

Numerical Investigation of Strain Distribution During Cyclic Expansion Extrusion (CEE)

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ABSTRACT

Strain distribution of Al 1100 was numerically investigated during cyclic expansion extrusion (CEE) process using finite element method (FEM). Die angle, corner fillet radius and die chamber diameter were considered as die parameters and friction factor and number of passes as process parameters. The effects of these parameters were investigated on the effective strain and strain homogeneity in the CEE process. Results showed that the decrease of friction factor along with the increase of die angle, corner fillet radius and number of passes lead to more homogeneous strain distribution, while chamber diameter has an optimal effect on the homogeneity. Material flow diagram of the deformation zone demonstrated that shear strains have a significant contribution to accumulated effective strain especially adjacent to the outer region of the sample. In comparison, in the central region of the CEE processed sample, normal strains exist as a dominant deformation route. Also, the results revealed that all the parameters except corner fillet radius (r) influence on the equivalent strain value.

1. Introduction

Processes with severe plastic deformation (SPD) may be defined as metal forming processes in which an ultra-large plastic strain is applied to create ultra-fine grained (UFG) and nanostructured metals [1-4]. Many investigations over the last decade have been devoted to the applications of SPD in processing materials due to the superior and unique mechanical and physical properties of these structures fabricated by SPD techniques [5, 6]. In this regard, various SPD techniques such as equal channel angular pressing (ECAP) [5, 7], accumulative rollbonding (ARB) [8, 9], high pressure torsion

(HPT) [10, 11], cyclic extrusion compression (CEC) [12, 13], and many other processes have been developed [5, 14, 15]. Cyclic expansion extrusion (CEE) process was proposed by Pardis et al. [16] as a modified counterpart of cyclic extrusion-compression (CEC) and based on this process, a new SPD method was proposed by Babaei et al. for production of UFG tubes, entitled as TCEE [17]. Also, an investigation introduces two new processing routes for CEE of rectangular cross sections [18]. In this newly proposed process, the extrusion part of the process is carried out after the material experiences expansion. Although there are some reported researches for

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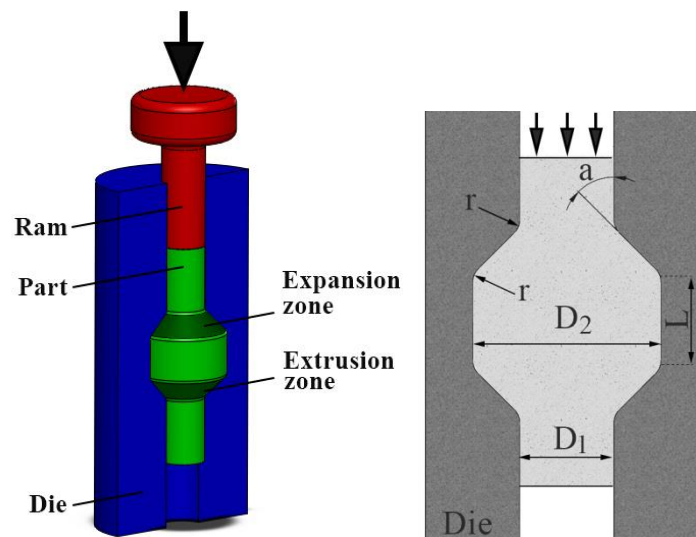


Fig. 1. Schematic illustrations of CEE process and die design parameters

investigation of strain distribution in CEC [19, 20]. Also, some researchers work on mechanical aspects of the process and analyze them by means of the finite element method (FEM) [21]. This technique is a new method that has not been studied in detail. In this article, FEM simulations are used to investigate the effects of the mentioned parameters on strain distribution in CEE process of circular cross sections. Schematic illustrations of the CEE process and die parameters are shown in Fig. 1. The CEE method is a cyclic process in which the cross-section of the material is increased to the chamber diameter (D_2) and subsequently is extruded to initial diameter (D_1) while the material is passing the deformation zone (DZ). Thus, the material undertakes two half cycles including expansion and extrusion. When the material passes through the DZ, the total accumulated strain can be calculated theoretically by Eq. (1) [16]. The first logarithm represents the strain in the expansion half-cycle and the second in the extrusion half-cycle.

$$\bar{\epsilon} = \ln \left(\frac{D_2^2}{D_1^2} \right) - \ln \left(\frac{D_1^2}{D_2^2} \right) \quad [1]$$

The materials undertake both expansion and extrusion in each pass and after n passes the accumulated strain in DZ can be measured by Eq. (2):

$$\bar{\epsilon} = 4 n \ln \left(\frac{D_2}{D_1} \right) \quad [2]$$

One of the advantages of the CEE process in comparison with CEC is that the force needed to extrude the material is supposed to provide a proper amount of back-pressure for the expansion. Therefore, no external back-pressure system is required.

