Deformation Behavior in Tubular Channel Angular Pressing (TCAP) Using Triangular and Semicircular Channels

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In this paper, two different (triangular and semicircular) channel types were investigated in tubular channel angular pressing (TCAP) suitable for deforming cylindrical tubes to large strains without changing the tube dimensions. To examine the effects of the channel geometry on the strain distribution and deformation behavior during the TCAP process, finite element method (FEM) simulations and an analytical model were employed. The FEM results demonstrate that equivalent plastic strains of 2.15 – 2.9 and 2.35 – 2.6 were achieved after applying one pass TCAP in the triangular and semicircular channels, respectively. The mean values of the equivalent plastic strains were almost identical for both cases, but the strain through the thickness with semicircular channel was more homogeneous than that in the triangular channel. Tube thinning in the early stages of the process was observed as a result of tensile circumferential strains, but this can be compensated by the back pressure effect resulting from the next shear zones and also compressive circumferential strain resulting from the decreasing tube diameter. While the strain values for both channel types were similar, the required load for the semicircular channel was lower than that of the triangular channel.

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1. Introduction

There has been much interest in recent years in improving material properties through grain refinements using severe plastic deformation (SPD). The commonly used methods are equal channel angular pressing (ECAP), high pressure torsion (HPT), and accumulative roll bonding (ARB). Of these methods, the ECAP is an especially attractive processing technique. Despite the need for high strength tubes in a wide range of industrial applications, few studies have been undertaken to produce ultrafine grained tubular parts using SPD methods. Through understanding the beneficial capabilities of the ECAP, an effective process suitable for processing tubes to very high strains, called the tubular channel angular pressing (TCAP) method, was proposed by the authors. In that work, the TCAP process using a triangular channel was applied to an AZ91 magnesium alloy and significant grain refinement was achieved. While plastic deformation of AZ31 alloy was recently investigated, we rarely could find reports on the SPD of the AZ91 alloy. Owing to certain advantages of high Al content, the AZ91 series magnesium alloys show good castability and many potential applications.

The principle of the TCAP is shown in Fig. 1. The constrained tube between the inner and outer dies is pressed by a hollow cylindrical punch into a tubular angular channel. The tube material is then pressed through the tubular angular channel in which three shear events occur during one cycle.

In the present paper, the effects of the channel geometry on the deformation behavior are investigated via the finite element method (FEM) and experiments. Analytical modeling was used to calculate the equivalent plastic strains. Also, an experimental test based on a grid method was used to validate the analysis and FEM results.

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2. Analytical Modeling

To calculate the accumulated strain, $\varepsilon_T$, resulting from the TCAP process, a model developed by Faraji et al. was used. For the channel geometry shown in Fig. 2(a) with channel angles $\psi_1$, $\psi_2$, and $\psi_3$, (135°, 90°, and 135°) and corner angles $\psi_1$, $\psi_2$, and $\psi_3$, (0°, 90°, and 0°), the following equations can be used:

$$
\varepsilon_T = \frac{3}{2} \sum_{i=1}^{3} \frac{2 \cot(\psi_i/2 + \psi_r/2) + \psi_r \csc(\psi_i/2 + \psi_r/2)}{\sqrt{3}} + 2\varepsilon_\theta.
$$

$$
\varepsilon_\theta = \frac{2}{\sqrt{3}} \varepsilon_\phi.
$$

$$\varepsilon_\phi = \varepsilon_r = \ln \frac{R}{R_0}.
$$
where the $\varepsilon_0$ is equivalent strain resulting from the peripheral normal strain $\varepsilon_0$. To calculate the accumulated strain, $\varepsilon_T$, resulting from the channel geometry shown in Fig. 2(b), it can be seen that there are two shear strains corresponding to the two shear zones of IV and V in which the curvature angles of $\psi_2$ and $\psi_2$ were 27.3°, and both channel angles of $\phi_4$ and $\phi_5$ were approximately 90°. Based on the similar method for the triangular channel, the following equation can be obtained for the semicircular channel:

$$\varepsilon_T = \sum_{i=4}^{5} \left[ \frac{2 \cot(\phi_i/2 + \psi_i/2) + \psi_i \cos(\phi_i/2 + \psi_i/2)}{\sqrt{3}} \right] + 2\varepsilon_0. \quad (4)$$

Equations (2) and (3) are also valid for the semicircular channel case.

