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Investigation of the Effect of Die Parameters on the Mechanical Properties of Pure Copper in The Combined Process of Torsional Extrusion and ECAP

S.A. Zamani[a], M. Bakhshi-Jooybari[a,*], H. Gorji[a], S.J. Hosseinipour[b], M. Hoseinzadeh-Amirdehi[c]

[a]Faculty of Mechanical Engineering, Babol Noshirvani University of Technology, Babol, Iran.
[b]Faculty of Materials and Industrial Engineering, Babol Noshirvani University of Technology, Babol, Iran.
[c]Islamic Azad University, Ayatollah Amoli Branch, Amol, Iran.

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Abstract

The production of fine-grained materials by Severe Plastic Deformation (SPD) methods has made these methods more attractive. The basic condition for producing specimens with better mechanical properties and more homogeneous structure is the application of high and uniform plastic strain. Many researchers have tried to modify the existing SPDs or introduce new techniques to achieve these goals. In this research, in order to improve the mechanical properties of the specimens, a new method is introduced, which is the combination of the two processes of torsional extrusion and ECAP. Then, by performing the design of experiments, the optimal die geometric parameters, including the internal angle of the ECAP channel α, the outer angle of the ECAP channel ψ, the length of the torsional region L, the ratio of large diameter to small diameter of the ellipse, m, and the torsional angle of the elliptical section, θ, were obtained 90.5°, 39°, 34mm, 1.65 and 120°, respectively.

1. Introduction

Ultrafine-grained (UFG) metals and alloys that can be manufactured and produced in different ways, could have superior mechanical properties such as high strength, high toughness, and good formability. Furthermore, compared to the same metal with normal grain size, their strength-to-weight ratio is much higher. Generally, polycrystals with the average grain size less than one micrometer could be considered as UFG materials. In recent years, several methods have been the subject of many research activities in the study and improvent of the mechanical properties of the these materials [1].

Based on the Hall-Petch relation, the yield strength of the material is proportional to the inverse of square root of its grain size [2].

$$\tau = \tau_0 + kd^{-1/2} \tag{1}$$

Where τ is the yield strength (GPa), d is the grain size (in nanometer), and τ_0 and k are material constants. In other words, when the grain size decreases, its strength increases. For example, a pure microcrystalline metal has a low yield strength due to the ease of formation and movement of dislocations within the grains. However, if the grain size of the pure metal is reduced to the nanometer or very small scale, the creating and moving mechanisms of dislocations could not

*Corresponding author: M. Bakhshi-Jooybari (Professor)
E-mail address: bakhshi@nit.ac.ir
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be activated in the limited nanometer space, therefore, the yield strength of the material would significantly increase.

During the implementation of the Severe Plastic Deformation (SPD) methods, severe strains are created in the specimen, while at the same time there is no significant change in its overall dimensions, resulting in the production of very fine grains in the specimen. Due to the high strength, good ductility and improved fatigue properties, ultrafine-grained metals and alloys, produced by various of SPD methods, have many applications in the manufacturing of medical equipment such as high-strength prostheses and implants, aerospace industries, military equipment and equipment related to sports, energy, electronics, and telecommunications [3].

Since copper has excellent electrical and thermal conductivity, it has been widely used in the manufacturing of electrical equipment. Because of that, and due to the increasing development of the electronics industry, and the increasing demand for the improvement of efficiency of the relevant equipment, it is necessary to improve its properties. Many researchers have tried to achieve high strength copper by alloying with elements such as beryllium, silver, titanium, and niobium. However, the main problem in these methods is the reduction of electrical conductivity. By further studies, it was found that by using SPD methods, the appropriate strength can be achieved without a significant reduction in the electrical conductivity of the material. Therefore, in this study copper has been selected as the working material.

Different processes have been developed during recent years for the implementation of severe strain, including Equal Channel Angular Pressing (ECAP)[4], High Pressure Torsion (HPT) [5], Accumulative Roll Bonding (ARB) [6], Twist Extrusion (TE) [7], Friction Stir Processing (FSP) [8], and recently Elliptic Cross-Section Equal channel Extrusion (ECSEE) [9].

ECAP is one of the most common processes of severe plastic deformation. According to the results of the previous research works, it can be anticipated that this process can significantly improve the mechanical properties of the specimen at the ambient temperature and its superplasticity and ductility properties at high temperatures. In this process, a specimen that is well-lubricated, is pressed into two intersecting channels, and a simple shear is applied to the specimen at the intersection of the channels. The schematic representation of this process is shown in Fig. 1, where α is the internal angle of the ECAP channel or channel angle, and ψ is the outer angle or the corner angle of the ECAP channel [10].

Kocisko et al. [11] investigated the effect of ECAP die channel angle on the speciemen deformation behavior and effective strain distribution at its cross-section. During their study, the geometry of the die was designed in order to increase the efficiency. Furthermore, in order to reach the maximum uniformity in the created deformation, they performed simulations using the DEFORM® software. For this purpose, the channel angle, outer radius, and inner radius of the die corner were considered as the main parameters, and the mean values of effective plastic strain were calculated. The results of the simulations depicted that by increasing the outer corner angle, the mean effective strain decreases. In addition, by determining the coefficient of strain non-uniformity in the lateral direction of the specimen, it was stated that after two process stages, the strain distribution at the cross-section of the sample became more uniform.

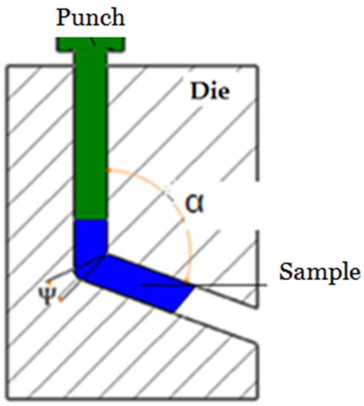


Fig. 1. Schematic of the ECAP process [10].

Bigelzimer et al. [12] by studying the kinematics of the twist extrusion process and comparing it with the ECAP process, found that the deformation mode in this method is pure shear similar to the the ECAP method, but unlike ECAP, it has two shear surfaces, one is vertical and the other is parallel to the direction of the specimen axis. Furthermore, in addition to stretching and combining of metal particles during the twist extrusion process, there is a semi-Eddy flow. According to these characteristics, they concluded that this method can prepare new opportunities for the creation of the microstructured materials and it has been practical and successful for the production of microstructured materials made of aluminum alloys, copper, and titanium.

Heydari et al. [13] numerically investigated the effects of die angle and cross-section of the extruded parts on plastic properties and microstructures of Aluminum 7050 alloy in twist extrusion. The specimens were simulated using dies with the angles of 20, 37, and 56 degrees with square, rounded-rectangular, and elliptical cross-sections. The aspect ratios of rectangular and elliptical cross-sections were also changed while keeping the cross-section area constant in order to investigate the effects of dimensions. Plastic strain distribution, grain size distribution, and the extrusion force were extracted under all conditions. The results indicated that the increase in the die angle significantly reduces the grain size and increases the extrusion force. Removing sharp corners in the cross-section also results in more uniform plastic strain distribution and reduction in extrusion force. Strain distribution is more uniform in specimens with elliptical cross-section and the plastic strain values are high in a larger area of the cross-section which results in a better homogeneity compared to the specimen with rounded rectangular cross-section.

The ECSEE process is another SPD method that was investigated and developed by Wang et al. [14]. This newly-developed method is a combination of twist cutting, extrusion, and upsetting, and does not have the main disadvantage of the conventional TE method, which is its limitation to extrude workpieces with only a rectangular cross-section. Since industrial raw materials have mainly circular cross-sections, the design of the twist extrusion process is probably limited to some specific industrial applications. This method can easily be performed with any standard extrusion equipment in order to cumulate torsional deformation by the purpose of modifying the materials.

