEC processing with different friction coefficients (μ). Here corner radius (r) is set to be 2 mm, and extrusion angle (θ) is 45°, respectively. To obtain quantitative information regarding the strain homogeneity, the TEPS distribution along radial direction ('A–B' in Fig. 3) and axial direction ('C–D' in Fig. 3) are plotted in Fig. 4. It can be seen that, at the condition of $\mu = 0.3$, the TEPS of surface is higher about 18% than that of center, because the friction force on the surface enhances the workpiece shear. With the friction coefficient decrease, the TEPS near surface of workpiece is decreased clearly, and the center TEPS is increased slightly. It reveals that the relative homogeneity of strain increased with the friction coefficients decreases. The simulated TEPS value is also compared with the theoretical value obtained by Eq. (1), as shown in Fig. 4b. The theoretical plastic strain after 4-passes CEC is about 5.67 in this study. About 87% of whole workpiece's TEPS is large than theoretical value at all friction conditions.

As shown in Fig. 3 and Fig. 4b, the TEPS distribution is inhomogeneous along the workpiece axis, and the TEPS values of both ends are lower than that of middle part of the workpiece after CEC. With the decreasing of friction coefficient, the uniform strain region in the middle part is obviously extended. Therefore, friction is a disadvantageous factor during CEC processing, which on the one hand increases the deformation inhomogeneousness and on the other hand may result in inner flaws of the workpiece[14]. Lubricant, such as graphite powder, is used to reduce the effect of friction in practical pressing process[4, 5].

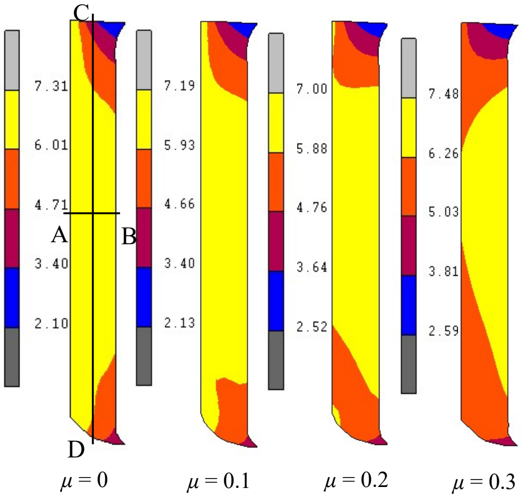


Fig.3 Distribution of the total equivalent plastic strain (TEPS) in the workpiece after 4-pass CEC processing with different friction coefficients.

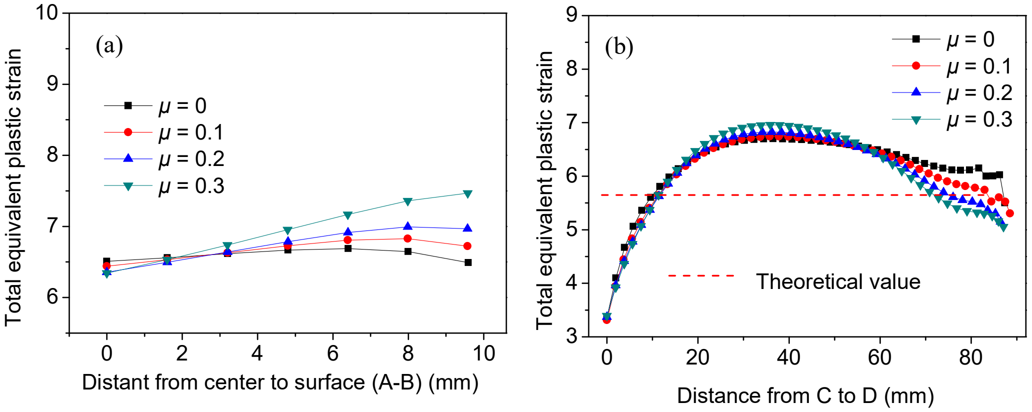
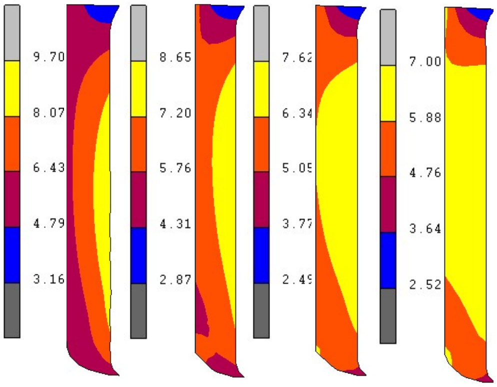


Fig.4 Variation curves of TEPS from (a) center to surface ‘A–B’ and (b) one end to another ‘C–D’ with different friction coefficients.

