

An investigation of force and pressure analysis during the process of equal channel angular pressing to M1 copper using finite element and upper-bound methods

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ABSTRACT

This article presents two methods to determine pressing forces to the M1 copper plate. The first approach employs the upper-bound method, and the second method combines numerical simulation with a central composite design. The upper-bound method uses physical analysis to determine the deformation zone and establish the division of the rigid block model. The findings were identical to the slip-line solution method. The results obtained from the three-dimensional simulation performed using Qform software combined with a central composite design have provided regression equations that help determine the force and punching pressure. The impact of each parameter on the pressing force is similar in both approaches, and the difference between the two methods is insignificant and falls within a dependable range.

Keywords: ECAP; Central composite design; M1 copper; Upper-bound method; Finite element method.

1. INTRODUCTION

Equal Channel Angular Pressing (ECAP) is a method of severe plastic deformation that has been extensively researched for its ability to produce materials with ultrafine-grained (UFG) structure, resulting in improved strength and ductility. Since Segal et al. introduced this technique in 1981 [1], it has been the focus of extensive global research. The principle of the ECAP technique involves pressing the workpiece through a die having two channels intersecting at a fixed angle of Φ (Fig. 1a). During the ECAP operation, the cross-section of the workpiece remains constant, allowing for multi-pass processing of samples to achieve the desired level of accumulated strain, typically in the range of 6–8 [2]. It is also possible to rotate the sample along its longitudinal axis during multiple passes, generating different routes (Fig. 1b) [3]. The process causes strain hardening in the workpiece, resulting in elevated pressure and making the punch breakable, particularly when employing ECAP with metal plates. Therefore, accurately finding the pressing force and punching pressure plays a vital role in improving the mechanical properties of materials and optimizing this technique.

In recent years, there has been a significant amount of research performed using theoretical calculations and Finite Element Method (FEM) to reveal the influence of technological parameters on the outcomes of this technology. Segal et al. [4] used the slip line solution method to determine the compressive stress in the deformation zone as well as the simple shear occurring at different channel angles and friction conditions. Perig and Laptev et al. utilized the upper-bound approach with rigid block models to determine the pressure in the deformation zone, as described in their paper [5, 6]. Despite its simplicity, this method produces erroneous results depending on how the hard blocks are divided in

the deformation zone. It cannot achieve as high a resolution as the slip-line method. The above calculation method needs to be improved to get more accurate results by dividing the deformation zone into small hard blocks.

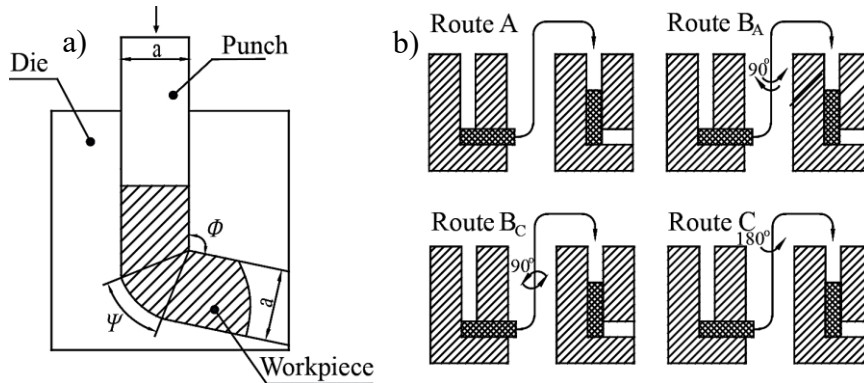


Figure 1. Concept of ECAP (a) and four Basis ECAP routes (b).

In addition to theoretical calculation approaches, the finite element method is commonly utilized to analyze material deformation and behavior in different conditions. The author of the article [7] used the CASFORM-2D/PC software to predict the force graph along the displacement and the distribution of accumulated strain field in the workpiece throughout multiple ECAP processes to aluminum bar-shaped materials. Ghosh et al., in their study [8], utilized the 3D finite element method to analyze the deformation response of an Al-Zn-Mg-Cu alloy subjected to three different ECAP processing routes, including A, B_C, and C. The simulation results significantly enhanced effective plastic strain with ECAP passes for all routes. However, route B_C exhibited better results compared to the other routes. The study described in the report [9] utilized the 3D-Deform software to examine load-displacement behavior, plastic deformation characteristics, and the uniformity of effective plastic strain in Al-1080 deformed by different forming processes, and the simulation result was in good agreement with the experimental results. The results demonstrate that the numerical simulation method can analyze and provide clear and precise outcomes, offering a foundation for conducting experiments.

