Deformation behavior in the tubular channel angular pressing (TCAP) as a noble SPD method for cylindrical tubes

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Abstract Tubular channel angular pressing is a recently developed technique for producing ultrafine grained and nanostructured tubular components. The current study dealt with the influence of the channel angles, friction coefficient and back pressure on the plastic deformation behavior and strain homogeneity in TCAP processing. The FEM results demonstrated that the equivalent plastic strains of 1.65–2.15, 2.15–2.85, and 2.5–3.75 have been achieved after applying one pass TCAP with channel angles of 120°, 90°, and 60°, respectively. Increasing the channel angle leads to lower equivalent plastic strain while obtaining better strain homogeneity. The homogeneity of the strain through the length of the processed tube is very good for all channel angles. Increasing the back pressure leads to slightly higher strain level while the strain homogeneity is decreased. Force results showed that lower loads were required for lower channel angles. It was also observed that for different values of coefficient of friction and channel angles, the load values converged to a constant value at the end of the process. Microstructural observations showed a significant decrease in grain size from the initial value of ~150 µm to about 1 µm.

1 Introduction

There has been a great deal of interest in recent years in improving material properties by grain refinements using severe plastic deformation (SPD) [1]. The most commonly used methods are equal channel angular pressing (ECAP) [2], high-pressure torsion (HPT) [3], and accumulative roll bonding (ARB) [4]. Yet there are other methods with different applications [5–14]. Of these various processes, ECAP is an especially attractive processing technique for several reasons. Appreciating the outstanding capabilities of ECAP, a noble and effective process named tubular channel angular pressing (TCAP) method suitable for processing tubes to very high strains was proposed for the first time by the authors [15]. In that work, the TCAP process was applied to AZ91 magnesium alloy and significant grain refinement was achieved. There are a few other methods which can produce ultrafine grains in tubular components such as the accumulative spin bonding (ASB) based on ARB [16] and high-pressure tube twisting (HPTT) [17] based on HPT. These methods inherit the disadvantages and limitations of ARB and HPT methods. It seems that the TCAP process could obviate all the limitations of these two methods and enjoys the advantages of ECAP in comparison with ARB and HPT [2]. The principle of tubular channel angular pressing is shown in Fig. 1. The constrained tube between inner and outer dies is pressed by a hollow cylindrical punch into a tubular angular channel. The tube material is pressed to the tubular angular channel and in one processing cycle as much as three shear events take place.

In the present paper, the effects of channel parameters, friction coefficient and back pressure (BP) on the deformation behavior are investigated by FEM and experiments.
2 FEM and experimental procedures

The commercial FEM code Abaqus/Explicit was used to perform the numerical simulation. An axisymmetric model was employed, where the geometrical dimensions and mechanical properties of specimens were the same as those of the experiment, making it possible to compare the simulation results with those obtained experimentally. Axisymmetric four node elements (CAX4R) were employed to model the sample. To accommodate the predetermined large strains during simulations, adaptive meshing (automatic remeshing) was employed. The arbitrary Lagrangian–Eulerian (ALE) adaptive meshing maintains a high-quality mesh under SPD by allowing the mesh to move independently with respect to the underlying material. The Coulomb friction and penalty method were used to model the contact between the die and the specimen. The die and the punch were modeled as analytical rigid parts. Experimental alloy properties and process parameters with their values are shown in Table 1. The mechanical properties of AZ91 alloy are shown in Fig. 2; they were obtained through a compression test at the TCAP processing temperature of 300°C and at a strain rate of $1 \times 10^{-5} \text{ sec}^{-1}$.

The material used in this study was a commercial AZ91 magnesium alloy. Cylindrical tubes of 20 mm in outer diameter, 2.5 mm in thickness, and 35 mm in length were machined from cast ingots. A TCAP die was manufactured from hot worked tool steel and hardened to 55 HRC and is shown in Fig. 1(c). The channel angles $\varphi_1$, $\varphi_2$, and $\varphi_3$ in the TCAP facility were 135°, 90°, and 135°, respectively. The angle of curvature $\psi_2$ was 90°, and both $\psi_1$ and $\psi_3$ were equal to 0°, as in Fig. 1. The specimens were subjected to TCAP at 300°C with a punch speed of 5 mm/min to minimize increases in the temperature during the deformation. The temperature increase was observed to be less than 5°C at a pressing speed of 11 mm/min [25]. The friction between the specimen and dies was reduced by applying MoS$_2$ as a lubricant.

