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ORIGINAL ARTICLE

An experimental investigation of casing effect on mechanical properties of billet in ECAP process

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Abstract Equal channel angular pressing (ECAP) is one of the most prominent severe plastic deformation (SPD) processes to achieve ultra-fine grained (UFG) structures. Using bimetallic specimens has been recently considered in this process. In the present study, the effects of casing with lower strength, compared to the billet, and the casing thickness on mechanical properties of ECAPed billet are investigated experimentally and by simulation. Bimetallic specimens of pure Cu and Al-7075 alloy with different dimensions are ECAPed in one pass at room temperature. The effect of casing and its thickness on the required forming load, the average amount of equivalent plastic strain and Vickers micro-hardness, and their distributions in cross section of billet, strain homogeneity, compression strength of billets, and stress distribution in the deformation zone are investigated.

Keywords ECAP · Casing · Finite element simulation · Strain distribution · Stress distribution

1 Introduction

Equal channel angular pressing (ECAP) is regarded as one of the most effective severe plastic deformation (SPD) processes in order to obtain the ultra-fine grained (UFG) structures and also to increase the strength of metals and alloys [1, 2]. In ECAP process, the specimen passes through two channels with equal cross sections, which have an intersection in the channel angle of φ and corner angle of ψ [3, 4]. Since the cross section of the specimen remains unchanged after the deformation process, the ECAP process can be used again after rotating of specimen by 90° or 180° in any direction [5]. During the process, very high plastic strain is imposed to the specimen [1]. After the first ECAP pass, a significant increase on the yield and ultimate strength amount of the material is observed and this increase of strength continues in the later passes with a slower rate [6–8]. The applied equivalent strain amount (ε_{eq}) after N passes on the ECAPed specimen, and the frictionless condition is expressed by Eq. (1) [1]:

$$\varepsilon_{eq} = N \Big/ \sqrt{3}\left[2\cot\left(\frac{\varphi+\psi}{2}\right) + \psi\csc\left(\frac{\varphi+\psi}{2}\right)\right] \quad (1)$$

where N, φ, and ψ represent the number of passes, the channel, and corner angles, respectively. The metallic alloy specimens in ECAP process that generally have circular or square cross section can be used in three ways of "solid specimen without casing" [2, 9, 10], "solid specimen with casing" [11–18], and "powders or chips inserted into the casing" [19, 20].

The first research about the ECAP process was conducted by Segal et al. in 1970s and 1980s on the metallic solid specimen [21, 22], and most of the next studies were focused on the pure and alloys metallic specimens without casing [2, 9, 10]. They were generally involved the investigation of mechanical properties such as hardness, static and dynamic strength, and also the micro-structure analysis of different alloys produced by ECAP process. Moreover, many studies have been achieved on the effects of various parameters of the process such as type of material, temperature, channel

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angles, back pressure, pressing velocity, friction condition, and applied strains by experimental, analytical, and numerical methods [2, 23–25]. Using a casing or capsule in ECAP process is a new idea, and it is classified into some categories depending on this fact that the specimen inserted in the casing or capsule is a metallic or non-metallic solid [11–18] or powder or chip [19, 20]. Since the copper has good frictional properties, the primary reason for using a casing in ECAP process was using a copper casing in the pressing process of materials like aluminum that has unfavorable frictional properties [11, 12, 20]. Later studies showed that using a casing or capsule for the billet promotes the deformation uniformity of the billet and may prevent from cracking during the process [16].

Eivani et al. [11] introduced a new method to produce bimetallic rods using ECAP process. By means of an aluminum core and a copper casing, due to the increase of joint shear strength, a better bimetallic joint was gained compared to the conventional extrusion process. In 2011, Zabardast et al. [12] showed that bimetallic Al/Cu rod can be produced by using cold ECAP process. They showed that cold welding strength of copper/aluminum increases by reducing the channel angle and the presence of corner angle reduces the cold weld quality. Djavanroodi et al. [13], in 2012, used a new method called covered tube casing (CCT) to increase the homogeneity and the strain distribution in ECAPed materials. They ECAPed the aluminum billets in copper casings up to four passes. Then, they investigated the strain distribution in the cross section and in longitudinal direction of the billet by using finite element simulation and experimental methods. They showed that one can achieve more homogeneous strain distribution using the casing in ECAP process compared to conventional ECAP. In a similar study, Shaeri et al. [14] investigated the effect of copper casing on the strain distribution and mechanical properties of ECAPed Al-7075 in two experimental and simulation methods. Their research demonstrated that by increasing the casing thickness, the strain homogeneity improved, and also the hardness and strength of the specimens were enhanced. ECAP of tubular specimens was first performed by Djavanroodi et al. [15] in 2013. They produced tubes with higher mechanical properties by inserting flexible polyurethane rubber pad inside the copper tubes with different wall thicknesses and ECAPing them in several passes. Their studies were conducted via experimental and simulation methods and included the investigation of effective strain magnitude, strain and hardness distributions and also the effect of casing thickness. Li et al. [16], in 2014, could use ECAP of the titanium grade 4 up to 8 passes, in 300 °C, by means of titanium billet encapsulated in copper capsules, without using back pressure, and they could significantly improve the tensile strength of titanium. It is noted that encapsulating means inserting billets into a casing or tube which has its both ends closed. In 2014, the effect of ECAP routes on ECAPed copper tubes was studied by Djavanroodi et al. [17]. They ECAPed copper tubes with rubber pads as a mandrel in various routes of A, B_A, B_C, and C up to three passes in 90° channel and experimentally investigated the effect of each route on the distribution and homogeneity of hardness. Djavanroodi et al. [18], in 2015, have presented three different tube ECAP methods. They used three types of materials, i.e., sand, rubber, and greases as the mandrels and then by inserting them into copper tubes and ECAPed these specimens up to three passes in C route and in 90° channel. They investigated the effect of mandrel type on the hardness distribution and maintenance of the ECAPed copper tubes tubularity.

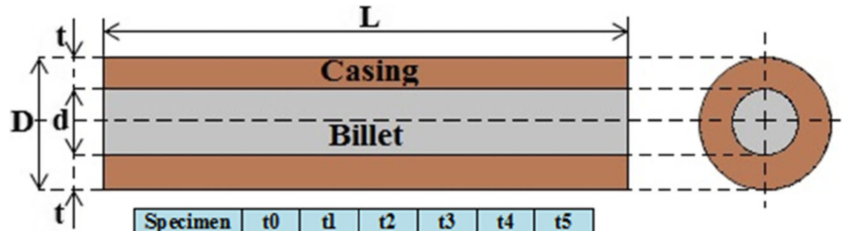
By applying the ECAP process, inhomogeneous strains are imposed on the cross section of specimen. The most inhomogeneity occurs near to the channel and corner angles or near the highest and lowest areas adjacent to the top and bottom surfaces of the billet, respectively [26–28]. By using the suitable ECAP route like B_C, one can increase the deformation homogeneity [17, 28, 29]. It has been shown recently that inserting the billet inside the casing as a specimen in the ECAP process can the increase deformation homogeneity or strain distribution in the billet material. Indeed, using the casing can improve the homogeneity of the mechanical properties of the billet material like hardness. For instance, inhomogeneous strains are applied on the casing at the top and bottom areas of specimen and the core material or billet is deformed homogeneously [13, 14, 16]. However, the effects of casing thickness on the strain-stress distribution, mechanical properties, and also the workability of the core material or billet have not been investigated so far. Making bimetallic rods with high interface strength [11], ultra-fine grain (UFG), and nanocrystalline (NC) homogeneous materials [16] used in aerospace, automotive and biomedical are some industrial applications of the current study.

Table 1 Chemical composition of Al-7075 alloy (%wt)

Al (base)	Zn	Mg	Cu	Fe	Si	Cr	Mn
88.99	5.78	2.73	1.47	0.36	0.34	0.21	0.05

Table 2 Chemical composition of pure copper (%wt)

Cu (base)	Fe	Zn	Cd	Pb	Ag	Si
99.921	0.027	0.024	0.008	0.005	0.003	0.002



Specimen	t0	t1	t2	t3	t4	t5
t (mm)	0	1	2	3	4	5
d (mm)	20	18	16	14	12	10
D (mm)	20					
L (mm)	140					

Fig. 1 Schematic geometry and accurate dimensions of bimetallic specimens

The purpose of the present study is to investigate the effect of casing with lower strength compared to billet and the casing thickness on the most effective parameters in ECAP process by using experimental and finite element simulation methods. In this research, the ECAP forming load, distribution and homogeneity of plastic strain, stress distribution, workability and mechanical properties of billet material are investigated.