Nowadays, products made with M1 copper material with an ultra-fine grain are becoming more popular, and ECAP is an effective method of producing this material. In this paper, the 3D-FEM method is employed to determine the force and pressure on the punch when pressing the M1 copper plate. This is compared to the upper-bound method, which is used in conjunction with the deformation zone division method, to evaluate the effect of technological parameters on the ECAP process of M1 copper. QForm software simulates and assesses the influence of various technical parameters, such as plate thickness, friction coefficient, and plate width, on the pressing force and punching pressure.

2. METHODS FOR DETERMINING PRESSING FORCE AND PUNCHING PRESSURE

2.1. Determine the ECAP force by using the upper-bound method

The cross-sectional area of an ECAP plate was divided into six symmetrical zones, as seen in Fig. 2a. Due to the presence of friction between the plate and the die cavity wall, the angle between MB, MC, and channel walls (η) is smaller than 90°, resulting in the formation

of a rigid metal area known as the "dead zone" (zone 4), where the material is not deformed [10, 11]. The zone 3 is a fan-shaped area where severe plastic deformation occurs. To obtain accurate results, the zone 3 was divided into n fan-shaped hard blocks with equal sizes and a central angle β . The zones 1 and 3 represent the regions with a moderate deformation level. The zone 1 and the zone 6 represent the material properties before and after deformation. The velocity distribution at the sliding interfaces of the rigid blocks corresponds to the blocks illustrated in Fig. 2b. It is possible to consider the velocities of the blocks 2 and 5 to be equivalent to those of the blocks 1 and 6. ($v_1 = v_2 = v$) [6].

The shear strength k equals the shear stress on the sliding surfaces of rigid blocks, which is determined by the flow stress σ_s following the equation $k = \sigma_s / \sqrt{3}$. The current study characterizes the frictional properties of the material using the Tresca friction law, which is expressed as $\tau_{yx} = \tau_{xy} = \tau = \mu k$. Here, μ is a friction coefficient between 0 and 1 [6].

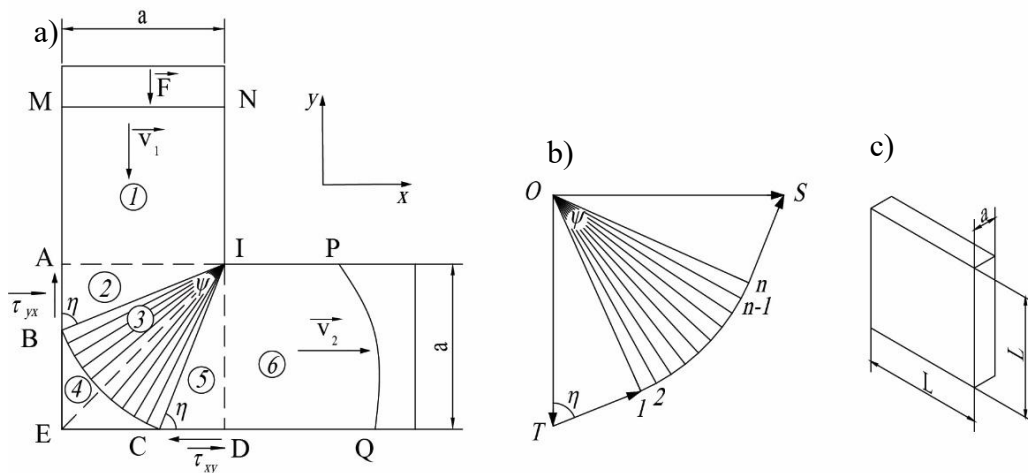


Figure 2. Deformation diagram (a); Velocities hodograph (b); Workpiece (c).

The work balance method was used to determine the punch pressure (p). The sum of the power of the external force is equivalent to the combined power of the internal force due to blocks mutually sliding and the power lost because of external friction:

$$w_{ext} = w_{int} + w_{fri} \quad (1)$$

Where, w_{ext} is the external force power, w_{int} is the internal force power, and w_{fri} is the power lost because of external friction.

Based on the deformation diagram and the corresponding velocities hodograph (Fig. 1a, b), the component values in Formula 1 were determined as follows:

$$w_{ext} = pav \quad (2)$$

$$w_{int} = 2kva \left[\cot \eta + 2n \tan \left(\frac{\beta}{2} \right) \right] \quad (3)$$

$$w_{fri} = 2\tau va \cot \eta + 2\tau vMA + 2\tau v \frac{IP + DQ}{2} \quad (4)$$

It is difficult to accurately measure the lengths of MA, IP, and DQ, so the total length of ME, EQ, IP, and NI is approximately two times the width of the workpiece L .