The main principles of the ECSEE process are illustrated in Fig. 2. The circular cross-sectional area of the specimen becomes oval in the first region of the die channel, which has the length of L_1. Then, in the second region, with a length of L_2, the specimen is twisted. Finally, in the third region, with a length of L_3, the elliptical cross-sectional area turns into a circular cross-section again. In the torsional deformation of the second region, the elliptical cross-section created by the first region, at an angle θ which is called torsion angle, gradually rotates to the beginning of the third region. A severe plastic deformation occurs without changing the cross-section of the specimen because of the specific shape of the die channel. This feature allows the specimen to be extruded repeatedly in order to accumulate deformation, modify the microstructure, and improve the properties of the specimen.

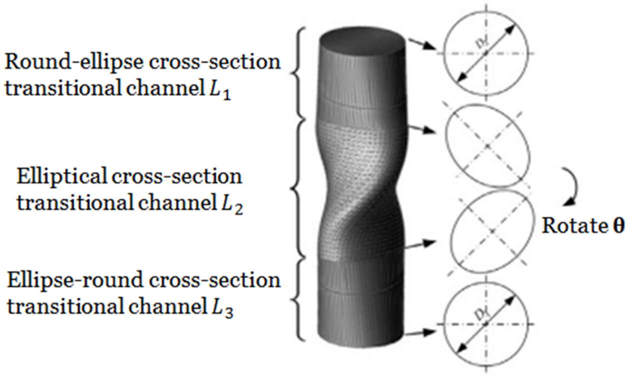


Fig. 2. Schematic diagram ECSEE [14].

For materials with high plastic deformability, the amount of elastic shear strain could be assumed negligible, and the plastic shear is approximately equal to the total deformation. So, the major deformation is in the simple shear state. Since there is no uniform strain state and its value changes by changing the radial position of the considered element of the specimen, the corresponding strain distribution is similarly non-uniform.

Another research was carried out by Wang et al. [15]. They optimized the dimensions of the extrusion die in the equal-channel with the elliptical cross-section. For this purpose, the lengths of the three regions of the extrusion channel, (L_1, L_2, L_3), the torsion angle, θ, and the ratio of large diameter to small diameter in the elliptical region of the channel, m, were considered as the design parameters, and the mean effective strain, ε_{ave}, and the deformation uniformity coefficient, α, which is itself a strain- related factor and can be obtained by the relation $(\varepsilon_{\max} - \varepsilon_{\text{in}})/\varepsilon_{\text{ave}}$, were considered as the optimization indexes. The optimal geometric dimensions of the die were determined using the Grey theory and the ECSEE optimal combination of process parameters were obtained as $\theta = 120°$, $m = 1.55$, $L_1 = 7$ mm, $L_2 = 10$mm, and $L_3 = 10$mm.

Iqbal et al. [16] optimized the die design parameters of TCAP which was developed to overcome the drawbacks of TE, and ECAP processes. They prepared specimens of AA6061 aluminum alloy with the size of $17 \times 27 \times 100$mm, the same as the die channel cross-section. This article focused on identifying the optimum TCAP die geometries for minimum punch load that will yield respectable imposed strain using Finite Element Analysis (FEA). Nine TCAP dies were designed by varying twist slope angle at 35°,45°, and 55°, and channel angle at 90°, 100°, and 110°. Based on the FEA results, among all the combinations, it is found that the die with twist slope angle of 45° and channel angle of 110° gives good strain rate with less punch load. Increasing the twist slope angle reduces the imposed strain, and for the die with the slope angle of 45° the strain distribution is homogeneous. Decreasing the slope angle of the TCAP die increases the punch load.

Since the main goal of all severe plastic deformation methods is the creation of the maximum uniform strain in the specimens and obtaining a finer graded structure, and therefore, a higher strength and hardness, it is necessary for each process to be repeated in some steps, so that by increasing the strain in each step, the desired value could be achieved. On the other hand, the SDP processes have some difficulties and it is very time consuming. Moreover, in proportion to the strain values, the hardness value usually does not have a good uniformity in different cross-sections of the specimens.

This study aimed to first of all introduce a new combined die, using the simultaneous capabilities of both elliptic cross-section, equal-channel extrusion, ECSEE, and ECAP processes in order to be able to reach the higher strength and hardness with better uniformity and with a minimum number of process stage repetitions. Due to the fact that the initial cross-sectional area of the specimen remains constant during the process, it is possible that the specimen can be extruded frequently for the purpose of strain accumulation which is necessary to modify the microstructure and to improve its mechanical properties. Since the geometric dimensions of the die can have significant effect on the mechanical properties of the produced specimen, in the next step, an attempt was made to determine the optimal geometric dimensions to achieve the desired mechanical properties.

2. Experimental Procedure

In this study, in order to perform experiments, four different sets of dies were used (Fig. 3).

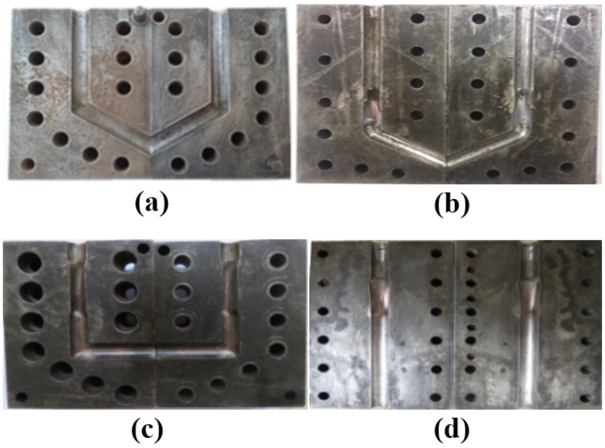


Fig. 3. a) ECAP die, b) First combined die, c) Optimal combined die, d) ECSEE die.

The first three dies are composed of two channels with the same diameter. In the ECAP die the channels are simple and uniform, but in the combined dies, the first channel includes the torsional region to convert the circular cross-sectional area of the specimen to elliptical, and vice versa. The fourth die is a single channel die with a torsional region. After entering, the specimen passes through the spiral channel due to the pressure of the punches, then enters the ECAP channel, and finally exits. Due to limitations, the value of torsion angle θ was assumed to be constant (120°) and four dies were manufactured. Table 1 depicts the geometric specifications of the manufactured dies.

In the table, α is the internal angle of the ECAP channel, ψ is the outer angle of the ECAP channel, L is the length of the torsional region, θ is the torsion angle of the ellipse, and m is the ratio of large diameter to small diameter of the ellipse. According to Fig. 4, when $m = 1$, it means that the cross-section is circular and when the value of m is more, the elliptical cross-section will be more elongated. In order to have a better control on the geometrical parameters, the large diameter was considered as a constant and the changes were made on the small diameter.

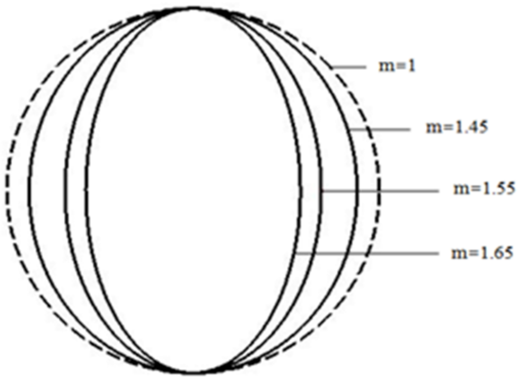


Fig. 4. Effect of changes in the m parameter on the cross-sectional geometry of the specimen.

Due to the dependence of the torsion angle on the radius of the elliptical cross-section, various diameters of the elliptical cross-section were considered in the manufactured dies according to Table 2.

All the dies are made of MO40 and consist of two symmetrical halves that were subjected to heat treatment after machining. In order to relieve the created stress after machining, first of all, the dies were preheated in the initial furnace at a temperature of about 600°C for 3.5 hours. Then, they were placed in a furnace at 860°C for about one hour, and then they were quenched by turbulent oil at about 50°C. After that, in order to perform precipitation hardening, the dies were placed in a furnace at 200°C for one hour and then tempered at 330°C, which eventually reached a hardness of about 55HRC. Then, the polishing process was performed in order to clean the inner surfaces of the dies, which include various channels. In order to properly position the two halves of the dies relative to each other, guide pins were used and both halves were connected to each other by using some screws.

Table 1
Geometric specifications of the manufactured dies.

