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Research Article

Investigation of Microstructure and Mechanical Properties of Al-6061 Tubes Processed by Tubular Channel Angular Pressing Process Having Trapezoidal Channel Geometry

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ABSTRACT

The many benefits of ultra-fine grained (UFG) tubes in the industry have led researchers to devise methods to increase the strength of tubes. Tubular channel angular pressing (TCAP) process is a new severe plastic deformation (SPD) technique to produce UFG tubes. In this research, at first, one pass of tubular channel angular pressing process with trapezoidal channel geometry is applied on Al-6061 samples. Then, mechanical properties such as yield strength, ultimate strength, hardness, and microstructure of the TCAPed samples are compared with the initial ones. In addition, effective strain and stress, processed load and deformation geometry during different stages of the tubular channel angular pressing process were investigated by finite element modeling. Finally, the results of the analytical model with finite element simulation were compared. It should be noted that the trapezoidal channel geometry has been used due to the high strain homogeneity and low force required for this channel geometry compared to other channel geometries. The microstructural results showed that the grain size of the initial samples was reduced from 92 µm to 785 nm in the TCAPed samples. The results of compression test showed that the yield strength and ultimate strength of the samples increased by 90% and 52%, respectively. The hardness of processed samples was also increased by 56% compared to the initial ones.

1. Introduction

SPD techniques have been developed to generate UFG materials in recent years [1, 2]. Several techniques exist in this regard, namely equal channel angular pressing (ECAP) [3, 4], accumulative spin-bonding (ASB) [5], equal channel angular rolling (ECAR) [6, 7], high-pressure tube twisting (HPTT) [8], constrained groove pressing (CGP) [9, 10], non-equal-channel angular pressing (NECAP) [11], and cyclic close die forging (CCDF) [12-14] among others. TCAP process, is an appropriate SPD technique for producing UFG tubes that was first proposed by Faraji et al. In the proposed process, triangular channel geometry was used to produce UFG AZ91 tubes at 300°C and they concluded that this process could refine the microstructure of the alloy from 150 µm to 1.5 µm [15]. In another study, Faraji et al. analyzed the triangular and semicircular channel geometry in the TCAP process by finite element method (FEM). They found that in both

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channel geometries, a good strain homogeneity was obtained along the length of the TCAPed sample, and the required force in the semicircular channel geometry was reduced [16]. Mesbah et al. exposed aluminum tubes to TCAP process with triangular channel geometry in three passes. In this study, the microhardness of the TCAPed tubes increased from 32.9 HV to 49.4 HV. Additioanally, by applying the TCAP process, the yield and ultimate strengths of the initial annealed samples increased by 2.5 and 2.28 times, respectively [17]. Reshadi et al. subjected AZ91 tubes at different temperatures and punch speeds under the TCAP process with triangular channel geometry and studied the mechanical properties and microstructure of TCAPed samples. They found that by increasing the punch speed at different temperatures, the yield and ultimate strengths increase significantly. In addition, by applying the process, the average grain size in the initial tubes decreased [18]. Mesbah et al. exposed 1060 pure aluminum tubes to the multi-pass TCAP process with triangular channel geometry and used electron back-scattered diffraction (EBSD) and transmission electron microscopy (TEM) analysis to study the microstructure. The results indicated that the average grain size of the TCAPed tubes decreases with an increase in several passes. Young modulus and hardness also increased by increasing process passes [19]. Since process load and homogeneity of strain are significant parameters in forming processes, it is desirable to use a die geometry that reduces energy consumption by reducing process load and increasing tube strength by rising strain homogeneity. According to research conducted by the finite element method in TCAP process with trapezoidal channel geometry, the process load is much less than the triangular channel geometry and approximately equal to the semicircular channel. Additionally, the strain homogeneity in this channel geometry is higher than the parallel tubular channel angular pressing method and the triangular and semicircular channel geometry [20]. The principle of the TCAP process with trapezoidal channel geometry is shown in Fig. 1(a).

