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Study on Equal Channel Angular Pressing Process of AA7075 with Copper Casing by Finite Element-response Surface Couple Method

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ABSTRACT

Equal channel angular pressing (ECAP) process of AA7075 billet with the copper casing is comprehensively investigated. Firstly, ECAP process is simulated based on finite element method (FEM) in ABAQUS software and then is verified in comparison to the experimental data. The design of experiments using response surface methodology (RSM) is performed in order to investigate the processing parameters. The main effect of four considered parameters (channel angle, corner angle, friction coefficient and thickness of casing) on the maximum required force and strain was studied. Also, the regression models for estimating the maximum forming force and strain are represented in high reliability using analysis of variance (ANOVA). The results indicated that channel angle by 93.5% of contribution is the most effective parameter on the required forming force. It is concluded that the thickness of copper casing does not affect the forming force. Also, all terms of the presented regression model are effective on the strain value, according to the obtained results. Based on ANOVA results, channel and corner angel are the most effective parameters on the strain by 80 and 16% of the contribution, respectively. Also, the friction coefficient and the thickness of copper casing have almost no significant effects on the strain.

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1. INTRODUCTION

Nowadays, the attention of researchers has been particularly attracted to the production of ultra-fine grained (UFG) structure, because of the physical and mechanical properties of these materials are significantly higher than ordinary materials [1]. In addition to high strength, the UFG materials have good deformation properties so that, even at the lower temperature and higher strain rates, they exhibit excellent superplastic properties [2]. In general, nanostructure materials are made by two main approaches of top-down and bottom-up. In the first approach, the nanostructure is created by connecting atoms and molecules. In the second approach, the nanostructure is produced by applying severe plastic deformation (SPD) processes on the materials with large macroscopic dimensions and coarse grains [3]. In this method, due to applying strain to the material, its structure changes and it is possible to modify the microstructure, reduce the grain size to the nanometer scale and improve the mechanical properties, especially the strength, without changing its apparent dimensions [4]. There are no limits on the applying of strain in these processes because the dimensions of the samples are remained constant and following that the achieving to high strain is easy in the material [5].

One of the SPD methods is the equal channel angular pressing (ECAP) for bulk materials. The die of this method consists of two channels with equal cross sections which have an intersection in the channel and corner angles. The schematic of the ECAP process is shown in Figure 1. The billet is inserted from one side of the channel, and then it is guided into the channel by the punch and passes through it. The billet is bent when it passes through the intersection of two channels; hence the created strain in the sample is purely shear strain at this stage. Since the dimensions of the cross-section of the billet remain unchanged, the pressing may be

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repeated several times to attain very high strains. Also, there is no possibility of cracking and fracturing of billet, because it is bound to the channel and a high hydrostatic stress is applied to the billet. One of the important parameters in the ECAP process is the amount of applied strain at each stage of deformation, which can be obtained as Equation (1) [6].

$$\varepsilon_{eq} = \frac{N}{\sqrt{3}}\left[2\cot\left(\frac{\phi+\psi}{2}\right)+\psi\csc\left(\frac{\phi+\psi}{2}\right)\right] \tag{1}$$

where Φ is the angle between the two channels, Ψ is the corner angle of intersection of two channels, and *N* is the number of passes.

Yu et al. [7] studied the effect of fine-grained Al-Mg-Si alloy on the mechanical and electrical properties in the ECAP process. They found that after the ECAP process, the mechanical properties and the electrical conductivity of samples were improved. Extruded ZK60 Mg alloy samples were processed in ECAP for four passes at 250 °C by Dumitru et al. [8] The results showed a reduction in the grain size and forming of high angle grain boundaries. Also, there was a slight increase in the recrystallization temperature. The tensile test revealed that after four passes of ECAP, the elongation to failure had increased about twice as much as extruded specimens. The pure titanium samples were processed for four passes using the ECAP by Zhao et al. [9]. They found that the grain size has decreased from 25 μm to 150 nm. Also, the results showed that hardness, tensile strength, and elongation to failure were significantly increased after the ECAP process. Goodarzy et al. [10] investigated the mechanical properties of 2024 Al alloy after the ECAP process. The hardness and yield stress of the samples were significantly increased. The ductility and work hardening exponent of the deformed specimens were decreased due to the formation of shear bands within the microstructure. Mostaed et al. [11] used the ECAP process in four passes for ZM21 Mg alloy. After the first stage of ECAP, they observed the UFG structure in the specimens. Also, the tensile test results revealed that the yield stress and the elongation to failure of samples were increased by the ECAP process. Tang et al. [12] investigated the effect of the ECAP process on the yield strength and elongation to failure of AZ80 Mg alloys. They concluded that the yield strength and the elongation to failure improved by 135% and 17% by ECAP process, respectively. Safari and Joudaki [13] studied the effect of performing the ECAP process at elevated temperature on the tensile strength of pure aluminum and aluminum alloy samples. Their results showed that high temperature reduces the tensile strength of AA6063 and pure Al samples by 5% and 12%, respectively. Djavanroodi et al. [14] investigated of the effect of channel angle and corner angle on the strain distribution behavior in the ECAP process. They introduced Φ=60° and Ψ=15° as optimal conditions for