Parameter	ECAP die	First combined die	Optimal combined die	ECSEE die
m	-	1.55	1.65	1.55
L (mm)	-	10	34	10
θ (Degree)	-	120	120	120
α (Degree)	120	120	90.5	-
ψ (Degree)	15	15	39	-

Table 2
Changes in the diameters of the manufactured dies.

m value	Small diameter
1	18.54
1.45	12.78
1.55	11.96
1.65	11.23
The value of large diameter is constant and equal to 18.54.	

Because of the nature of high forming force in the process, using long punches leads to the buckling of the punch. So, in order to prevent buckling, the round VCN 200 punches were divided into some smaller parts, as shown in Fig. 5.

Fig. 5. The manufactured punch, divided into smaller parts.

Quantometry experiments were performed in order to determine the chemical characteristics of the specimens. The chemical composition of the samples, obtained from quantometry test, is shown in Table 3. The mechanical and physical properties of the material are shown in Table 4. The stress-strain diagram of the specimens that was obtained from the the tensile test is shown in Fig. 6.

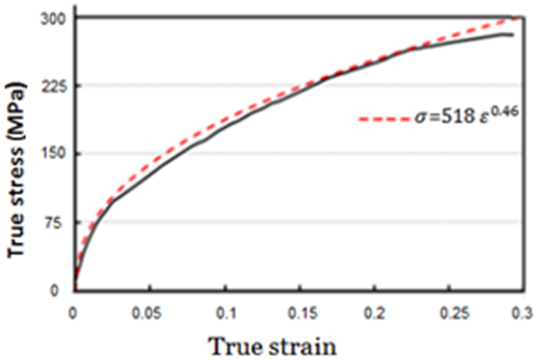


Fig. 6. True stress-strain curve of the annealed pure copper specimen.

Fig. 7 shows the common paths for performing the ECAP process. Among these paths, B_C is the most efficient one for the production of ultra-fine-grain materials. In this study, specimens were formed with this path, in a way that between the repeating steps, the specimens were rotated in a fixed direction by 90 degrees around their central axis [18].

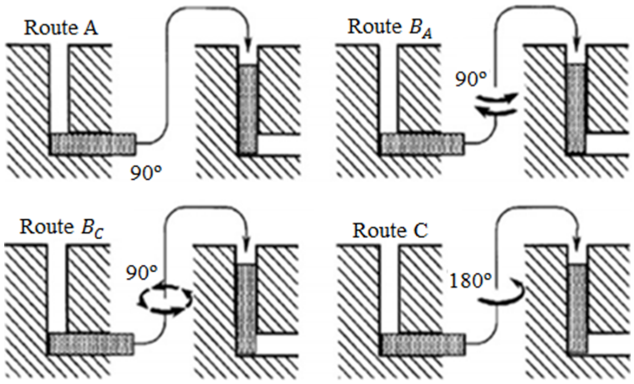
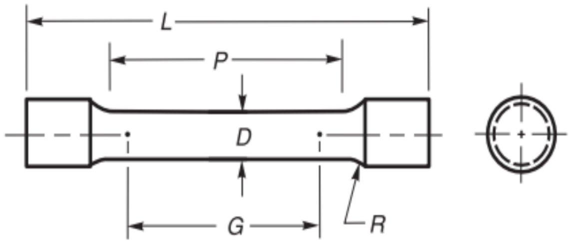


Fig. 7. Images of the four main paths in the ECAP process [18].

In order to compare the mechanical properties of the specimens, tensile and hardness tests were performed. To perform the tensile test, a ZwickRoell machine with a capacity of 10 tons and a displacement speed of 1mm/s was used. Furthermore, the dimensions of the specimens that were prepared for this test are based on ASTM-E8 standard and according to Fig. 8.



L	A	R	D	G
90	54	8	9	45

Fig. 8. Dimensions of the prepared specimen for the tensile test according to ASTM-E8 standard.

Table 3
Chemical composition of the copper specimen (weight percentage).

Mg	Ni	Pb	Zn	Sn	Mn	Cu
0.003	0.030	0.010	0.011	0.002	0.009	Base

Table 4
Mechanical and physical characteristics of the pure copper specimen [17].

Poisson's ratio	Young module (GPa)	Ultimate tensile strength (MPa)	Yield strength (MPa)	Density (kg/m^3)
0.343	128	270	180	8930

The Vickers hardness test was used in order to measure the hardness of the specimens using HVS-1000A Micro-Vickers Hardness Tester device according to ASTM E-384 standard. To perform the test, the amount of test compressive force was equal to 0.2kg and the pause time was 10 seconds.

In order to investigate the amount of hardness changes at different points of the cross-section of the specimens, some lateral cuts were made in each specimen near their exit place from the dies. Then, after cold mounting, the specimens get a fine surface by polishing and sanding. By this way, these specimens were prepared for hardness measurement. The etching solution used for engraving was a mixture of 3g of Iron (III) chloride, 1ml of hydrochloric acid, and 10ml of water.

As it is shown in Fig. 9, Hardness values were measured at various radial distances from the center to the perimeter of each specimen. In order to investigate the hardness distribution at the cross-sectional area of the specimens, the standard deviation in each case was calculated and finally compared to each other.

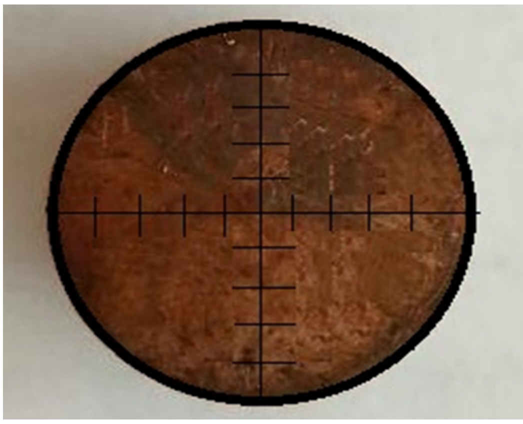


Fig. 9. Designated points for measuring hardness.

A hydraulic press with a capacity of 200 tons was used to apply the required force to perform the process. All processes were performed at a constant press speed of 1mm/s. In order to reduce the friction between the specimen and the die, the specimen was tapered after lubrication with the Teflon tape and the die channels were also lubricated.

3. Finite Element Analysis

In this research, In order to perform simulation, Abaqus/Explicit software 6.14 was used. Due to the elliptical spiral geometry of the die, the specimen and the die were 3D modeled and the workpiece was assumed isotropic. Furthermore, the Coulomb friction equation was used to consider the frictional conditions of the process. By performing simulations, the corresponding forming force vesus stroke curves were determined for different considered friction coefficients and by comparing the obtained curves with that of the experimental tests, the closest result for the coefficient of friction that is equal to 0.1, was selected for the simulations.

In order to make some limitations for the movement of the die, a displacement constraint was assigned to its reference point and a velocity constraint was applied for the punch. Furthermore, in order to create a three-dimensional model, the specimen was modeled using the C3D8I element as a deformable part and the die components were modeled by the R3D4 element as separate rigid parts.

In addition, Incompatible Modes elements were used to eliminate the Hourglass phenomenon in the simulations. For the purpose of determining the most appropriate size of the elements, preventing the increase of computation time, and obtaining accurate results in the simulations, the convergence analysis was performed in the simulation. By this way, by changing the size of the elements, the corresponding amount of forming force was investigated. Finally, it was observed that if the size of each element is equal to 0.7 and its quantity is 10372, there is no significant change in the amount of force and there is just an increase in the time of simulation. Fig. 10 shows an example of a simulated image related to the first combined die.

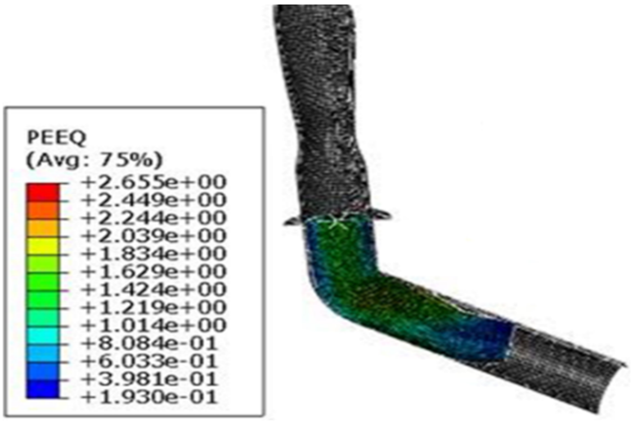


Fig. 10. Simulated strain values in the first combined die.