2 Materials and experimental procedure

2.1 Materials

In the present study, the commercial pure copper is used as the casing material and Al-7075 alloy is utilized as the core or billet material. The chemical compositions of these two materials, obtained by emission spectrometry method, are shown in Tables 1 and 2.

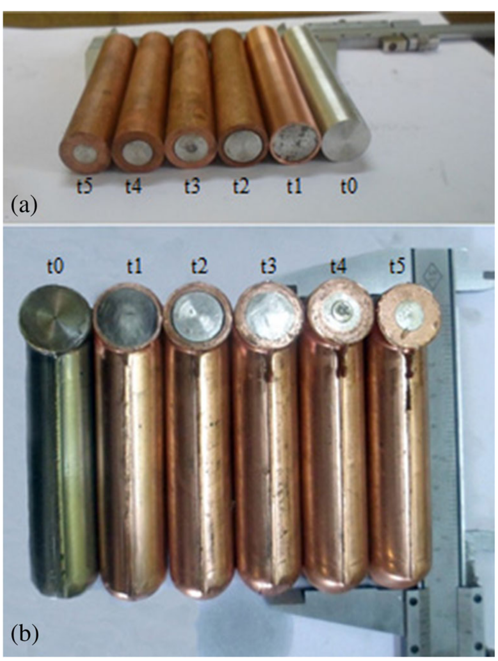


Fig. 2 Bimetallic specimens, **a** before ECAP and **b** after one pass of ECAP in 90° channel

The copper cylindrical tubes are produced with outer diameter (*D*) of about 20 mm, length (*L*) of 140 mm, and different thicknesses (*t*) of 1, 2, 3, 4, and 5 mm as the five types of casings. For billets also, rods with 140 mm length and diameters (*d*) of 20, 18, 16, 14, 12, and 10 mm are used. The workpieces are annealed to gain structural homogeneity. For pure copper and Al-7075 alloy, the workpieces are put in the furnace with temperatures of 600 and 415 °C for 1 h, respectively, and they are cooled in the shutoff furnace. After the annealing heat treatment and to make the ECAP specimens, the billets are inserted into their casings with an interference fit, so that six specimens under the titles of t0, t1, t2, t3, t4, and t5 are obtained. In order to facilitate the naming of each ECAP process performed in each billet, the "t*i*" parameter is used, in which $i = 0, 1, 2, 3, 4, 5$ shows the casing thickness value per millimeters. According to this definition, t0 represents the specimen without casing and t1 to t5 represent the bimetallic specimens with casing wall thickness of 1 to 5 mm, and they also refer to the related ECAP process. In Fig. 1, the geometry and accurate dimensions of bimetallic specimens are shown, schematically. Figure 2a shows the ECAP specimens before the process.

Fig. 3 The used ECAP die with channel diameter of 20 mm and channel angle and corner angle of 90° and 20°, respectively

Fig. 4 Used hydraulic press of 200 t nominal capacity

2.2 ECAP process

ECAP process is performed at room temperature (25 °C), using a hydraulic press and with nominal capacity of 200 t, and at a ram speed of 0.65 mm/s. To perform the ECAP process, a die with circular cross section of 20 mm diameter and channel angle of $\varphi = 90°$ and corner angle of $\psi = 20°$ are used. The used ECAP die and hydraulic press are shown in Figs. 3 and 4, respectively. Through Eq. (1), one can show that by considering the geometrical angles of the die, a strain approximately equal to one is applied to the ECAPed specimen in each pass [13]. To reduce the friction force, MoS_2 lubricant is applied between the specimens and the inner wall of the die channel. All the specimens with different casing thicknesses underwent one pass of forming. Figure 2b shows the bimetallic specimens after one pass of ECAP process.

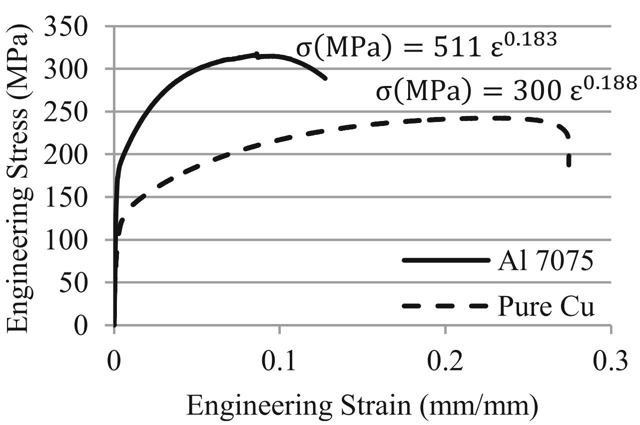


Fig. 5 Engineering stress-strain curve of annealed pure copper and Al-7075 alloy

2.3 Experimental tests

In this study, a variety of tests such as the tensile, compression, and Vickers micro-hardness tests are conducted to investigate the mechanical properties of the specimens. To determine the tensile strength of pure copper and Al-7075 alloy, after annealing heat treatment, the tensile test is used under the standard of ASTM E8-00. A small size and round dumbbell shape specimen with effective diameter of 6 mm is prepared and put under the tensile test by means of universal testing machine of Zwick-Z250 with strain rate of 0.001 s^{-1} [14]. Figure 5 shows the engineering stress-strain curves resulting from tensile test.

To investigate the mechanical properties of one pass ECAPedAl-7075 billets during the processes t0 to t5, the compression test is used under the standard of ASTM E9-89a. Cylindrical samples are made from annealed Al-7075 and also from the middle part of ECAPed billets t0 to t5. The diameter of the samples for the annealed Al-7075 and the specimens of t0 to t5 are 20, 18, 16, 14, 12, 10, and 8 mm, respectively, and the ratio of the height to diameter for all samples is considered as 1.7. It is noted that the direction of the compression samples is in the billet extrude direction. The compression tests are performed by the universal test machine of Zwick-Z250 and with the strain rate of 0.001 s^{-1} [30] by lubricating the contact surfaces by the MoS_2 lubricant. Figure 6 demonstrates the samples of compression test before and after the test.

Vickers micro-hardness test is also conducted to determine the hardness profile in the aluminum billet cross section and in the vertical and horizontal directions. The ECAPed specimens are cut from the middle of the

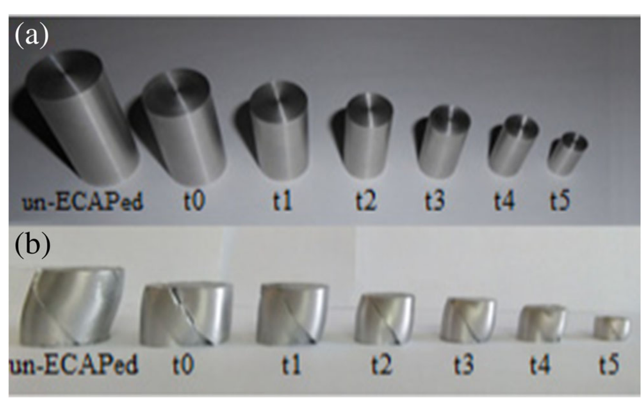


Fig. 6 Compression test samples, **a** before the test and **b** after the test

specimen and perpendicular to the extrude direction or the longitudinal axes. The annealed aluminum cross section and all aluminum billets resulting from the t0 to t5 processes are prepared using the grind papers number 100, 400, 600, 1000, 1200, and 2000 and finally are polished with alumina particles in 0.5 and 0.3 μm sizes manually and automatically, respectively, up to a mirror-like finish. All values of Vickers micro-hardness are calculated by a Buehler micro-hardness tester, under a load of 1 kgf and a dwell time of 10 s. Each micro-hardness value is the mean hardness of 5 points.