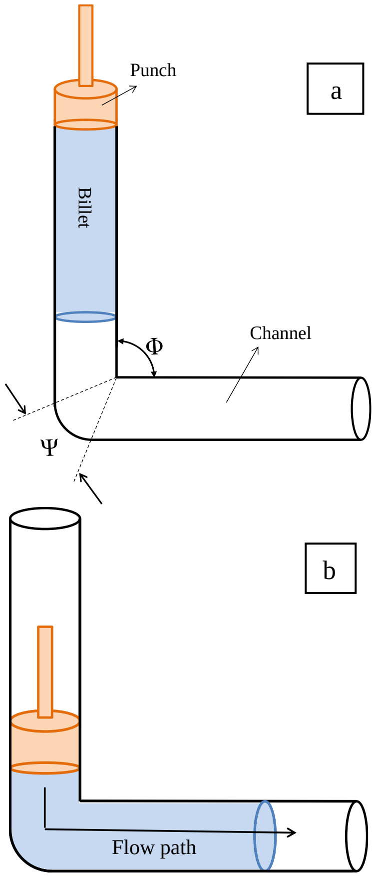


Figure 1. Schematic of a) before and b) after the ECAP process

achieving uniform strain distribution. A proper die for the ECAP process was designed and constructed by Reihanian et al. [15]. The mechanical properties and deformation behavior of pure Al have been investigated. Also, the effect of the pass numbers on the microstructure of the material is discussed. The significant increase in hardness and yield stress has been observed after the ECAP process.

Design of experiments (DOE) is one of the important issues in scientific researches to reduce the number of experiments, cost and time. Also, its purpose is simultaneous investigation effects of changing several parameters on an output variable and finding the optimal conditions. One the most important methods of DOE that are used in scientific studies especially in engineering investigations is response surface methodology (RSM). Lqbal et al. [16] studied the twist extrusion forming on the AA6082-T6 Al alloy. For this purpose, they used the RSM to investigate the effects of forming load, temperature, and number of passes on the tensile strength and hardness of samples. Balta et al. [17] obtained the relationship between the welding parameters of steel tube and their mechanical properties using the RSM. They studied the effects of friction pressure, friction time, forging pressure and forging time on the tensile strength, elongation and petal crack length. The results showed that there is a little difference between the prediction results of RSM and the experimental results. Hasan-nejad et al. [18] used the RSM to examine the effects of blank holder force, die nose radius, punch nose radius, blank radius, and friction coefficients parameters on the forming load and thickness reductions of the produced brass-steel laminated sheets in the deep drawing process. They simulated the designed experiments by using the finite element (FE) model, which the obtained results showed a good correlation with the experimental results. Teimouri and Ashrafi [19] investigated the effects of die geometry and fluid pressure on the thinning ratio and punch force in the hydrodynamic deep drawing process of Al 7075. Also, they used the desirability approach to determine the desired parameters to achieve the minimum thinning and forming force simultaneously. The results indicated that the punch and die corner radiuses and fluid pressure have significant effects on the response parameters. Guo and Tang [20] used the RSM to determine the limiting sheet diameter in the deep drawing process to predict the early quality before production of samples. Also, it should be noted that the obtained results had a good correlation with the simulation results.

Naseri et al. [21] experimentally investigated the ECAP process of 7075 aluminum alloys. They stated that some age-hardenable aluminum alloys are difficulty to process by ECAP at room temperature. In this case, to use a casing is a new idea in ECAP. They used a copper casing that has good frictional properties due to the possibility of cracking aluminum because of its undesirable frictional properties. They reported that by using of copper casing the required force forming is decreaced and the hardness is increased.

The comprehensive investigation of a process especially when numerous parameters affect that process is experimentally difficult, costly and time-consuming. According to the literature, DOE methods can be effective in these situations. The comprehensive study of ECAP processes as one the most important UFG approaches seems to be necessary. For this purpose, the ECAP process of 7075 Al alloy with copper casing is simulated using a FEM model. The simulation process is verified in comparison to experimental results reported in literature [21]. The most important parameters are selected as input and their effects on the required force and strain were investigated using RSM. In fact, the aim and innovation of the present paper are a comprehensive study of the effect of important processing parameters of the ECAP process and the effect of using the casing for samples by the FEM-RSM couple method. It also provides optimal conditions for simultaneously achieving the minimum forming required force and the maximum strain. So that such a comprehensive study was not seen in the literature. Therefore a comprehensive study is performed and helpful results are demonstrated using the combination of the FEM-RSM model.

2. FINITE ELEMENT (FE) SIMULATION

In order to investigate the effects of processing parameters and casing thickness on the maximum required force and the strain in ECAP process, the finite element software of Abaqus/CAE 6.12-3 was used. The die and punch were modeled as analytical rigid according to the presented dimensions in Figure 2. Deformable form is used to model samples that including billet and casing as shown in Figure 3. The AA7075 and copper have been utilized as the billet and casing in this process, respectively. The used Holloman equations for AA7075 and copper are $\sigma=642\varepsilon^{0.35}$ and $\sigma=297\varepsilon^{0.443}$, respectively according to the experiments results reported in literature [22, 23]. Figure 4 shows the stress-strain diagram for AA7075 and copper. Also the properties of the AA7075 and copper are given in Table 1. The friction coefficient is considered between aluminum billet and copper casing, because they should not have relative movement on each other during the ECAP process [21]. The billet and casing have been meshed using tetrahedral elements. The number of elements was selected based on the mesh sensitivity test and by considering the lower modeling time. The final sample after ECAP process respect to strain is shown in Figure 5.