In order to validate the performed simulations, the results of a sample simulation that had been done for the ECSEE process, with parameters L: 10mm, m: 1.35, and θ: 606°, were compared with the experimental results as shown in Fig. 11. As can be seen, it has the maximum error of nearly 6%. It should be noted that in order to validate the results of the simulation, the maximum forming force required for the first pass of the process in the simulation was compared to that of the experimental test according to Table 5. In order to make a better comparison, the experimental test was repeated three times.

Table 5
Comparison of simulation results and experimental tests results.

	Maximum forming force (kN)	Error %
Simulation	90	-
Experimental test 1	94	4
Experimental test 2	98	9
Experimental test 3	95	5
Average error percentage	-	6

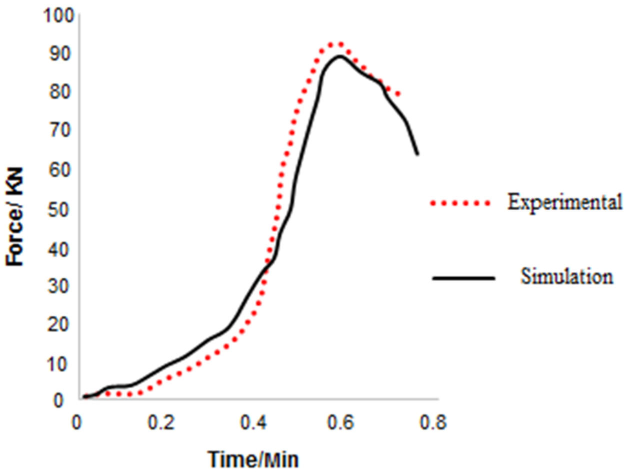


Fig. 11. Validation of finite element simulation with experimental results.

4. Design of Experiments by Using Response Surface Method (RSM)

In general, when it is needed to perform experimental tests for a study with k variables and n levels for each variable, the total number of experiments would be nk, which means that the number increases exponentially. Considering this issue, in the present study with five three-level variables shown in Table 6, it was necessary to perform 243 different experiments that is very difficult to perform. Therefore, Design of Experiments (DOE) method was used to reduce the number of experiments. Proper discretization of the response space and selection of the best and most important test modes to evaluate the process was the main purpose of the design of experiments.

Table 6
Values of test variables at three levels.

Parameter	Level 1	Level 2	Level 3
m	1.45	1.55	1.65
L (mm)	30	32	34
θ (Degree)	60	90	120
α (Degree)	90	105	120
ψ (Degree)	35	37	39

To perform the design of experiments, the Design Expert software was used. According to the number of parameters, the expected accuracy, and other considered parameters, the test matrix, which includes 46 different modes, was designed which can be seen in Table 7. For each of these conditions, the respective simulations were performed separately. Since the main purpose in all severe plastic deformation processes is the creation of higher strain in the specimen by the minimum forming force, the maximum required force for the forming and the strain that is created were determined for each test. Then, by the help of optimization process, the appropriate combination of input parameters that can create the maximum strain in the specimen with the minimum force could be determined.

5. Optimization

Since the main aim of this study is reducing the amount of required forming force and increasing the amount of strain created in the specimen simultaneously, the optimal function theory was used. For this purpose, the allowable range of optimization and the type of their desirability in terms of maximum and minimum were assigned to all parameters and responses. Table 8 shows the range of these parameters. It is necessary to determine the weight and desirability of the parameters in the Design Expert software. Accordingly, the same weight was applied to input parameters and the same desirability was given to output parameters (responses) that are force and strain. After entering the information about the parameters and the responses in terms of weight and desirability in the Design Expert software, all the different states or combinations of the parameters were examined and the more desirable combination was known as the optimal combination. Table 9 shows the desirability percentage and optimal parameters.

Finally, in order to check the accuracy of the answer, a simulation with optimal composition parameters was performed. The results are shown in Table 10. As can be seen, the amount of difference between the results of the experimental design and simulation by the software is negligible and the measurement error is not a considerable amount.

6. Results and Discussion

6.1. Experimental Test

Experimental tests were performed by four ECAP dies with 120° channel angle, first combined die, optimal combined die, and ECSEE die in order to compare the mechanical properties of specimens and the strength and hardness values of the specimens. The obtained results are as follows:

Table 7
Experimental design matrix.

Run	Factor 1 A: m	Factor 2 B: θ	Factor 3 C: L	Factor 4 D: ψ	Factor 5 E: α	Response 1 Force	Response 2 Strain
1	1.55	120.00	32.00	35.00	105.00	522399	1.48702
2	1.55	90.00	32.00	37.00	105.00	393131	1.50753
3	1.55	90.00	32.00	37.00	105.00	393131	1.50753
4	1.55	90.00	32.00	35.00	120.00	318964	1.20872
5	1.55	60.00	32.00	37.00	120.00	322060	1.12416
6	1.45	90.00	32.00	39.00	105.00	292671	1.04678
7	1.55	120.00	30.00	37.00	105.00	366651	1.52123
8	1.45	90.00	30.00	37.00	105.00	302268	1.04326
9	1.55	90.00	32.00	37.00	105.00	393131	1.50753
10	1.55	90.00	30.00	37.00	120.00	315238	1.25633
11	1.55	90.00	34.00	37.00	90.00	442003	1.23445
12	1.55	60.00	34.00	37.00	105.00	303771	1.49023
13	1.55	60.00	32.00	39.00	105.00	527452	1.5508
14	1.65	90.00	30.00	37.00	105.00	458323	1.45937
15	1.65	90.00	32.00	37.00	120.00	381783	1.14764
16	1.55	90.00	34.00	37.00	120.00	317419	1.24614
17	1.65	90.00	32.00	37.00	90.00	381407	1.63253
18	1.65	90.00	34.00	37.00	105.00	447305	1.6321
19	1.55	90.00	32.00	37.00	105.00	393131	1.50753
20	1.55	120.00	32.00	37.00	90.00	337353	1.664
21	1.65	90.00	32.00	35.00	105.00	467829	1.64783
22	1.55	90.00	32.00	39.00	120.00	364185	1.20852
23	1.55	90.00	30.00	35.00	105.00	366092	1.43412
24	1.55	90.00	34.00	35.00	105.00	321184	1.44212
25	1.55	90.00	32.00	35.00	90.00	443153	1.3908
26	1.45	90.00	32.00	37.00	90.00	558396	1.74103
27	1.65	120.00	32.00	37.00	105.00	374314	1.72764
28	1.55	60.00	30.00	37.00	105.00	341818	1.48906
29	1.55	90.00	32.00	37.00	105.00	393131	1.50753
30	1.45	90.00	34.00	37.00	105.00	295582	1.05713
31	1.55	120.00	32.00	39.00	105.00	427660	1.51017
32	1.55	90.00	34.00	39.00	105.00	384976	1.73037
33	1.55	60.00	32.00	37.00	90.00	434752	1.86479
34	1.65	90.00	32.00	39.00	105.00	444568	1.46712
35	1.55	90.00	32.00	37.00	105.00	393131	1.50753
36	1.55	60.00	32.00	35.00	105.00	448593	1.48821
37	1.45	90.00	32.00	37.00	120.00	272605	0.847496
38	1.45	90.00	32.00	35.00	105.00	292905	1.05598
39	1.55	90.00	32.00	39.00	90.00	403192	1.55809
40	1.55	120.00	34.00	37.00	105.00	409596	1.5924
41	1.55	120.00	32.00	37.00	120.00	395582	1.14543
42	1.45	120.00	32.00	37.00	105.00	314366	1.18172
43	1.45	60.00	32.00	37.00	105.00	330799	1.175
44	1.55	90.00	30.00	39.00	105.00	378360	1.41915
45	1.65	60.00	32.00	37.00	105.00	458965	1.72798
46	1.55	90.00	30.00	37.00	90.00	526419	1.83111

6.1.1. Strength

Fig. 12 shows the graphs related to the amount of change in the strength values of the specimens by changing the type of die. Numerical values of the yield strength and the ultimate tensile strength of specimens are shown in Table 11.