3 Finite element simulation

In order to analyze the required force in ECAP process and also to investigate the effective stress and strain distributions in the ECAPed aluminum billets during t0 to t5 processes, the finite element software of Abaqus/CAE 6.12-1 is used. The die and the press ram in the form of analytical rigid elements and of R3D4 (a four-node three-dimensional bilinear rigid quadrilateral) type and the specimens including billets and casings in the form of flexible and of C3D8R (an eight-node linear brick, reduced integration, hourglass control) are modeled according to the presented dimensions in Fig. 1. The channel and corner angles of the die are considered as 90° and 20°, respectively, and the die channel diameter is supposed as 20 mm. Figure 7 represents a view of configuration of the ECAP process components including the die, press ram, billet, and casing in the software interface. Holloman equation ($\sigma = K\varepsilon^n$) inserted in the software is resulted from the power function superimposed on the plastic region of the engineering strain-stress curve. Using the tensile test of the annealed pure copper and Al-7075 alloy, the equations $\sigma(MPa) = 300\ \varepsilon^{0.188}$ and $\sigma(\mathrm{MPa}) = 511\ \varepsilon^{0.183}$ are obtained. Figure 5 expresses the Holloman equation for the annealed pure copper and Al-7075. The friction coefficient of 0.1 [31] and 1 [14] are used between the die-casings and between the billet-casings, respectively. The friction coefficient of 1 means that there is no sliding or movement between the aluminum billet and the copper casing in their interface during the ECAP process [14]. The die is fixed in all degrees of freedom, and the specimen is assembled in the entrance channel. Ram speed is considered as 0.65 mm/s according to the experimental value. In order to reach the correct simulation results, after eliminating the dependency of the results to the billet and casing elements number, the optimum element number is determined. By comparing the resultant force from simulation with those of experimental test for each process of t0 to t5, the simulation results are relied on. The number of elements of ram and die, due to the

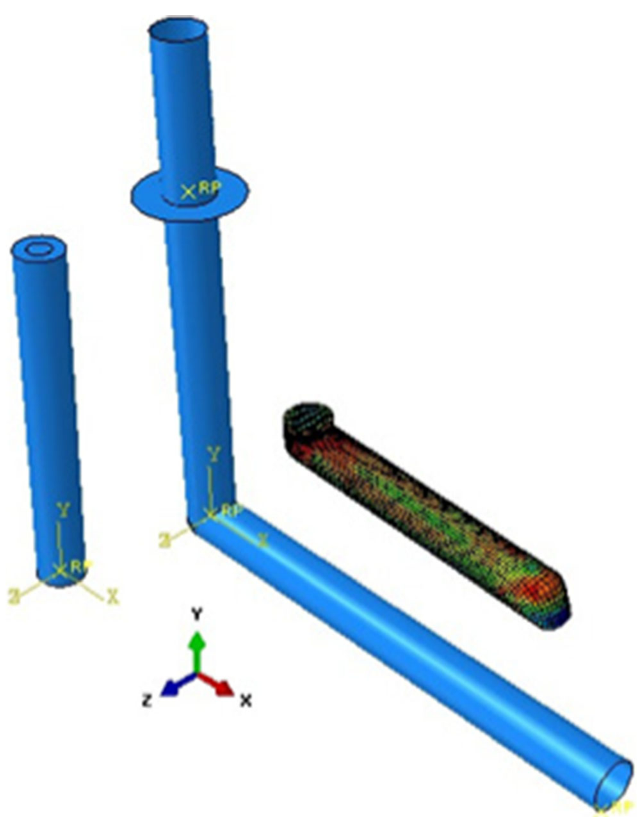


Fig. 7 A view of the composition of the ECAP process components including the die, press ram, billet, and casing in the software interface

Table 3 The number of default elements for ram and die and the optimum elements for billets and casings

	t0	t1	t2	t3	t4	t5
Billet	14,694	12,462	9300	6324	5580	4092
Casing	0	3627	3441	6510	9207	7812
Die	3472					
Ram	50					

Table 4 Comparing the maximum simulation force and the experimental one in t0 to t5 processes

ECAP	Maximum force (kN)	
	Exp.	FEM.
t0	196	201
t1	180	185
t2	152	158
t3	135	141
t4	125	130
t5	112	116

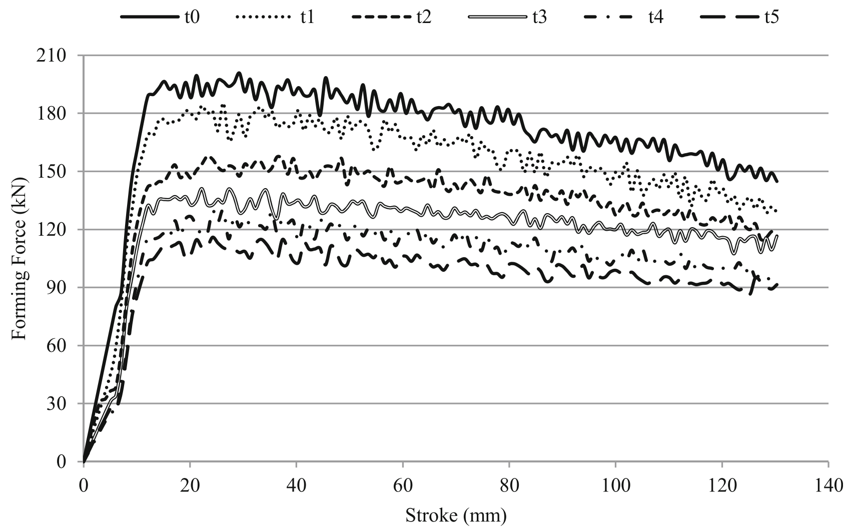


Fig. 8 Comparing the force-displacement diagrams in t0 to t5 processes

rigidity, is used by relying on the software and the default values. The optimum element number in each specimen including billet and casing and also the number of default elements for ram and die are presented in Table 3. The aim of using FE simulation in this study is to analyze the force of the processes t0 to t5, to investigate the stress distribution in the simple shear region in the interface of two channels, and also to study the equivalent plastic strain distribution in the cross-section perpendicular direction toward the extrude direction.

4 Results and discussion

4.1 Load analysis

The force analysis of the processes t0 to t5 are performed using two methods of FE simulation and experimental test, and a good agreement is obtained between the numerical and experimental results. As it is obvious in Table 4, the maximum value of the resultant force of simulation is higher than the experimental ones with a negligible and acceptable error percentage. Figure 8 also shows the load diagrams according to the displacements in t0 to t5 processes. As expected, by increasing the casing thickness, due to the volume increase of the material with lower strength and volume reduction of the material with higher strength which is Al-7075, the forming force decreases [13]. Hence, it can be concluded that by using softer casing, compared to the billet, and choosing higher thickness, the required force for forming reduces significantly. If the billet material like aluminum has unfavorable frictional properties, one can reduce the forming force by using casings made of materials with better frictional properties as copper which can prevent from the harmful effects of friction between the inner wall of the die channel and the specimen [11, 12].

4.2 Strain and hardness distribution

The main reason for the significant increase of the mechanical properties like strength and hardness in the first

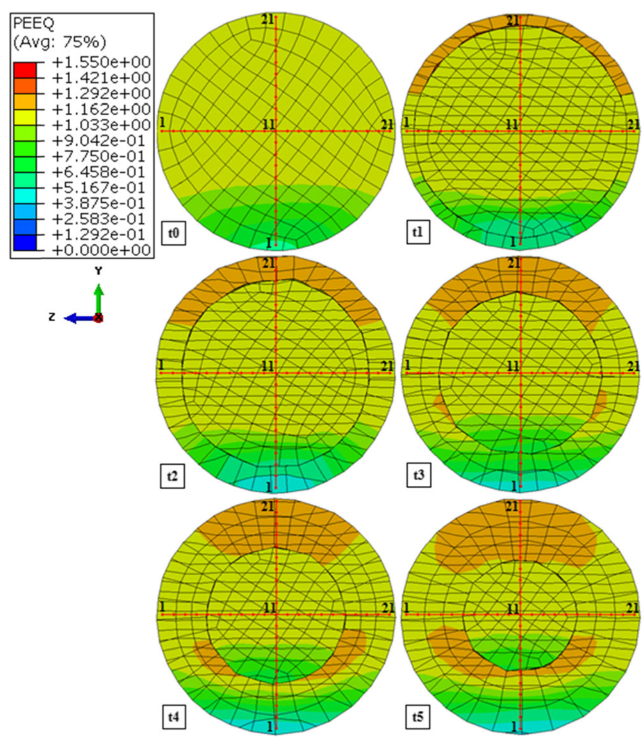


Fig. 9 Equivalent plastic strain distribution in billets cross section of t0 to t5