3. FEM VALIDATION

In order to verify the simulation results of present study, the maximum force is compared to the experimental results of Naseri et al. [21]. The simulation conditions

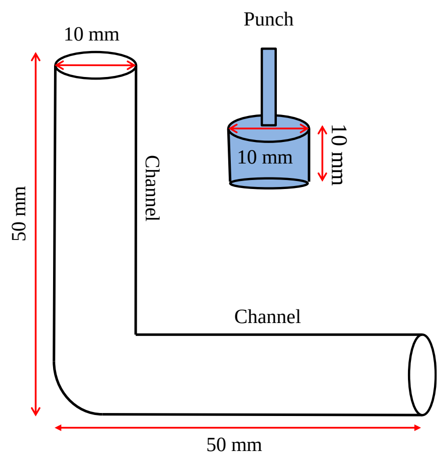


Figure 2. Schematic geometry and dimensions of die and punch

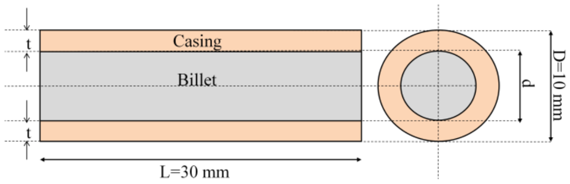


Figure 3. Schematic geometry and dimensions of samples

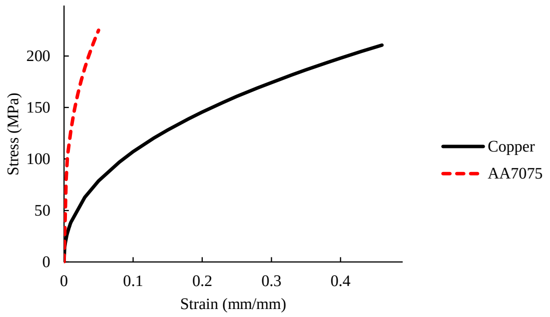


Figure 4. The stress-strain diagram of AA7075 and copper [22,23]

TABLE 1. Mechanical and physical properties of materials [22,23]

Materials	Properties				
	Yield stress (MPa)	Ultimate stress (MPa)	Young's modulus (GPa)	Density (kg/m^3)	Poisson's ratio
AA7075	103	228	71.7	2810	0.33
Cu	33.3	210	110	8930	0.343

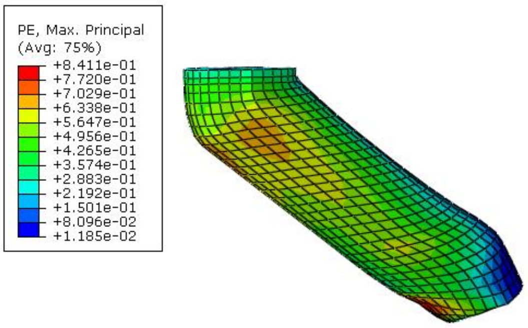


Figure 5. The FEM simulation of final sample after ECAP process respect to strain

from literature [21] are given in Table 2. The comparison results are presented in Table 3. According to Table 3, the simulation results of present study have a good correlation with experimental results of Naseri et al. [21] and maximum difference between the experimental and simulation maximum force is almost 4.5%; therefore, the simulation of this study is highly authenticated.

TABLE 2. Conditions of validation runs [21]

Run	t (mm)	d (mm)	D (mm)	L (mm)
R1	0	20	20	140
R2	1	18		
R3	2	16		
R4	3	14		
R5	4	12		
R6	5	10		

TABLE 3. Maximum force validation

Run	Maximum force (kN)		
	Experimental [23]	Simulation (present study)	Difference (%)
R1	196	194	1.02
R2	180	182	1.11
R3	152	152	0.00
R4	135	141	4.44
R5	125	128	2.40
R6	112	109	2.68

4. RESPONSE SURFACE METHODOLOGY (RSM)

RSM is one of the mathematical and statistical techniques that is used to optimize response variables in the presence of various factors. This method saves time and cost by reducing the number of experiments. Furthermore, the RSM accurately predicts the interactions of different independent variables that change at the same time on the response variable. Another advantage of the RSM is its non-linearity model, which improves the modeling accuracy. Therefore, in addition to evaluating the best level, this model finds the exact value that optimizes the design. The most recommended types of RSM designs are Box-Behnken and central composite designs (CCD). CCD is used for the design of experiments in this study [24-26]. Equation (2) shows the second-order polynomial for the RSM [27, 28].

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j}\sum \beta_{ij} x_i x_j + \varepsilon \tag{2}$$

In Equation (2), y is the response variable, β_0, β_i, β_{ii} and β_{ij} are constants, linear, quadratic and interaction coefficients, respectively. x_i and x_j are the independent variables and ε is the statistical error. The correctness of regression model is determined using the R^2 that obtained by analysis of variance (ANOVA). So that R^2 to be closer to one, the model will be more efficient.