Table 8
Ranges and weights assigned to process parameters and responses for the optimization purpose.

	Goal	Lower limit	Upper limit	Importance
L	Is in range	30	34	-
m	Is in range	1.45	1.65	-
α	Is in range	90	120	-
ψ	Is in range	35	39	-
θ	Is in range	60	120	-
Strain	Is maximum	0.847496	1.74103	5
Force	Is minimum	295582	526419	5

Table 9
Optimal composition parameters obtained from Design Expert software.

L	m	α	ψ	θ	Force	Strain	Desirability
34	1.65	90.52	39	120	1.63315	286079	0.8956

Table 10
Comparison of the obtained results from Design Expert software and simulation.

Response	RSM-DA	Simulation	Error
Force	286079	295784	3.2%
Strain	1.63315	1.54930	5.13%

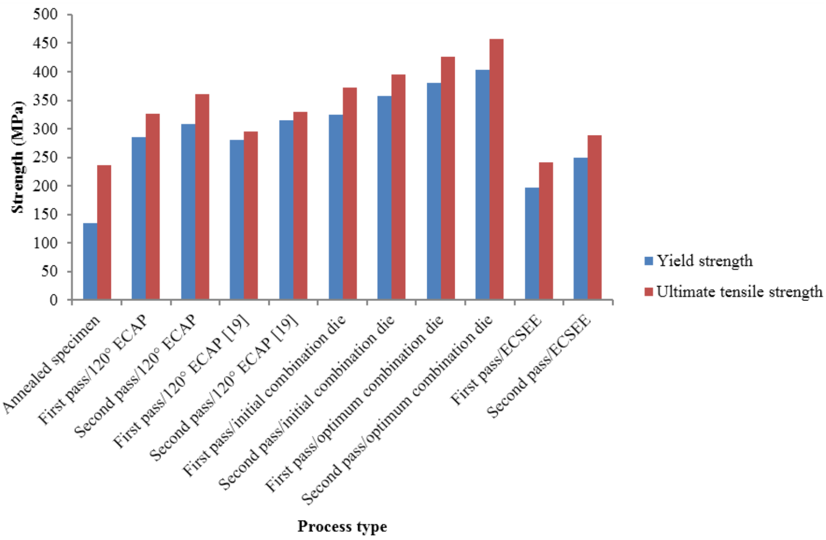


Fig. 12. Changes in the strength of the specimen by changing the type of die.

Table 11
The values of the measured yield strength and ultimate tensile strength.

Process	Yield strength (MPa)	Ultimate tensile strength (MPa)
Annealed specimen	135	237
First pass/initial combination die	325	372
Second pass/initial combination die	358	395
First pass/optimum combination die	381	426
Second pass/optimum combination die	404	458
First pass/ECSEE	197	242
Second pass/ECSEE	250	288
First pass/120° ECAP	285	327
Second pass/120° ECAP	309	360
First pass/120° ECAP [19]	280	295
Decond pass/120° ECAP [19]	315	330

According to the results of Table 11, the yield strength of the specimen in the first pass of the first combined die is 325MPa, which increased by 65% and 14% respectively in comparison to the ECSEE and ECAP dies. In the second pass, this parameter is equal to 358MPa that shows an increase of 43% and 16% compared to the mentioned dies respectively. Moreover, the ultimate tensile strength in the first pass of the first combined die is 372MPa, which increased by 54% and 14% compared to the ECSEE and ECAP dies respectively, and increased by 37% and 10% in the second pass. From this results, it can be anticipated that by using a combination of the two dies, the strength values of the specimens could be improved. For the optimal condition of the combined die for both passes of the forming, there is the maximum growth in the yield strength when it is compared to other dies. Additionally, compared to the annealed specimen it improved threefold. Furthermore, its ultimate tensile strength has the maximum value compared to other dies and by comparison to the annealed specimen, it is a twofold increase.

In order to verify the results of the ECAP die in this study with the die that was used in the reference 16, a comparison was made and it can be anticipated that the values of yield strength in both dies are almost the same and the ultimate strength in the ECAP die of the present study is about 9% higher than the mentioned source. It is because of the effects of some factors such as the outer angle of the ECAP channel, the type of lubricant, etc.

6.1.2. Hardness

Fig. 13 shows the related changes in the hardness values at different points of the specimens cross-section in each die. According to the diagrams, it is clear that there is a gradual upward trend for hardness changes in all dies from the center of the specimen to the their surfaces and their hardness in their outer surfaces have the highest values.

The maximum value of hardness is for the optimal combined die and its mean value for the second pass is 155.6 Vickers and compared to the mean hardness of the annealed specimen which is 44.4 Vickers, so a significant growth could be seen in the hardness value. The mean value of the hardness of the specimen in the first pass of the first combined die is 124.4 Vickers. When it is compared to the ECSEE and ECAP dies, 48% and 23% increase could be seen respectively and in the second pass is equal to 137.2 Vickers, which increased by 43% and 17% compared to the mentioned dies. Thus, the combination of the two mentioned dies and using the combined die can improve the hardness value of the specimen. Furthermore, the standard deviation of the hardness distribution in the ECAP die is 9.8 and in the combined die is 4.1. This significant decrease shows that by adding the helical channel to the ECAP die, specimens with a much more homogeneous structure can be accessible which is one of the main goals of any severe plastic deformation process.

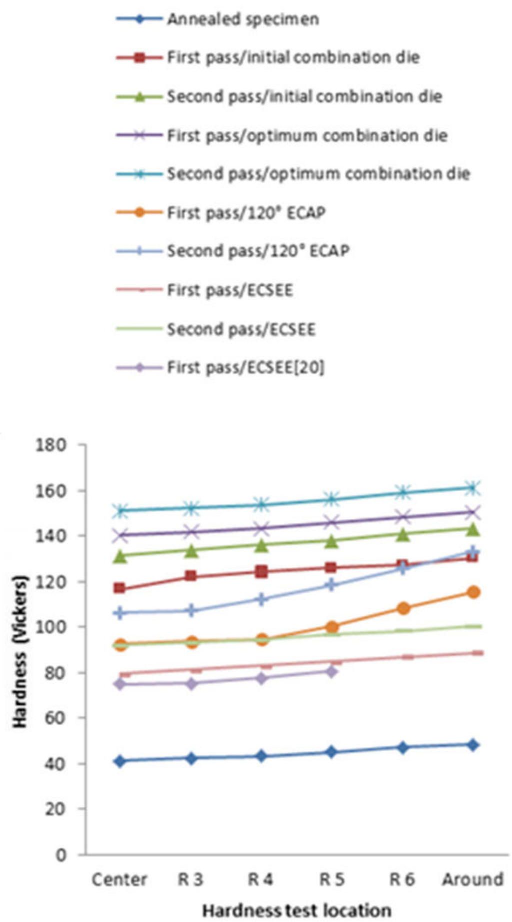


Fig. 13. Effect of the place of measurement and the process type on the specimens hardness.

6.2. Simulation

6.2.1. Effects of The Values of Design Parameters on Forming Force

Fig. 14 shows the effect of changes in channel angle (α), the ratio of large diameter to small diameter of the ellipse (m), the torsion angle (θ), the length of thetwisted region of the die (L) and the corner angle (ψ) on the the forming force.

As can be seen, the required force to form the specimen increases while the value of m increases which is due to the change of the specimens cross-section from the circular state to the elliptical state. Furthermore, by decreasing the m value, the cross-section of the specimen becomes more circular and therefore the amount of the force decreases. Moreover, by increasing the amount of channel angle, the forming force decreases, which is due to the reduction of shear stress in the forming region that facilitates the forming process. In addition, as it can be seen, changes in the three parameters θ, L and ψ, namely the torsion angle, the length of the die twisted region, and the corner angle, have not significant effect on the amount of forming force.

