A New Approach for Achieving Excellent Strain Homogeneity in Tubular Channel Angular Pressing (TCAP) Process

G. Faraji[a,*], F. Reshadi[a], M. Baniasadi[a]

[a] *Department of mechanical Engineering, Faculty of Engineering, University of Tehran, Tehran, Iran.*

ARTICLE INFO

Article history:

Received 28 Dec. 2013
Accepted 11 Jan. 2014
Available online 25 Feb. 2014

Keywords:

Tubular channel angular pressing
Trapezoidal channel geometry
Finite element method
Plastic deformation

ABSTRACT

Tubular channel angular pressing (TCAP) is a recently invented severe plastic deformation technique for producing UFG tubes. Plastic deformation analysis using the finite element method (FEM) was carried out to investigate the effects of trapezoidal channel geometry on strain inhomogeneity index (SII), strain level and required load compared to the previously-used channel geometries. The results showed that SII decreases to 0.003 in the case of trapezoidal channel while it is 0.13 and 0.24 in the cases of semicircular and triangular channel types, respectively. It means that excellent strain homogeneity is achieved in TCAP processing using trapezoidal channel geometry. The required load for the trapezoidal channel was 41% lower than that for the triangular channel but it is almost the same for semicircular channel. From the point of view of better strain homogeneity and requiring lower process load, TCAP processing using trapezoidal channel is an excellent technique for producing UFG tubes.

1. Introduction

Ultra fine grained (UFG) and nanostructured materials exhibit excellent properties such as high strength at ambient temperature and high-speed superplastic deformation at elevated temperatures[1]. Severe plastic deformation (SPD) techniques have become a progressing direction of research in nanoscience and nanotechnology for industrial production of ultra-fine-grained (UFG) metals with enhanced mechanical or functional properties[2]. The commonly used SPD techniques suitable for bulk and sheet materials are equal channel angular pressing (ECAP)[3], high pressure torsion (HPT)[4], and accumulative roll bonding (ARB) [5] as well as other uncommon and recently developed methods[6-12]. Despite the need for high strength tubular components in a wide range of industrial applications, few studies have been undertaken to produce ultrafine grained tubular parts using SPD methods due to lack of appropriate SPD method suitable for deforming tubes. 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 for the first time by the

Corresponding author:
E-mail address: ghfaraji@ut.ac.ir (Ghader Faraji).

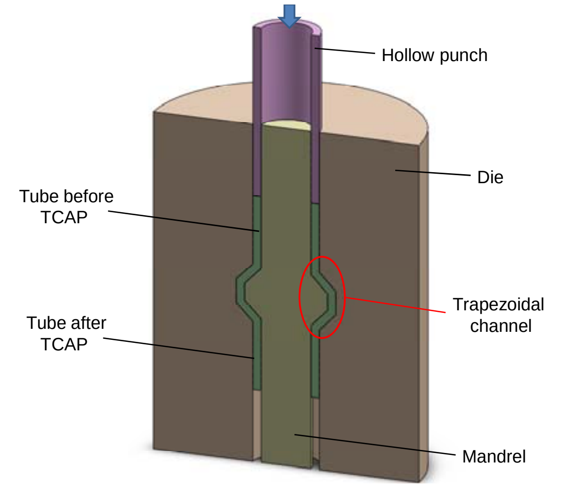

Fig. 1. Schematic of the tubular channel angular pressing (TCAP) using trapezoidal channel

present authors [13,14]. Faraji et al. [13] proposed TCAP process using triangular and semicircular channels which were previously investigated using FEM and experiments.

In the present paper, TCAP process using trapezoidal channel is proposed. The effects of the new designed trapezoidal channel geometry on the deformation behavior are investigated via FEM. Analytical modeling was used to calculate the equivalent plastic strains. As it is shown in Fig 1, in TCAP process the constrained tube between the inner and outer dies is pressed by a hollow cylindrical punch into a tubular angular channel with trapezoidal geometry. To investigate the effects of trapezoidal channel and its advantages compared to triangular and semicircular channels, three channel geometries are considered.