2. FEM Procedure

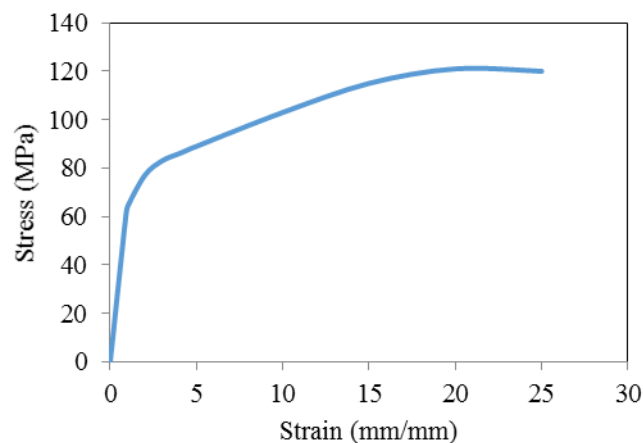
Simulations were done using the commercial DEFORM-3D software. An automatic remeshing was employed in the simulations to accommodate the imposed large strains to further the accuracy of the results. It is necessary to properly define the material behavior, boundary conditions and FEM parameters like elements and solving method. 1/16 of the work-piece and dies were simulated in the FEM because of the symmetric nature of the process. Die angle (a), corner fillet radius (r), and die chamber diameter (D_2) were considered as die parameters as shown in Fig. 1. Also, friction factor (m), and number of passes were considered as process parameters for the investigation of the equivalent strain. The parameters and their values used in the simulations are listed in Table 1. The initial diameter of the cylindrical sample and the length of the chamber (L) are equal to 10 mm. FE parameters used for simulations are given in Table 2. The engineering stress-strain curve of Al 1100 is shown in Fig. 2 [22].

Table 1. Variable parameters and simulation condition

Variable parameter	Levels	Other parameters				
		a (°)	r (mm)	D_2 (mm)	m	n
Die angle (a)	30, 45, 60, 75, 90	-	1	20	0.1	3
corner fillet radius (r)	0.5, 1, 1.5, 2	45	-	20	0.1	3
die chamber diameter (D_2)	15, 20, 25	45	1	-	0.1	3
friction factor (m)	0, 0.3, 0.6, 0.9	45	1	20	-	3
number of passes (n)	2, 4, 8, 16	45	1	20	0.1	-

Table 2. FE parameters used for simulations

Parameter	Value	
	Die	Workpiece
Material	Rigid	Al 1100
Temperature (°C)	20	20
Density (g/cm ³)	-	2.71
Young's modulus (GPa)	-	70
Poisson's ratio	-	0.33
Type of elements	Tetrahedral	

**Fig. 2.** Material behavior of Al 1100 at room temperature[22].

3. Results and Discussion

3.1. Strain Distribution in Deformation Zone

Because of the accumulation of redundant material in the chamber, both expansion and extrusion will not usually occur in each pass for all elements of the material. In addition, the material experiences shear strains in the DZ. Fig. 3(a) shows the deformation velocity field (to the left side) and deformation flow-net diagram (to the right side). In Fig. 3(a) circle compression depicts normal strains (which can be calculated theoretically from Eq. 1) and circle rotation shows shear strains. Along the center line, normal strain contribution of effective strain is dominant and thus the theoretical equation is in good agreement with the FEM results (Fig. 3(b)).

3.2. Strain history

Fig. 4 shows the strain history of five elements initially placed in the cross section of the cylindrical sample and move with the material flow in the CEE process. It can be seen that for each element, the strain increases gradually with an approximately constant slope in 16 passes of the CEE process. It is obvious from this figure that by increasing the distance of the element from the center line the accumulated strain increases. This is due to the additional shear strains in these areas.

3.3. Die parameters

Fig. 5 shows the distribution of equivalent strain in the work-piece after 3 passes of the CEE process with different die angles. Other

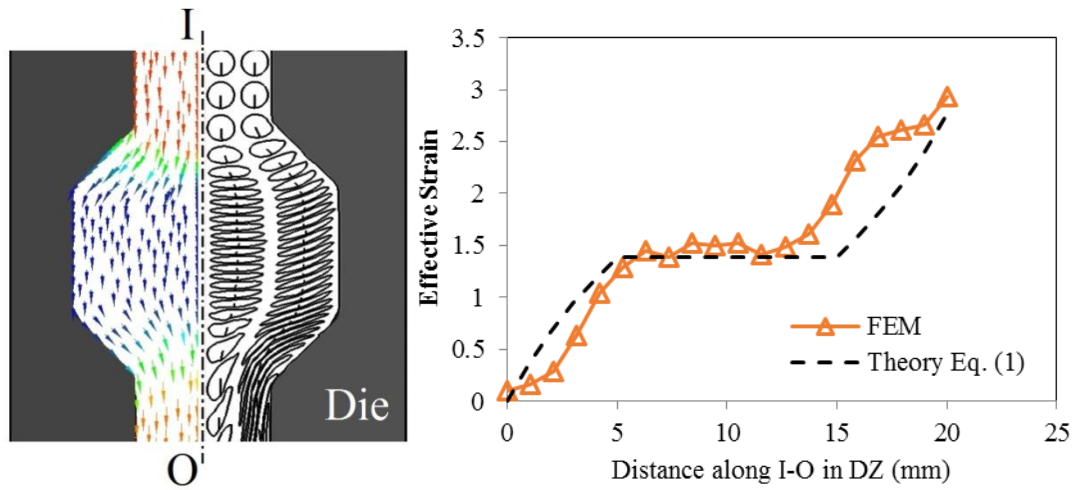


Fig. 3. Strain distributions in DZ (a) and effective strain along the center line (b); $\alpha=45^\circ$, $r=1\text{mm}$, $D_2=20\text{mm}$ and $m=0.1$