In the present study, the angle between the two channels (Φ), the corner angle (Ψ), and friction coefficient (μ) as ECAP process parameters and the thickness of casing (t) were considered as variable parameters. Their effects were investigated on the maximum force and strain distribution as the criteria in DOE approach by using FEM-RSM couple method. For this purpose, according to the processing and applicable conditions in the validated simulation, by applying lower and higher levels of variable parameters, according to Table 4 the experiments were designed in accordance with the CCD procuring 31 experiments using Minitab software as shown in Table 5.

TABLE 4. The considered levels of variable parameters

Parameters	Levels	
	Low	High
Φ (deg)	82.5	127.5
Ψ (deg)	7.5	22.5
μ	0.038	0.112
t (mm)	1	3

5. RESULT AND DISCUSSION

The simulation process of ECAP samples was performed according to the design of experiments and the conditions set as Table 5. The obtained results for the maximum force and the strain are reported in Table 6.

5. 1. Maximum Force

5. 1. 1. Contribution The contribution of each parameter on the maximum force is expressed based on the results of analysis of variance (ANOVA) tool of RSM method as Table 7. The results indicate that Φ is the most effective parameter on the maximum force and has a significant contribution of 93.5%. After Φ, μ and Ψ are the second and third effective parameters on the maximum force by contribution of 3.8 and 2.5%, respectively. Also, the results illuminate that *t* has not influence on the maximum force.

TABLE 5. Design of experiments according to RSM

	Parameters			
Run	Φ (deg)	Ψ (deg)	μ	t (mm)
1	127.5	7.5	0.112	3
2	82.5	7.5	0.038	1
3	105.0	15.0	0.075	2
4	82.5	7.5	0.038	3
5	105.0	15.0	0.075	2
6	127.5	7.5	0.112	1
7	105.0	15.0	0.075	2
8	105.0	15.0	0.075	2
9	82.5	22.5	0.112	3
10	105.0	15.0	0.149	2
11	127.5	7.5	0.038	3
12	82.5	22.5	0.038	1
13	82.5	22.5	0.112	1
14	127.5	22.5	0.038	1
15	105.0	15.0	0.075	0
16	105.0	15.0	0.075	4
17	127.5	7.5	0.038	1
18	82.5	7.5	0.112	1
19	105.0	15.0	0.075	2
20	60.0	15.0	0.075	2
21	82.5	22.5	0.038	3
22	105.0	15.0	0.075	2
23	82.5	7.5	0.112	3
24	105.0	0.0	0.075	2
25	105.0	30.0	0.075	2
26	127.5	22.5	0.038	3
27	105.0	15.0	0.001	2
28	127.5	22.5	0.112	1
29	150.0	15.0	0.075	2
30	127.5	22.5	0.112	3
31	105.0	15.0	0.075	2

TABLE 6. The results of the obtained maximum force and strain from FEM simulation

Run	Maximum force (kN)	Strain (mm/mm)
1	15.3	0.95
2	49.6	1.82
3	22.2	1.11
4	50.3	1.82
5	22.2	1.11
6	15.7	0.82
7	22.2	1.11
8	22.2	1.11
9	41.0	1.46
10	29.5	1.33
11	10.7	0.72
12	47.9	1.12
13	49.7	1.23
14	11.0	0.75
15	21.6	0.89

16	22.2	1.04
17	13.0	0.72
18	74.9	2.12
19	22.2	1.11
20	75.5	2.24
21	39.2	1.28
22	22.2	1.11
23	72.9	2.25
24	22.3	1.60
25	20.6	0.88
26	10.5	0.76
27	18.3	1.02
28	16.2	0.74
29	7.4	0.63
30	15.2	0.84
31	22.2	1.11

TABLE 7. Contribution of parameters on the maximum force

Parameters	Contribution (%)	Rank
Φ	93.5	1
Ψ	2.5	3
μ	3.8	2
t	0.2	4

5. 1. 2. Main Effect of Parameters Main effect of considered parameters on the maximum force is shown in Figure 6. According to Figures 6(a) and 6(b), by increasing Φ and Ψ, the required force for the ECAP process is reduced. By increasing Φ from 75 to 100° and Ψ from 5 to 15° the maximum force decreases 48 and 18%, respectively. By increasing Φ and Ψ, the sample flows through a less bending path; therefore, the lower forming force is needed. But as can be seen, with a further increase in Φ (from 125 to 150°) and Ψ (from 25 to 30°), the maximum force remains almost constant. In fact, increasing Φ and Ψ to a certain amount reduces the maximum force, due to the increase in ease of movement, and the further increase will not have much effect on the force. Also, Figure 6(c) illustrates that increasing μ increases the required force. By increasing μ, the maximum force is increased 48%. The contact between the sample and the channel justifies this occurrence. Increasing friction coefficient between the casing and the inner surface of the channel increases the forming force to confront with the friction force in the opposite direction. As shown in Figure 6(d), the t does not have significant effect on the forming force as the ANOVA results illuminated.

5. 1. 3. Regression Model Using the ANOVA results, the regression model to calculate the maximum force was obtained using Equation (3).