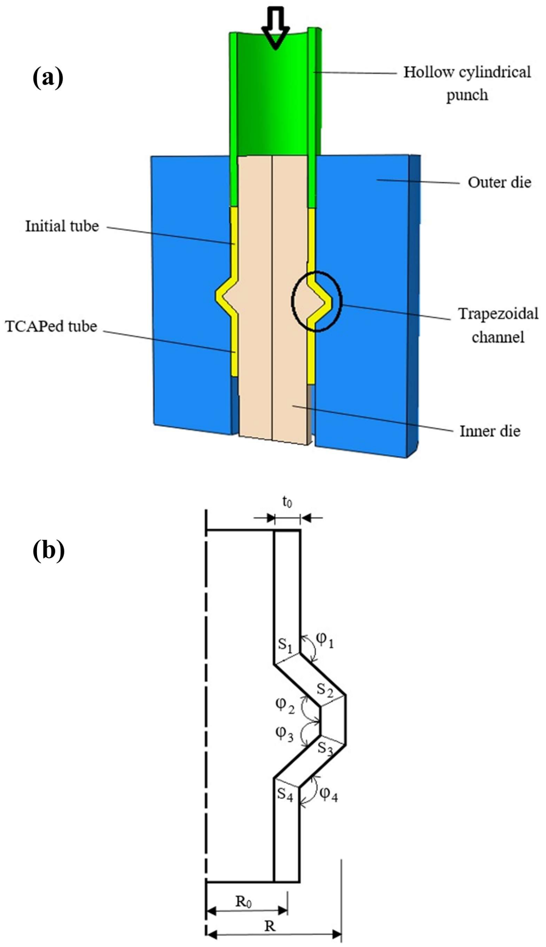

Fig. 1. (a) Schematic of the tubular channel angular pressing (TCAP) with trapezoidal channel, (b) processing parameters.

In this process, a space is provided between the inner and outer die to place the tube and with the pressure from the hollow cylindrical punch on the upper surface of the tube, the material of the tube is compressed in the trapezoidal channel and undergoes severe plastic deformation. At the end of the process, the tube returns to its initial dimensions, which is one of the features of SPD methods. As shown in Fig. 1(b), four shear planes S_1, S_2, S_3 and S_4 are formed in the cross section of the channel. In the TCAP process with this geometry of channel, where the angles of channel and curvature are 135° and 0°, respectively, the effective strain ($\bar{\varepsilon}$) can be obtained as follows [20]:

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

In this research, tube samples made of Al-6061 were first subjected to the TCAP method with trapezoidal channel geometry. It is necessary to mention that this channel geometry has never been used experimentally. After that, mechanical properties of the TCAPed samples were compared with the initial annealed ones. Finally, after experimental studies, FEM simulation of TCAP process and comparison of analytical model with numerical simulation results were studied and analyzed.

2. Experimental and Numerical Procedures

2.1. Materials and procedures

In this research, Al-6061 tubes have been used. Their chemical composition is listed in Table 1. To prepare the samples, tubes with a length of 35 mm, thickness of 2.5 mm and outer diameter of 20 mm were prepared from aluminum ingots. Before the process, all samples were subjected to the annealing heat treatment at 350°C for 2 h. The material of the die was made of hot working steel and treated at 55 HRC. Aiming at easy separation of the tube samples from the die, the outer die was made into a two-piece cone. Table 2 lists the parameters of the die and Fig. 2 shows the die components, aluminum samples and the assembly of the die components and punch. A hydraulic press working at ambient temperature and punch speed of 10 mm/min was utilized. Therefore, the structure of aluminum tubes was ultra-fined. Molybdenum disulfide was also utilized as a lubricant to decrease the friction.