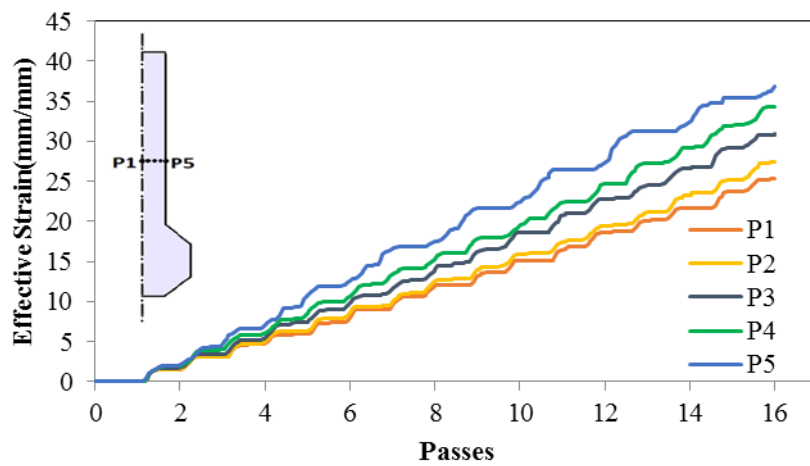


Fig. 4. Strain history of 5 elements in the cross section of the cylindrical sample, $\alpha=45^\circ$, $r=1\text{mm}$, $D_2=20\text{mm}$, and $m=0.1$

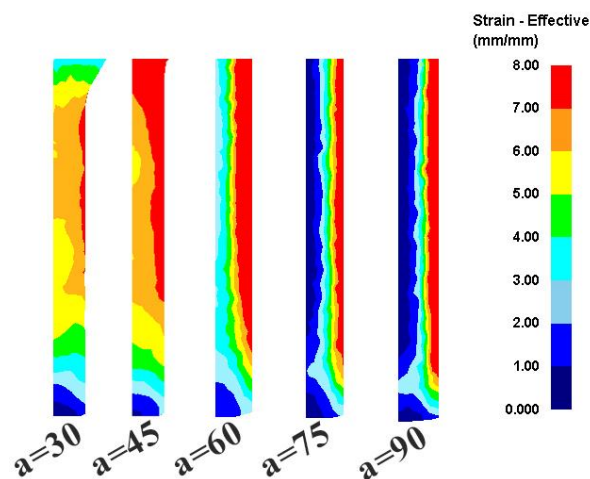


Fig. 5. Distribution of equivalent strain in the work-piece after 3 passes of the CEE process with different die angles

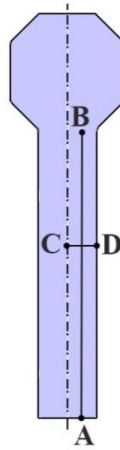


Fig. 6. Illustration of the paths for investigation of strain distribution in longitudinal (A-B) and lateral (C-D) directions

process parameters were considered as $D_2=20$ mm, $r=1$ mm, $\mu=0.1$ and $v=1$ mm/s. As can be seen, the increase in die angles from 30° to 90° results in more inhomogeneity in the strain distribution. This result is in good agreement with the work done on ZK60 alloy in CEC by Lin et al. [19].

The lines A-B and C-D are defined (as illustrated in Fig. 6) to investigate the distribution of equivalent strain during and after the process. The distributions of equivalent strain along these lines are shown at different die angles in Fig. 7. This figure shows that the homogeneity in the longitudinal direction does not vary widely with an increase in the die angle, while the strain distributions from center to the surface vary in the broad range. However, the change in strain distribution for 30° , 45° and 75° , 90° is not remarkable, and only a little increase in strain is observed. It is obvious that this inhomogeneity with an increase of die angle is due to the inability of the work-piece to fluent material flow in DZ.

As discussed earlier, lower die angle has more uniform strain. Although the 45° angle has more strain value in comparison with that of 30° , both show almost similar strain homogeneity. As more strain is more desirable in severe plastic deformation processes, it can be concluded that within the 5 investigated angles above, angle of 45° is the most appropriate for more uniformity and strain value.

Corner radius has been investigated with

variations from 0 to 2 mm with 0.5 mm steps. Fig. 8 shows the distribution of equivalent strain in the work-piece with increasing corner radius after 3-pass CEE. Other process parameters were considered as $D=20$ mm, $\theta=45^\circ$, $\mu=0.1$ and $v=1$ mm/s. The figure shows that strain homogeneity increases with increasing radius, although this increase is not that significant. This result shows a good agreement with the work done on ZK60 alloy in CEC by Lin et al. [19].

Fig. 9 shows longitudinal and lateral strain distribution in the work-piece with different corner radii. It can be seen that longitudinal strain distribution does not have any variation. However, lateral distribution varies with a small slope and radius 0 has the most inhomogeneity because of less fluency in the material flow, and the strain of the surface is more than the center in comparison with other radii. However, except radius 0, other radii do not have a significant difference with each other and homogeneity is nearly identical.

As discussed above, homogeneity does not change widely with a variation of radius except $r=0$. The case of $r=0.5$ mm has a strain homogeneity of 1, 1.5 and 2 while the strain value is more than others. So, within the five investigated radii $r=0.5$ would be the most appropriate value for more uniformity and strain value.

The diameter of the chamber is the other factor investigated for strain distribution with the values of 15, 20, 25 mm. Other process

