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Research Article

Strain Distribution in Equal Channel Angular Pressing of AM60 Magnesium Alloy

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ABSTRACT

In this research, the equal channel angular pressing (ECAP) process of AM60 magnesium alloy was investigated by the finite element simulation as well as experimental test. The effect of process parameters on required force and strain distribution was also assessed. The simulation results were verified by the experimental tests. Using the full factorial design of experiments, effects of friction and process temperature were explored. The results indicated that an increase in the friction coefficient will significantly enhance the amount of pressing force (4-fold). Also, the effect of friction on process force was higher at lower temperatures and decreased with the rise of temperature. An increment in the friction coefficient from 0.02 to 0.08 raised the maximum strain by 9%. Furthermore, the maximum strain showed enhancement with temperature elevation.

1. Introduction

Researches over the past decades have shown that ultrafine-grained and nanostructured materials can offer extraordinary properties to meet the needs of various industries [1]. One of the mechanical methods developed for producing the ultrafine-grained materials is the equal channels angular pressing (ECAP) process. ECAP is a severe plastic deformation process first introduced by Segal et al. in the 1970s and 1980s [2]. This technique applies a die with two angularly-spaced cross-sectional channels. After locating the specimen inside the channel, it passes through the angled channel under the pressing pressure. Structural modification occurs during the passage through the corner of the two-channel joint under a relatively large shear strain resulting in the microstructure refinement of the sample and improvement of its mechanical properties [3-4]. The success of this method highly depends on selecting the right parameters and the proper design of the die. The microstructure and mechanical properties of processed Mg alloys have been extensively studied [5-8]. The significant reduction in grain size in this process may be attributed to the recrystallization phenomenon of AM60 Mg alloy [9-11]. Moreover, the increased strength and improved fatigue behavior of Mg alloy in the ECAP process can promote its potential usage in various industries [12-14]. However, non-uniform strain distribution in the sample section is considered as the deficiency of this procedure [15-17]. Besides experimental works, simulations and computational analyses should also be used to select proper parameters and better understand the behavior of material deformation. Finite element (FE) is a powerful method for analyzing the metal forming processes such as ECAP

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[18-22]. In recent years, magnesium alloys have been considered a promising candidate for automotive, military, electronics, aerospace, and special medical applications due to its excellent properties such as high strength-to-weight ratio, good recyclability, resistance to heat changes as well as biocompatibility and corrosion resistance in body fluids [23-28]. Some researchers have simulated the effect of ECAP process parameters for magnesium alloys. Hu et al. [29] studied the impact of die parameters on the strain distribution in ECAP of AZ31 magnesium alloy. They expressed that the die with an inner round corner and the channel angle of 90^{o} can offer homogenous deformation. Ren et al. [30] simulated the ECAP process of AZ31 magnesium alloy using the finite element method. They predicted the microstructure evolution in the process. Figueiredo et al. [31] studied the ECAP processing of ZK60 magnesium alloy. They demonstrated that segmentation during the ECAP may be decreased by increasing the channel angle and strain rate sensitivity. Also, their FE simulation indicated that strain distribution is related to the channel angle and strain rate sensitivity. So that a decrease in the strain rate sensitivity and increase in the channel angle led to strain more uniform distribution.

So far, the interaction effect of the friction coefficient and operation temperature on the strain distribution in the ECAP of magnesium alloys have not been investigated by the researchers. Regarding the advantages and importance of magnesium alloys, in this study, the ECAP process for the AM60 magnesium alloy was numerically simulated using the ABAQUS finite element software which was further validated by experimental tests. Then, the effect of operating temperature and friction coefficient on the strain and required force are also addressed.

2. Experimental Procedure

Materials used in this study include casting magnesium alloy AM60-B (containing magnesium 93.74, aluminum 5.82, manganese 0.297, zinc 0.110, calcium 0.024, copper 0.0061, Iron 0.003wt.%). Initial cylindrical samples with a diameter of 12 mm and length of 80 mm, were processed using the turning operation. ECAP die has an L-shape rounded cavity with a diameter of 12 mm, channel angle of $\Phi = 90^{o}$, and the corner angle of $\Psi = 20^{o}$. Since the ECAP process needed a high amount of load, the die should be designed in a way that it could maintain its sustainability under high load and pressure. To hold and keep two pieces of die in the adjacent, shell steel with a conical angle was used and mounted on a steel tray (Fig. 1-a). The ECAP die was employed to perform the experimental process. The die model was a semi-cone with two perfectly symmetrical pieces, which were cut by half. The circular cross-section of the channel with a 12-mm diameter was machined by a CNC milling machine. Finally, two symmetric pieces were joined together and the desired channel was made with 0.02 mm tolerance. The considered die is shown in Fig. 1-b.