To investigate the microstructure and grain size of initial and TCAPed samples, a Leitz Metallux 3 Stereo Zoom optical microscope based on ASTM E3 and ASTM E112 was used [22, 23]. For this purpose, necessary samples from the center part of tubes were cut. Then, they were hot mounted and ground. After that, the surface of the samples was polished. In addition, Keller's reagent (95 ml H_2O, 2.5 ml HNO_3, 1.5 ml HCl and 1.0 ml HF) was used for etching according to the ASTM E407 standard [24]. After preparing metallographic samples, their microstructure was examined using an optical microscope.

Because the length of the samples was not sufficient to form a ring, standard samples could not be separated from them for compression testing. As a result, the test

Table 1. Chemical composition of Al-6061 samples [21]

Composition	Si	Fe	Cu	Mn	Cr	Mg	Zn	Ti	Al
wt.%	0.40	0.70	0.15	0.15	0.04	0.80	0.25	0.15	Base

Table 2. Die parameters and their values (i in symbols is from 1-4)

Parameter	φ_i	ψ_i	R/R_0	R_0 (mm)	T (mm)
Value	135°	0°	1.5	8.75	2.5

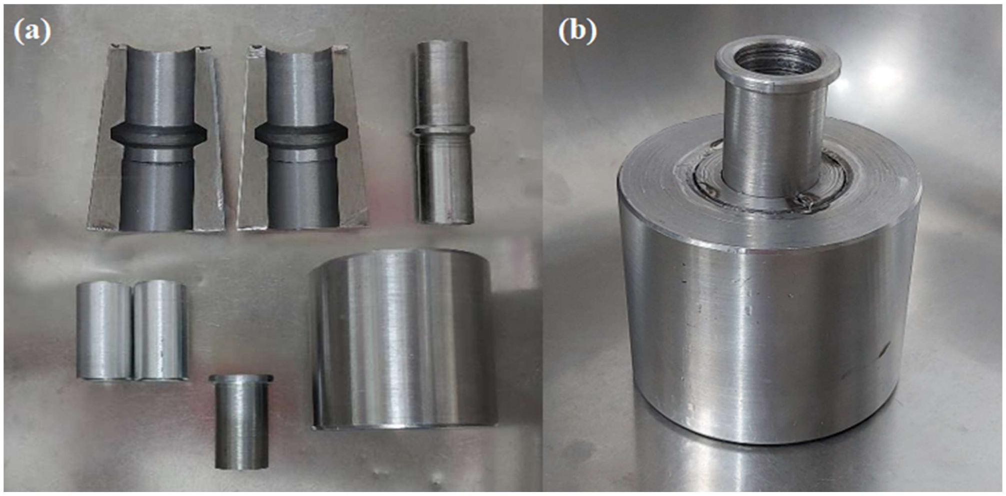

Fig. 2. (a) TCAP die components with trapezoidal channel geometry and initial aluminum samples, (b) assembled of die components and punch.

was performed on samples with the same initial dimensions under a strain rate of 0.001 s^{-1} at room temperature. The prepared samples were subjected to the compression test and their stress-strain diagrams were obtained. Lubricant was also used to reduce the friction. STM-250 compression test machine and powerful STM-Controller software were used to perform this test.

In this test, to prepare the samples, rings with a height of 10 mm were taken out of the central part of the tubes. After mounting, grinding and polishing operations were performed on the samples. According to ASTM E384-05A standard [25], the samples were subjected to Zwick/Roell ZHµ microhardness tester for 10 s under 100 g load. The average hardness was then reported from three points to obtain the final hardness.

2.2. Finite element modeling

ABAQUS software was utilized to simulate the current TCAP method with trapezoidal channel geometry. CAX4R elements were used to mesh the tube. In the loading process, because of axial deformations, a motion constraint was considered for the punch, which was applied in the direction of the vertical axis. In the loading diagram, the axial progress was considered smoothly to bring the results closer to reality. The process time was considered 0.1 s, which is large enough to model a quasi-static process. The tube was modeled deformable and the outer die, mandrel and hollow cylindrical punch were assumed to be rigid. The mandrel and die were fixed by applying a constraint and the advance was applied to the hollow cylindrical punch.