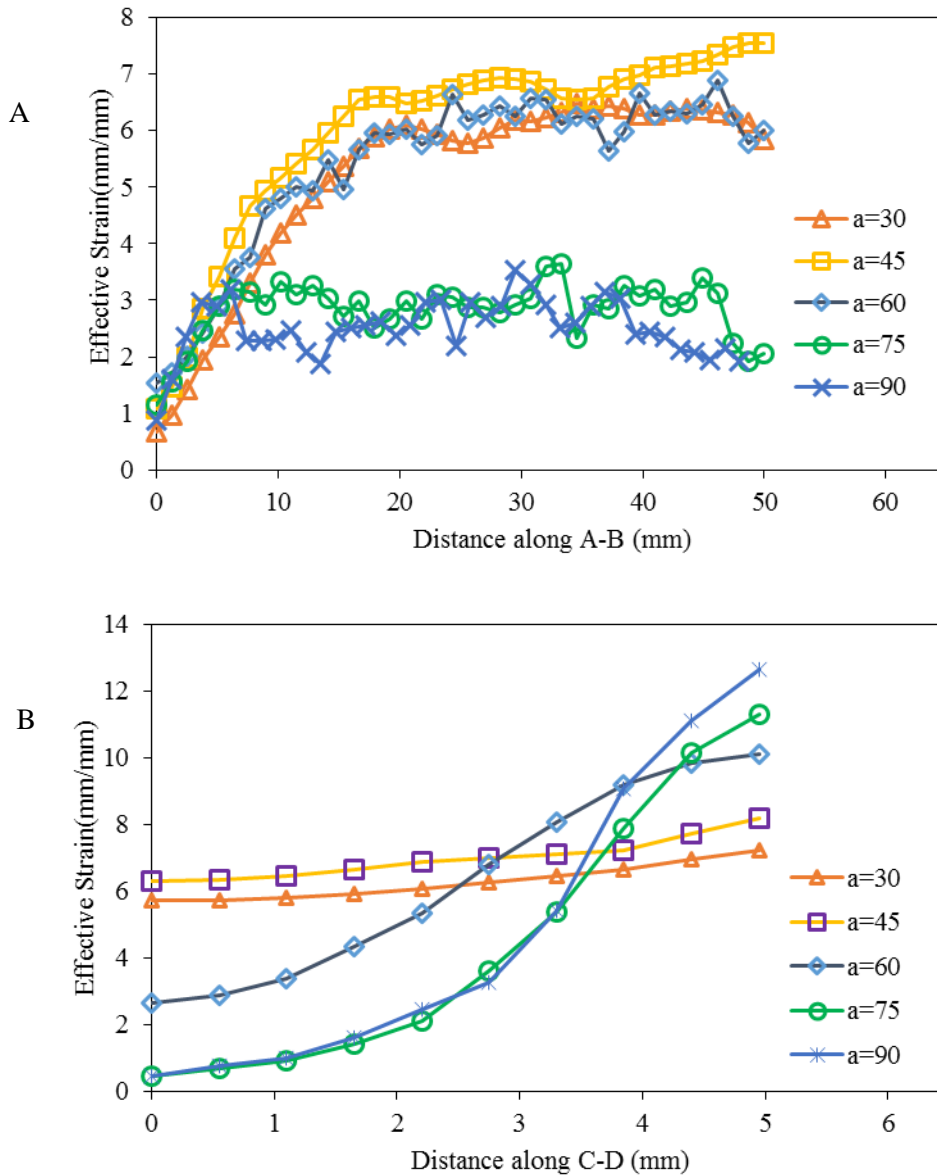


Fig. 7. Distribution of equivalent strain along the A-B and C-D lines in the work-piece at die angles of 30° to 90°

parameters were considered as $r=1$ mm, $a=45^\circ$, $m=0.1$ and $v=1$ mm/s. Strain distribution is shown in Figs. 10 and 11. These figures show that the chamber diameter has a very small impact on strain homogeneity, and as can be seen in the Fig. 10, 11(a), the value of strain increases and because the slope of curves is almost equal, so the homogeneity for 3 cases is almost the same. However, in Fig. 11(b), the slope of the curve for 15 mm has a jump in the middle and variation of strain is more than other diameters. Also, the curve of the diameter

of 25 mm has a bump while, in the diameter of 20 mm, it is almost smooth. Therefore, it can be concluded that the most appropriate longitudinal homogeneity is available for diameter of 20 mm.

As discussed before, chamber diameters do not change the lateral strain homogeneity, but for longitudinal strain distribution, 20 mm diameter gives more uniform strain compared to the others. Also, the comparison of the diameters of 20 and 25 mm shows that the diameter of 25 mm produces more waste

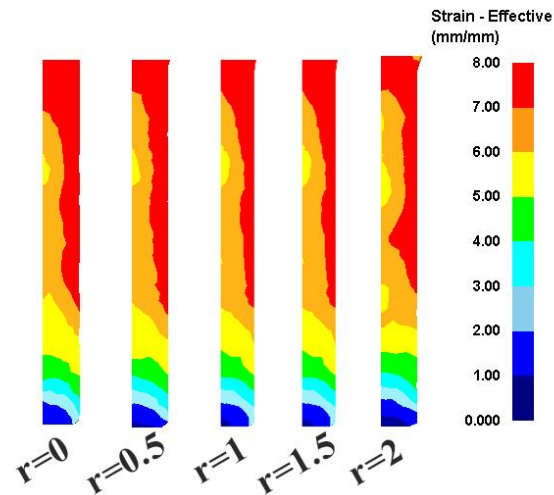


Fig. 8. Distribution of equivalent strain in the work-piece with increasing corner radius after three passes of CEE