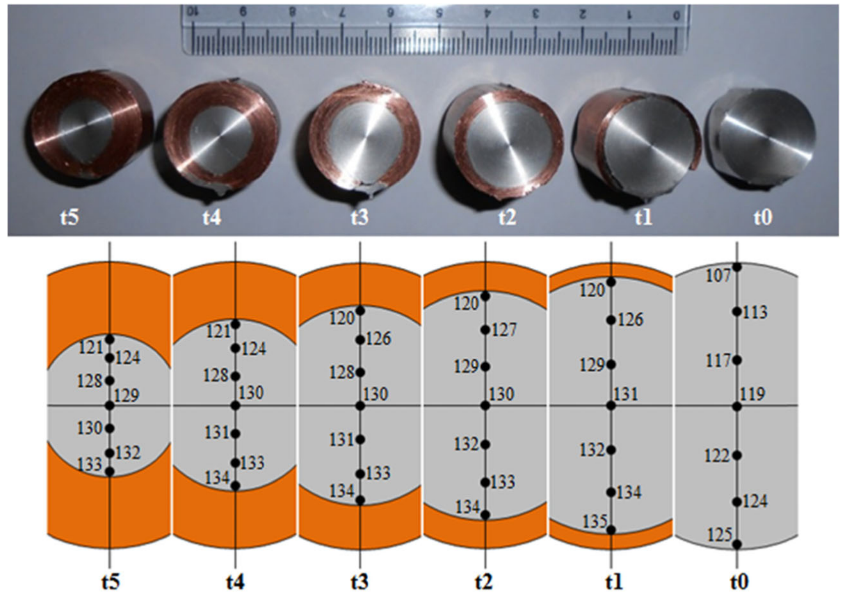


Fig. 10 The prepared samples for micro-hardness test and Vickers micro-hardness values in the vertical direction of the billets t0 to t5

ECAP pass can be attributed to the dislocation rearrangement, formation of dislocations, accumulations, increasing of dislocation density, and fineness of the grains [5, 32]. The other reason for improvement of mechanical properties can also be stated as follows. By increasing the applied high strains, the low-angle grain boundaries (LAGBs) are transformed into the high-angle grain boundaries (HAGBs) through absorption of dislocations. Then, an array of ultra-fine grains separated by high-angle grain boundaries is produced and by increasing the pass numbers the fractions of HAGBs increase [2]. Since the applied strains influence the hardness value [32], investigation of strain distribution in each process of severe plastic deformation like ECAP can help to predict the improvement of mechanical properties such as strength and hardness. Hence, the strain behavior of the billet cross section with different casing thicknesses is investigated in this study. Figure 9 reveals the equivalent plastic strain distribution in billet cross section of t0 to t5. According to the coordinate axes shown in Fig. 7, one can easily find that the cutting plane has a parallel normal vector with *x*-axis or in the direction of the exit channel of the die. The shown cross sections in Fig. 9 are the results of intersection of cutting plane and the deformed specimens such that the plastic strain distribution in the final quarter of the specimen is shown as colorful contour. To determine the strain profile, two vertical and horizontal lines parallel to the *y*- and *z*-axes are drawn in the middle of the cross section and the strain values for 21 determined points are calculated. To investigate the effect of applied plastic strains on the values of hardness in the billet cross section, the specimens t0 to t5 are cut perpendicularly toward the extrusion direction or the exit channel direction. After preparing the surface of cross section, the

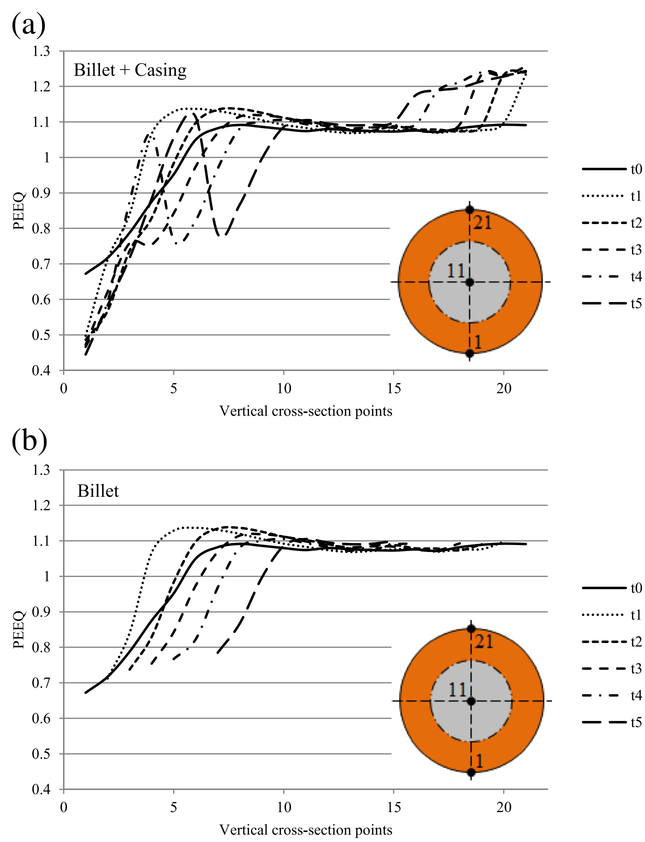


Fig. 11 Plastic strain distribution in vertical direction **a** billet and casing and **b** billet

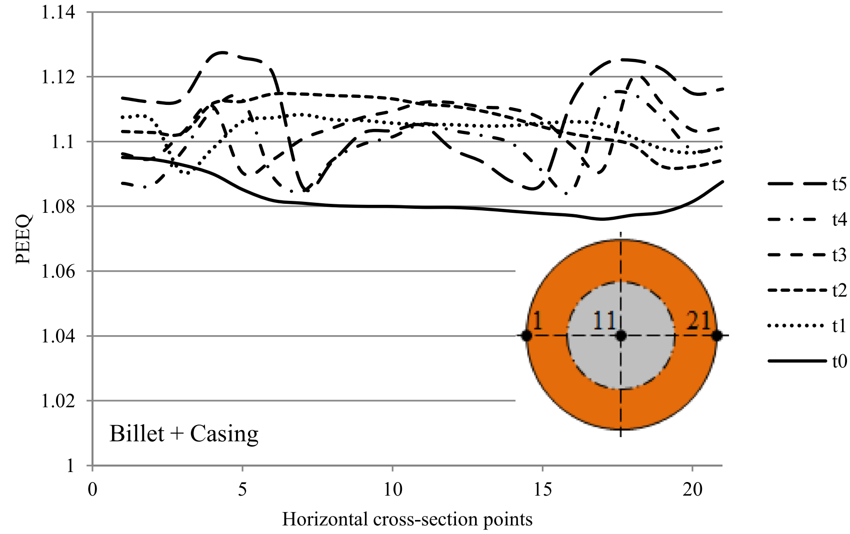


Fig. 12 Plastic strain distribution in horizontal direction in all specimens of t0 to t5