The interaction effects of various design parameters on the forming force are shown by three-dimensional procedure diagrams in Fig. 15. By using these diagrams, two design parameters can be investigated simultaneously and the effects of their changes on the amount of forming force can be observed. According to these diagrams, it can be seen that different parameters have different effects on the forming force. For instance, according to Fig. 15a, it can be anticipated that if the value of θ is assumed to be constant, the amount of forming force decreases with increasing α, by the way, at the amount of 90°, it reaches to its maximum value and in the amount of 120°, it is in its minimum value. Additionally, according to the Fig. 15b and 15c, it can be observed that the effect of the channel angle on the amount of forming force is more than the effect of the parameters L and ψ. These results have also been obtained according to Fig. 14.

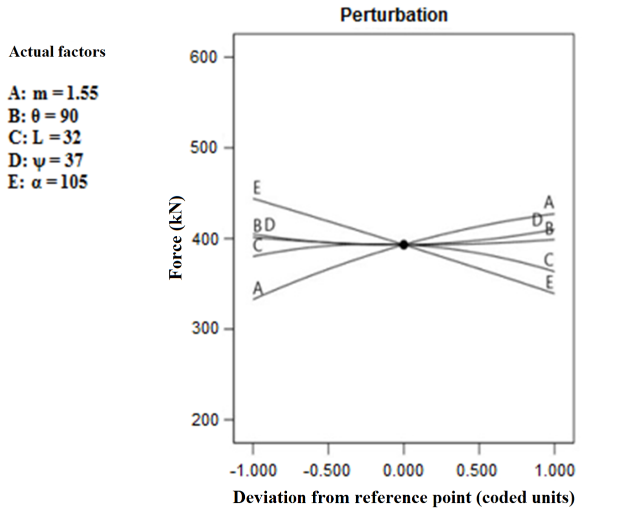
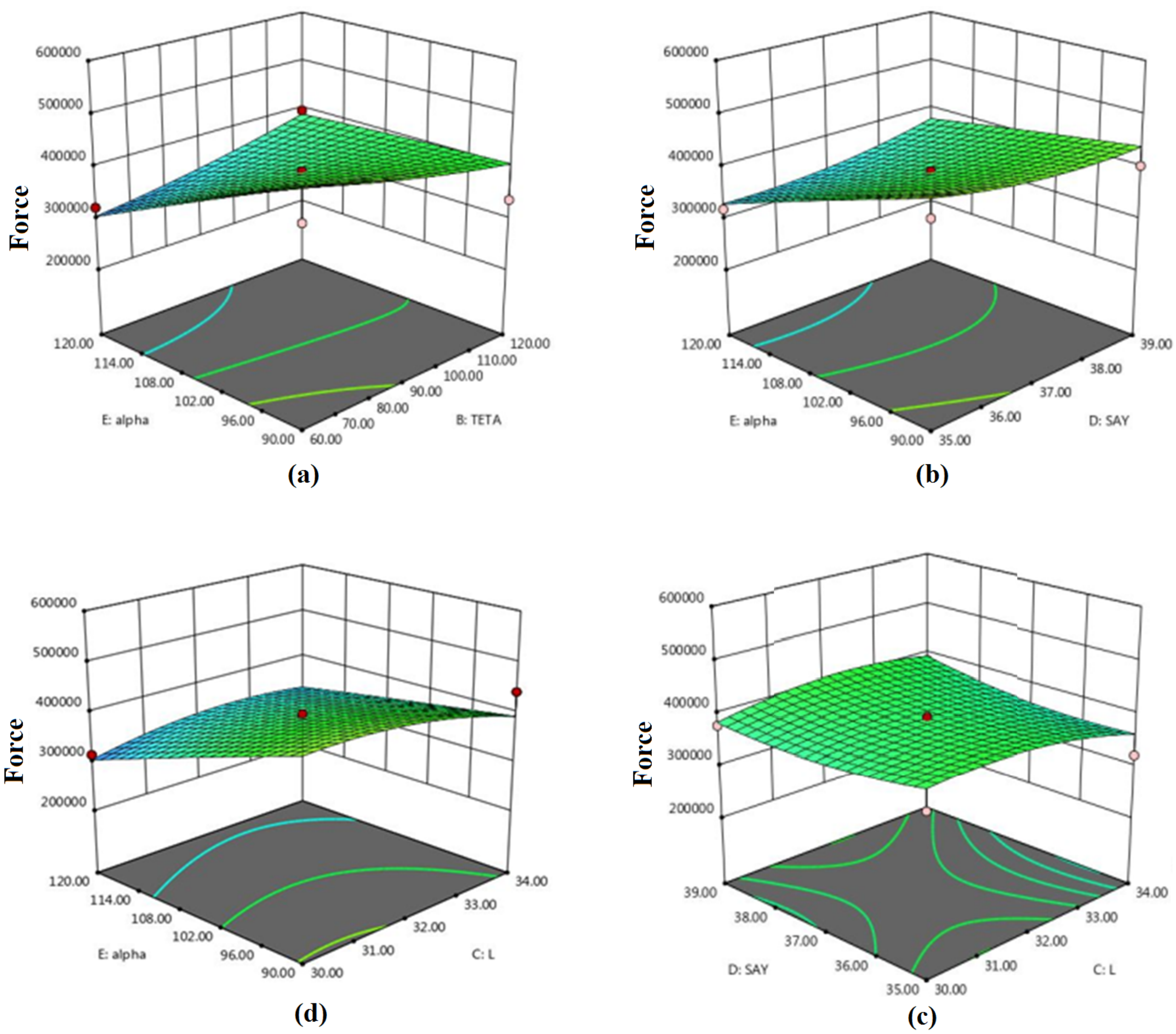


Fig. 14. Effect of changes in various design parameters on the amount of the forming force.