| Parameter               | Value  | Parameter               | Value       |
|-------------------------|--------|-------------------------|-------------|
| Young’s modulus ($E$)   | 41 GPa | $R/R_0$                 | 1.5         |
| Poisson’s ratio ($\nu$) | 0.35   | $\varphi_2$            | 60°, 90°, 120° |
| Density ($\rho$)        | 1.78 g/cm$^3$ | $\psi_1 = \psi_3$     | 0°          |
| Friction coefficient ($\mu$) | 0, 0.025, 0.05, 0.075 and 0.1 | $\psi_2$     | 90°          |
| Back pressure (MPa)     | 0, 10 and 100 | Temperature (°C)      | 300         |

Fig. 1 (a) Schematic illustration of TCAP processing and (b) process parameters [15]. (c) TCAP die picture

Fig. 2 Stress-strain curve of AZ91 at 300°C
3 Results and discussion

Figures 3(b) to (d) show equivalent plastic strain contours to three different channel angles ($\phi_2$) 60°, 90°, and 120° when no back pressure was used and the friction coefficient was 0.05. It could be seen from the contour colors corresponding to three different angles that the smaller angle led to higher equivalent plastic strain values and worst strain homogeneity. Quantified strain values for TCAP processed tube with three different channel angles are shown in pass plots of Fig. 3(e). It is clear that the equivalent plastic strain is increased as the channel angle is decreased. The equivalent plastic strains of 1.65–2.15 (1.9 ± 0.25), 2.15–2.85 (2.5 ± 0.35), and 2.5–3.75 (3.125 ± 0.625) have been gained after applying one pass TCAP with channel angles of 120°, 90°, and 60°, respectively. In other words, strain variations corresponding to channel angles of 120°, 90°, and 60° are 13.1%, 14%, and 20%. This means that the effect of channel angle on strain homogeneity for angles of $60^\circ < \phi_2 < 90^\circ$ is very low but it is higher for angles of $90^\circ < \phi_2 < 120^\circ$. From Fig. 3 it is clear that the highest equivalent plastic strain takes place in the inner surface of the processed tube for all channel angles. It is clearly different from conventional ECAP. In conventional ECAP when the friction coefficient is 0.05, the lowest strain value occurs in the outer surface layer due to the corner gap [19]. From Fig. 3(d) at the shear zone $I$ (Fig. 1(b)) the highest strain was obtained in the inner surface, being opposite to ECAP. It may be because of
the existence of peripheral strain in TCAP (does not exist in ECAP) which forces the tube toward the inner punch surface.

Figure 4 shows the material flow and deformation geometry during different stages of TCAP processing with different channel angles. Figures 4(a), 4(d), and 4(g) show deformation geometry in the early stages of TCAP with channel angles of 60°, 90° and 120°, respectively. It can be seen that in this stage in all cases there is some thinning in the tube thickness. It is because of tensile peripheral strain ($\varepsilon_{\theta}$) resulted from the increase in the tube diameter [15]. $\varepsilon_{\theta}$ is related to $R/R_0$ and this value is constant for all channel angles, therefore maximum tube thinnings for all cases are equal. Figures 4(b), 4(e), and 4(h) show the material flow geometry after passing through the shear zone II. It could be seen that there is not any tube thinning in this stage. It is because of that the back pressure effect resulting from shear zone II which compensated for the tube thinning in the early stage. Also, when the tube passes the shear zone II to III there is a compressive peripheral strain which increases the tube thickness and it achieved to the initial thickness. From Figs. 4(c), 4(f), and 4(i) it is clear that the material in the die corner region I almost fills but it does not take place in the shear zone of III. It is also taking place in conventional multi pass ECAP. Kim [20] mentioned that it is because of back pressure effects resulting from the next shear zones on the initial one. If the die corner corresponds to shear zone III, in which there is not any consequent shear zone, it can be seen that die corner filling is not complete.