Coulomb friction and penalty method were employed for friction between tube and dies. The friction coefficient, due to the use of MoS_2 lubricant in the process, was assumed to be 0.05 [26]. The size of the elements was considered equal to 0.4 mm after checking the mesh sensitivity change. Due to the large strains and deformations, the method of adaptive meshing or automatic remeshing was used. To reduce the solving time, mass scaling was used, and the proportion of internal and kinetic energy was controlled. The tubes were made of Al-6061. Table 3 shows the elastic properties of Al-6061. The plastic properties were also considered according to the compression test results for the initial annealed sample at room temperature and the constant strain rate.

Table 3. Elastic properties of Al-6061

Parameter	**Density, ρ (kg/m^3)**	**Young's modulus, E (GPa)**	**Poisson's ratio, ν**
Value	2700	68.9	0.33

3. Results and Discussion

3.1. Experimental results

Fig. 3 shows the initial and TCAPed aluminum tube. During the TCAP process with trapezoidal channel geometry, the initial tube increases in diameter and then returns to its initial dimensions and as a result the tube material undergoes severe strains, and the mechanical properties of the tube are improved.

The TCAP process has been effective in reducing the grain size of the initial sample. Applying one pass of TCAP process with trapezoidal channel geometry reduced the microstructure of the initial sample from 92 µm to 785 nm. In a similar study in the TCAP process on 1060 annealed aluminum using TEM micrographs, it has been concluded that the grain size was reduced from 53 µm to 460 nm in the first pass of the process [17]. Therefore, the use of trapezoidal channel geometry in the TCAP process can increase the mechanical properties by reducing the grain size of the samples.

The initial annealed sample has a background with elongated grains. The TCAPed aluminum sample, on the other hand, has a background with equiaxed grains. This

Fig. 3. Initial and TCAPed aluminum tube.

result has also been demonstrated by other researchers in various processes. They concluded that the elongated grains and sub-grains change to the equiaxed grains by increasing the number of passes [17, 27].

The engineering stress-strain diagram of samples before and after annealing heat treatment as well as after the TCAP process is shown in Fig. 4. As can be seen, the annealing heat treatment reduced the strength and increased the relative elongation of the initial aluminum samples. Additionally, the diagram of annealed aluminum sample is very different from the sample undergoing process. It is obvious that by performing the TCAP process on the initial annealed aluminum sample, the amount of stress has increased significantly. After performing one pass of the TCAP process on the initial annealed samples, their yield and ultimate strengths increased. By applying the compression test on the initial annealed sample, according to the annealing heat treatment before the TCAP process, the yield strength, the ultimate strength, and the relative elongation rate were 73.55 MPa, 127.54 MPa, and 28.2%, respectively. After applying one pass of the TCAP process, these parameters changed to 139.42 MPa (89.56% increase), 193.34 MPa (51.59% increase), and 9.52% (66.24% decrease), respectively. This means that applying one pass of the TCAP method increases the strength and decreases the ductility of the initial sample. The results obtained from other SPD processes are similar to the results of this study. The results of the one-pass PTCAP process on 6061 annealed aluminum tubes also showed that the ultimate strength and relative elongation in the processed samples increased by 54% and decreased by 62%, respectively [27].