2. Experimental

The accumulated strain ($\bar{\varepsilon}$) resulting from the TCAP processing using trapezoidal channel, was calculated using a model developed by Faraji et al. [14] which was obtained by common engineering plasticity formulas. For the channel geometry shown in Fig 2(a) with four channel angles $\varphi_i = 135^\circ (i = 1-4)$, four shear planes ($S_1 ... S_4$) and curvature angles $\psi_i = 0^\circ (i = 1-4)$, the following equations can be used:

$$\bar{\varepsilon}_T = \sum_{i=1}^{4}\left[\frac{2\cot(\varphi_i/2 + \psi_i/2) + \psi_i \operatorname{cosec}(\varphi_i/2 + \psi_i/2)}{\sqrt{3}}\right] + \frac{4}{\sqrt{3}}\ln\frac{R}{R_0} \qquad [1]$$

In this work all curvature angles were considered to be equal to zero. Hence:

$$\bar{\varepsilon}_T = \sum_{i=1}^{4}\left[\frac{2\cot(\varphi_i/2)}{\sqrt{3}}\right] + \frac{4}{\sqrt{3}}\ln\frac{R}{R_0} \qquad [2]$$

In the cases of triangular and semicircular channel geometries considering zero curvature angles the following equations can be used respectively:

$$\bar{\varepsilon}_T = \sum_{i=1}^{3}\left[\frac{2\cot(\varphi_{it}/2)}{\sqrt{3}}\right] + \frac{4}{\sqrt{3}}\ln\frac{R}{R_0} \qquad [3]$$

$$\bar{\varepsilon}_T = \sum_{i=1}^{2}\left[\frac{2\cot(\varphi_{ic}/2)}{\sqrt{3}}\right] + \frac{4}{\sqrt{3}}\ln\frac{R}{R_0} \qquad [4]$$

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, allowing a direct comparison of 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 (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 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 the ECAP [15] and TCAP processes [16]. 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 ºC and at strain rate of $1\text{x}10^{-5}$ sec^{-1}.

3. Results and Discussion

Figures 4(a-c) show the FE models corresponding

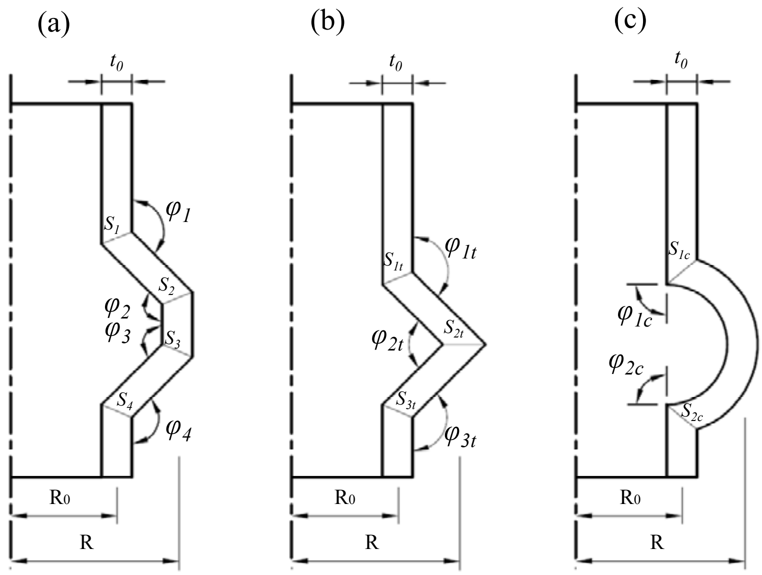

Fig. 2. Processing parameters in the TCAP processing using (a) trapezoidal, (b) triangular and (c) semicircular channel geometries (Curvature angles were considered equal to zero.)

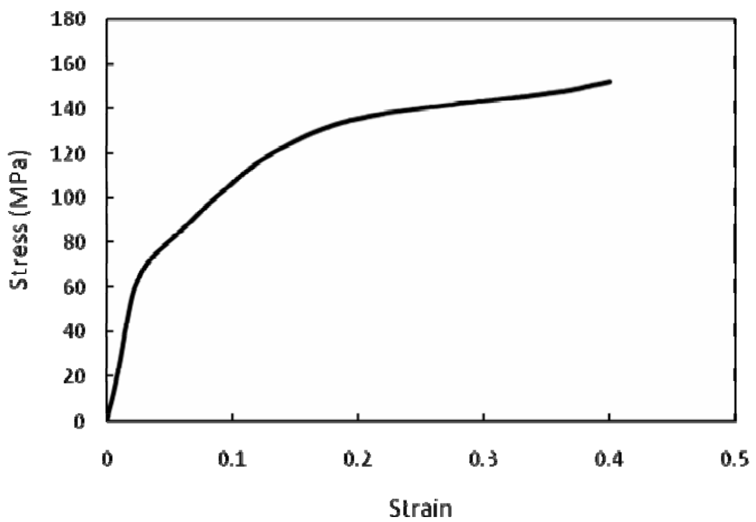

Fig. 3. Stress-strain curve of AZ91 at 300º C [14]