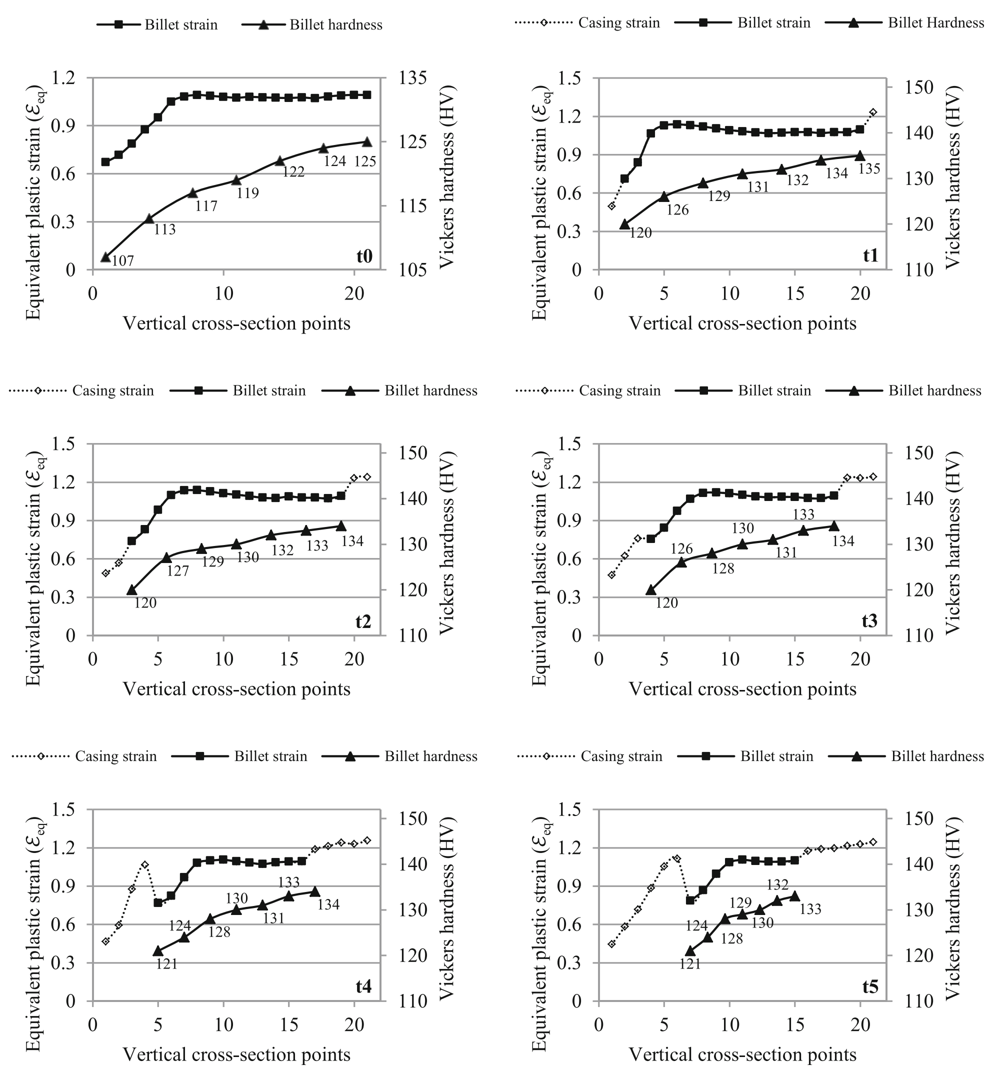


Fig. 13 Strain and hardness distribution in the vertical direction in the billet cross sections t0 to t5

Vickers micro-hardness test is performed in 7 points with equal distance in both horizontal and vertical directions. Figure 10 shows the prepared samples for the micro-hardness test and also the hardness values in the vertical direction. The hardness values in the horizontal direction in each six specimens of t0 to t5 are approximately equal to the hardness value in the center of cross section, and no significant change was observed in the hardness value in the length of the horizontal line in the samples. The yellow uniform distribution of strain in the horizontal line is obvious in Fig. 9.

Figure 11a, b shows the equivalent plastic strain values in the vertical direction for the specimen (billet and casing) and billet, respectively. As it is seen in the interface of casing and billet, there is a strain inhomogeneity and the casing endures higher strains (Fig. 11a). In the billet, however, the strain value increases from the minimum value in the lowest point (close to the corner angle) to the maximum value in the highest point (near to the channel angle) with a certain rate (Fig. 11b). It is noted that the strain in the horizontal direction in all billets of t0 to t5 has no significant change and is similar to the results of Prell et al. [27] and is approximately equal to the strain at the center of the billet. It can be observed that the strain values of t0 in horizontal direction are almost less than those of t1 to t5, and the values are nearly between 1.08 and 1.13. Moreover, there are sudden and significant changes in strain values at the interface of casing and billet, similar to the vertical direction, because of difference between the flow behaviors of billet and casing during the deformation (see Fig. 12).

The strain and hardness distribution in the vertical direction of the billet cross sections t0 to t5 are shown in Fig. 13. As it is obvious, the hardness follows a trend somehow similar to the plastic strain and close to the results of Djavanroodi et al. [13]. There is an ascending trend in billets t0 to t5 from the lowest to the highest points of the cross section. In the strain distribution of all billets from t0 to t5, the strain values from the lowest to the highest point in each billet consist of two ascending and almost constant regions. The ascending region is certainly the main cause of the strain inhomogeneity and consequently the hardness, due to the tangible changes of strain in each point. When casing is used, the ratio of the constant region length to the ascending region significantly increases in the t1 specimen compared to the t0 and this ratio decreases from t1 to t5 (see Fig. 13). Since the constant region has an approximate maximum strain of 1.1, one can expect that by using the casing, the mean strain in the vertical direction in billet t1 increases compared to billet t0 and the mean strain value reduces from

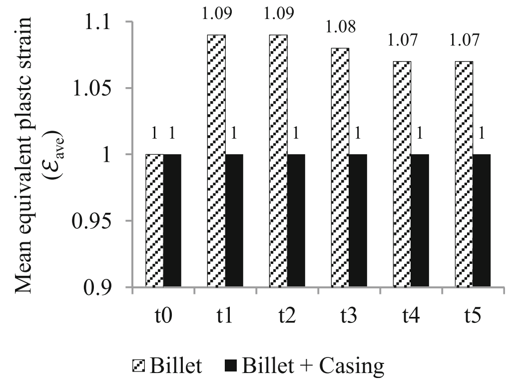


Fig. 14 Mean plastic strain in the vertical direction in the cross section of the specimens

t1 to t5. By measuring the mean strain value in the vertical direction of the billet cross section from t0 to t5, this issue is confirmed. Figure 14 reveals that the mean strain value increases by using a casing in the t1 process compared to the t0, and this value reduces from t1 to t5 slightly. It shows that the mean strain in the first pass increases significantly. The mean strain value in the whole specimen including casing and billet is independent on the casing thickness and is equal to 1. Figure 14 shows the dependency of the applied strain to the channel and corner angles and also to the number of the passes. If the casings have lower strength compared to the billet, then there is more possibility for the billet deformation and flow during the forming which leads to higher mean strains in the billets. In t0 process, the billet has no casing and is deformed in a rigid die; hence, the formed mean strain is lower than those of billets t1 to t5.

As aforementioned, one of the reasons for increasing the hardness is application of high plastic strains which lead to more dislocations and improvement of mechanical properties like hardness and strength. Figure 15 shows the mean hardness value in the vertical direction of billet cross sections t0 to t5. It is observed that in ECAP process on Al-7075, the

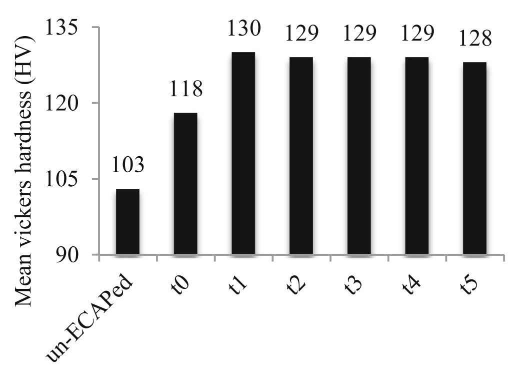


Fig. 15 Mean Vickers micro-hardness in the vertical direction in the cross section of the specimens