After substituting the values in Formulas 2, 3, and 4 into formula 1 with the approximate conditions $\tan(\beta/2) \approx \beta/2$; $n \rightarrow \infty$, the relative pressure in the ECAP process can be determined as follows:

$$\frac{p}{2k} = 2\eta - \frac{\pi}{2} + [\mu + 1] \cot \eta + \mu \left(\frac{L}{a} - 1 \right) \quad (5)$$

According to upper bound theory, the minimum of $p/2k$ is the best estimate of real working pressure. The value η that accomplishes the minimum was achieved using the well-known extremum condition $d(p/2k)/d\eta = 0$. Formula 6 can be used to calculate these numbers.

$$\frac{d(p/2k)}{d(\eta)} = 2 - \frac{\mu + 1}{\sin^2(\eta)} = 0 \quad (6)$$

The angle between MB, MC, and channel walls was determined as follows:

$$\eta = \arcsin \left(\sqrt{\frac{\mu + 1}{2}} \right) \quad (7)$$

The relative pressure value obtained by substituting η into formula 5 is:

$$\frac{p}{2k} = 2 \arcsin \left(\sqrt{\frac{\mu + 1}{2}} \right) - \frac{\pi}{2} + \sqrt{1 - \mu^2} + \mu \left(\frac{L}{a} - 1 \right) \quad (8)$$

The relative pressure value $p/2k$ (8) and the angle η (7) are identical to the results obtained from the slip line solution method conducted by Segal et al. [4, 6].

For a specific sample, the punch force in the ECAP technique with a plate of dimensions $a \times L \times L$ is:

$$F = \frac{2aL\sigma_s}{\sqrt{3}} \left(2 \arcsin \left(\sqrt{\frac{\mu + 1}{2}} \right) - \frac{\pi}{2} + \sqrt{1 - \mu^2} + \mu \left(\frac{L}{a} - 1 \right) \right) \quad (9)$$

2.2. Finite element method

In this report, the ECAP technique was conducted in a cold environment with different technological parameters. During the simulation, the friction coefficient (μ) between the workpiece and the tools, as well as the velocity of the punch ($v = 15$ mm/s), were maintained at a constant value. In addition, the potential for heat rise in the workpiece and heat transfer with the tools were considered. The material of the workpiece is M1 copper, and the data was used in the materials library of the established QForm software. The material used for the tool is X12MΦ, which was established in the software and had a hardness of 59 HRC at a temperature of 20 °C. The ECAP simulation employs geometric modeling consisting of two semi-dies, a punch, and a workpiece (Fig. 3).

Formulas 9 show that the force depends on four parameters: a , μ , L , and σ_s . However, the value σ_s remains constant for each material. Therefore, plate width (a), plate thickness (L), and friction coefficient (μ) are some technological factors that change when

conducting the simulation process. The plate width varies between 40 mm and 80 mm. The selected friction coefficient values are 0,1; 0,2; and 0,3 which correspond to good lubrication conditions, moderate lubrication conditions, and bad lubrication conditions when applied at cold temperatures [12]. The plate thickness varies between 6 mm and 12 mm. The result of the simulation is the maximum force throughout the pressing stroke (F_{max}). In addition to determining the force for equipment selection, assessing the punch pressure is also necessary. This parameter plays a vital role in examining the durability and bending of the punch when designing tools.

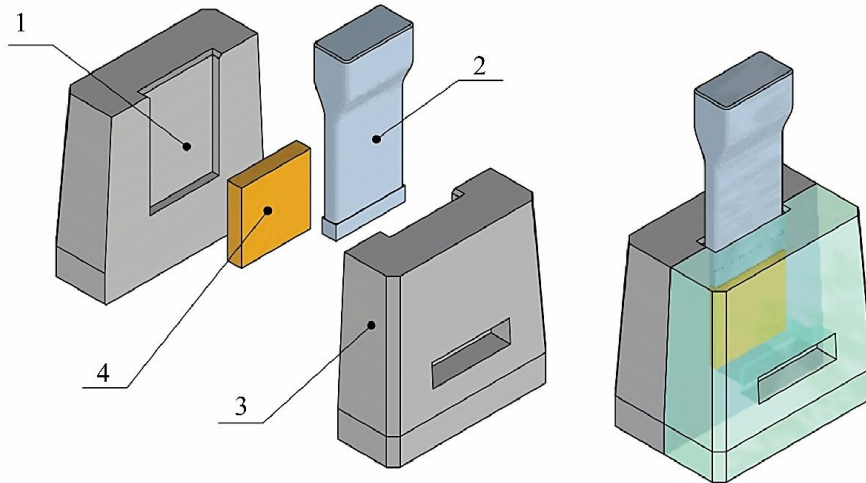


Figure 3. ECAP process geometry model:
1, 3 – Two semi-dies; 2 – Punch; 4 – Workpiece.