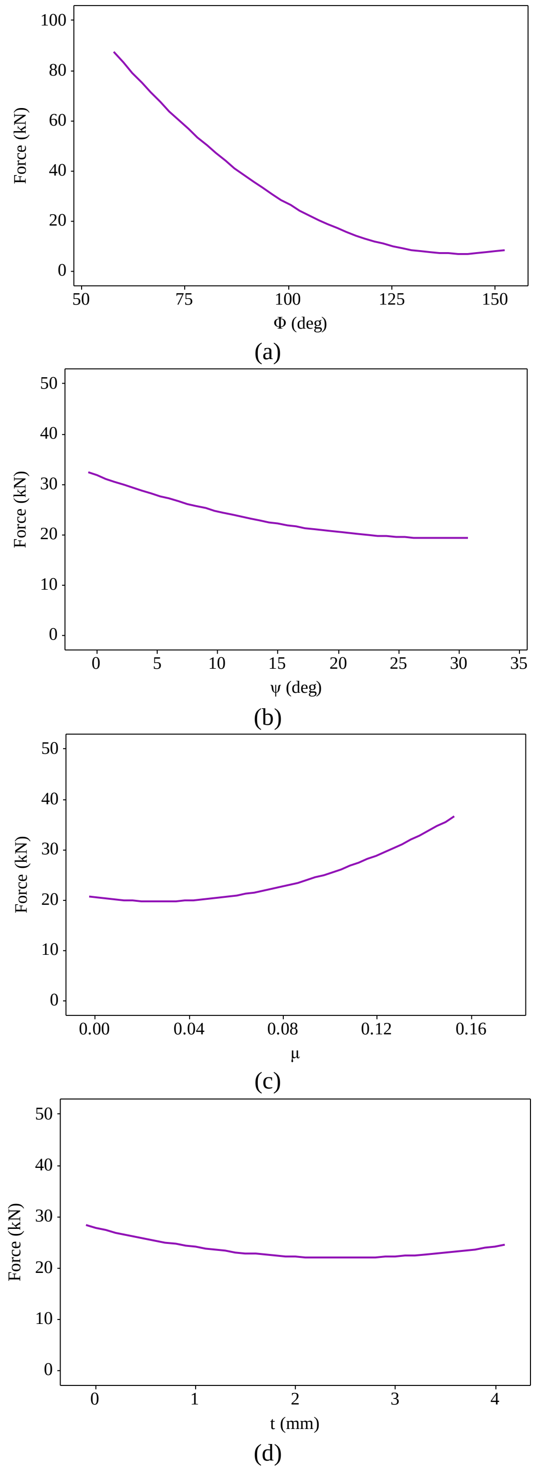


Figure 6. Main effect of a) Φ, b) Ψ, c) μ, and d) *t* on the maximum force

$$Maximumforce = 264.7 - 3.530\phi - 2.57\psi + 357\mu - 6.97t + 0.01153\phi^2 + 0.0150\psi^2 + 1060\mu^2 + 0.96t^2 + 0.02529\phi\times\psi - 2.57\phi\times\mu + 0.0404\phi\times t - 9.34\psi\times\mu - 0.124\psi\times t - 1.8\mu\times t \quad (3)$$

According to the ANOVA results, R^2 value is 95.4%, that shows the obtained model is efficient and can be used to estimate the maximum force with high reliability. The P-value results for each term of regression model of maximum force are presented in Table 8. According to the default error which is considered by Minitab software (i.e. 5%), a P-value smaller than 0.05 shows that the corresponding parameter has a significant contribution in the maximum force. In other words, a P-value larger than 0.05 indicate that the corresponding parameter can be eliminated from the model due to its ineffectiveness.

According to the results given in Table 8, t can be deleted among the linear terms and among the square and interaction terms, Φ^2 and Φ×Ψ have significant contribution, respectively and the other terms can be ignored. Finally, the regression model is presented using Equation (4).

$$Maximumforce = 264.7 - 3.530\phi - 2.57\psi + 357\mu + 0.01153\phi^2 + 0.02529\phi\times\psi \quad (4)$$

5. 1. 4. Interaction Effects of Parameters Since Φ×Ψ had a significant contribution, the interaction effect of Φ and Ψ on the maximum force is investigated in Figure 7 by surface and contour plots. The results indicate that in all values of Ψ, the force decreases by increasing Φ, but the effect of Φ is more significant in the lower Ψ. Also, the changes of Ψ have a noteworthy effect in the lower Φ and by increasing Ψ, the force reduces, while changes of Ψ are almost effectless in large Φ. Finally, according to Figure 7(b), it is revealed that high values of Φ and low values of Ψ are suitable for reducing the forming force.

TABLE 8. Obtained P-value for terms of regression model of maximum force using the ANOVA

Terms of regression model	P-value
Φ	0.000
Ψ	0.016
μ	0.005
t	0.442
Φ^2	0.000
Ψ^2	0.438
μ^2	0.190
t^2	0.381
Φ×Ψ	0.008
Φ×μ	0.152
Φ×t	0.531
Ψ×μ	0.087
Ψ×t	0.520
μ×t	0.963

5. 2. Strain

5. 2. 1. Contribution The ANOVA results show the contribution of parameters on the strain as presented in Table 9. According to the results, Φ with contribution of 79.8% affect the strain as the most effective parameter. Ψ and μ are the next effective parameters on the strain. The contribution of Ψ and μ on the strain is 15.9 and 3.4%, respectively. Also, t has a contribution lesser than 1% on the strain.