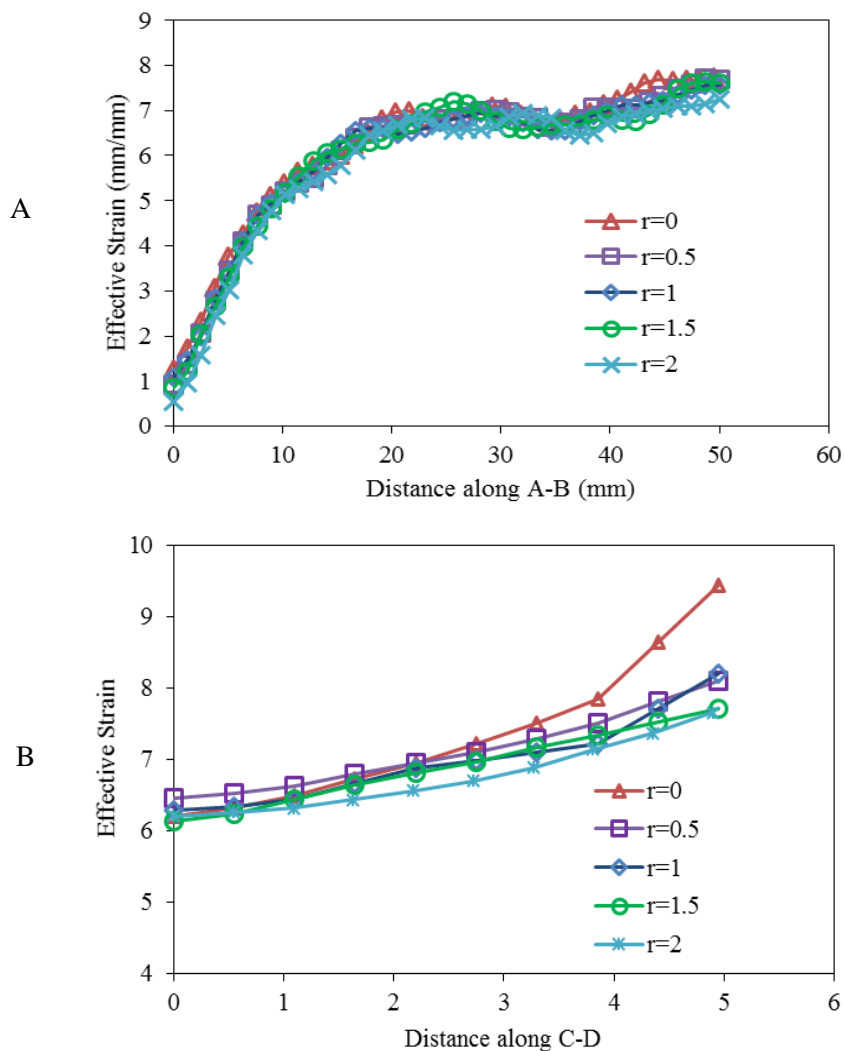


Fig. 9. Longitudinal and lateral strain distribution in the workpiece with corner radii of 0 to 2

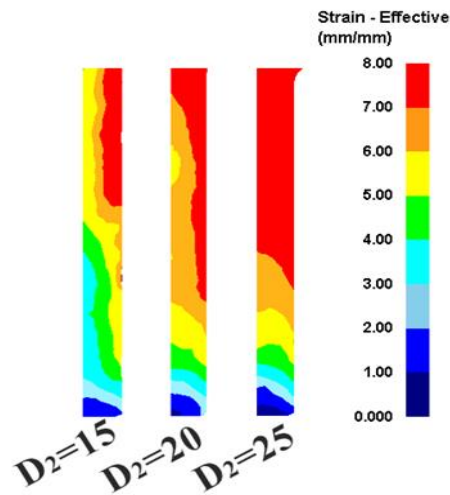


Fig. 10. Distribution of equivalent strain in the work-piece with increasing chamber diameter after threepasses CEE process

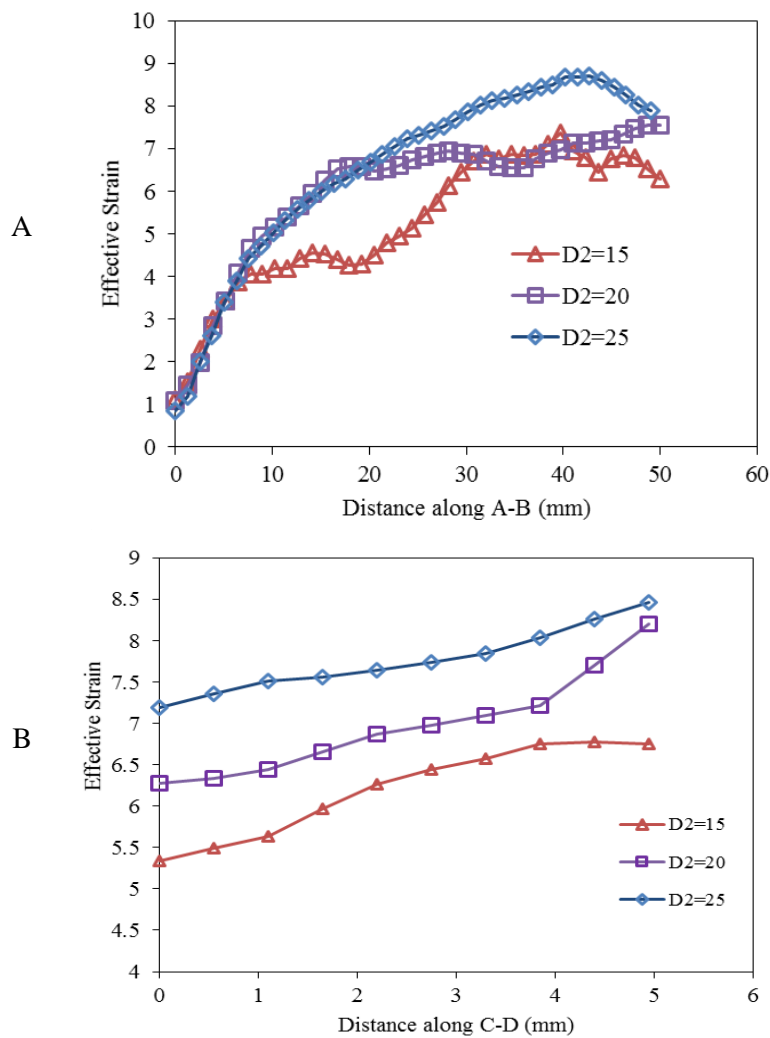


Fig. 11. Longitudinal and lateral strain distribution in the work-piece with chamber radiuses of 15, 20, 25 mm