3. FEM Procedures

A commercial FEM code Abaqus/Explicit was used to perform the numerical simulations. An axisymmetric model was employed, where the geometrical dimensions and mechanical properties of the specimens were identical to those of the experiment, in order to directly compare the simulation results with those obtained experimentally. Axisymmetric four node elements (CAX4R) were employed to model the sections. To accommodate the predetermined large strains during the simulations, adaptive meshing was employed. The arbitrary Lagrangian–Eulerian 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 consider the contact between the die and the specimen. The die and the punch were modeled as analytical rigid parts. The Coulomb friction coefficient was assumed to be 0.05, which is a typical value in cold metal forming. The experimental alloy properties and their values are shown in Table 1. The mechanical properties of the AZ91 alloy shown in Fig. 3 were obtained through a compression test at the TCAP processing temperature of 300°C and at strain rate of $1 \times 10^{-5}$ s$^{-1}$. Temperature changes were ignored according to the slow pressing speed and low strength of the workpiece.

4. Results and Discussion

To compare the equivalent plastic strain levels in the TCAP processed samples using the two channel types (triangular and semicircular), the strains across the cross-section were analyzed. As illustrated in Figs. 4(a) and 4(b), three nodes of N1, N3, and N5 for the triangular type channel and N2, N4, and N6 for the semicircular channel in the TCAP processed sample were examined. Figures 4(c) and 4(d) show the equivalent plastic strain contours corresponding to the two channel types. From this figure, it can be seen that the strain level corresponding to the triangular channel die is higher than that in the semicircular channel. Careful examinations of the head shapes in both channel dies.
demonstrated that the head has a rather symmetric form in the triangular channel, while it is nonsymmetric in semicircular channel as found in the conventional ECAP. This phenomenon can be explained by the number of shear zones and channel angles. The head shape in the semicircular channel, which is similar to route A in the conventional multi-pass ECAP, is in good agreement with Kim’s results as presented in Ref. 13. The head shape in the triangular channel type TCAP processing is similar to the route C result of the conventional parallel ECAP, which is in good agreement with Raab’s results in Ref. 15. The path plots of the equivalent plastic strain through thickness, from inside to outside, for both samples are presented in Fig. 5. The scanning paths are indicated in Figs. 4(c) and 4(d). The strain using the semicircular channel demonstrates uniform strain distribution, although the average strain values are almost identical in both cases.

Figure 6 shows the material flow and deformation geometries during the different stages of the TCAP processing. Figures 6(a) and 6(d) illustrate the deformation geometries in the early stages of the TCAP processing with triangular and semicircular channels, respectively. It can be seen that there is thinning in the tube, which is due to the tensile peripheral strain \([\varepsilon_0 \text{ in eq. (3)}]\) resulting from the increase in the tube diameter.\(^9\) Figure 6(b) shows that the back pressure effect resulting from the shear zone of II can compensate the tube thinning. Also, when the tube passes through shear zone II to III, there is compression peripheral strain which causes an increase in the tube thickness. These explanations are also valid for Figs. 6(e) and 6(f): for the semicircular channel case, the tube thinning is compensated with the back pressure effects resulting from the shear zone V and compression peripheral strain when the tube diameter decreased. From Fig. 6(c), it is clear that the material in the die corner corresponding to shear zone I almost fills the channel, but it does not in shear zone III. This also occurs in the conventional multi-pass ECAP. Kim\(^{13}\) mentioned that this is caused by the back pressure effects resulting from the next shear zones on the initial shear zone. In the die corner corresponding to shear zone III in which there is no consequent shear zone, it can be seen that the die corner filling is incomplete.

The deformation history that developed along the radial direction during the TCAP processing with both the triangular and semicircular channels is depicted in Figs. 7(a) and 7(b), respectively. As can be realized from Fig. 7(a), there are three different zones with sharp changes in the equivalent plastic strain curves while there are two sharp changes in Fig. 7(b). These sharp changes correspond to the shear zones of I, II, and III corresponding to the triangular channel, and IV and V corresponding to the semicircular channel. In these shear zones, the equivalent plastic strain had a sharp change resulting from the intense shear strains.