Considering the tail part of the tube end in Figs. 4(c), 4(f), and 4(i), it seems that increasing the channel angle above 90° makes the tail move toward the outer die, and decreasing the channel angle below 90° pushes the tail toward the inner die surface. For the channel angle of 90° has almost no tendency to move sideways holds its symmetric form. This phenomenon in TCAP is similar to equal channel multi-angular pressing (ECMAP) introduced by Kim [20] or to parallel ECAP which was proposed by Raab [21].

In the case of channel angle of 120° it could be seen in the marked region of Fig. 4(h) that there is a material separation from the die surface. This has also been observed in the conventional ECAP with $\Phi = 120^\circ$ [19]. In the next stage material separation decreases because of back pressure effect is shown in Fig. 4(i). Also, it is clear that the separation region position changes after passing the shear zone III. In other words the separation region before and after the shear zone III are near the inner and outer punch surfaces, respectively. It may be because of the above explanation about parallel ECAP [21] and ECMAP [20] in which the deformation direction is changed after passing the consequent shear zones.

The deformation history developed along the radial direction during the TCAP processing with different channel angles of 60°, 90°, and 120° is depicted in Figs. 5(a)–5(c), respectively. As can be realized from Fig. 5, there are three different zones with sharp changes in equivalent plastic strain curves. These sharp changes correspond to the shear zones of I, II, and III. In these shear zones the equivalent
plastic strain experiences intense shear strain magnifying itself as a sharp discontinuity. The distance between sharp changes increases by increasing the channel angles. This is due to the fact that the higher channel angles lead to longer distances to be passed. The difference between equivalent plastic strain values for the nodes N1, N2, and N3 increases when the deformation proceeds. It means that the deformation homogeneity in TCAP processing increases when the channel angle increases. As mentioned above the equivalent plastic strain values of 1.65–2.05 (1.9 ± 0.25), 2.15–2.85 (2.5 ± 0.35), and 2.5–3.75 (3.125 ± 0.625) have been obtained after applying one pass TCAP with channel angles 120°, 90°, and 60°, respectively. These are reasonable variations and may be considered as good strain homogeneity in TCAP processing in comparison with other severe plastic deformation processes. Strain homogeneity is superior in comparison with the HPTT process [17] in which the shear component varies between 2 and 14. Also, TCAP has good strain homogeneity in comparison with conventional ECAP specially processing with route A [22, 23]. The last parts of the curves in Fig. 5 are constant in all cases. It means that the equivalent plastic strain remains constant after passing
the tube from the last shear zone. In other words, processing with TCAP leads to excellent deformation homogeneity through the length of the tube.

Figures 6(a)–6(c) represent the effective stress contours for TCAP processed sample with channel angles of 120°, 90° and 60°, respectively. As is well established, analyzing the effective stress contours in the deformation zone may generate some information about shear deformation and plastic zones [24]. Inadequate plastic zones indicate the regions not being subjected to the plastic deformation. From Fig. 6 it can be seen that there are fully plastic regions between consequent shear zones for specimens processed with TCAP with different channel angles. Continuous stress contours of plastic zone for all cases show that strain homogeneity is achievable. Figure 6(d) shows the effective stress values occurring for the tube thickness. It could be realized that the appropriate channel angle with good stress homogeneity is 90°. Figures 6(a) and 6(d) show that TCAP processing with channel angle 120° leads to the worst stress homogeneity. This may be due to the tube separation regions from die surfaces formed in the different stages of the process as a result of deformation characteristics.

Figure 7 illustrates the calculated load versus ram displacement curves for TCAP processing with different channel angles while no BP was used and friction coefficient was 0.05. It can be seen that the load history curves for three channel angles are totally different. Process load is increased when the channel angle decreases. However, there are three slope changes for all the cases. These slopes decreased with increase in the channel angle values. An important feature in force diagrams is that all curves converge near the end. As is seen in the figure the peak load position is increased by increasing the channel angle. It is because the tube passing trace is increased by increasing the channel angle by considering the geometry of Fig. 1(b). It may be attributed to the friction force. By considering the Coulomb friction type the friction force is related to friction coefficient which could be considered to be constant and normal force. If the tube length during the TCAP process is divided into two sections including the lengths before and after the last shear zone (III) it could be realized that the hydrostatic pressure in the region before shear zone III is higher while it is going to be zero in the region after shear zone III. It means that the normal force in the region before shear zone III is higher while in the region after the shear zone III it is going to be zero. When the process is preceded, the tube length before the shear zone III is decreased and the tube length after shear zone III is increased. It means that the friction force is decreased when the process is preceded. So, the total force is decreased in all channel angles.