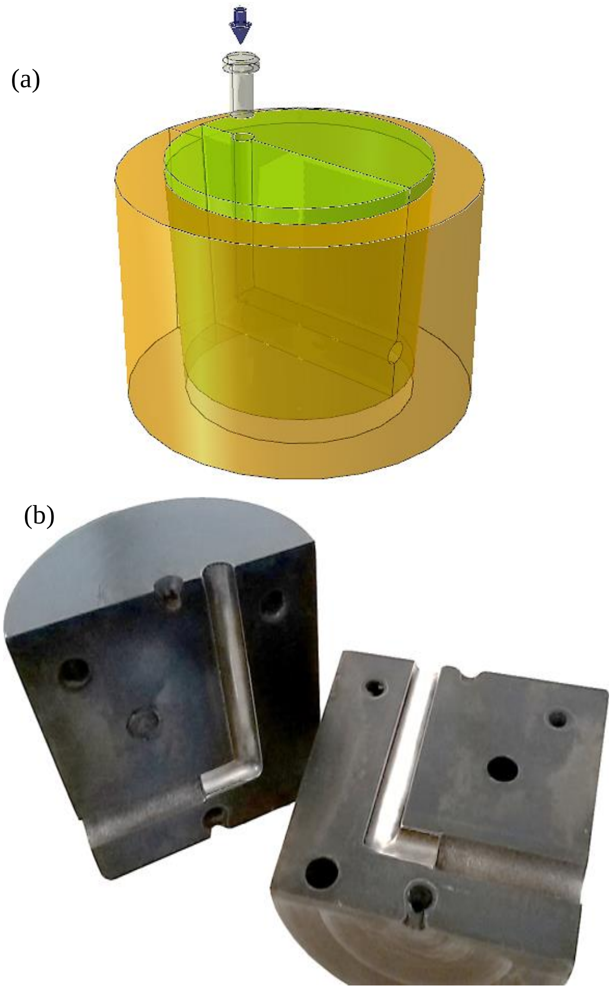

Fig. 1. Schematic of a) set of ECAP die b) insert of ECAP die with cylindrical channel c) A sample processed by the ECAP.

(c)

Fig. 1. Continue

The die material was selected from tools steel (H13), which underwent a thermal process to obtain 54RC hardness. Then, the inner section of the channel was polished and the die was hardfaced using the nitration process to obtain 62RC hardness. Nitration is a superficial process used to increase hardness, wear resistance, corrosion, and fatigue strength. Therefore, the nitration process was carried out to prevent the malfunction of die due to the possible contact of punch with the inner surface of the channel and scalding due to the frictional force between the specimens. Also, the shell and tray were tools steel (H13).

The die should be heated to reach the desired temperature to carry out the process at temperatures higher than room temperature. In doing so, the ceramic heater system was employed. The temperature could be adjusted and controlled by a thermocouple mounted on the die. In the ECAP process, the required force was applied to the sample by servo-hydraulic press machine (SANTAM – STD 1000) with a rated capacity of 100 tons and useful courses of 300 mm. The machine had a load cell device to measure the pressing force and derivate the force-displacement curve. To elevate the temperature of tested specimens, an Exciton-Atash 1200 electric furnace with a temperature range of 100 to 1200°C (accuracy of ±10°C) was used. For the ECAP process, first, the sample was placed in the furnace to reach the desired temperature. At the same time, by placing the die on the lower jaw of the press machine, the direction of the punch was adjusted with the die channel; they were lubricated by the desired lubricant. Afterward, the ceramic heater was also adjusted to the required temperature and the die temperature was raised to the required value. The piece was immediately immersed in the lubricant and placed in the die process. The isothermal condition between piece and die was established by restarting the pressing process at the speed of 10mm/min after a short pause and the temperature was measured by a digital thermometer. Eventually, a sample processed by the ECAP is shown in Fig. 1-c.

3. Simulation of the process

ABAQUS 6-11 finite element software was used to simulate the ECAP process. In this modeling, the workpiece was considered as a ductile cylindrical sample, but due to the slight deformation of the die in the experimental state, it was considered rigid. The experimental observation of the present study showed insignificant die deformation during the process. Therefore, in designing the geometry of the die in a simulation environment, die was considered as a discrete rigid body resulting in a reduction of analysis time. Finally, the desired model for die and punch was designed in the tubular and cylindrical shell, respectively. Besides, the dimensions and geometry of the die were considered in accordance with the die in the experimental method, such that the diameter and length of the billet sample were 12 and 88 mm, respectively. Moreover, the diameter of the channel was 12mm, external angle (φ) was set to 90° and the internal angle (ψ) was adjusted at 20°. To determine the contact condition, the friction type was Coulomb and the friction values varied according to the design of the test. Stress-strain curves of AM60 alloy in different temperatures were considered to assess the mechanical behavior of the material [18]. To mesh billet piece, 8-node cube element (C3D8R) and 1760 elements were employed. Fig. 2 depicts the finite element model of the process and the meshing of the initial billet. In order to identify the optimal mesh size for modeling, the sensitivity to mesh was evaluated by calculating the amount of force required for the process. According to the relationship between the size of elements and the amount of force required for the process in simulation (Fig. 3), the force value was stable in elements with 2mm and smaller size. Therefore, an optimal mesh size of 2 mm was considered in the simulation process.