The difference between the equivalent plastic strain values in the nodes of N1, N3, and N5 increases when the deformation proceeds, while the difference between the curves of Fig. 7(a) is larger than Fig. 7(b). This indicates that the deformation homogeneity in the TCAP processing with a semicircular channel is better than that of the triangular channel, while the mean values equivalent plastic strain for both channels were similar at approximately 2.5 through one pass. The equivalent plastic strain values of 2.15–2.9 and 2.35–2.6 were gained after applying one pass TCAP using the triangular and circular channels, respectively. This is a reasonable variation and may be considered as good strain homogeneity in the triangular channel and very good in the semicircular channel for the SPD processes. The strain homogeneity is superior in comparison with the HPT process\(^{16}\) in which the shear component varies between 2 and 14. Also, the proposed method has good strain homogeneity in comparison with the conventional ECAP, particularly when route A processing is considered\(^{17}\) The
The final sections of the curves in Fig. 6 are constant in all cases. This indicates that the equivalent plastic strain remains constant after passing through the tube from the last shear zone. That is, the TCAP processing leads to superior deformation homogeneity along the length of the tube.

Table 2 shows the calculated equivalent plastic strains calculated using eqs. (1) and (4), and the mean equivalent plastic strain values resulting from the FEM outputs through the one pass TCAP for the triangular and semicircle channels. From this table it can be realized that there are good agreements between the FEM and analytical results in the triangular channel and the semicircular channel, showing approximately 7% and 8% differences, respectively.

Figures 8(a) and 8(b) represent the effective stress contours for both the triangular and semicircular channels. As is well established, analyzing the effective stress contours in the deformation zone may generate some information about the plastic deformation and plastic zones. Inadequate plastic zones indicate the regions where the samples were not subjected to plastic deformation. From Fig. 8 it can be seen that there are fully plastic regions between two consequent shear zones for both channel types. In addition, a split inadequate plastic zone near the outer radius is also observable in the semicircular channel. It is due to the change in stress sign: tensile before the split region and compressive after that region. Continuous stress contours of the plastic zone for both cases demonstrate that the strain homogeneity is achievable.

Figure 9 shows the simulated load versus the ram displacement curves for the TCAP processing with triangular and semicircular channel dies. Generally, load-displacement curves include a valuable piece of information of materials and processing. It was found that the load history curves of the two channel types were different while the processing conditions, e.g. the total amount of deformation, tube material, etc. were the same. This can be attributed to the hardening of the material and a less homogeneous severe deformation due to the back pressure effect.13) This is an important issue to be considered from the process design viewpoint. For the triangular type channel, there are three zones with sharp changes while in the steady state when the tube material passes from shear zone III. These sharp changes are related to the three shear zones that cause the shear deformation in the tube material. As mentioned in the above sections, this sharp change occurred in the equivalent plastic strain curves. In the load curve corresponding to the semicircular channel die, two sharp changes occurred that corresponded to the two shear zones in the inlet and outlet of
the tubular channel. Unlike the load curve for the triangular channel in which there was not a decrease in the load value, there was a descending behavior in the semicircular channel. This may be attributed to the lack of the back pressure effect and decrease in the friction force rather than the triangular channel in which there is an additional shear zone II.

5. Conclusions

In this paper, two different channel types (triangular and semicircular) were considered in the TCAP process suitable for deforming cylindrical tubes. To examine the effects of the channel geometry on the strain distribution and the deformation behavior during the TCAP process, FEM simulations with Abaqus/Explicit code were employed. Also, an analytical model was proposed to calculate the plastic strain value for the TCAP processing with these two channel types. The FEM results demonstrated that equivalent plastic strains of 2.15–2.9 and 2.35–2.6 developed after the application of one pass TCAP corresponding to the triangular and circular channels, respectively. While the mean values of the equivalent plastic strains were almost identical, the strain homogeneity through the thickness of the semicircular channel was better than the triangular and the required load was lower. The strain homogeneity through the length of the processed tube was very good for both channel types. Tube thinning occurred as a result of some tensile peripheral strains in the early stages of the process but it could be compensated by the back pressure effect resulting from the next shear zones and also the compression peripheral strain resulting from the tube diameter decreasing.

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