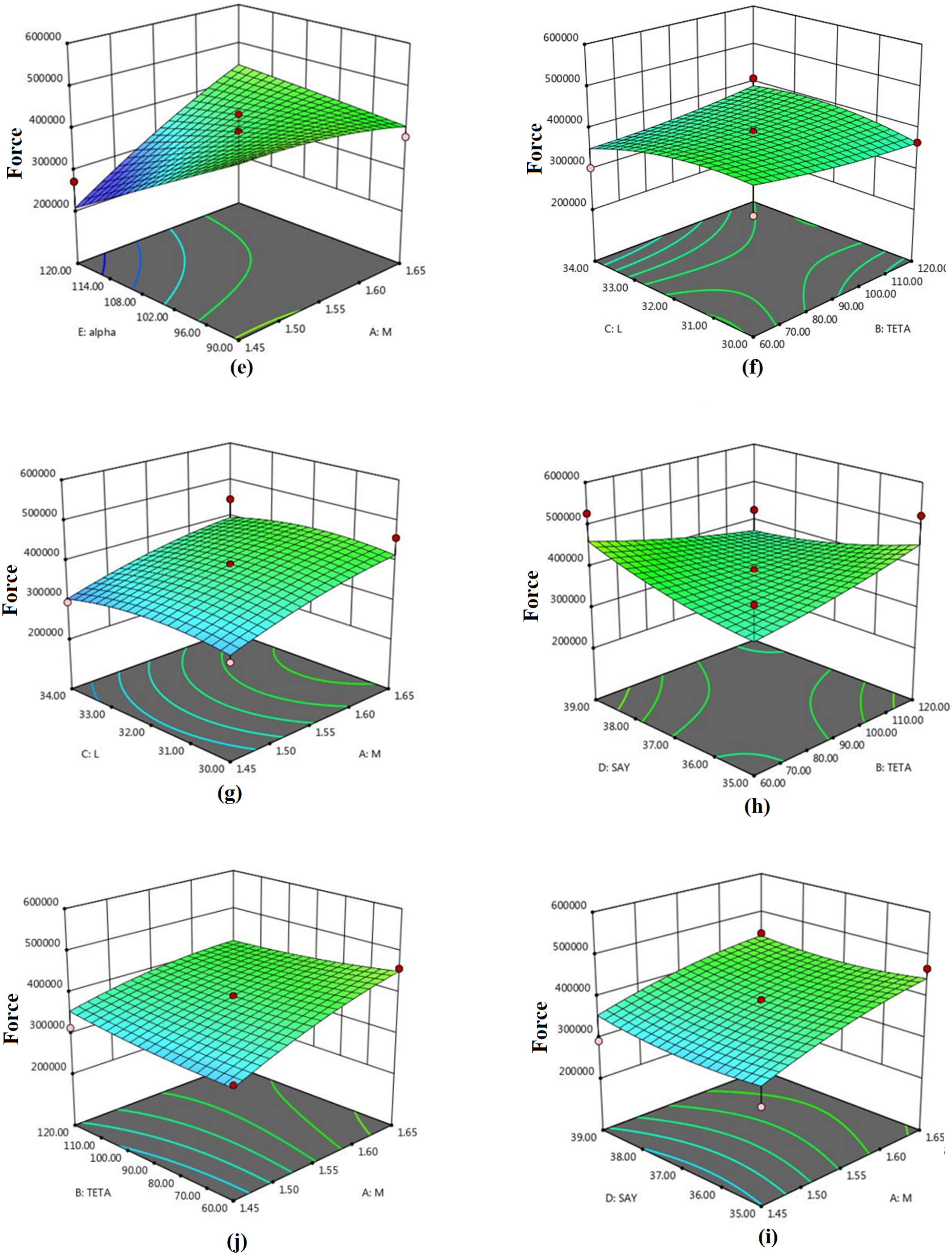


Fig. 15. Interaction of design parameters on the amount of the forming force

6.2.2. The Effects of Design Parameter Values on The Amount of Strain

The effects of changes in various design parameters including the channel angle (α), the corner angle (ψ), the length of the twisted region (L), the ratio of large diameter to small diameter of the ellipse (m) and the torsion angle (θ) on the maximum created strain in the specimen are shown in Fig. 16. According to this figure, it can be assumed that by increasing the size of the m parameter, the amount of strain increases, which is due to the fact that the cross-section of the specimen deviates from the circular state and becomes more elliptical. Furthermore, by reducing the amount of the channel angle, deformation in the corners becomes harder and then the amount of strain increases. On the other hand, when it increases, the material flow would be easier and as a result, the amount of strain reduces. It is also observed that changes in the three parameters of θ, L and ψ have less effects on the strain value.

According to Fig. 17, the interaction of the design parameters and the strain created could be seen by the three-dimensional surface diagrams.

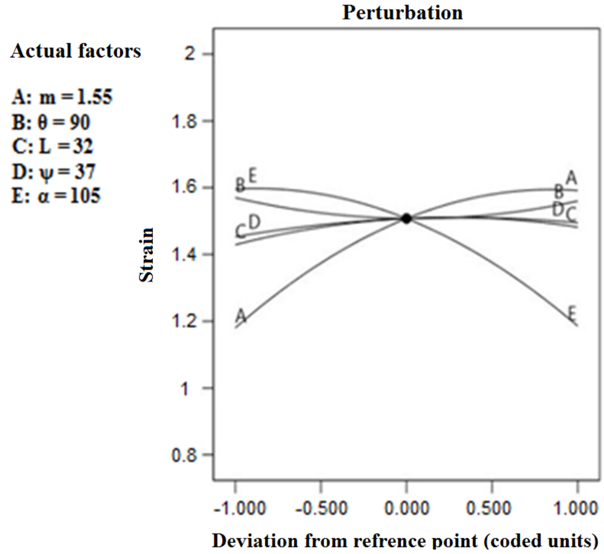
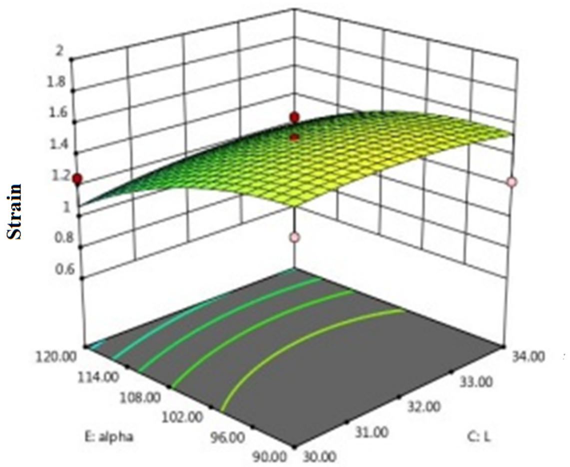
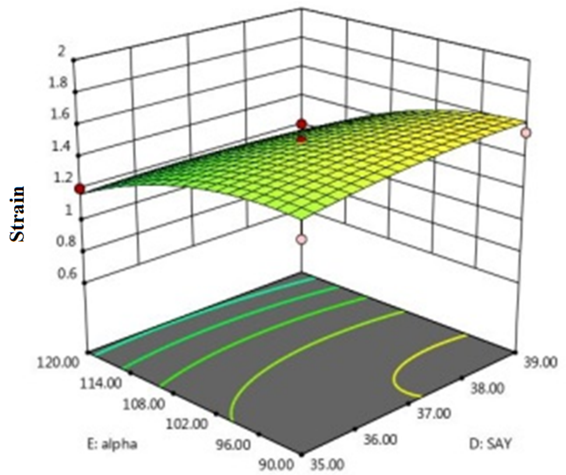


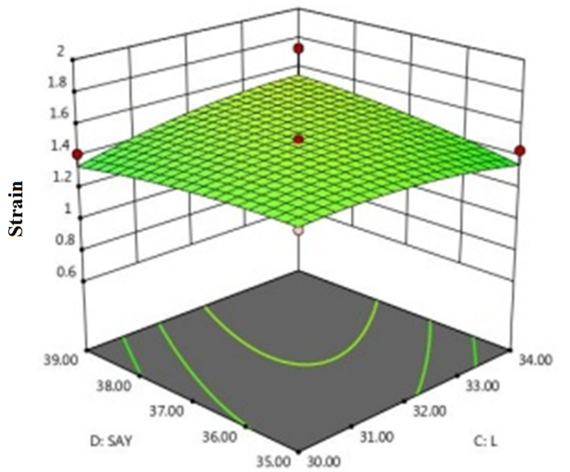
Fig. 16. Effect of changes in various design parameters on the amount of the strain.



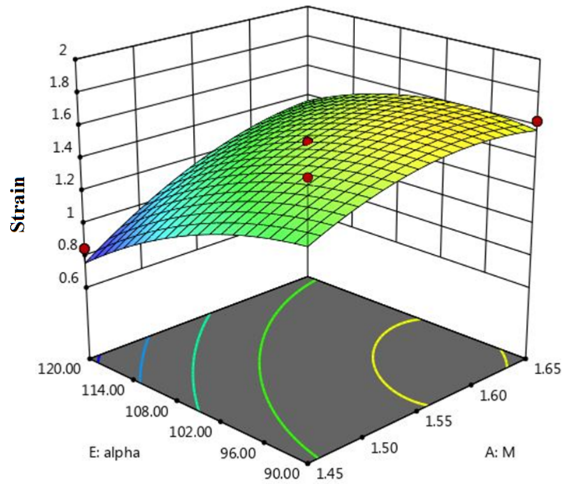
(a)



(b)



(c)



(d)