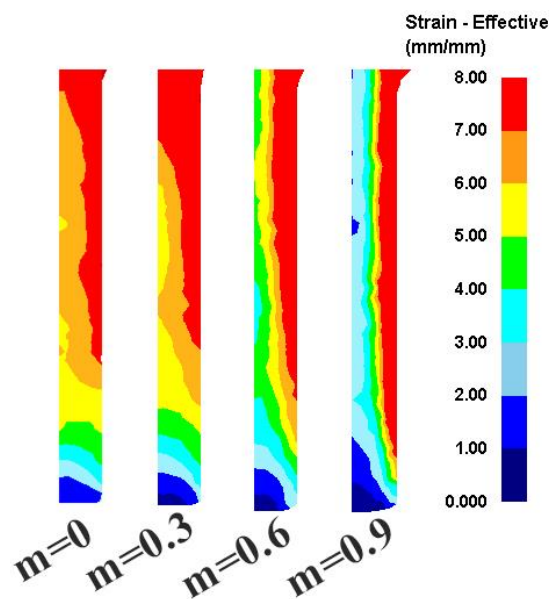


Fig. 12. Distribution of equivalent strain in the work-piece with variation of the friction factor after 3-pass CEE

material compared to 20 mm; thus, the diameter of 20 mm gives better results than the other investigated diameters.

3. 4. Process parameters

The effect of friction factor has been investigated with values of $m=0, 0.3, 0.6, 0.9$. Other process parameters were considered as $r=1$ mm, $a=45^\circ$, $D_2=20$ mm and $v=1$ mm/s. Fig. 12 shows strain distribution in the final part after 3-pass CEE. As can be seen, strain distribution is so impressionable of friction and the strain of the center of the part is lower than the strain of the surface. This is also verified by the slope of the curves of Fig. 13(a). As the friction force on the surface increases, it results in the material flow at the surface to be more difficult than the center [23]. Therefore, the strain of the surface will become more than the center. It reveals that with decreasing of friction factor, the homogeneity of strain increases clearly. This result exhibits a good agreement with the work done on CEC of ZK60 alloy by Lin et al. [19]. However, the longitudinal strain distribution is not more dependent on the friction as it is shown in the Fig. 13(b). The slopes are almost equal, and it can be concluded that homogeneity will not vary in the length of the part with a change of

the friction factor.

The effect of friction has been discussed above, and it has been concluded that reduction of friction factor results in more uniform strain distribution. Though the friction is not practically more changeable, the lowest friction factors are more desirable to reach more homogeneous strain distribution.

Fig. 14 shows the effect of the number of passes on strain distribution. The number of passes was considered as 2, 4, 8, and 16. It is obvious that with an increase of passes, the value of strain will enhance because more strain-hardening is applied on the work-piece as shown in Fig. 14. As can be seen in this figure, strain homogeneity reduces with the increase of pass numbers. In the pass numbers of 8 and 16, distribution of different colors is almost identical in the figures, but the maximum strain in the color bars increases with the increase of the pass numbers. So, it shows that the variation of strain and inhomogeneity enhances with the increase of passes.

Fig. 15 shows longitudinal and lateral strain distribution in the work-piece in different number of passes. The increase of curves slopes in Fig. 15 demonstrates that both longitudinal and lateral homogeneity decrease