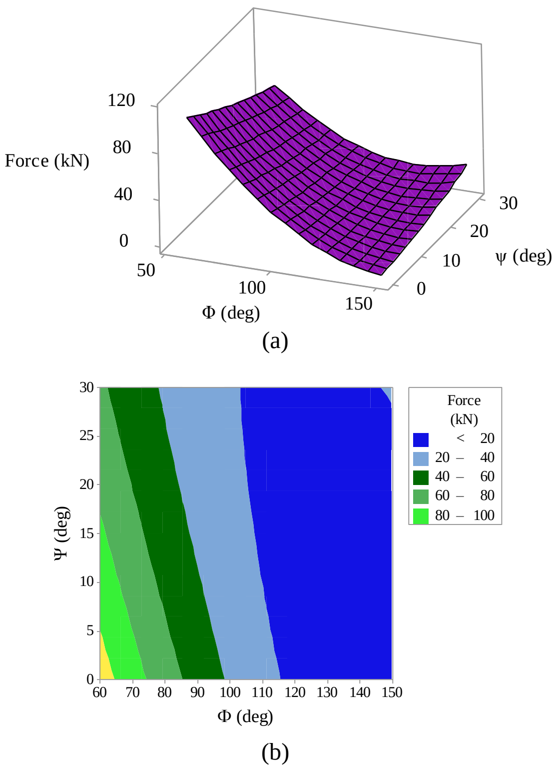


Figure 7. Interaction effect of Φ and Ψ on the maximum force a) surface plot b) contour plot

TABLE 9. Contribution of parameters on the strain

Parameters	Contribution (%)	Rank
Φ	79.8	1
Ψ	15.9	2
μ	3.4	3
t	0.9	4

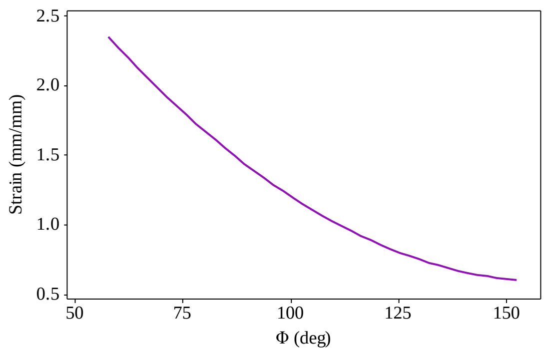
5. 2. 2. Main Effect of Parameters Main effect of considered parameters on the strain is shown in Figure 8. Figure 8 shows that by increasing Φ and Ψ the strain decreases. By increasing Φ from 75 to 125° and Ψ from 5 to 20° the strain reduces 55 and 21%, respectively. It can be explicated that by increasing Φ and Ψ, the sample flows easily from the intersection of two channels, it bends a little and subjected to less shear forces, therefore lower strain is generated. Also, Figure 8 reveals that the effects of μ and t have almost no significant effects on the strain as shown by ANOVA results in previous section.

5. 2. 3. Regression Model The obtained regression model based on the ANOVA results for the strain is expressed as Equation (5). The results illuminate that R^2 parameter for regression model of strain is 99.81%. Therefore, the regression model has a high reliability to estimate the strain of ECAP samples.

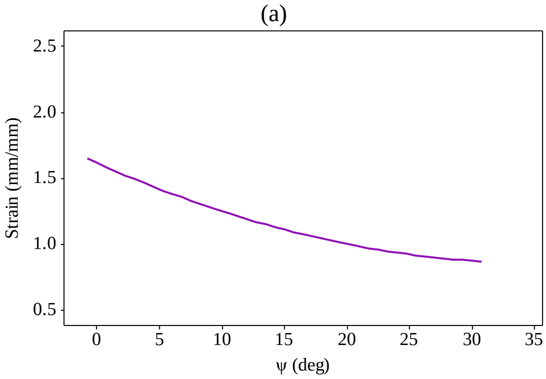
$$\begin{aligned}&Strain = 6.141 - 0.06360\phi - 0.14386\psi + 6.28\mu + 0.1780t + 0.000165\phi^2\\&0.000606\psi^2 + 13.39\mu^2 - 0.03413t^2 + 0.001035\phi\times\psi - 0.04745\phi\times\mu\\&-0.000783\phi\times t - 0.1600\psi\times\mu + 0.002103\psi\times t + 0.708\mu\times t\end{aligned} \quad (5)$$

According to the P-value results that are given in Table 10, it is clear that all terms of regression model have a significant contribution on the strain since all P-values are lesser than 0.05.