The value of the punch pressure is calculated by formula 10:

$$P = \frac{9,81F_{max}}{1000aL} \text{ (MPa)} \quad (10)$$

3. RESULT AND DISCUSSION

3.1. Simulation results

3.1.1. Stress and strain after simulation

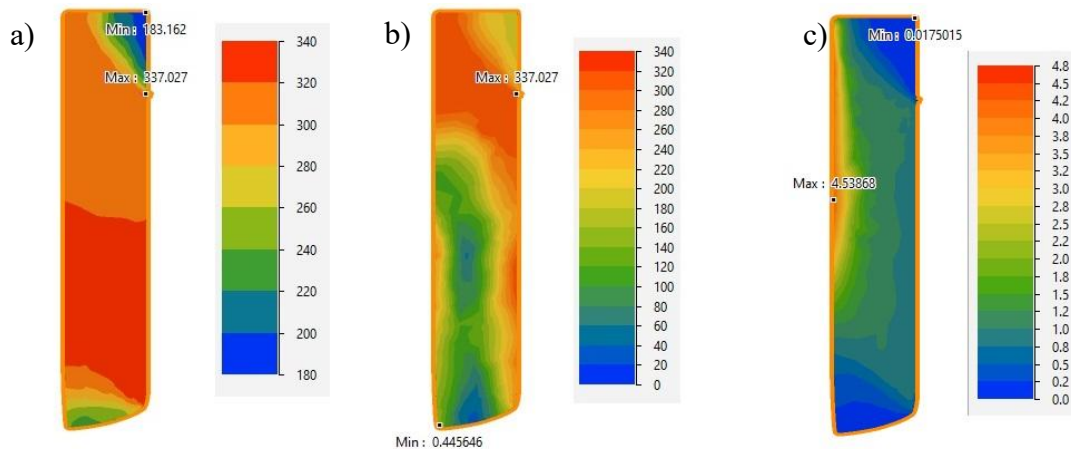


Figure 4. Flow stress (a); Effective stress (b); Plastic strain (c).

The strain stress field is crucial for examining the deformation process and ensuring the product remains without defects. Figure 4 shows the flow stress, effective stress, and plastic strain field of the workpiece with a width of 50 mm, a thickness of 10 mm, a friction coefficient of 0,2, and a pressing speed of 15 mm/s. The highest flow stress value is 337 MPa, while the lowest is 183 MPa. However, most of this value falls from 300 MPa to 340 MPa throughout the product. The stress reaches its highest value of 337 MPa near the channel corner, where server plastic deformation occurs. The plastic strain value at the bottom of the workpiece reaches a maximum of 4,5. However, this value often falls within 0,5 to 1,5 for all positions when pressed once. Thus, to attain significant accumulated strain, it is imperative to carry out the process 6 to 8 times.

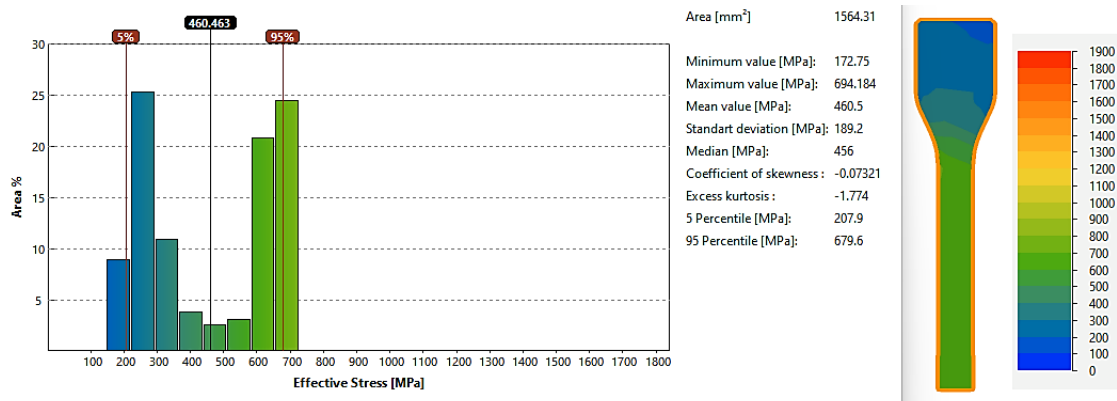


Figure 5. Effective stress field on the punch.