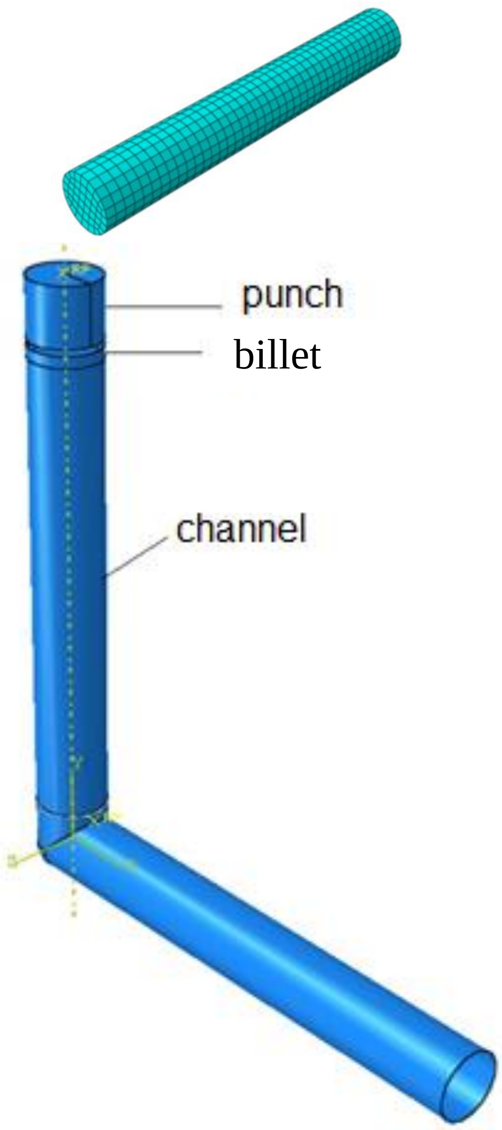

Fig. 2. Finite Element Modeling and meshing for simulating the ECAP process.

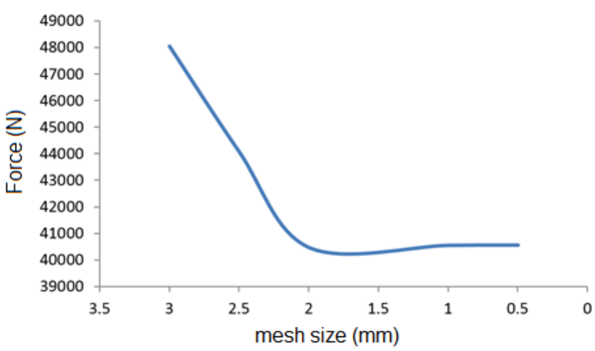

Fig. 3. Mesh sensitivity diagram via process force.

The effect of friction coefficient and process temperature was also addressed by designing 12 tests according to a full factorial design. Based on Table 1, three temperature levels (180, 250, and 320°C) were considered in all tests. Also, the Coulomb friction coefficient was applied at 4 levels (0.02, 0.04, 0.06, and 0.08).

Table 1. Design of experiments

Exp. No	Friction coefficient (μ)	Temperature (°C)
1	0.02	180
2	0.04	180
3	0.06	180
4	0.08	180
5	0.02	250
6	0.04	250
7	0.06	250
8	0.08	250
9	0.02	320
10	0.04	320
11	0.06	320
12	0.08	320

4. Results and Discussion

In this section, the results of the simulation tests are evaluated and the variations of the force and strain distribution are discussed and analyzed.

4.1. Verification of the simulation

The simulation results were verified by their comparison with the experimental findings at 250°C (Fig. 4). As seen in Fig. 4, the simulated force variation is almost the same as the experimental one. The difference between the force values could be due to the non-real boundary conditions of the simulation process (such as friction coefficient). In the process simulation, the Coulomb friction coefficient value was considered as 0.08.

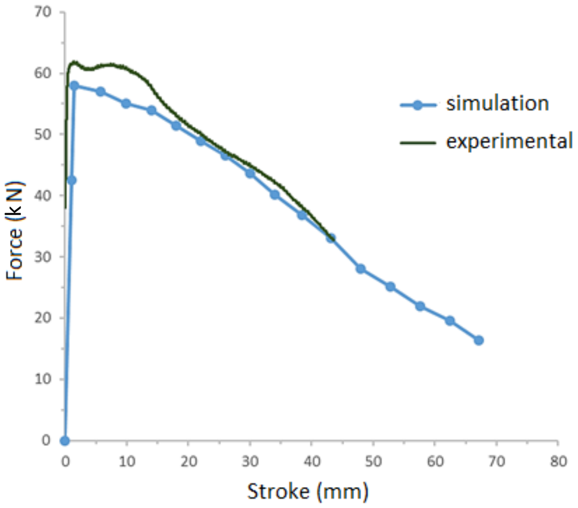

Fig. 4. The variations of force-displacement for experimental and simulation process.

4.2. Force of the process

The results showed the significant effect of two parameters (temperature and friction) on the required force of pressing. As shown in Fig. 5, the increase in the friction coefficient led to an increase in the required force of the process, and the highest value was obtained at a friction coefficient of 0.08. However, the increase in temperature has significantly declined the force required for the ECAP process, which can be assigned to an increase in temperature giving rise to an increment in the slip systems and their activation in the material, thus the material needed less stress to yield. On the other hand, an increase in temperature provided a condition for grain growth. Thus upon the dynamic recrystallization of the material during the ECAP process, the main factor would be the growth of new microstructured grains. Therefore, temperature control plays a decisive role in the process. Accordingly, it not only should be effective in reducing the required force of the process but also it should prevent the growth of the grains; as by growing the material's grain size, the mechanical properties will be significantly reduced.