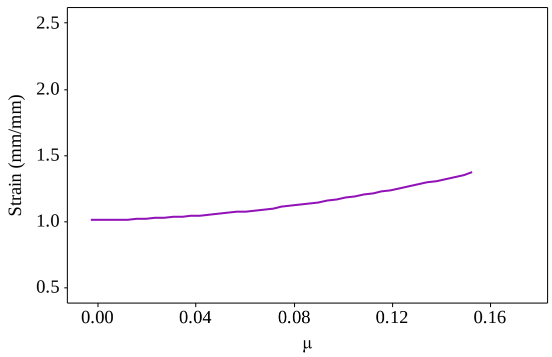
5. 2. 4. Interaction Effects of Parameters Since t has little effect on the output and for brevity, the interaction effect of the other three parameters (i.e. Φ, Ψ



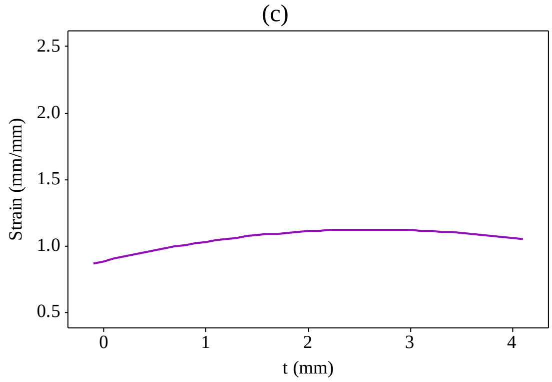
(a)



(b)



(c)



(d)

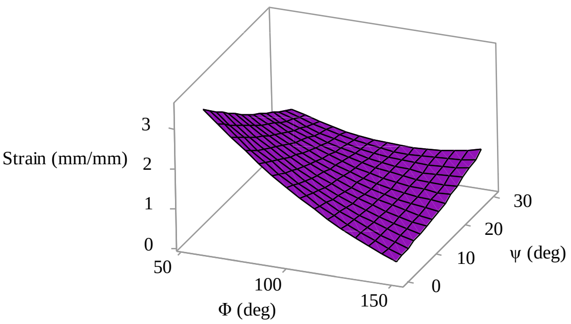
Figure 8. Main effect of a) Φ, b) Ψ, c) μ, and d) *t* on the strain

TABLE 10. Obtained P-value for terms of regression model of strain using the ANOVA

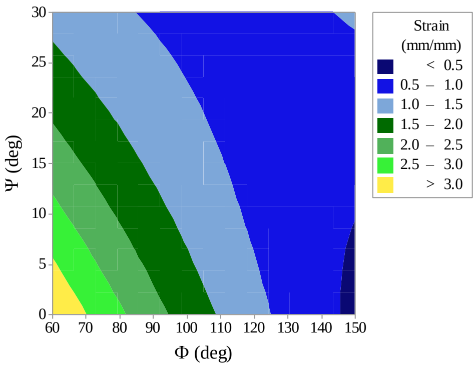
Terms of regression model	P-value
Φ	0.000
Ψ	0.000
μ	0.000
t	0.000
$Φ^2$	0.000
$Ψ^2$	0.000
$μ^2$	0.002
t^2	0.000
Φ×Ψ	0.000
Φ×μ	0.000
Φ×t	0.019
Ψ×μ	0.000
Ψ×t	0.034
μ×t	0.001

and μ) will be examined on the strain. The interaction effect of Φ and Ψ on the strain is shown in Figure 9 by surface and contour plots. It can be seen that increasingΦ in the lower values of Ψ has led to significant reduction in the strain, whereas in the larger values of Ψ, have not significant effect on the strain. Also, by increasing Ψ in all values of Φ, the strain decreases but the effect of Ψ is more significant in the lower values of Φ. As shown in Figure 9(b), lower Φ and Ψ values are required to achieve high strain.

Figure 10 shows the interaction effect of Φ and μ on the strain. By increasing Φ, the strain reduces in all values of μ. Also, contrary to larger values of Φ, the strain enhances sharply by increasing of μ in the lower values of Φ. The contour plot also shows that the highest strain is obtained at low values of Φ and high values of μ.

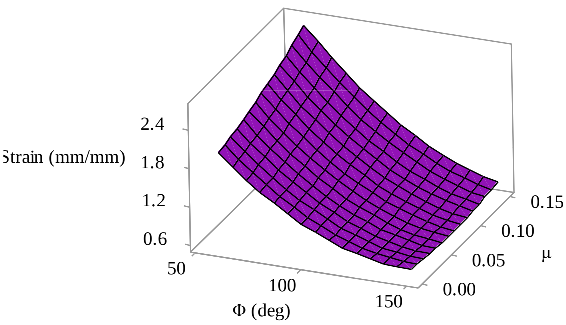


(a)

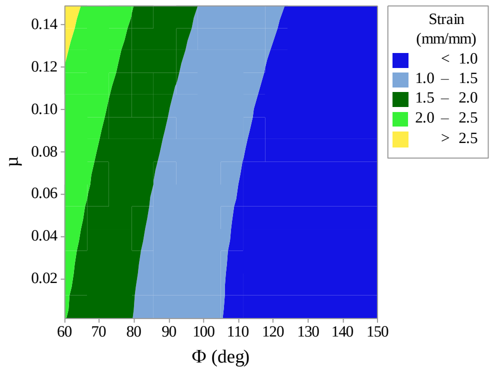


(b)

Figure 9. Interaction effect of Φ and Ψ on the strain a) surface plot b) contour plot