Figure 5 displays the stress in the punch at the point of maximum force. The maximum value reaches 694 MPa, while the minimum is 172 MPa. The significant stress value ranges from 600 MPa to 690 MPa. The value falls within the permissible range for the tool material.

3.1.2. Central composite design matrix

The central composite method in the traditional response surface technique makes accurate predictions across the whole design space. Also, it is easy to find and design points that are outside the range for simulated ($\pm\beta$). This article used this methodology to predict the pressing force and pressure formula to control the technological parameters.

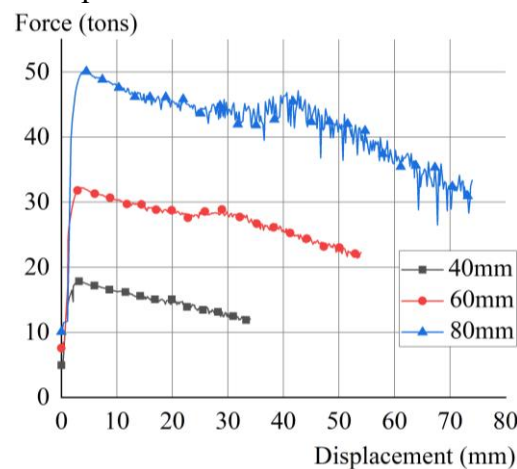


Figure 6. Force-displacement relationship during ECAP.

Figure 6 illustrates the force-displacement relationship for three workpieces of varying widths, providing a historical overview of the forces exerted on the punch. The friction coefficient and thickness values are set to central values. In the initial stage, the force rapidly increases, reaching its maximum value at approximately 3 - 5 mm from the beginning of the stroke (when performed at a velocity of 15 mm/s). Subsequently, the force decreases linearly because the surface area of contact between the workpiece and the die decreases due to more metal escaping through the outlet channel. The results of the compression procedures using various technological parameters, as per the central composite design matrix, are presented in tables 1 and 2.

Table 1. Value of coded variables.

Parameters	Symbol	Variation level				
		Lowest	Low	Center	High	Highest
		$-\beta$	-1	0	+1	$+\beta$
Thickness (a), mm	x_1	3,955	6	9	12	14,045
Friction coefficient (μ)	x_2	0,032	0,1	0,2	0,3	0,368
Width (L), mm	x_3	26,364	40	60	80	93,636

Table 2. Central composite design matrix with coded and actual variables.

No.	Coded variables			Actual variables			Simulating measured responses	
	x_1	x_2	x_3	s (mm)	μ	L (mm)	Force (Tons)	Pressure (MPa)
1	-	-	-	6	0,1	40	13,97	571,024
2	+	-	-	12	0,1	40	23,53	480,894
3	-	+	-	6	0,3	40	21,74	888,623
4	+	+	-	12	0,3	40	31,74	648,686
5	-	-	+	6	0,1	80	35,09	717,152
6	+	-	+	12	0,1	80	54,13	553,141
7	-	+	+	6	0,3	80	65,47	1338,043
8	+	+	+	12	0,3	80	85,1	869,616
9	-1,682	0	0	3,955	0,2	60	27,28	1127,866
10	1,682	0	0	14,045	0,2	60	51,92	604,391
11	0	-1,682	0	9	0,032	60	24,75	449,625
12	0	1,682	0	9	0,368	60	54,63	992,445
13	0	0	-1,682	9	0,2	26,364	13,34	551,530
14	0	0	1,682	9	0,2	93,636	75,94	884,005
15	0	0	0	9	0,2	60	39,15	711,225
16	0	0	0	9	0,2	60	39,79	722,852
17	0	0	0	9	0,2	60	39,61	719,582
18	0	0	0	9	0,2	60	39,29	713,768
19	0	0	0	9	0,2	60	39,72	721,580
20	0	0	0	9	0,2	60	39,52	717,947