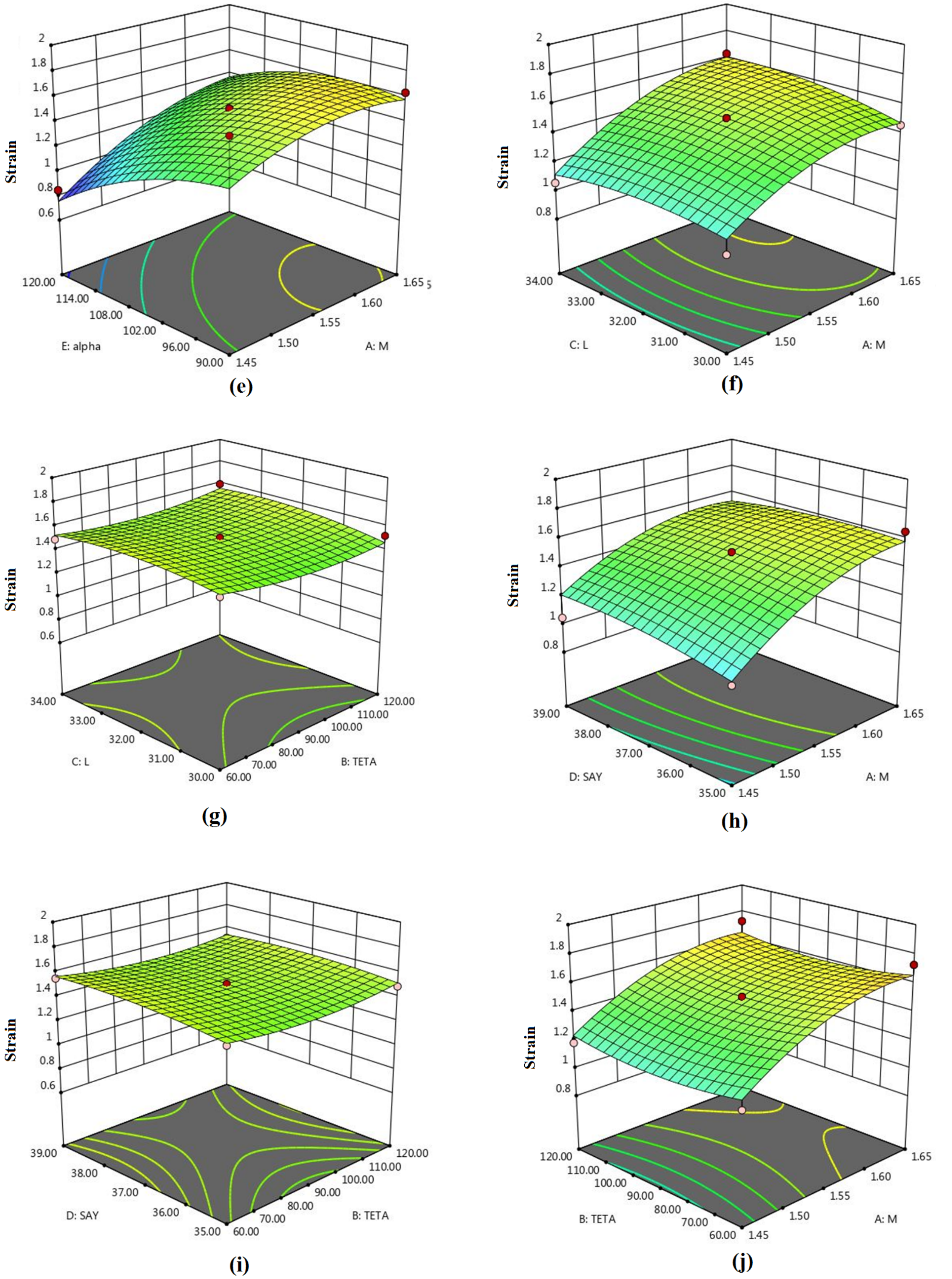


Fig. 17. Interaction of design parameters on the amount of the strain

By using these diagrams, it is possible to investigate two design parameters simultaneously and the effect of their changes on the amount of strain created in the specimen can be observed. Moreover, it can be seen that different parameters have different effects on the amount of the created strain. For example, according to Fig. 17a, it can be observed that if the value of L is assumed to be constant, the amount of the strain decreases by increasing the channel angle, in a way that while it is 90°, the strain is in its maximum value and reach to its minimum when α is 120°. Additionally, according to the Fig. 17b and 17c, it can be observed that the effect of the channel angle on the amount of forming force is more than the effect of other parameters including L and ψ. These results have also been obtained according to Fig. 16.

7. Conclusions

In this study, the effect of combining the two processes of torsional extrusion and ECAP as well as die design parameters on the mechanical properties of pure copper was investigated. The results are as follows:

1. The yield strength of the specimen in the first pass of the initial combined die is equal to 325MPa, which shows increases of 65% and 14% respectively compared to the ECSEE and ECAP dies and in the second pass it reaches to 358MPa which shows a growth of 43% and 16%, respectively. Furthermore, the ultimate strength in the first pass is equal to 372MPa which increased by 54% and 14% compared to ECSEE and ECAP dies and show increases of 37% and 10% in the second pass. It can be concluded that by combining the two mentioned dies and making a combined die, it is possible to improve the strength values of the specimen.

2. After making a comparison of the ECAP die used in this study with the ECAP die used in the reference 19, it was concluded that the values of yield strength in both dies are almost the same and the amount of ultimate strength in the ECAP die of the present study is about 9% higher than those obtained from the reference 19. There are some other factors such as the channel angle, the lubricant type, etc. that can be influential in this case.

3. The yield strength in the optimal combined die has the maximum growth compared to other dies and in the first pass its value increased from 135MPa (before performing the process) to 381MPa, and in the second pass its value increased to 404MPa which is about three times higher than the initial value. Furthermore, the ultimate strength in the optimal combined die had maximum growth in a way that in the first pass, there is an increase on its value from 237MPa (before performing the process) to 426MPa, and in the second pass, its value increased to 158MPa, which almost doubled compared to the initial value.

4. The yield strength in the first pass of the optimal combined die have increased by 17% compared to the initial combined die and the ultimate strength have increased by 16% compared to the initial combined die. In the second pass, the yield strength has increased by 13%. Furthermore, there is a 16% growth for the value of ultimate tensile strength of the optimal combined die compared to the initial combined die. This depicts that the optimal die can be able to achieve better results than the initial die.

5. By analyzing the hardness values of the specimens, it can be anticipated that there is a gradual upward trend of hardness changes in all dies from the center of the specimens to their outer surfaces around the specimens and the amount of hardness in their surroundings and surfaces has the highest value. The maximum amount of hardness was created by the optimal combined die. Its mean value in the second pass is equal to 155.6 Vickers and compared to the average hardness of the annealed specimen, which is 44.4 Vickers, it increased by near three and a half times.

6. The average value of the hardness in the first pass of the initial combined die is equal to 124.4 Vickers. When this value is compared to the ECSEE and ECAP dies, it shows increases of 48% and 23%, respectively. In the second pass of the process, this value is equal to 137.2 Vickers, which shows growth of 43% and 17% compared to the above mentioned dies and showed that by combination of the two dies and the making of the combined die, the hardness values of the specimens could be increased significantly. Furthermore, the standard deviation of the hardness distribution in the ECAP die is 9.8 and in the combined die is 4.1. This significant reduction shows that by adding a helical channel to the ECAP die, specimens with a much more homogeneous structure can be accessible which is one of the main goals of any severe plastic deformation process.

7. By Analyzing the comparison that has been made to validate the results of the ECSEE die in this study with the ECSEE die in the refernce 20, it can be seen that the average hardness value in the first pass of this study is 84 Vickers and in the mentioned study is 77 Vickers and that is 9% higher than the above mentioned source.

8. The mean value for the hardness in the first pass of the optimal combined die shows a 16% increase compared to the initial combined and in second pass of the process, this value is equal to 13% and showed that better results can be achieved by the optimal die.

9. As the ratio of the large diameter to the small diameter of the ellipse (m) increases, the amount of the required forming force and strain created in the specimen increase too. It is because of this fact that the cross-section of the specimen deviates from the circular state and approaches the elliptical shape. When m parameter decreases, the cross-section of the specimen approaches a circular shape and the force and the amount of strain accordingly.

10. By increasing the channel angle (α), the amount of shear stress in the deformation region decreases, hence, making it easier to form and the amount of require force to form and the created strain in the specimen reduce accordingly. Conversely, as the value of decreases, the shear stress increases and the deformation at the corners becomes more difficult, it leads to an increase in the amount of forming force and strain too. In addition, changes in the three main parameters θ, L, ψ, namely the torsion angle, the length of the die twisted region and the corner angle, have less effect on the values of the forming force and strain.

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