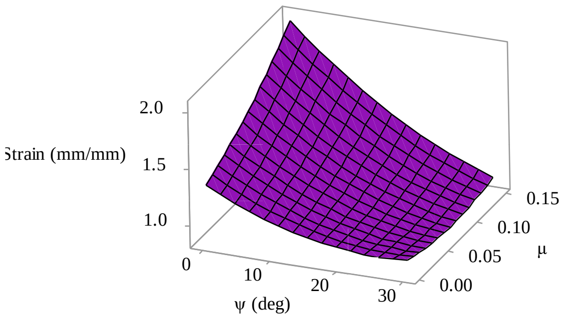
(a)



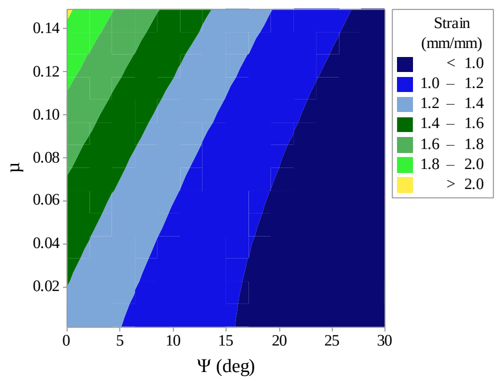
(b)

Figure 10. Interaction effect of Φ and μ on the strain a) surface plot b) contour plot

Also, the interaction effect of Ψ and μ on the strain is presented in Figure 11 by surface and contour polts. According to Figure 11, increasing Ψ decreases the strain, while its effect is more significant in the larger values of μ. The increasing μ in the lower values of Ψ causes increasing the strain. But in the larger values of Ψ, there is no significant effect of μ on the strain. The strain increases by decreasing Ψ and increasing μ.



(a)



(b)

Figure 11. Interaction effect of Ψ and μ on the strain a) surface plot b) contour plot

6. OPTIMIZATION

Based on the prediction of Minitab software using the RSM method, the optimal conditions for minimizing the maximum required force and maximizing the strain are Φ=93.64°, Ψ=0°, μ=0.001, and t=1.62 mm. Under these conditions, the maximum force and strain are obtained 32.65 N and 1.72, respectively, by presented regression models.

7. CONCLUSION

In this study, a verified finite element simulation of the ECAP process of billet with the casing was studied. RSM was implemented in order to the investigation of the process in proposed 31 tests. The channel angle, corner angle, friction coefficient, and the casing thickness of the samples were introduced as variable parameters and the maximum force and strain were considered as the output parameters. The most important results are listed below:

- The most effective parameters in the order of significance on the maximum force are: channel angle, friction coefficient and corner angle.
- The most effective parameters in the order of significance on the strain are: channel angle, corner angle and friction coefficient.
- The thickness of copper casing has almost no significant effects on the maximum force and strain.
- The required forming force was reduced by increasing channel and corner angles and decreasing the friction coefficient.
- The strain was increased by decreasing channel and corner angles and increasing friction coefficient.
- The high accuracy regression models for estimating the required force and strain were obtained using ANOVA results.
- The interaction effects of parameters were investigated and it was revealed that the minimum required force is obtained at high values of Φ and low values of Ψ.
- The interaction effects of parameters showed that the maximum strain is obtained at low values of Φ and Ψ.
- The optimal conditions for reducing the maximum required force and increasing the strain in the ECAP process were predicted as Φ=93.64°, Ψ=0°, μ=0.001, and t=1.62 mm.

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Persian Abstract

چکیده

در این کار، فرآیند اکستروژن در کانال‌های هم مقطع زاویه‌دار برای میله آلومینیوم ۷۰۷۵ با پوشش مس بطور کامل بررسی شده است. ابتدا این فرآیند با استفاده از مدل اجزای محدود توسط نرم افزار آباکوس شبیه‌سازی شده و سپس صحت‌سنجی مدل در مقایسه با نتایج تجربی تایید شده است. به منظور بررسی تاثیر پارامترهای فرآیندی، طراحی آزمایش‌ها به وسیله روش رویه پاسخ صورت گرفت و تاثیر چهار پارامتر در نظر گرفته شده(زاویه کانال، زاویه گوشه، ضریب اصطکاک و ضخامت پوشش) بر روی حداکثر نیروی مورد نیاز و کرنش مورد مطالعه قرار گرفت. همچنین با استفاده از تحلیل واریانس، مدل رگرسیونی با قابلیت اطمینان بالا برای برآورد حداکثر نیرو و کرنش ارائه شده است. نتایج نشان داد که زاویه کانال تاثیرگذارترین پارامتر بر روی حداکثر نیروی مورد نیاز می‌باشد که به میزان ۹۳/۵٪ مشارکت دارد. آشکار گردید که ضخامت پوشش مسی تاثیر قابل ملاحظه‌ای بر روی نیروی شکل‌دهی نداشته است. همچنین مطابق نتایج بدست آمده مشخص شد که تمامی متغیرهای ارائه شده در مدل رگرسیون بر میزان کرنش تاثیر می‌گذارند. نتایج آنالیز واریانس نیز حاکی از این است که زاویه کانال و خم گوشه به ترتیب با ۸۰ و ۱٦ درصد مشارکت، موثرترین پارامترها بر روی کرنش می‌باشند و تقریبا تاثیر پارامترهای ضریب اصطکاک و ضخامت پوشش مسی قابل چشم‌پوشی هستند.