3.1.3. Results

The cubic model is applied to determine the regression equation for calculating the pressing force (F) using coded variables:

$$F = 39,55 + 7,3x_1 + 8,88x_2 + 18,61x_3 + 0,1288x_1x_2 + 2,39x_1x_3 + 5,67x_2x_3 + 0,01x_1^2 + 1,79x_3^2 + 0,78x_1^2x_2 \quad (11)$$

The regression equation for calculating the pressing force (F) using actual variables:

$$F = 2,512 + 3,068a - 14,708\mu - 0,533L - 15,228a\mu + 0,04aL + 2,836\mu L - 0,173a^2 + 0,00448L^2 + 0,87a^2\mu \quad (12)$$

The quartic model is used to determine the regression equation for calculating the punching pressure (p) using coded variables:

$$p = 717,81 - 155,63x_1 + 161,38x_2 + 98,85x_3 - 56,78x_1x_2 - 37,8x_1x_3 + 56,5x_2x_3 + 52,44x_1^2 + 1,14x_2^2 - 19,33x_1x_2x_3 + 16,46x_1^2x_2 + 12,25x_1^2x_3 + 35,32x_1x_2^2 - 12,99x_1^2x_2^2 \quad (13)$$

The regression equation for calculating the punching pressure (p) using actual variables:

$$p = -470,544 + 170,591a + 10234,026\mu + 4,675L - 1835,492a\mu - 3,221a\mu L + 76,034a^2\mu - 1,210aL + 57,238\mu L - 7,688a^2 - 22173,627\mu^2 + 0,068a^2L + 3775,576aL^2 - 144,353a^2\mu^2 \quad (14)$$

To assess the impact of technological parameters on the pressing force and punching pressure, equations 11 and 13 are rewritten as follows:

$$F(x_1, 1, 1) = 74,50 + 9,82x_1 + 0,79x_1^2 \quad (15)$$

$$F(1, x_2, 1) = 69,65 + 15,46x_2 \quad (16)$$

$$F(1, 1, x_3) = 56,65 + 26,67x_3 + 1,79x_3^2 \quad (17)$$

$$p(x_1, 1, 1) = 1035 - 234x_1 + 68,16x_1^2 \quad (18)$$

$$p(1, x_2, 1) = 687,92 + 158,23x_2 + 23,47x_2^2 \quad (19)$$

$$p(1, 1, x_3) = 759,15 + 110,47x_3 \quad (20)$$

By comparing the coefficients in equations 15, 16, and 17, it is evident from the results that the plate width (x_3/L) has the most significant impact on the pressing force (F), followed by the friction coefficient (x_2/μ), and the plate thickness (x_1/s) has the least influence. Like punching pressure (p), based on equations 18, 19, and 20, the impact of plate thickness (x_1/s) is the most significant, followed by the friction coefficient (x_2/μ), and finally, the plate width (x_3/L) has the least influence.

Estimated contour plots can help predict the pressing force and punching pressure value in any zone of the calculated domain, as shown in Figs. 7 and 8. The pressing force value in Fig. 7 indicates that it is proportional to all three technological parameters. Fig. 8 suggests that the punching pressure value is inversely proportional to the thickness plate and proportionate to the width plate and friction coefficient. This provides the foundation for determining and choosing the most effective parameters, guaranteeing that the workpiece achieves the proper dimensions while reducing the pressing force and punching pressure.

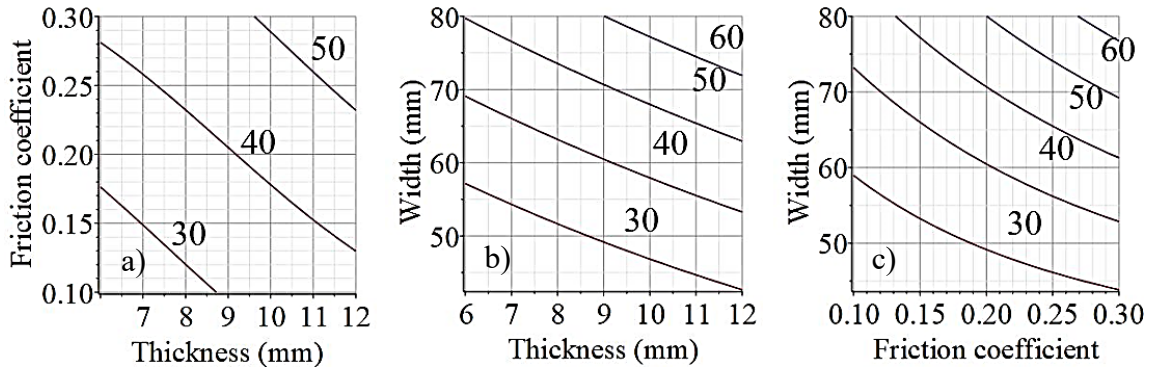


Figure 7. Impact of technological parameters on pressing force according to the FEM method.