3.2. Effect of corner radius

Die corner angle is another important parameter during CEC processing. The effects of corner radius on the strain distribution are simulated with μ = 0.2, θ = 45°, and v = 8 mm/s respectively. Fig. 5 represents the diversification of TEPS distribution in the workpiece after 4-passes CEC processing with different corner radii. It is obviously that the corner radius has a significant effect on the strain distribution. With the increasing of corner radius, the maximum value of TEPS is decreased. Compare with the condition of r = 0, the maximum TEPS, which located in the surface of workpiece, is decreased about 38.5 % from 9.7 to 7.0 at condition of r = 2. As a result, the uniform strains region is obviously extended. Therefore, in order to improve the strain homogeneity during CEC processing, a relative large corner radius should be used.

The TEPS value along radial direction ‘A–B’ and axial direction ‘C–D’ are plotted in Fig. 6. It can be seen that, with the increase of corner radius, the TEPS in surface of workpiece is decreased dramatically (Fig. 6a). However, the TEPS in center almost keep in same values. As a result, the strain homogeneity is improved with the increases of corner radius. Djavanroodi et al[16] have recently shown that the increase of the corner radius can improve the metal flow in the deformation region and decrease the deformation concentration.



r = 0 mm *r* = 1 mm *r* = 1.5 mm *r* = 2 mm

Fig.5 Distribution of the TEPS in the workpiece after 4-pass CEC processing with different corner radii.

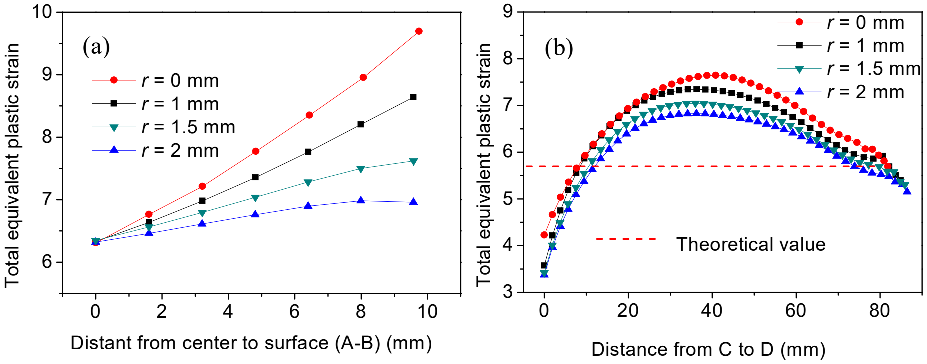
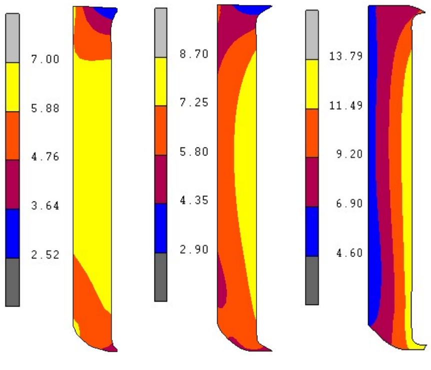


Fig.6 Variation curves of TEPS from (a) center to surface 'A–B' and (b) one end to another 'C–D' with different corner radii.

3.3. Effect of extrusion angle

Fig. 7 represents the distribution of TEPS in the workpiece after 4-passes CEC processing with different extrusion angles. Here other process parameters are set as $\mu = 0.2$, $r = 2$ mm, and $v = 8$ mm/s respectively. It can be seen that with the increases of extrusion angles from $\theta = 45°$ to $\theta = 90°$, the maximum value of TEPS is increased markedly from 7.00 to 13.79, it is almost doubled in value. On the other hand, with the increase of extrusion angle, the strain distribution becomes more inhomogeneous.

Fig. 8 represents the TEPS distribution along the marked lines 'A–B' and 'C–D' within the workpiece for different extrusion angles. It shows that the extrusion angle has a severe influence on the strain homogeneity. With a high extrusion angle that $\theta = 90°$, though the TEPS maximum value is much higher, the TEPS in the center is almost same to the low extrusion angle condition. Obviously, the high extrusion angle is detrimental to strain homogeneity.



$\theta = 45°$ $\theta = 60°$ $\theta = 90°$

Fig.7 Distribution of the TEPS in the workpiece after 4-pass CEC processing with different extrusion angles.

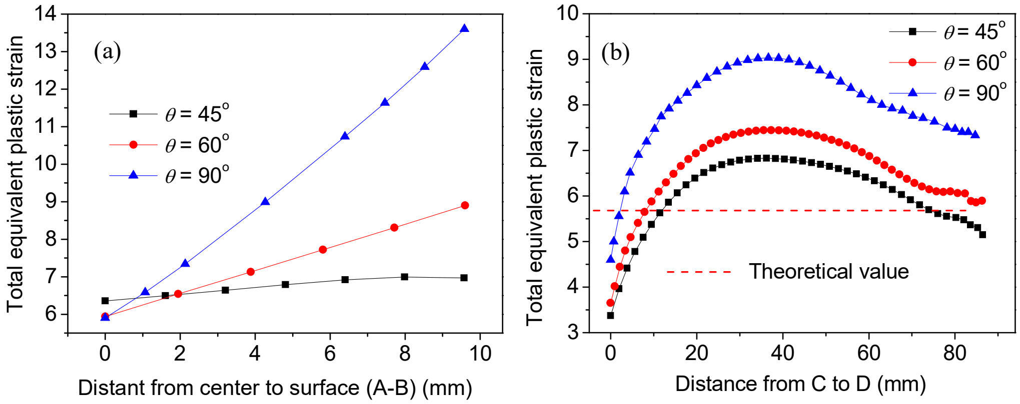


Fig.8 Variation curves of TEPS from (a) center to surface ‘A–B’ and (b) one end to another ‘C–D’ with different extrusion angles.