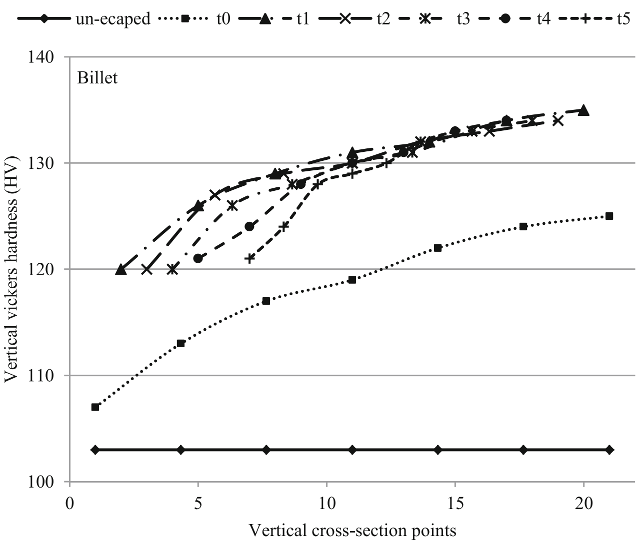


Fig. 16 Vickers micro-hardness profile in the vertical direction in the cross section of the specimens

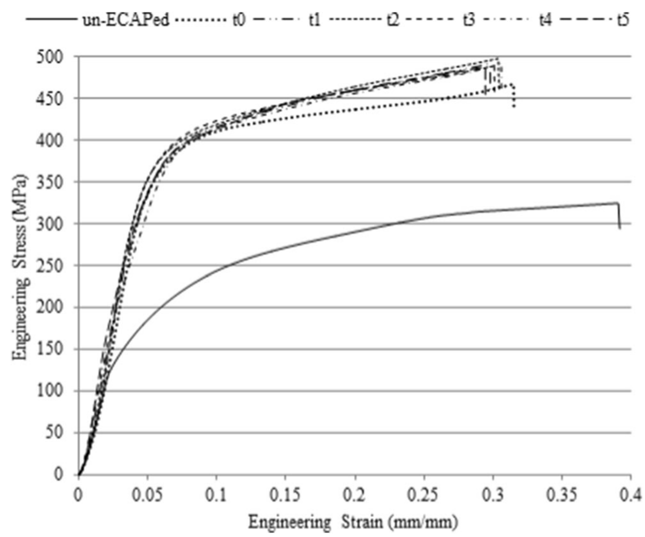


Fig. 18 Engineering stress-strain curve resulting from the compression test of the annealed Al-7075 and billets t0 to t5

hardness increases significantly and the mean hardness of billet t1 is higher than that of the billet t0. By increasing the casing thickness, the mean hardness value reduces slightly from t1 to t5, compared to billet t0. According to the relationship between the plastic strain and hardness, the mean hardness values in Fig. 15 follow a similar trend to the mean strain in Fig. 14. Figure 16 also shows the hardness profile in the vertical direction in annealed Al-7075 and billets t0 to t5, where the tangible increase of hardness in billet with casing compared to one without casing is observed.

One of the important parameters in severe plastic deformation processes is to obtain the homogeneous and high strains [28]. In ECAP process, due to factors such as friction force between the specimen and the die wall, the existence of a dead zone or corner gap high strains with inhomogeneous distribution is applied to the specimen [28, 33–36].

These values increase from the lowest to the highest point of the cross section (Fig. 13). The inhomogeneity index of c_i is used to investigate the homogeneity of the effective strain distribution on the ECAPed specimen cross section [13, 37]. The strain inhomogeneity index is defined as

$$c_i = \frac{\varepsilon_{\max} - \varepsilon_{\min}}{\varepsilon_{\text{ave}}} \qquad (2)$$

where $\varepsilon_{\max}$, $\varepsilon_{\min}$, and ε_{ave} show the effective strain values calculated by the simulation method.

The effect of the casing thickness on the strain homogeneity in the vertical direction of the ECAPed billet

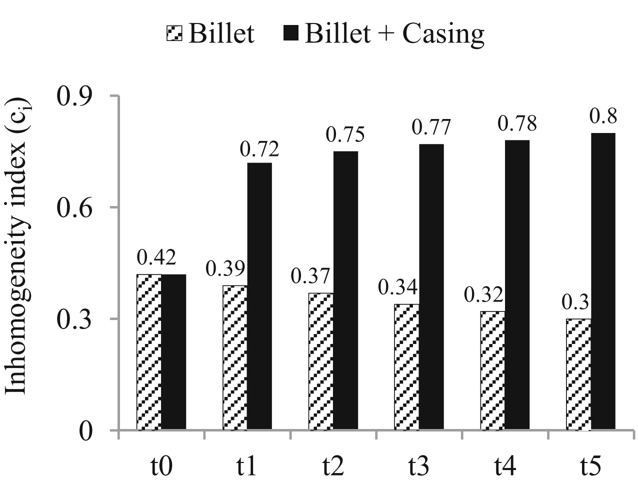


Fig. 17 The effect of casing thickness on the inhomogeneity index in billets t0 to t5

Table 5 Yield strength, ultimate strength, and elongation resulting from the compression test of the annealed Al-7075 and billets t0 to t5

	Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)
Un-ECAPed	116	325	39.3
t0	317	468	31.5
t1	352	492	29.8
t2	347	490	30.4
t3	344	489	30
t4	350	493	30.6
t5	348	488	29.5

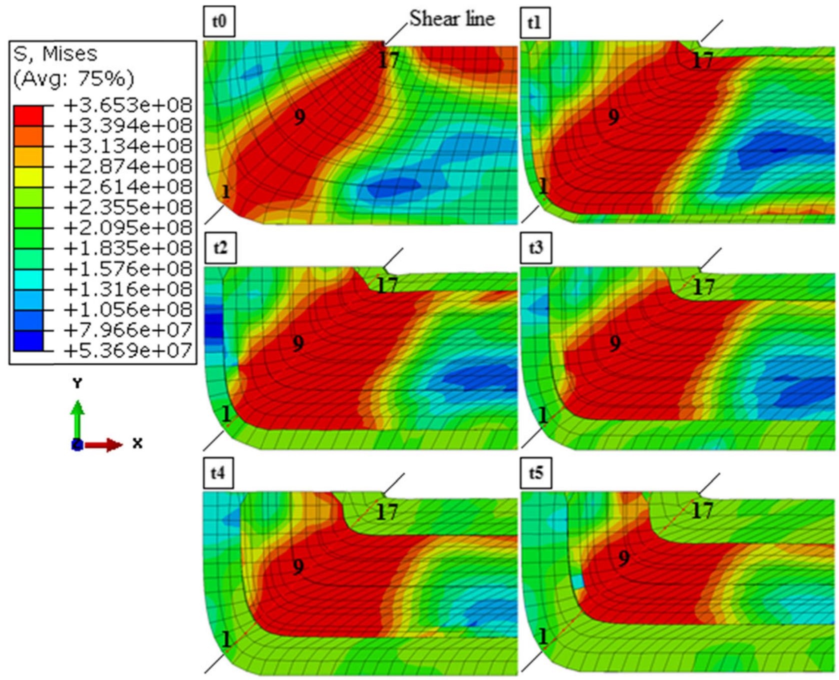


Fig. 19 von Mises stress distribution on specimen in the intersection of two channels and shear line of 45°

cross section is shown in Fig. 17. By increasing the casing thickness, the strain distribution in the billet becomes more homogeneous and its value decreases in the specimen. In fact, the dead zone near to corner angle of the channel (ψ) is filled by the casing; hence, it has no important influence on the billet flow. In addition, use of a copper with good frictional properties reduces the friction force effects on the strain inhomogeneity.

The strain distribution homogeneity of the billet material can be increased by the aid of casing in the ECAP process. Improvement of deformation homogeneity leads to have more uniformity in the mechanical properties of the UFG/NC materials [13, 14, 16]. To produce accurate and high strength tools or parts in biomedical implants and automotive and aerospace applications, the materials have to possess uniformity in the mechanical properties which can be obtained using casing in the ECAP process. Moreover, a comparison between the effects of the casing and the capsule on the mechanical properties and micro-structural evolution of the billet in ECAP process can be considered for the future researches.