Analysis of variance was used for a more accurate analysis of the tests. To this end, the normal distribution of data was evaluated by the Anderson–Darling method [32]. Then, the effect of temperature and friction coefficient on the process force was analyzed by ANOVA to evaluate the main and interactive effect.

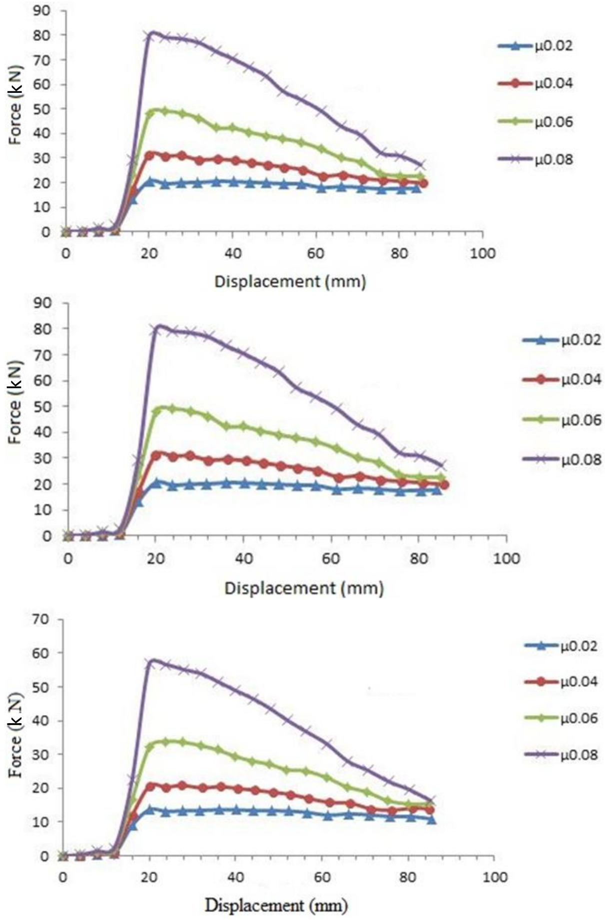

Fig. 5. The process force at different temperatures a) 180 ℃ b) 250 ℃ c) 320 ℃.

The normal distribution of the data was confirmed according to Fig. 6 and the p-value obtained from the Anderson- Darling test (P-value> 0.05). The analysis of variance relative to the p-value is shown in Table 2. Accordingly, operation temperature and coefficient of friction (μ) affected the force. Moreover, considering the R-Sq value over 90%, the model is sufficiently adequate.

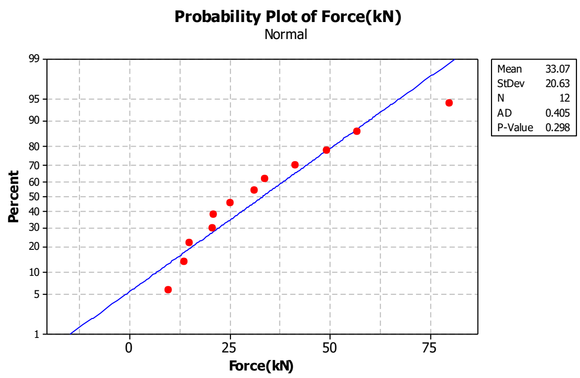

Fig. 6. The diagram of the normal distribution for the process force.

Table 2. ANOVA results for Process force

Source	DF[1]	Seq SS[2]	Adj SS[3]	Adj MS[4]	F[5]	P-value[6]
μ	3	3447.02	3447.02	1149.01	31.83	0.000
Temperature	2	1018.48	1018.48	509.24	14.11	0.005
Error	6	216.56	216.56	36.09		
Total	11	4682.06				
S = 6.00780 R-Sq = 95.37% R-Sq(adj) = 91.52%						

[1] Degrees of freedom, [2] Sequential sum of squares, [3] Adjusted sums of squares, [4] Adjusted mean squares, [5] Factor effect, [6] Probability value

The main effect graphs show some differences between level means for the parameters. The main effects of parameters for the force are shown in Fig. 7. As seen in Fig. 6, an increase in friction coefficient from 0.02 to 0.08 resulted in a 4-fold increase in the force, which showed the important role of friction and type of lubricant on ECAP process of magnesium alloy. This result is in line with the reports in Refs [33-34]. Moreover, by increasing temperature from 180 to 320° C the required force almost became half. Fig. 8 depicts the interaction effects of parameters indicating the higher effect of friction on process force at lower temperatures.