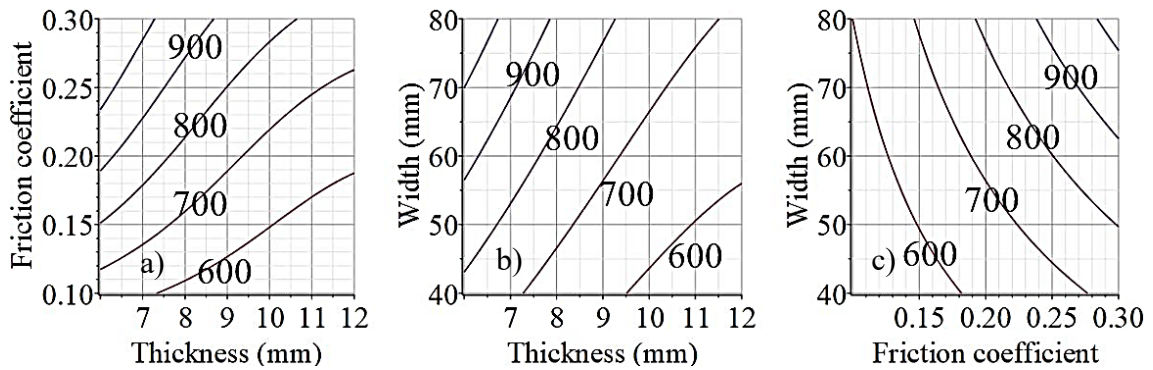


Figure 8. Impact of technological parameters on punch pressure according to the FEM method.

3.2. The result ascertained using the upper-bound method

To make a precise comparison between the FEM and upper-bound approaches mentioned above, it has been ensured that the input values used in both methods are identical. After simulation, the flow stress value fell within 300 to 340 MPa (section 3.1.1). Therefore, choosing a flow stress value within this range is recommended for formula 9 ($\sigma_s = 325\text{MPa}$). Fig. 9 shows contour plots that describe the influence of the two technological variables on the pressing force, while the remaining variable is at the central value. The results obtained by the upper-bound method are highly similar to those obtained by the simulation method.

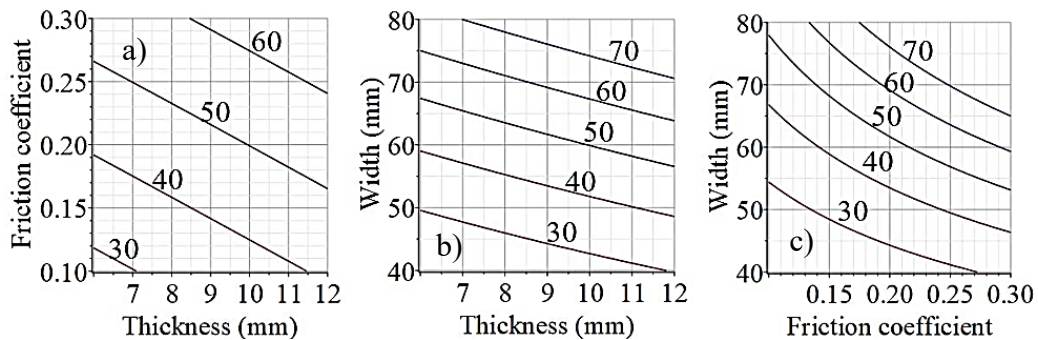


Figure 9. Impact of technological parameters on pressing force according to the upper-bound method.

3.3. Analyzing and assessing the outcomes

To assess and contrast the simulation and upper-bound methods, use a graph that illustrates the influence of each parameter on the force value (Fig. 10) while the remaining variables are at the central value. The impact of each parameter on the force value is identical in both methods. Nevertheless, as the friction parameters and workpiece width rise, the difference between the two methods also increases. Theoretical calculations result in a greater value than simulated calculations because the upper-bound method assumes that friction at all locations on the surface is at its maximum value $\mu_s \sigma_s / \sqrt{3}$. However, the value of friction calculated by the simulation depends on the position on the surface of the workpiece. For the influence of the thickness plate (Fig. 10a), the difference between the two methods is 8,8 to 7,7 tons (27% to 17%). Regarding the friction coefficient (Fig. 10b), the difference between the two methods spans from 3,7 to 12,7 tons (12% to 26%). For the influence of the plate width (Fig. 10c), the difference between the two techniques is from 3,7 to 16,11 tons (13% to 27%). The deviation between the two methods is entirely acceptable when calculating the pressing force.