to the trapezoidal channel compared to semicircular and triangular channel types. The path plots of the equivalent plastic strain through thickness, from inside to outside, for all three cases are presented in Fig 5. As can be seen, the strain level in trapezoidal channel case is almost the same as for semicircular channel case. The strain level in triangular case is a bit higher than the other cases. From this figure the best strain homogeneity could be observed for trapezoidal case and the worst one corresponds to triangular case. The strain using the trapezoidal channel demonstrates uniform strain distribution compared to semicircular channel, although the average strain values are almost identical in both cases. The equivalent plastic strain values of 3.04-3.85, 2.48-2.81 and 2.62-2.63 were obtained after applying one pass TCAP using the triangular, semicircular and trapezoidal channels, respectively. This is a reasonable variation and may be considered as very excellent strain homogeneity in the trapezoidal and good in triangular and semicircular channel for the SPD processes. Internal microstructure homogeneity and consequently homogeneity in the hardness

Table 1. Physical properties of AZ91 experimental alloy

Parameter	Value
Young's modulus (E)	41 GPa
Poisson's ration (ν)	0.35
Density (ρ)	1.78 g/cm3

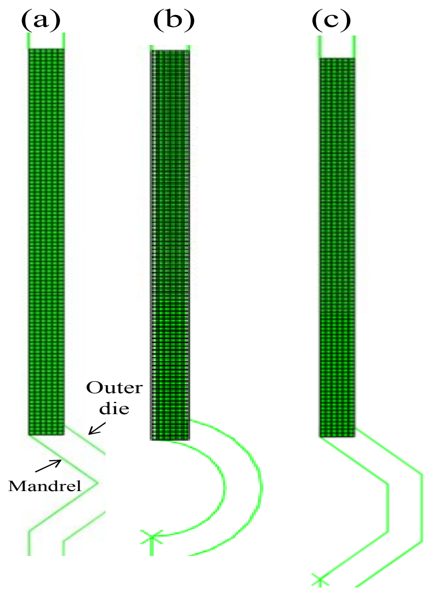

Fig. 4. FEM model and meshed tube cross section in the (a) triangular, (b) semicircular and (c) trapezoidal channels

measurements is greatly affected by homogeneity of induced plastic strains [17-19]. Therefore, strain inhomogeneity index was defined to show the strain inhomogeneity as $SII = (\varepsilon_{Max} - \varepsilon_{Min}) / \varepsilon_{Ave.}$, where ε_{Max}, ε_{Min} and ε_{Ave} indicate maximum, minimum and average equivalent plastic strains, respectively [20]. Strain inhomogeneity indexes (*SII*) through the tube thickness for three channel types and two other SPD methods suitable for cylindrical tubes are shown in Fig 6. The lower the strain inhomogeneity index, the better the strain homogeneity. From this figure TCAP processing using trapezoidal channel leads to excellent strain homogeneity through the tube thickness. The strain inhomogeneity index is about 0.003 in TCAP processing with trapezoid channel geometry, while it is 0.033, 0.13, 0.24 and 1.4 corresponding to PTCAP [21], TCAP with semicircular channel, and TCAP with triangular channel and HPTT [22], respectively. In other words, strain homogeneity in TCAP processing using the trapezoidal channel geometry is approximately eleven times better than PTCAP [21,23], fifty three times better than TCAP processing using semicircular channel, eighty times better than TCAP processing using triangular channel and four hundred sixty times better than HPTT [22]. Having very excellent strain homogeneity is the first advantage of TCAP process using the trapezoidal channel geometry.