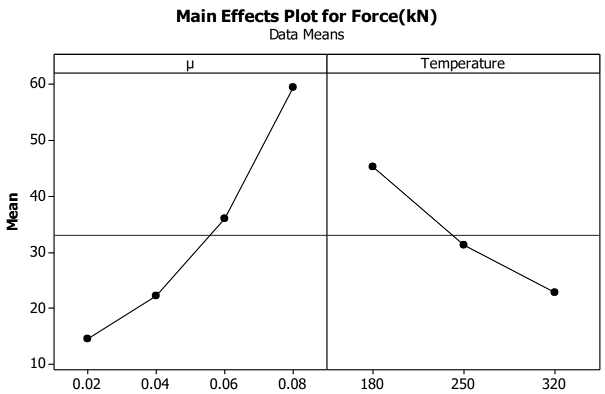

Fig. 7. The diagram of the main effects for the process force.

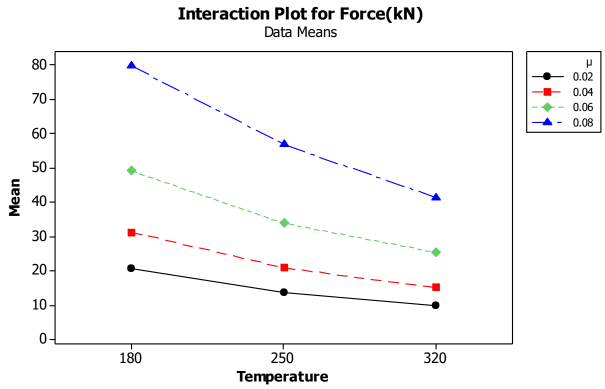

Fig. 8. The diagram of the interactive effect of the parameters.

4.3. Distribution of strain

As mentioned, the ECAP process is principally based on the application of severe plastic strain. The applied strain modifies the material structure and, as a result, improved the mechanical and metallurgical properties. According to the geometry of the die and the flow of matter inside the channel, the applied strain can differ, and usually has a non-uniform distribution. As shown in Figs. 9-11, the friction between the inner surface of the channel and the specimen filled the corners of the channel leading to a larger deformation. In other words, the filling of the channel corners with the material flow during the process resulted in higher plastic shear strains on the sample section, which is desirable for the process. Evidence also suggested more strain in the upper half of the sample for all conditions, due to the small amount of bending in the specimen during the passage from the outer corner of the channel, while in the upper half, the material it is almost subjected to shear strain. Despite the effect of the little amount of friction on corner filling [35]. An increase in friction results in a significant increase in the required pressing force deteriorating the conditions for the successful operation. It is necessary to choose an appropriate lubricant to reduce the friction coefficient in the process. The deeper evaluation demonstrated that with an increase in friction coefficient, the maximum strain is also increased, which results in more non-uniform strain distribution. However, an increase in temperature has no significant effect on maximum strain and uniformity of strain distribution.