4.3 Mechanical properties

Figure 18 shows the engineering stress-strain curve obtained from the compression test of the annealed Al-7075 specimen and the six ECAPed billets t0 to t5. It is seen that during ECAP process, the yield and ultimate strength of all ECAPed billets increase significantly compared to the annealed Al-7075. It is also observable that the compression strengths of the billets t1 to t5 are approximately equal to each other and slightly higher than that of the t0. Moreover, one can find that the billets t1 to t5 have nearly similar elongations, but their values are a little less than that of the t0. Furthermore, a significant increase of strength in billet t0 compared to the annealed Al-7075 and in billets t1 to t5 compared to t0, due to the casing effect, is completely evident (Table 5). The results demonstrate that by using a casing with any thickness, one can produce billets with higher strength that can be attributed to the high strains

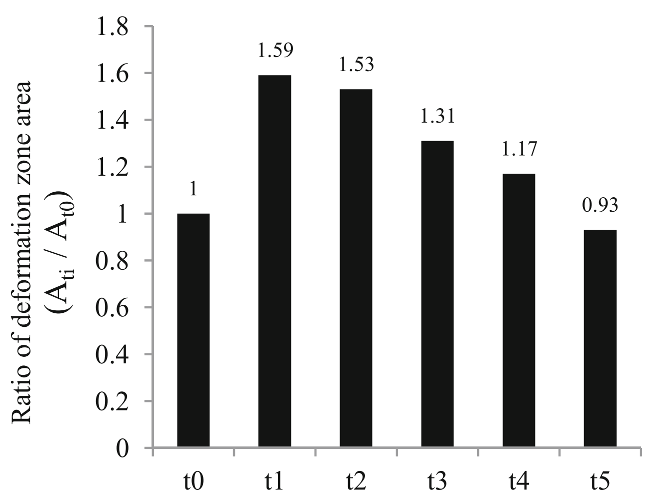


Fig. 20 The ratio of deformation region area of billets t0 to t5 to that of the t0

applied to billets t1 to t5, compared to t0. Applying more strain leads to movement and rearrangement of dislocations and improves the mechanical properties such as strength and hardness.

4.4 Stress distribution

Deformation and strains in ECAP process are caused by applying shear on the specimen in the intersection of two channels which in turn has influence on the effective stresses of the specimen in mentioned region. In dies with channel angle of 90°, this shear stress is applied to the shear region in the form of a 45° angle [5]. To investigate the stress distribution in this region, a cutting *x-y* plane is used. A simple shear line with a 45° angle is drawn in the intersection region using 17 points of equal distance for each specimen from t0 to t5. Figure 19 demonstrates the von Mises stress distribution in the region and the simple shear line for specimens of t0 to t5.

Figure 20 shows that the area (*A*) influenced by the maximum von Mises stress in the intersection region is larger in

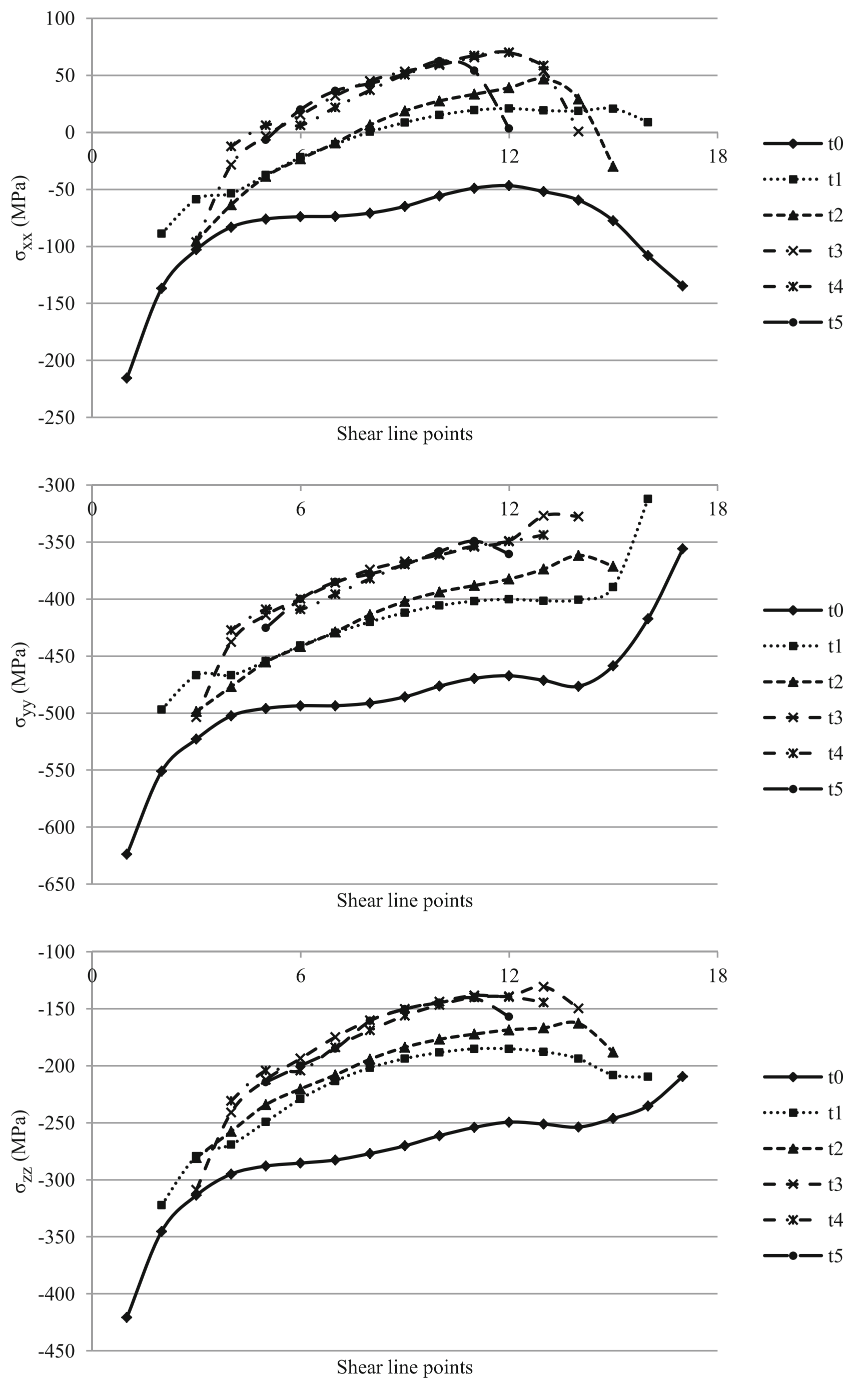


Fig. 21 The normal stress values of σ_{xx}, σ_{yy}, and σ_{zz} in the shear line of billets t0 to t5

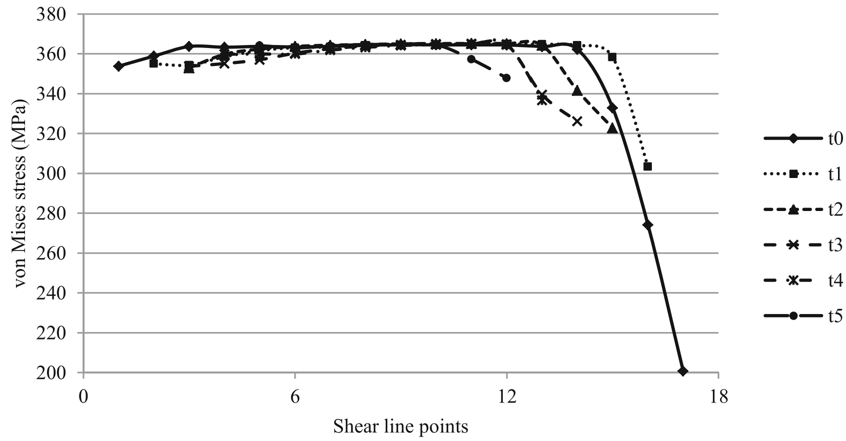


Fig. 22 von Mises stress values in the shear line of billets t0 to t5

billets with casing compared to the billet without that. Using AutoCAD software, the ratio of the area of the maximum stress of the billets t0 to t5 to the billet t0 is calculated (A_{ti}/A_{t0}). The results reveal that when casing is used, larger area is influenced by the higher stress and effective strain. Moreover, by increasing the casing thickness, this area decreases. Generally, the usefulness of the casing effect on the increasing of deformation region volume is always significant and cannot be ignored (Fig. 20).

Figures 21 and 22 show the normal stress values of σ_{xx}, σ_{yy}, σ_{zz}, and von Mises stress in 17 points on the shear line of billets t0 to t5. The results demonstrate that by increasing the casing thickness, the absolute value of the normal stress reduces. However, the von Mises stress values do not change significantly which shows that the casing does not affect the workability of the materials considerably.