Fig 7 shows the simulated load versus the ram displacement curves for the TCAP process with trapezoidal channel geometry compared to triangular and semicircular channels. It was found that the load history curves of the three channel types were different, while the processing conditions, i.e. the total amount of deformation, tube material, etc. were the same. This is an important issue to be considered from the die design viewpoint. From Fig 7 it could be observed that the peak load corresponding to the TCAP process using trapezoidal channel geometry is lower than (approximately 41%) that using triangular channel geometry. The peak loads in both trapezoid and semicircular are almost the same. However, rerquiring lower process load is the second advantage of the TCAP process with trapezoidal channel. So, from the point of view of better strain homogeneity and requiring lower process load which are two main challenges in SPD of materials, the TCAP process using the trapezoidal channel is an excellent technique for producing UFG and nanostructured tubes. An interesting feature in the force history is that all curves approach the same values after the displacement of 30 mm. It may be attributed to the friction force, which is a normal force multiplied by a friction coefficient in the Coulomb friction model [13]. The tube during the TCAP process is divided into two parts, i.e. the regions before and after the last shear zone. The hydrostatic pressure is higher in the regions before the last shear zone than that after the last shear zone. It means that the normal force in the region before the last shear zone is higher, while in the region after the last shear zone it is going to be zero. When the TCAP process proceeds, the tube length

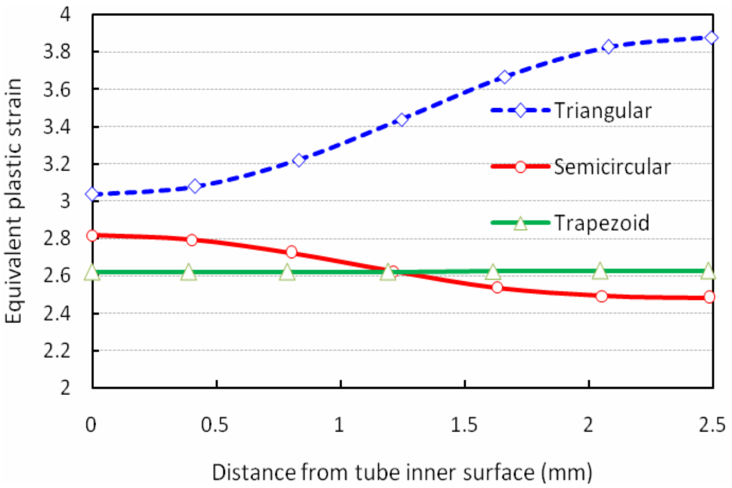

Fig. 5. Path plot of the equivalent plastic strain through the thickness, from inside to outside, for trapezoidal channel compared to other cases (The paths are indicated by arrows in Fig. 4(d-f).)

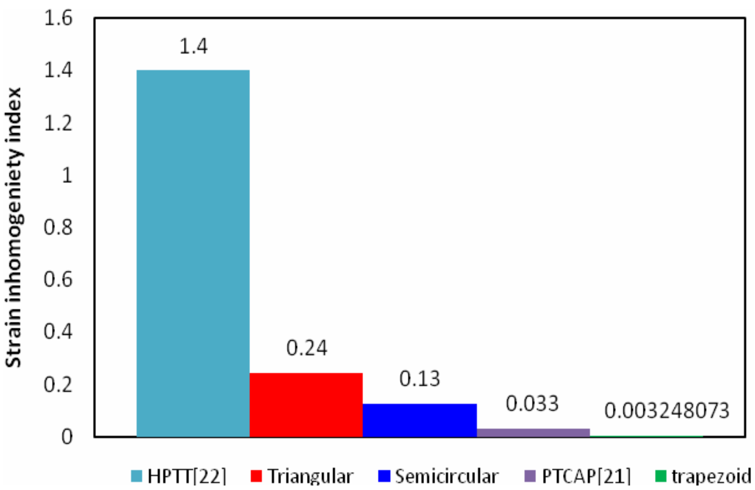

Fig. 6. Strain inhomogeneity index in three channel types compared to other SPD methods

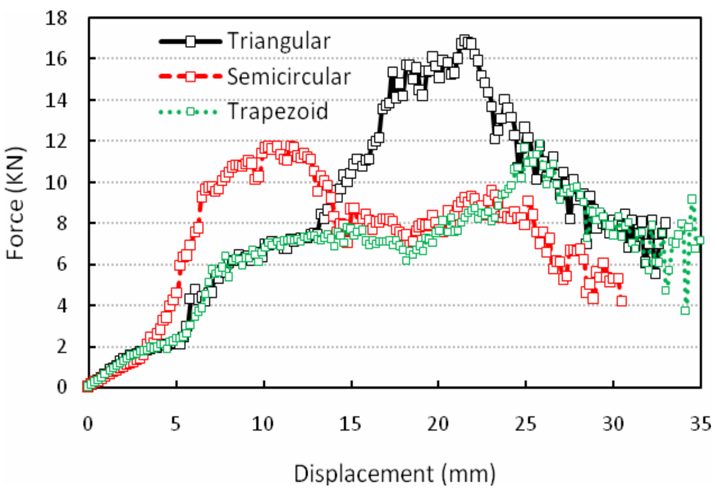

Fig. 7. FE calculated processed load in TCAP processing with trapezoidal channel geometry compared to triangular and semicircular channels