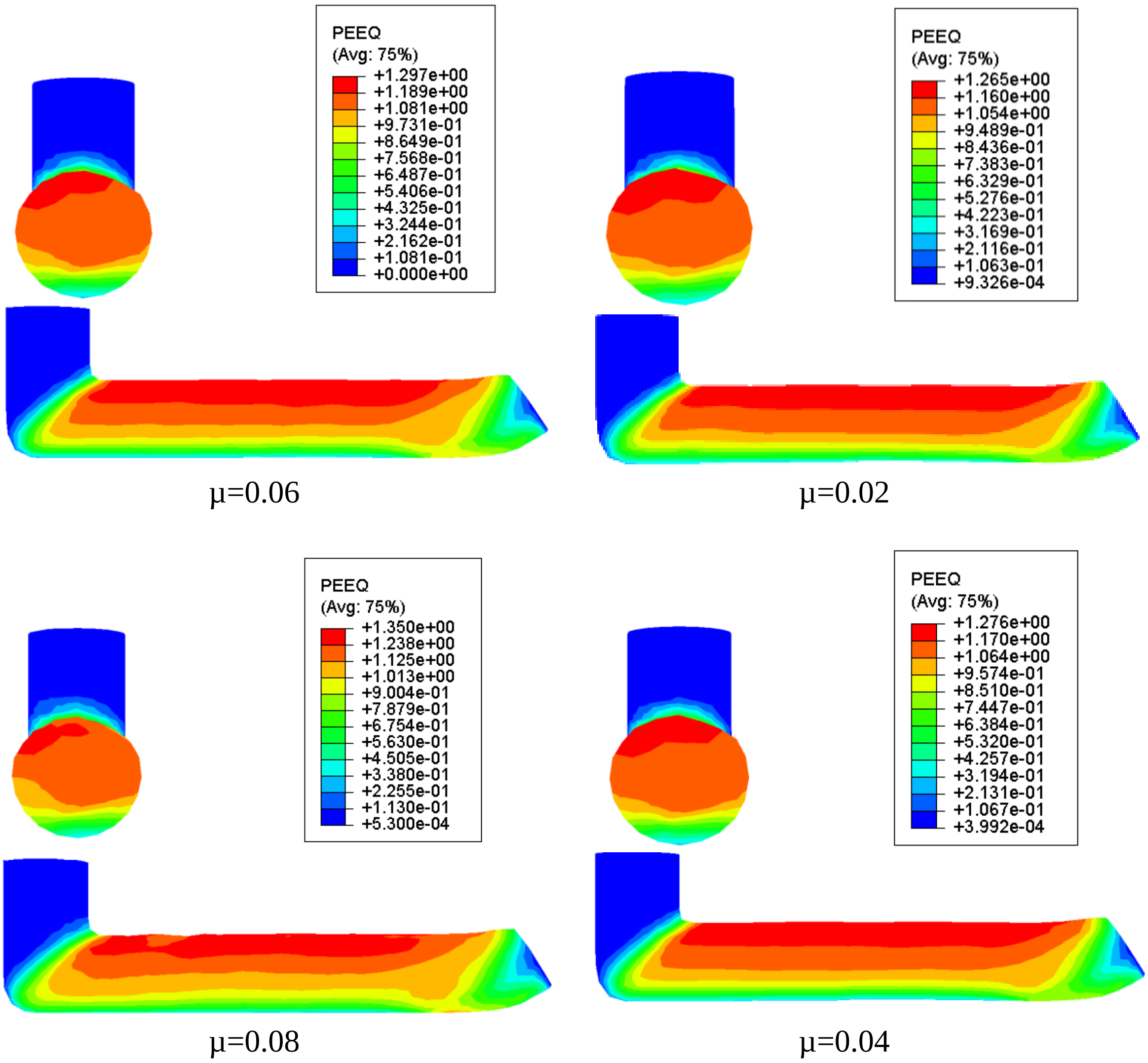

Fig. 9. The strain distribution in different friction coefficients at the T=180°C.

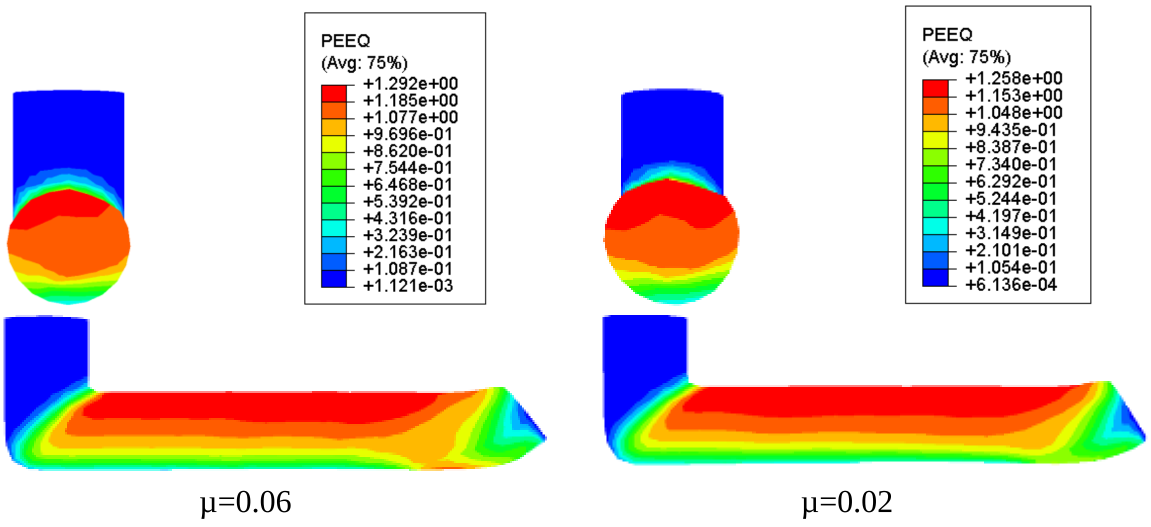

Fig. 10. The strain distribution in different friction coefficients at T=250°C.

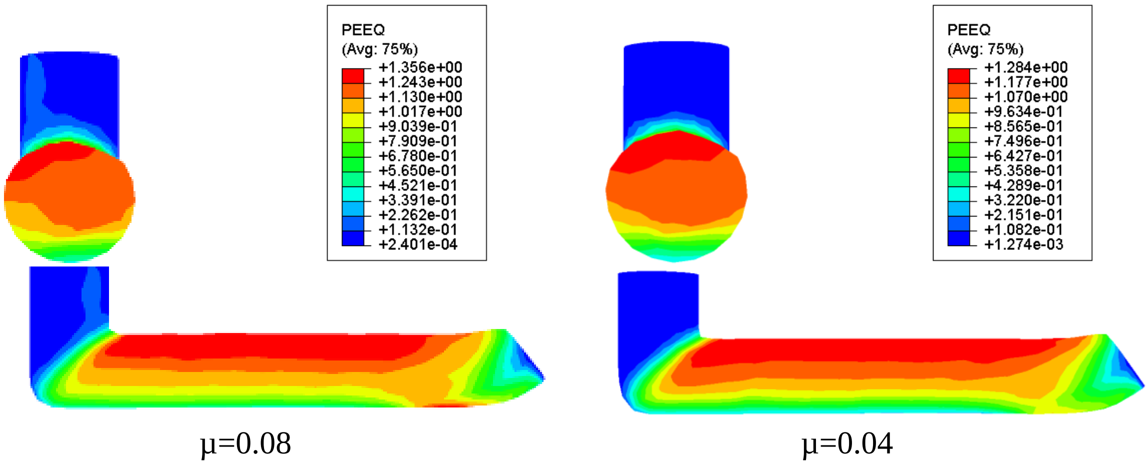

Fig.10. continue.