5 Conclusions

The following points are the general results of the experimental and simulation analyses of the casing effect of pure copper and its thickness on the mechanical properties and the strain and stress distribution in billet Al-7075 in ECAP process. Generally, use of casing can cause the following:

1. Reduction of the required force for forming
2. Increase of mean strain in the billet. However, by raising the casing thickness, the value of mean strain reduces slightly.
3. Obtaining higher mean hardness in billet, and by increasing the casing thickness, the mean hardness value reduces slightly
4. Improving strain homogeneity in the billet significantly
5. Increasing the compression strength in the billet. However, increasing of the casing thickness does not have significant effect on the strength of the billet.
6. Increasing the area of the deformation region in the intersection of two channels. Moreover, increasing the casing thickness reduces the area of shear region.
7. Reduction of compression normal stress in the shear line of billet. However, it does not affect the workability of the billet significantly.

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References

1. Iwahashi Y, Wang J, Horita Z, Nemoto M, Langdon TG (1996) Principle of equal-channel angular pressing for the processing of ultra-fine grained materials. Scr Mater 35(2):143–146
2. Valiev RZ, Langdon TG (2006) Principles of equal-channel angular pressing as a processing tool for grain refinement. Prog Mater Sci 51(7):881–981
3. Xu C, Langdon TG (2003) Influence of a round corner die on flow homogeneity in ECA pressing. Scr Mater 48(1):1–4
4. Xu C, Langdon TG (2007) The development of hardness homogeneity in aluminum and an aluminum alloy processed by ECAP. J Mater Sci 42(5):1542–1550
5. Nakashima K, Horita Z, Nemoto M, Langdon TG (2000) Development of a multi-pass facility for equal-channel angular pressing to high total strains. Mater Sci Eng A 281(1):82–87
6. Zhao X, Yang X, Liu X, Wang X, Langdon TG (2010) The processing of pure titanium through multiple passes of ECAP at room temperature. Mater Sci Eng A 527(23):6335–6339
7. Zhang Y, Figueiredo RB, Alhajeri SN, Wang JT, Gao N, Langdon TG (2011) Structure and mechanical properties of commercial purity titanium processed by ECAP at room temperature. Mater Sci Eng A 528(25):7708–7714
8. Zhao X, Yang X, Liu X, Wang CT, Huang Y, Langdon TG (2014) Processing of commercial purity titanium by ECAP using a 90 degrees die at room temperature. Mater Sci Eng A 607:482–489
9. Cornwall LR, Hartwig KT, Goforth RE, Semiatin SL (1996) The equal channel angular extrusion process for materials processing. Mater Charact 37(5):295–300

10. Valiev RZ, Islamgaliev RK, Alexandrov IV (2000) Bulk nanostructured materials from severe plastic deformation. Prog Mater Sci 45(2):103–189
11. Eivani AR, Taheri AK (2007) A new method for producing bimetallic rods. Mater Lett 61(19):4110–4113
12. Zebardast M, Taheri AK (2011) The cold welding of copper to aluminum using equal channel angular extrusion (ECAE) process. J Mater Process Technol 211(6):1034–1043
13. Djavanroodi F, Daneshtalab M, Ebrahimi M (2012) A novel technique to increase strain distribution homogeneity for ECAPed materials. Mater Sci Eng A 535:115–121
14. Shaeri MH, Djavanroodi F, Sedighi M, Ahmadi S, Salehi MT, Seyyedein SH (2013) Effect of copper tube casing on strain distribution and mechanical properties of Al-7075 alloy processed by equal channel angular pressing. The Journal of Strain Analysis for Engineering Design 48(8):512–521
15. Djavanroodi F, Zolfaghari AA, Ebrahimi M, Nikbin KM (2013) Equal channel angular pressing of tubular samples. Acta Metallurgica Sinica (English Letters) 26(5):574–580
16. Li Y, Ng HP, Jung HD, Kim HE, Estrin Y (2014) Enhancement of mechanical properties of grade 4 titanium by equal channel angular pressing with billet encapsulation. Mater Lett 114:144–147
17. Djavanroodi F, Zolfaghari AA, Ebrahimi M, Nikbin K (2014) Route effect on equal channel angular pressing of copper tube. Acta Metallurgica Sinica (English Letters) 27(1):95–100
18. Djavanroodi F, Zolfaghari AA, Ebrahimi M (2015) Experimental investigation of three different tube equal channel angular pressing techniques. Kovove Materialy 53:27–34
19. Yapici GG, Karaman I, Luo ZP, Rack H (2003) Microstructure and mechanical properties of severely deformed powder processed Ti–6Al–4V using equal channel angular extrusion. Scr Mater 49(10):1021–1027
20. Pham Q, Jeong YG, Hong SH, Kim HS (2006) Equal channel angular pressing of carbon nanotube reinforced metal matrix nanocomposites. Key Eng Mater 326-328:325–328
21. Segal VM (1977) The method of material preparation for subsequent working. Patent of the USSR 575892
22. Segal VM, Reznikov VI, Drobyshevskii AE, Kopylov VI (1981) Plastic working of metals by simple shear. Russ Metall 1:99–105
23. Djavanroodi F, Ebrahimi M (2010) Effect of die channel angle, friction and back pressure in the equal channel angular pressing using 3D finite element simulation. Mater Sci Eng A 527(4):1230–1235
24. Djavanroodi F, Ahmadian H, Koohkan K, Naseri R (2013) Ultrasonic assisted-ECAP. Ultrasonics 53(6):1089–1096
25. Djavanroodi F, Ahmadian H, Naseri R, Koohkan K, Ebrahimi M (2016) Experimental investigation of ultrasonic assisted equal channel angular pressing process. Archives of Civil and Mechanical Engineering 16(3):249–255
26. Zhao X, Yang X, Jia J, Qi B (2014) The evolution of hardness homogeneity in commercially pure Ti processed by ECAP. Journal of Wuhan University of Technology-Materials Science Edition 29(3):578–584
27. Prell M, Xu C, Langdon TG (2008) The evolution of homogeneity on longitudinal sections during processing by ECAP. Mater Sci Eng A 480(1):449–455
28. Alhajeri SN, Gao N, Langdon TG (2011) Hardness homogeneity on longitudinal and transverse sections of an aluminum alloy processed by ECAP. Mater Sci Eng A 528(10):3833–3840
29. Stolyarov VV, Zhu YT, Alexandrov IV, Lowe TC, Valiev RZ (2001) Influence of ECAP routes on the microstructure and properties of pure Ti. Mater Sci Eng A 299(1):59–67
30. Yu X, Li Y, Wei Q, Guo Y, Suo T, Zhao F (2015) Microstructure and mechanical behavior of ECAP processed AZ31B over a wide range of loading rates under compression and tension. Mech Mater 86:55–70
31. Djavanroodi F, Ebrahimi M (2010) Effect of die parameters and material properties in ECAP with parallel channels. Mater Sci Eng A 527(29):7593–7599
32. Ahmadabadi MN, Shirazi H, Ghasemi-Nanesa H, Nedjad SH, Poorganji B, Furuhara T (2011) Role of severe plastic deformation on the formation of nanograins and nano-sized precipitates in Fe–Ni–Mn steel. Mater Des 32(6):3526–3531
33. Semiatin SL, Delo DP, Shell EB (2000) The effect of material properties and tooling design on deformation and fracture during equal channel angular extrusion. Acta Mater 48(8):1841–1851
34. Prangnell PB, Harris C, Roberts SM (1997) Finite element modelling of equal channel angular extrusion. Scr Mater 37(7):983–989
35. Shan A, Moon IG, Ko HS, Park JW (1999) Direct observation of shear deformation during equal channel angular pressing of pure aluminum. Scr Mater 41(4):353–357
36. Yoon SC, Kim HS (2008) Finite element analysis of the effect of the inner corner angle in equal channel angular pressing. Mater Sci Eng A 490(1):438–444
37. Figueiredo RB, Aguilar MTP, Cetlin PR (2006) Finite element modelling of plastic instability during ECAP processing of flow-softening materials. Mater Sci Eng A 430(1):179–184