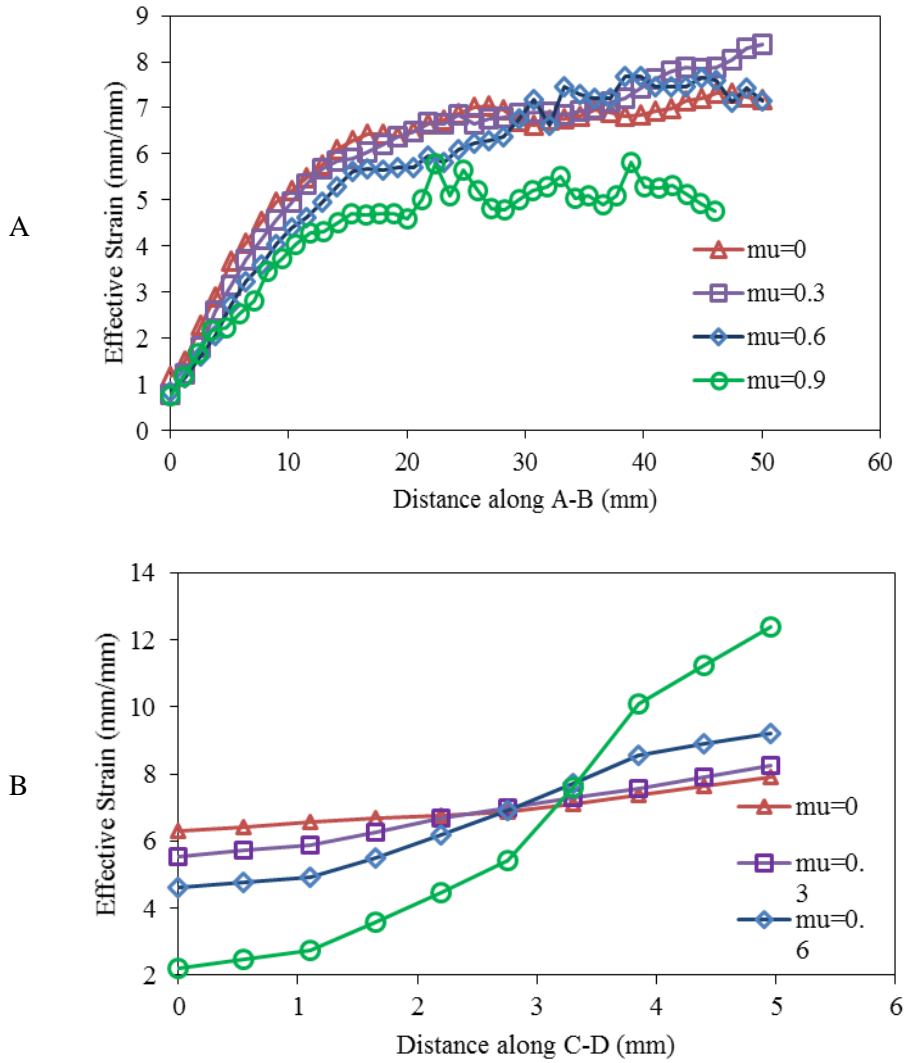


Fig. 13. Longitudinal and lateral strain distribution in the work-piece with the friction factors of 0, 0.3, 0.6 and 0.9

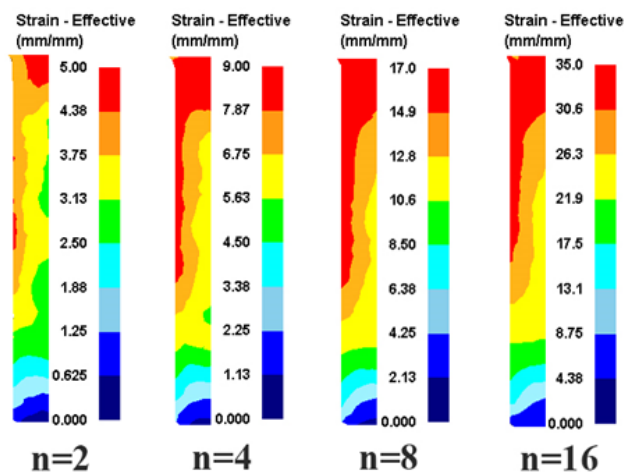


Fig. 14. Distribution of equivalent strain in the work-piece with increase the number of passes

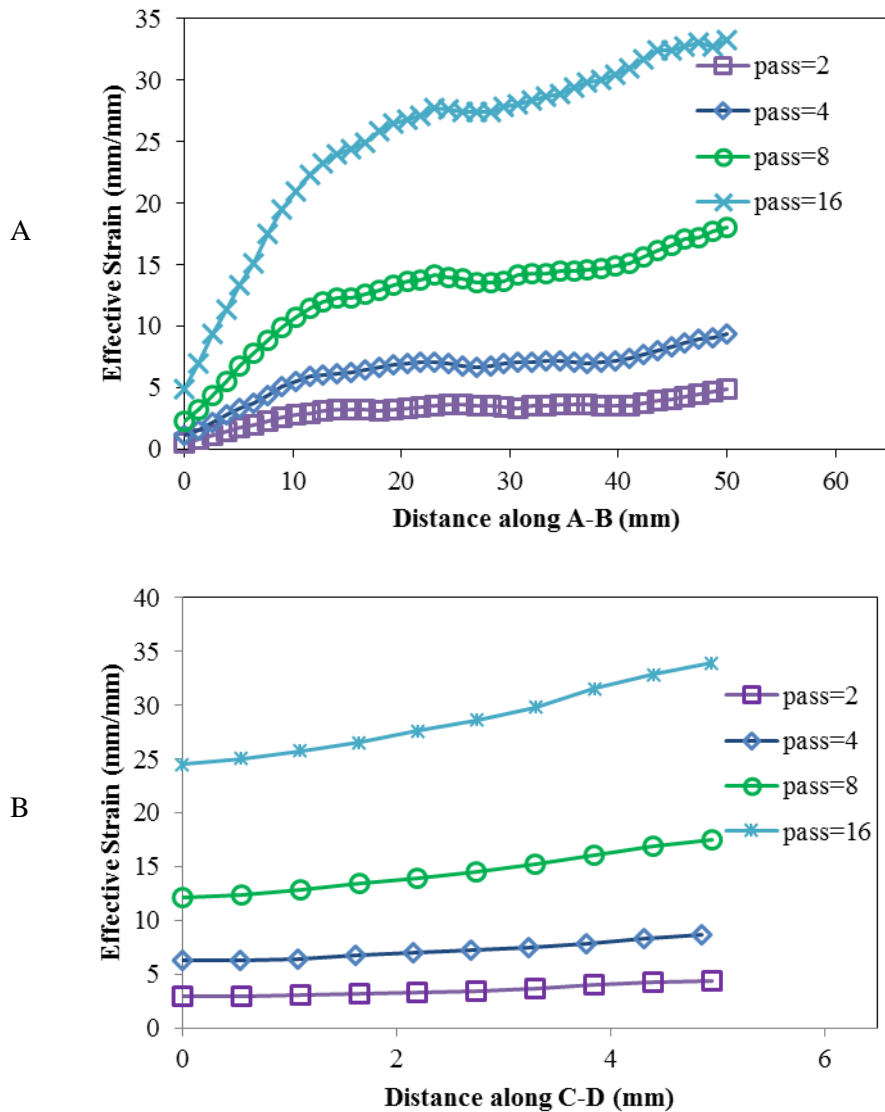


Fig. 15. Longitudinal and lateral strain distribution in the workpiece with passes of 2, 4, 8 and 16.

with increase the numbers of passes. Also, it is obvious in the figure that the values of strain enhance with the increase of passes. This result is in agreement with the work done on ZK60 alloy CEC in by Lin et al.[24].