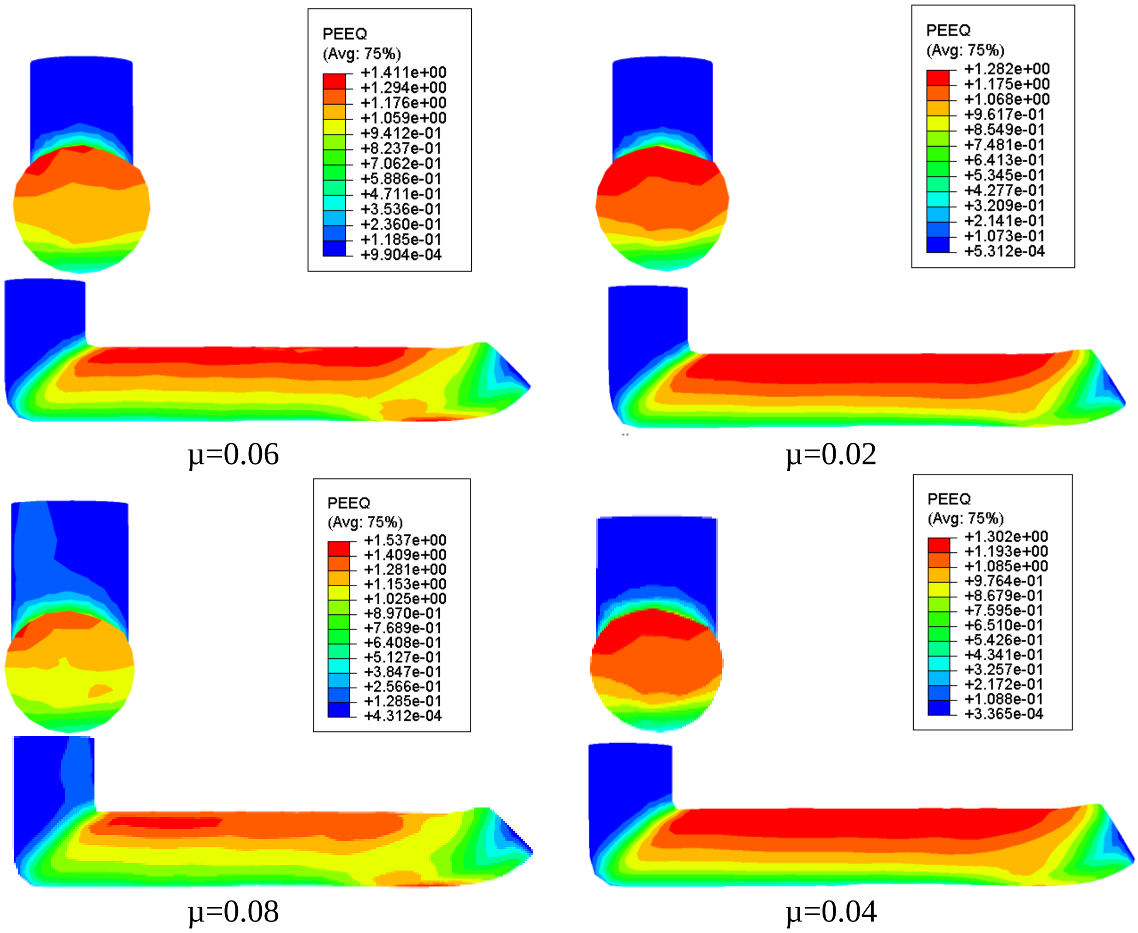

Fig. 11. The strain distribution in different friction coefficients at T=320°C.

The strain values of the designed die to model and theoretically calculate at different temperatures and different friction values are presented in Fig. 12. By considering the die geometry, the strain value in a pass was shown in Eq. 1, which was introduced by Iwahashi [36]. In this work, by considering the geometry parameter, the value of the strain reached one. The strain value is shown in Fig. 12 at a constant linear and independent of temperature and friction coefficient. While the maximum applied strain on the piece is increased by increasing the friction [37-38].

$$\varepsilon_N = \frac{N}{\sqrt{3}}\left(2\cot\left(\frac{\varphi+\psi}{2}\right) + \psi \csc\left(\frac{\varphi+\psi}{2}\right)\right) \qquad (1)$$

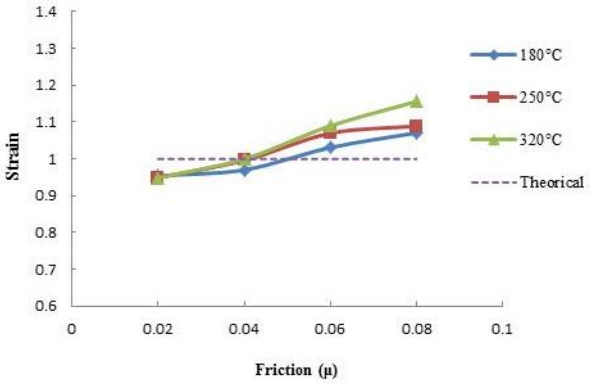

Fig. 12. The strain values for theoretically modeling at different friction and temperature.