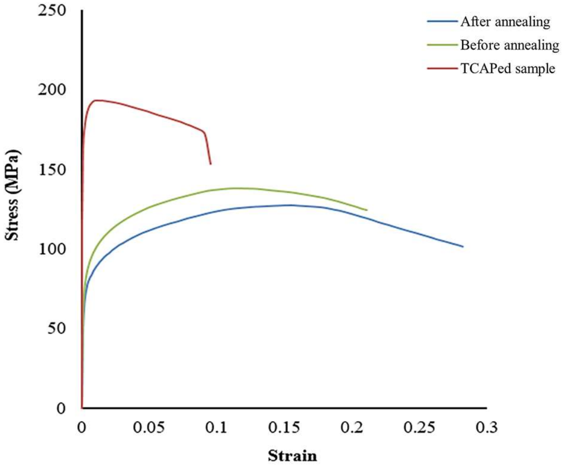

Fig. 4. Engineering stress-strain diagrams for aluminum samples.

Fig. 4 shows that in the annealed aluminum sample, the areas with uniform strain bearing are greater than those with non-uniform strain. By applying the TCAP method, although the values of both uniform and non-uniform strains are reduced, the relative elongation before the necking point is less than after that process. This is due to the instability of premature plastic in the processed samples compared to the initial annealed ones, resulting in faster necking. Premature necking is a result of a decrease in the work hardening rate. The strain rate sensitivity has also increased for the TCAPed tube in the diagram [28, 29].

The increase in strengths can be attributed to the two mechanisms of work hardening and fine graining of the TCAPed samples [30, 31]. Dislocations are formed in the TCAP process or in SPD methods in general by creating cold work on the material. In the method performed, because the sample has undergone severe deformation during the process, the density of dislocations increases. Therefore, their collision with each other and with obstacles increases and more stress is needed to move the dislocations (work hardening mechanism).

The creation of severe strains in the aluminum sample forms the boundaries of the dislocation, and the coarse grains of the initial annealed sample are subdivided into smaller units. As a result, the grain boundaries are drawn closer to each other and a structure with smaller grain size is formed (fine-graining mechanism) [32].

By performing Vickers microhardness test, the hardness of the initial and the TCAPed samples was 59 HV and 92 HV, respectively. As a result, by applying the TCAP process to the initial samples, the hardness has been increased by 55.93% and is in accordance with the results obtained from the strength of the samples. The hardness of the TCAPed samples is significantly increased by the fine graining as well as the accumulation of dislocations in the structure.

3.2. Numerical simulation results

Fig. 5(a) shows the path between nodes N_1 and N_2 along the thickness of the Al-6061 tube in the TCAP using trapezoidal channel. The equivalent plastic strain diagram for the intended path is shown in Fig. 5(b). As it is clear, the equivalent plastic strain values are slightly different from each other and as a result the strain homogeneity has increased along the thickness of the TCAPed tube, which is also true with the results of the TCAP process with triangular channel geometry for AZ91 alloy [15]. By increasing the homogeneity of the strain in the TCAPed aluminum sample, homogeneity in hardness and microstructure is achieved [33-35].

Fig. 6 shows the equivalent plastic strain (PEEQ) and effective stress color contours for the aluminum sample in the TCAP using trapezoidal channel. The effective stress contours in any research can give enough information about the areas under plastic deformation [36]. The red areas have undergone fully plastic deformation. These areas are located between the shear zones S_1 and S_2 as well as S_3 and S_4. There is also an area between the shear zones S_2 and S_3 that has undergone insufficient plastic deformation. The cause of these shear zones can be related to the creation of tensile and compressive stresses before and after the shear zones S_2 and S_3, respectively.