4 Conclusions

The equivalent plastic strain distributions in the ZK60 during multi-pass CEC processing at 350 ℃ with different process parameters were investigated using finite element method, with a view to providing an optimized die geometries and deformation parameters. The main conclusions are as follows:

(1) The strain distribution is inhomogeneous in the workpiece after CEC processing, and the strain value of both ends are lower than that of middle part. The equivalent strain value of about 82% to 90% of workpiece are large than theoretical value in this study. The process parameters have significant effects on the strain distribution. The strain homogeneity can be improved by adjust the process parameters.

(2) The strain distribution is severely effected by die geometries, such as extrusion angle and die corner radius. A high corner radius and a low extrusion angle can improve the metal flow in the deformation region, and then improve the strain homogeneity.

(3) Friction between die and workpiece is detrimental to strain homogeneity during CEC processing, but its influence is relative lower than the die geometry.

References

[1] RICHERT J, RICHERT M. A new method for unlimited deformation of metals and alloys [J]. Aluminium, 1986, 62 (8): 604–607.

[2] CHEN Y J, WANG Q D, LIN J B, ZHANG L J, ZHAI C Q. Fabrication of bulk UFG magnesium alloys by cyclic extrusion compression [J]. J

Mater Sci, 2007, 42: 7601–7603.

[3] LEE S W, YEH J W. Microstructural evolution and superplasticity of Al-5.8Mg-0.23Mn alloys processed by reciprocating extrusion [J]. Metall Mater Trans A, 2005, 36: 2225–2234.

[4] LIN J B, WANG Q D, CHEN Y J, HANS J R. EBSD characterization of microstructure and texture of ZK60 alloy processed by cyclic extrusion and compression [J]. Trans Nonferrous Met Soc China, 2010, 20: 2081-2085.

[5] LIN J B, WANG Q D, PENG L M, PENG T. Effect of the cyclic extrusion and compression processing on microstructure and mechanical properties of as-extruded ZK60 magnesium alloy [J]. Mater Trans, 2008, 49: 1021-1024.

[6] RICHERT M, LIU Q, HANSEN N. Microstructural evolution over a large strain range in aluminum deformed by cyclic-extrusion-compression [J]. Mater Sci Eng A, 1999, 260: 275–283.

[7] WANG Q D, LIN J B, PENG L M, CHEN Y J. Influence of cyclic extrusion and compression on the mechanical property of Mg alloy ZK60 [J]. Acta Metall Sin, 2008, 44: 55–58.

[8] RICHERT M, KORBEL A. The effect of strain localization on mechanical properties of Al99,992 in the range of large deformations [J]. J Mater Process Technol, 1995, 53: 331–340.

[9] ORUGANTI R K, SUBRAMANIAN P R, MARTE J S, GIGLIOTTI M F, AMANCHERLA S. Effect of friction, backpressure and strain rate sensitivity on material flow during equal channel angular extrusion [J]. Mater Sci Eng A, 2005, 406: 102-109.

[10] DUMOULIN S, ROVEN H J, WERENSKIOLD J C, VALBERG H S. Finite element modeling of equal channel angular pressing: Effect of material properties, friction and die geometry [J]. Mater Sci Eng A, 2005, 410–411: 248–251.

[11] JIANG H, FAN Z G, XIE C Y. 3D finite element simulation of deformation behavior of CP-Ti and working load during multi-pass equal channel angular extrusion [J]. Mater Sci Eng A, 2007.

[12] PETRESCU D, SAVAGE S C, HODGSON P D. Simulation of the fastener manufacturing process [J]. J Mater Process Technol, 2002, 125–126: 361–368.

[13] THAM Y W, FU M W, HNG H H, YONG M S, LIM K B. Study of deformation homogeneity in the multi-pass equal channel angular extrusion process [J]. J Mater Process Technol, 2007, 192–193: 121–127.

[14] ZHAO W J, DING H, REN Y P, HAO S M, WANG J, WANG J T. Finite element simulation of deformation behavior of pure aluminum during equal channel angular pressing [J]. Mater Sci Eng A, 2005, 410–411: 348–352.

[15] GAVRUS A, MASSONI E, CHENOT J L. An inverse analysis using a finite element model for identification of rheological parameters [J]. J Mater Process Technol, 1996, 60: 447–454.

[16] DJAVANROODI F, SABEGHI M, ABRINIA K. Analysis of the parameters affecting warping in radial forging process [J]. Am J Applied Sci, 2008, 5(8): 1013-1018.