Similar to force data analysis, the normal distribution of data was evaluated to carry out a statistical analysis of maximum strain data. According to Fig. 13 and the p-value obtained from the Anderson- Darling test ($p>0.05$), the data are normally distributed. The analysis of variance for data with respect to the p-value is shown in Table 3. Accordingly, operation temperature and coefficient of friction (μ) significantly affected the force.

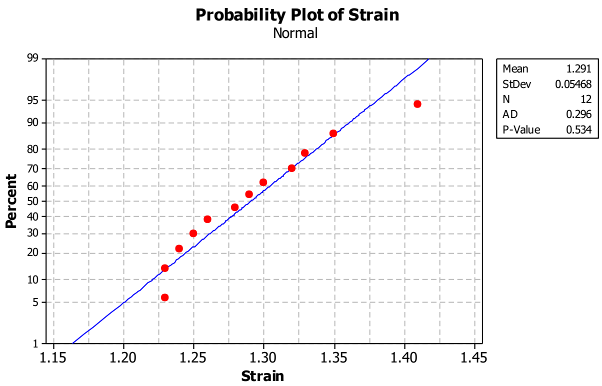

Fig. 13. The diagram of the normal distribution for the strain.

Figure 14 shows the main effects of parameters on the maximum strain. Accordingly, by increasing the friction coefficient from 0.02 to 0.08 the maximum strain showed an increment from 1.25 to 1.36 (9%) reflecting the effect of friction and lubricant on strain value obtaining from the ECAP process of magnesium alloys. This can be assigned to the filling of the corner of the die by material flow due to an increase in friction between piece and channel and applying more concentrated and higher strains to the sample's cross-section leading to more plastic deformation. Similar results were reported in Refs [33] and [34]. However, operation temperature has no significant effect on the strain, so that an increase in the temperature from 180 to 320°C enhanced the strain from 1.25 to 1.32 (6%).

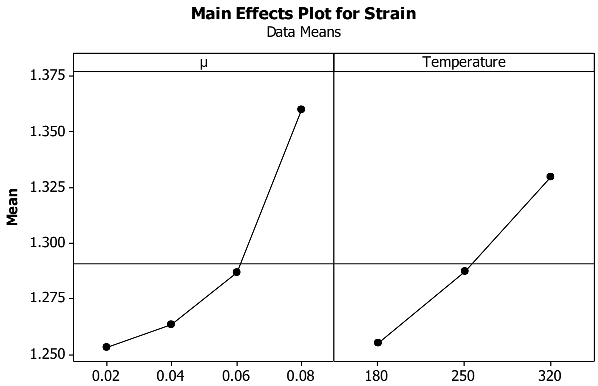

Fig. 14. The diagram of main effects for strain.

Figure 15 shows the interactive effects of the parameters. It is observed that the effect of friction on the maximum strain at different temperatures is approximately the same.

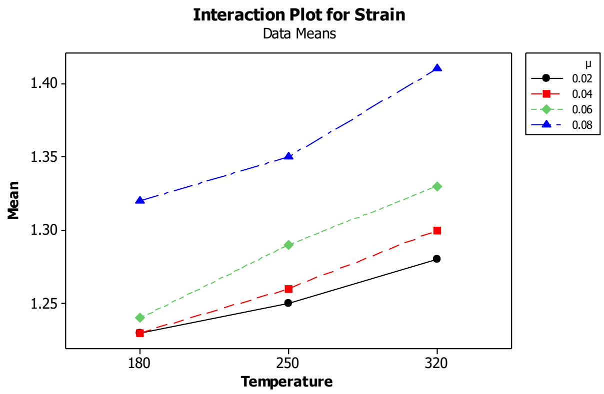

Fig. 15. The diagram of the interactive effect of parameters on the strain.

Table 3. ANOVA for strain

Source	DF	Seq SS	Adj SS	Adj MS	F	P
μ	3	0.0208917	0.0208917	0.0069639	61.15	0.000
Temperature	2	0.0113167	0.0113167	0.0056583	49.68	0.000
Error	6	0.0006833	0.0006833	0.0001139		
Total	11	0.0328917				
S = 0.0106719	R-Sq = 97.92%	R-Sq(adj) = 96.19%				

5. Conclusion

In this study, the effect of temperature and friction parameters in the ECAP process of AM60 magnesium alloy was investigated both experimentally and numerically. By designing and implementing the necessary tests, the force of pressing and strain distribution were analyzed using ANOVA, and main and interactive diagrams.

In general, the results can be summarized as follows:

1- The comparison of the force curve, obtained from simulation and experimental tests, confirm the accuracy of the simulation.

2- By increasing the friction coefficient, the pressing force was significantly enhanced (4-fold). Besides, the effect of friction on the process force was higher at lower temperatures, i.e. the process force declined by raising the temperature.

3- By increasing the friction coefficient from 0.02 to 0.08, the maximum strain value showed a 9% increment reflecting the effect of the friction and lubricant on the strain obtained from the ECPA process of magnesium alloys. Moreover, an increase in the temperature led to strain enhancement as well.

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