The equivalent plastic strain achieved during the deformation is shown in Fig. 8. In all frictional cases, the equivalent plastic strain in the TCAP processed tube was smaller along the outer surface than in the other regions, while it
was high in the inner surface in the cases with friction coefficients from 0 to 0.075. It can also be seen that the strain values after shear zone II for the friction coefficient of 0.075 were higher than the other cases. Figure 8(e) shows the friction coefficient of 0.1, causing the highest strain value in the tail region. The high strain in this region is due to the high back pressure effect under high friction, which is explained in the following section.

Figure 9 shows the predicted equivalent plastic strain through the tube thickness shown by the arrows in Fig. 8. The theoretical equivalent plastic strain calculated from the constitutive equations of the TCAP proposed by Faraji et al. [15] is also presented in Fig. 9, showing a single uniform value across the tube thickness. The theoretical equations did not take into account the influence of the material behavior and friction. Hence, the theoretical equivalent plastic strain is a straight line with a value of approximately 2.69. The FEM simulated equivalent plastic strain curves have the same trend for different friction coefficients: the strain decreases with the position from the inside to the outside. It should be noted that the different friction coefficients derived from different trends in equivalent plastic strain curves in the conventional ECAP, which was noted by Nagasekhar et al. [18]. The maximum equivalent plastic strain occurs in the inner surface of the tube and the minimum occurs in the outer surface of the tube. In the outer surface, the equivalent plastic strain value is increased by increasing the friction coefficient. Also, it can be seen that the mean value of the FEM results is almost identical to the theoretical value. Thus, there is a reasonably good agreement between the average strain of the FEM and the theoretical analysis.

Figure 10 shows the calculated load plotted against the ram displacement curves for the TCAP with various friction coefficients. The processing load increases with the friction coefficient due to the additional energy spent in recovering the deformation resistance in the surface. There are three slope regions in all cases, corresponding to the three forming zones. The slope decreases with decreasing friction co-

![Figure 9](image1.png)  
Fig. 9 Equivalent plastic strain versus distance from the inner surface of the processed tube in comparison with theoretical results [15]

![Figure 10](image2.png)  
Fig. 10 FEM calculated pressing load versus ram displacement during TCAP processing with friction coefficients of 0, 0.025, 0.05, 0.075 and 0.1 in comparison with experimental results (BP = 0 and \( \phi_2 = 90^\circ \))

![Figure 11](image3.png)  
Fig. 11 Equivalent plastic strain contours of TCAP processed tube with back pressures of (a) 100 MPa, (b) 10 MPa and (c) equivalent plastic strain path plots (in all cases \( \mu = 0.05 \) and \( \phi_2 = 90^\circ \))

efficient. An important feature in the force curve is that all curves tend to converge, which may be attributed to the fric-
Fig. 12  (a) An AZ91 workpiece after the process of the TCAP, (b) optical micrographs of the initial sample showing a mean grain size of ∼150 µm, (c) typical microstructures of experimental alloy after single pass TCAP with mean grain size of ∼1 µm.

4 Conclusions

The influence of the channel angles, friction coefficient and back pressure effect on the plastic deformation behavior and strain homogeneity in TCAP processing were investigated using FE and experiments. The results were as follows:

(1) The FEM results demonstrated that equivalent plastic strains of 1.65–2.15, 2.15–2.85, and 2.5–3.75 have been obtained after applying one pass TCAP with channel angles of 120°, 90°, and 60°, respectively.
(2) Increasing the channel angle leads to lower equivalent plastic strain, meanwhile better strain homogeneity.

(3) The strain homogeneity through the length of the processed tube is very good for all channel angles.

(4) There are equal tube thinnings for all cases as a result of some tensile peripheral strains in the early stages of the process but it could be compensated for by back pressure effect resulting from next shear zones and also compression peripheral strain resulting from tube diameter decreasing.

(5) Results for the force values showed that the lower loads are required for lower channel angles. Also the required loads for different channel angles are converged to a constant value near the end of the process.

(6) Microstructural observations showed a significant decrease in grain size from the initial value of ∼150 µm to about 1 µm.

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