As discussed above, increasing the number of passes causes increase of the strain value and decrease of the strain homogeneity. Therefore, the most appropriate condition cannot be chosen, because two parameters are in conflict with each other. Therefore, according to the desired conditions (more strain value or more strain homogeneity) better conditions can be chosen.

4. Conclusions

The effects of the process and die parameters on strain distribution were investigated during the CEE process of the Al 1100 samples. Results show that the die angle and friction factor have the most effect on lateral strain homogeneity. Therefore, the strain of the center of the part is much lower than surface strain with the increase of die angle and friction factor. Number of passes and die corner radius have lower effect on strain homogeneity in comparison with die angle and friction factor; however, the center strain of the part is also lower than surface strain with increase of pass

numbers and decrease of die corner radius. Chamber diameter has a very small effect on lateral strain distribution, but it has more effect on longitudinal homogeneity compared to other parameters so that homogeneity enhances with the increase of diameter. Other parameters have very low impact on longitudinal strain distribution. Material flow diagram of deformation zone showed that shear strains have significant contribution in accumulated effective strain especially adjacent to die surface.

References

- Horita, Z., Nanomaterials by Severe Plastic Deformation. International Conference on Nanomaterials by Severe Plastic Deformation 2006: Materials Science Forum. 1050.
- Rosochowski, A., Processing metals by severe plastic deformation. *Solid State Phenomena*, 101, 2004, pp. 13-22.
- Rosochowski, A., L. Olejnik, and M. Richert, Metal forming technology for producing bulk nanostructured metals. *Journal of Steel and Related Materials–Steel GRIPS*, 2, 2004, pp. 35-44.
- Valiev, R., et al., Producing bulk ultrafine-grained materials by severe plastic deformation. *JOM*, 58(4), 2006, pp. 33-39.
- Azushima, A., et al., Severe plastic deformation (SPD) processes for metals. *CIRP Annals - Manufacturing Technology*, 57(2), 2008, pp. 716-735.
- Babaei, A. and M. M. Mashhadi, Characterization of ultrafine-grained aluminum tubes processed by Tube Cyclic Extrusion–Compression (TCEC). *Materials Characterization*, 95(0), 2014, pp. 118-128.
- Valiev, R. Z. and T. G. Langdon, Principles of equal-channel angular pressing as a processing tool for grain refinement. *Progress in Materials Science*, 51(7), 2006, pp. 881-981.
- Huang, X., et al., Microstructural evolution during accumulative roll-bonding of commercial purity aluminum. *Materials Science and Engineering: A*, 340(1–2), 2003, pp. 265-271.
- Saito, Y., et al., Ultra-fine grained bulk aluminum produced by accumulative roll-bonding (ARB) process. *Scripta Materialia*, 39(9), 1998, pp. 1221-1227.
- Zhilyaev, A. P., et al., Experimental parameters influencing grain refinement and microstructural evolution during high-pressure torsion. *Acta Materialia*, 51(3), 2003, pp. 753-765.
- Zhilyaev, A. P. and T. G. Langdon, Using high-pressure torsion for metal processing: Fundamentals and applications. *Progress in Materials Science*, 53(6), 2008, pp. 893-979.
- Richert, M., Q. Liu, and N. Hansen, Microstructural evolution over a large strain range in aluminium deformed by cyclic-extrusion–compression. *Materials Science and Engineering: A*, 260(1), 1999, pp. 275-283.
- Zhang, J. A new bulk deformation method–Cyclic extrusion. in *Materials Science Forum*. 2007. Trans Tech Publ.
- Faraji, G., et al., TEM analysis and determination of dislocation densities in nanostructured copper tube produced via parallel tubular channel angular pressing process. *Materials Science and Engineering: A*, 563(0), 2013, pp. 193-198.
- Faraji, G. and M. Mousavi Mashhadia, Plastic deformation analysis in parallel tubular channel angular pressing (PTCAP). *Journal of Advanced Materials and Processing*, 1(4), 2013, pp. 23-32.
- Pardis, N., et al., Cyclic expansion-extrusion (CEE): A modified counterpart of cyclic extrusion-compression (CEC). *Materials Science and Engineering: A*, 528(25–26), 2011, pp. 7537-7540.
- Babaei, A., M. M. Mashhadi, and H. Jafarzadeh, Tube cyclic expansion-extrusion (TCEE) as a novel severe plastic deformation method for cylindrical tubes. *Journal of Materials Science*, 49(8), 2014, pp. 3158-3165.
- Pardis, N., et al., Development of new routes of severe plastic deformation through cyclic expansion–extrusion process. *Materials Science and Engineering: A*, 613(0), 2014, pp. 357-364.

19. Lin, J.-b., et al., Finite element analysis of strain distribution in ZK60 Mg alloy during cyclic extrusion and compression. *Transactions of Nonferrous Metals Society of China*, 22(8), 2012, pp. 1902-1906.
20. Lin, J., et al., Study on deformation behavior and strain homogeneity during cyclic extrusion and compression. *Journal of Materials Science*, 43(21), 2008, pp. 6920-6924.
21. Rosochowski, A., R. Rodiet, and P. Lipinski, Finite element simulation of cyclic extrusion-compression. *Metal Forming*, 2000, pp. 253-259.
22. Azimi, A., et al., Mechanical properties and microstructural evolution during multi-pass ECAR of Al 1100-O alloy. *Materials & Design*, 42(0), 2012, pp. 388-394.
23. Faraji, G., et al., The role of friction in tubular channel angular pressing. *Rev. Adv. Mater. Sci*, 31, 2012, pp. 12-18.
24. Lin, J., et al., Study on deformation behavior and strain homogeneity during cyclic extrusion and compression. *Journal of materials science*, 43(21), 2008, pp. 6920-6924.