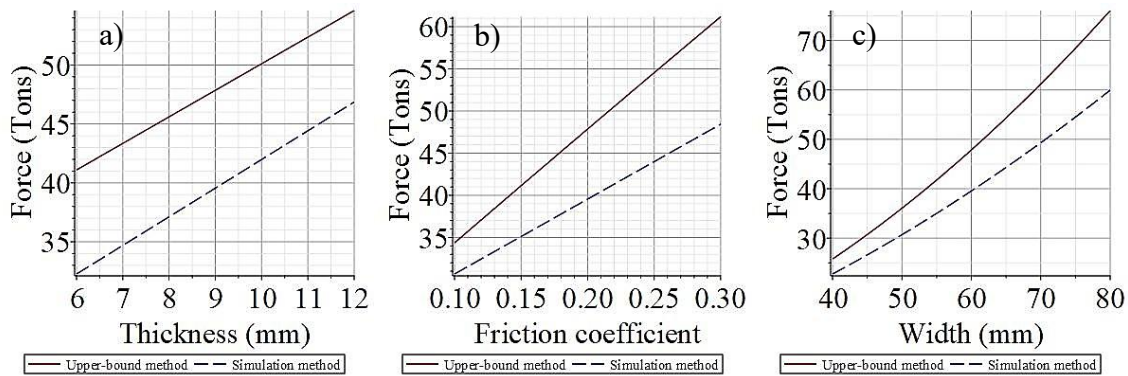


Figure 10. Compare the impact of technological variables on the force in both the upper-bound and simulation methods.

As a result, when applying the ECAP technique to M1 copper at a cold temperature with a specific thickness, width, and friction coefficient within the studied range, it is recommended to use the simulated formula for more consistent results. When utilizing the ECAP process on plates made of different metals and with an extensive range of studies, the theoretical formula can be used as a standard to determine the necessary technological parameters via preliminary calculations.

4. CONCLUSIONS

This paper uses the Qform software to simulate and compare them to the upper-bound method to examine how technological parameters affect the ECAP process of M1 copper materials. It is possible to arrive at some of the following conclusions based on the analysis:

1. Determining pressing force and punching pressure using the upper-bound method perfectly agrees with the slip line solution method that Segal et al. previously explained.
2. Equations 11-14 have been formulated utilizing the simulation method, integrating the response surface approach with a central composite design to predict the pressing force and punching pressure when applying the ECAP technique to M1 copper material.

Additionally, the aim is to evaluate the influence of technological parameters on the desired outcome.

3. Theoretical and simulated force calculations demonstrate significant similarities regarding the impact of parameters. However, the results obtained by the upper-bound method have greater value due to the inability to accurately consider friction effects on the surface between the tools and the workpiece.

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TÓM TẮT

Phân tích lực và áp lực ép trong quá trình ép qua kênh gấp khúc tiết diện không đổi với vật liệu đồng M1 bằng phương pháp phần tử hữu hạn và định trị trên

Nghiên cứu này đưa ra hai phương pháp tính toán lực theo lý thuyết bằng phương pháp định trị trên và sử dụng mô phỏng số kết hợp với quy hoạch tâm xoay trong quá trình ép qua kênh gấp khúc vật liệu đồng M1 dạng tấm dày với ba thông số bao gồm chiều dày phôi, hệ số ma sát và chiều rộng phôi. Phương pháp định trị trên sử dụng các phân tích vật lý để xác định vùng biến dạng, thiết lập sự phân chia mô hình khối cứng và đạt được kết quả giống với phương pháp giải lưới đường trượt. Kết quả thu được từ mô phỏng ba chiều được thực hiện bằng phần mềm Qform kết hợp với quy hoạch mô phỏng tâm xoay đã đưa ra được các phương trình hồi quy giúp xác định lực và áp lực lên dụng cụ. Ảnh hưởng của từng tham số đến lực ép là tương tự nhau ở cả hai phương pháp, sự chênh lệch giữa hai phương pháp không lớn và nằm trong phạm vi có thể tin cậy được.

Từ khoá: ECAP; Quy hoạch tâm xoay; Đồng M1; Phương pháp định trị trên; Phương pháp phần tử hữu hạn.