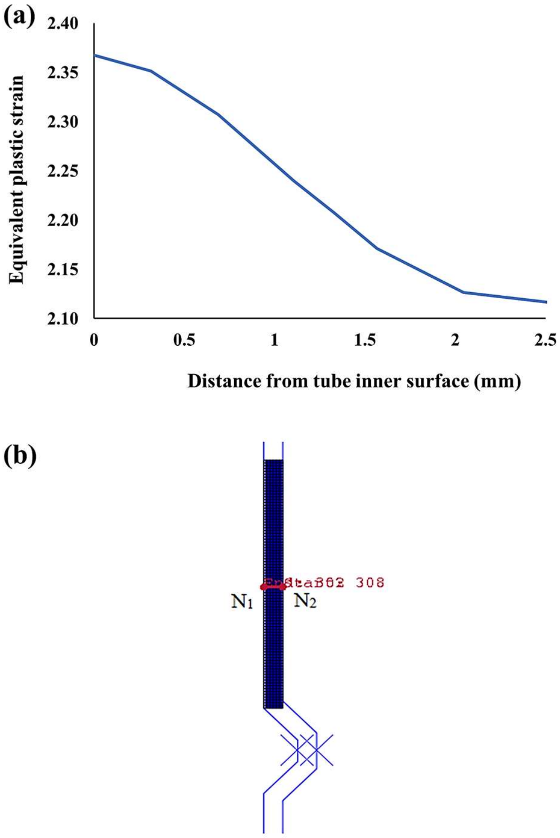

Fig. 5. (a) Selective nodes at the sample cross-section in the finite element model of the trapezoidal channel geometry, (b) equivalent plastic strain along the sample thickness from inner to outer surface.

Fig. 7 shows the diagram of force versus displacement of aluminum tube in the TCAP using trapezoidal channel. Such diagrams can give important information about the materials and how the process is performed [37-40]. As shown in the diagram, step I refers to the part where the tube fills the area of the shear zone S_1 and, as a result, the force is increased. In step II, the tube fills the area of the shear zone S_2 and the force increases once more. In step III, the tube is placed between the shear zones S_2 and S_3 and the force is almost constant. However, the movement of the punch has not stopped. In step IV, the entire tube is passed through the shear zone S_4, and as a result, the force is increased again and reaches its maximum value. Step V deals with elastic recovery and in this step, the force is reduced. This reduction in force is related to the frictional forces and the convergence of the diagram to a constant value. This

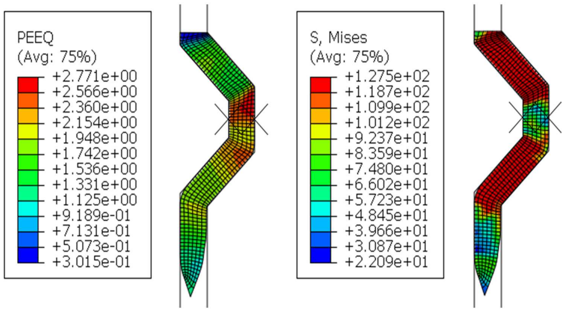

Fig. 6. Finite element results for equivalent plastic strain and effective stress contours during the TCAP process with trapezoidal channel geometry.

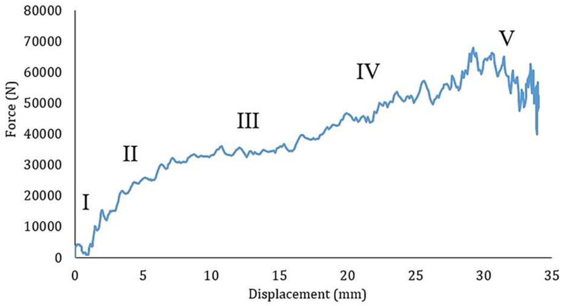

Fig. 7. Force-displacement diagram in TCAP process with trapezoidal channel geometry.