before the last shear zone decreases and the tube length after the last shear zone increases. Therefore, the total force is converged in all cases. Qualified load-displacement curve in TCAP process with trapezoidal channel is shown in Fig 8. It shows that deformation during the TCAP process with trapezoidal channel takes place in five different stages. In stage I, the sample fills the die corner corresponding to the shear zone S_1 by upsetting, which can be observed from the increase of the required load. In stage II, the material fills the die corner corresponding to the shear zone S_2 and the tube passes from this zone. In stage III, the force remains monotonously constant as the ram displacement continues. This region corresponds to the region between the shear planes S_2 and S_3. In stage IV, the load gradually increases to achieve its peak value and only the tube end fills the final shear plane S_4 corner. Elastic recovery takes place in stage V because of which the force lowers gradually as the deformation progresses [15]. Decreasing the force in this stage may also because of friction effects and the above mentioned point that all load displacement curves in Fig 7 are converged to a constant value. After passing the tube material from the last shear plane S_4, the required load remains almost uniformly constant.

Fig 9 shows the material flow and deformation geometries during the different stages of the TCAP process with the trapezoidal channel geometry. Fig 9(b) illustrates the deformation geometries in the early stages of the TCAP process with the trapezoidal channel. It can be seen that there is thinning in the tube head, which is due to the tensile peripheral strain resulting from the increase in the tube diameter. Fig 9(c) shows that the tube thinning remains constant and is not compensated in the region between the shear planes S_2 and S_3 (Fig 2(a)), so that the tube head passes from shear planes S_3. The tube thinning is compensated when passes from shear planes S_3 as a result of peripheral compression strain which is because of decrease in the tube diameter (Fig 9(d) and 9(e)). Also, the back pressure effect resulting from the next shear zones on the initial shear zone could help the tube thinning compensation. This also occurs in the conventional multi-pass ECAP. Kim [24] mentioned that this is caused by the natural back pressure effects resulting from the next shear zones on the initial shear zone. The final shape of the tube shown in Fig 9(f) seems to be the same as the initial shape and dimension. It is an important feature of SPD methods that the final shape and dimension of the processed sample are the same as the initial, which allows the imposing of higher strain.

Table 2 shows the calculated equivalent plastic strains using Eq. (2) and the mean equivalent plastic strains values resulting from the FEM outputs through the one pass TCAP using the trapezoidal channel geometry. From this table it can be realized that there are good agreements between the FEM and analytical results showing approximately 8.3% difference. FE calculated strain is 8.3% lower than that obtained from the analysis. It is due to the corner gap formation shown in Fig 9(f) which causes the increase in the actual curvature angle Ψ_3 and consequently the decrease in the calculated strain (Eq. (1)).

From Fig 9(f) it could be observed that in the die corner corresponding to the shear plane S_4 in which there is no consequent shear plane, the die corner filling is incomplete (shown by a circle mark), while all previous die corners are completely filled.

Fig 10 represents the effective stress contours for the TCAP processed tube with the trapezoidal channel geometry. As it is well established, analyzing the effective stress contours in the deformation zone may generate information about the shear deformation and plastic zones [15]. Inadequate plastic zones indicate the regions where the samples were not subjected to fully plastic deformation. From Fig 10 it can be seen that there are fully plastic regions between the consequent shear zones S_1 and S_2 and also between S_3 and S_4. In addition, an insufficiently fully plastic zone is also observable in the region between the shear zones S_2 and S_3. It is due to the change in the stress sign which is tensile before the shear zone S_2 and compressive after the shear zone S_3.