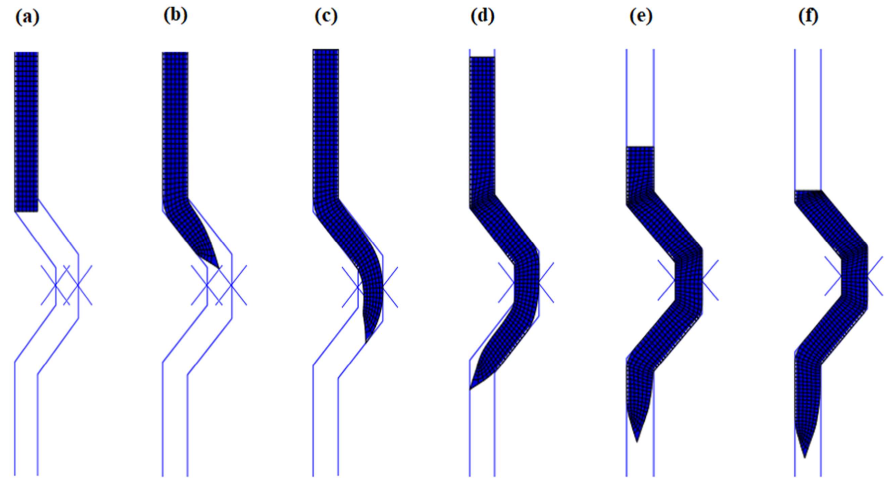

Fig. 8. Different stages of aluminum tube material flow in trapezoidal channel geometry of TCAP process.

convergence can be one of the positive points of this diagram after the 30 mm displacement.

Fig. 8 shows how the tube material flows in the trapezoidal channel geometry in the TCAP process. In Fig. 8(b), a thinning is created at the end of the tube. This thinning is due to the increase in tube diameter and the resulting tensile peripheral strain before the shear plane S_2 at this stage. In Fig. 8(c), this thinning has not yet been compensated and remains constant. It is obvious that this thinning is compensated by the tube diameter reduction and the creation of compressive peripheral strains after the shear plane S_3 that is shown in Figs. 8(d) and 8(e). The effect of back pressure can also be significant in this compensation. This has also occurred in the multi-pass ECAP [41]. In Fig. 8(f), the tube returns to its initial dimensions, which is the reason why the process is SPD.

Comparison of the results between the two methods of FEM and analytical model (Eq. (1)) in the one-pass TCAP process using trapezoidal channel geometry for the equivalent plastic strain parameter is presented in Table 4. The difference between these two methods is calculated at 14.08% and as a result there is a good agreement between them.

Table 4. Equivalent plastic strain obtained from the analytical model and FEM.

Parameter	Value
Equivalent plastic strain (analytical model)	2.84
The mean equivalent plastic strain (FEM)	2.44
Error	14.08%

4. Conclusion

In this research, one SPD technique, namely the TCAP process with trapezoidal channel geometry, was used to produce UFG Al-6061 tubes. After that, mechanical properties and microstructure of samples, as well as FEM simulation of the process and comparison of analytical and numerical model results, were investigated. The results obtained in this paper are as follows:

1. Examination of microstructure obtained from the initial annealed and the TCAPed aluminum tubes using optical microscopy micrographs shows that due to the TCAP process with trapezoidal channel geometry, an effective reduction in grain size of the initial sample has been done and the grain size has been reduced from 92 µm to 785 nm. Additionally, the initial sample has a background with elongated grains and the processed sample has a background with equiaxed grains.
2. The results of compression test showed that the TCAPed aluminum samples are associated with an increase of approximately 90% in yield strength, 52% in ultimate strength and 66% decrease in relative elongation compared to the initial samples.
3. The results of the microhardness test on initial and processed tubes showed that the hardness of the TCAPed samples is associated with a 56% increase compared to the initial ones.
4. An investigation into the effective strain distribution

by finite element method in the TCAP process with trapezoidal channel geometry showed that the strain homogeneity is very good along the thickness of the TCAPed aluminum sample. Strain homogeneity also increases microstructure and hardness homogeneity.

5. The creation of tensile peripheral strains causes the tube thinning in the early stages of the TCAP process and this thinning in the subsequent shear zones is compensated by back pressure and creation of compressive peripheral strains as the result of decrease in tube diameter.
6. The results of the analytical model and the FEM numerical simulation shows a good agreement between them and the difference between these results is obtained at 14.08%.

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Conflict of Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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