4. Conclusions

Tubular channel angular pressing (TCAP)

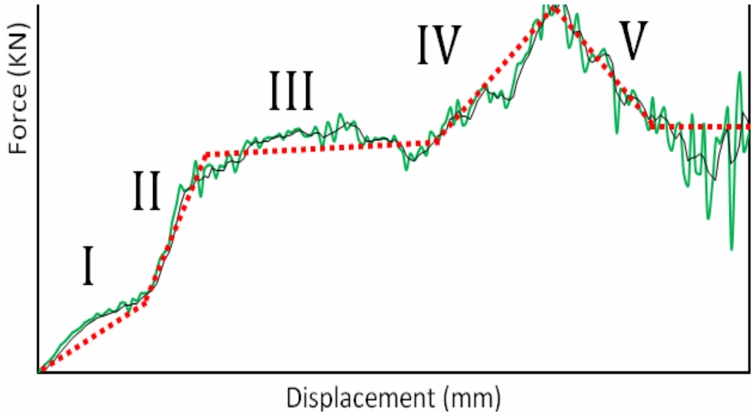

Fig. 8. Load-displacement diagram in the TCAP process with the trapezoidal channel geometry

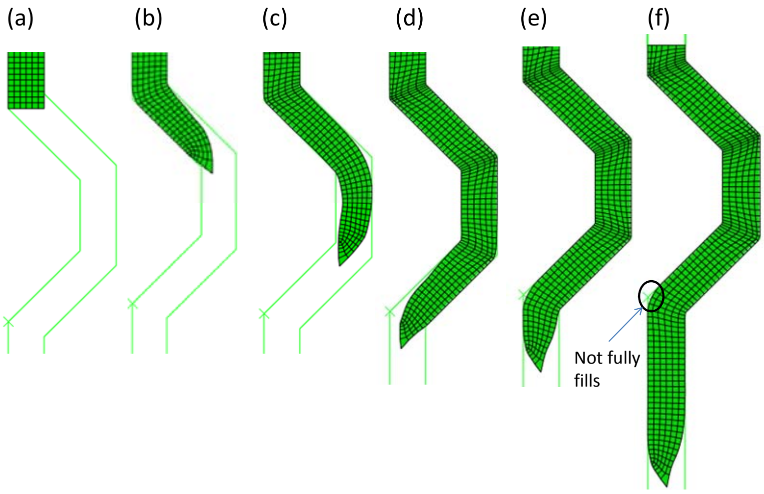

Fig. 9. The material flow and deformation geometries during different stages of the TCAP processing with trapezoidal channel geometry

Table 2. Equivalent plastic strain value resulted from FE and analysis

Parameter	value
Equivalent plastic strain (analysis)	2.84
The mean equivalent plastic strain (FE)	2.62
Difference (%)	8.3%

using trapezoidal channel as a new designed TCAP was proposed. Plastic deformation analysis using finite element method (FEM) was carried out to investigate the effects of trapezoidal channel on strain inhomogeneity index (SII), strain level and the required load compared to the previously used channels (triangular and semicircular). The results showed that SII decreases to 0.003 in the case of trapezoidal channel, while it is 0.13 and 0.24 in the cases of semicircular and triangular channel types, respectively. It means that very excellent strain homogeneity is achieved in the TCAP process using the trapezoidal channel geometry and strain homogeneity is 43 and 80 times better than semicircular and triangular channels, respectively. The required load for the trapezoidal channel was 41% lower than that for the triangular channel but it is almost the same for the semicircular channel. From the

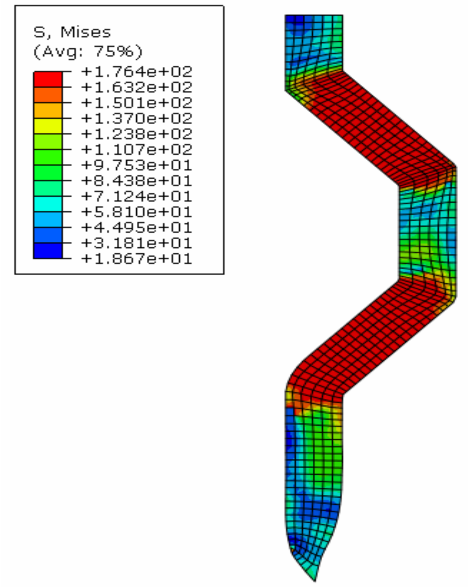

Fig. 10. FEM predictions of the effective stress contour during the TCAP processing with trapezoidal channel geometry

point of view of better strain homogeneity and requiring lower process load which are two important challenges in SPD of materials, the TCAP process using the trapezoidal channel is an excellent technique for producing UFG and nanostructured tubes.

Acknowledgment

The authors would like to acknowledge the financial support of Iran National Science Foundation (INSF) for this research.

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