

# EFFECT OF ECAP ROUTES ON STRAIN TO M1 COPPER PLATE

## ẢNH HƯỞNG CỦA CÁC LỘ TRÌNH ECAP ĐẾN BIẾN DẠNG ĐỐI VỚI PHÔI DẠNG TẤM DÀY VẬT LIỆU ĐỒNG M1

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### ABSTRACT

This study utilizes 3D simulations to assess the influence of four different ECAP routes on the mean strain and strain homogeneity on the M1 copper plate. After six passes, the simulation results significantly improved the mean strain and strain homogeneity. The mean plastic strain increases significantly when applied along route BC, while it decreases most along route A. The strain homogeneity is best when used along route A and poor when applied along route C throughout the entire volume. However, when examining a cross-section 20mm away from the sample head, which represents the features in the center of the sample, it is clear that applying through route C leads to a greater degree of uniform deformation than routes B<sub>A</sub> and B<sub>C</sub>. The results showed that route A is suitable for pressing when the entire material is required. However, routes B<sub>A</sub> and B<sub>C</sub> are utilized when a significant mean strain is desired and only a uniform material section is used.

**Keywords:** ECAP process, ECAP routes, copper M1, 3D simulation, strain homogeneity.

### TÓM TẮT

Nghiên cứu này sử dụng mô phỏng 3D để đánh giá ảnh hưởng của các 4 lộ trình ép qua kênh gấp khúc tới biến dạng và sự đồng đều biến dạng đối với phôi dạng tấm dày vật liệu đồng M1. Kết quả mô phỏng cho thấy sau 6 lần ép, biến dạng trung bình và độ đồng đều biến dạng đều cải thiện lên đáng kể. Biến dạng trung bình tăng cao nhất khi ép qua lộ trình B<sub>C</sub> và thấp nhất khi ép qua lộ trình A còn độ đồng đều biến dạng tốt nhất với lộ trình A và kém nhất là lộ trình C trên toàn bộ thể tích. Tuy nhiên, khi xét tại mặt cắt ngang cách đầu phôi 20 mm đại diện cho tính chất ở trung tâm phôi cho thấy, khi ép qua lộ trình C cho mức độ đồng đều biến dạng tốt hơn lộ trình B<sub>A</sub> và B<sub>C</sub>. Kết quả cho thấy, lộ trình A phù hợp khi yêu cầu sử dụng toàn bộ vật liệu sau khi ép còn lộ trình B<sub>A</sub>, B<sub>C</sub> được sử dụng khi yêu cầu biến dạng trung bình lớn và chỉ cần sử dụng một phần đồng nhất của vật liệu.

**Từ khóa:** ECAP, lộ trình ECAP, đồng M1, mô phỏng 3 chiều, đồng đều biến dạng.

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### 1. INTRODUCTION

In recent years, UFG materials have become known as critical materials in aerospace, manufacturing, and other sectors due to their exceptional mechanical and physical characteristics. UFG metal is considerably more durable than conventional materials, enabling the construction of significantly lighter structures. The most feasible method for producing UFG metal is severe plastic deformation (SPD), which subjects it to considerable accumulated strain without substantially altering its original shape and size [1]. Several methods of SPD, including high-pressure torsion (HPT), cyclic extrusion compression (CEC), and equal channel angular pressing (ECAP),... can be used to manufacture ultrafine-grained (UFG) materials for metals and alloys. The high-pressure torsion (HPT) method allows for achieving highly high strains without causing significant damage to the sample or tool. Nevertheless, this technique is limited to compact workpieces and exhibits non-uniform deformation directly proportional to the radius [2]. The cyclic extrusion compression (CEC) method can create high hydrostatic pressure, letting the material deform plastically while maintaining its shape [3, 4]. However, the equipment required to conduct this procedure is highly complex since controlling the back pressure to shape the workpiece along the die cavity is difficult. Therefore, this research suggests using the equal channel angular pressing (ECAP) method to investigate the ultrafine-grained (UFG) material manufacturing process. This approach has gained widespread use and popularity,

facilitating handling of large workpieces with relatively simple equipment.

The principle of the ECAP technique involves pressing the workpiece through a die having two channels intersecting at a fixed angle of  $\Phi$  and the outer corner of  $\psi$  (Fig. 1a) without changing the original cross-sectional area of the workpiece. It is also possible to rotate the sample along its longitudinal axis during multiple passes, generating different routes (Fig. 1b) [5]. The equivalent plastic strain value after undergoing  $N$  passes is determined by the formula 1 [1]:

$$\epsilon_{eq} = \frac{N}{\sqrt{3}} \left[ 2 \cot\left(\frac{\phi + \psi}{2}\right) + \psi \operatorname{cosec}\left(\frac{\phi + \psi}{2}\right) \right] \quad (1)$$

During the ECAP procedure, workpieces can undergo different routes by being axially rotated after each pressing. Fig. 1b displays four ECAP processing routes that have been found based on the rotation of the sample [6].

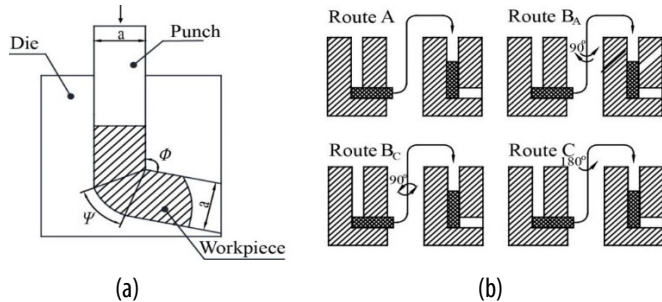


Fig. 1. Concept of ECAP (a) and four basis ECAP routes (b)

Different ECAP routes can lead to distinct strain levels, grain microstructures, and technical characteristics. Recently, many researchers have examined various issues when investigating the impact of ECAP routes. Abhishek Ghosh et al. [7] employed the finite element method to analyze the deformation of a bar-shaped AL-Zn-Mg-Cu alloy after applying the ECAP process through three different routes: A, B<sub>C</sub>, and C. The simulation findings indicate that the most optimal outcomes are achieved using the B<sub>C</sub> route. Mohamed Osman et al. [8] utilized Deform 3D software to simulate the deformation process of Ti-50.8% Ni bar billets along the BC route. The findings indicate an increase in the cumulative average strain and the formation of an ultrafine-grained (UFG) structure. However, inhomogeneity is still present across the planes. Mohamed Ibrahim [9] conducted simulations to examine the efficacy of ECAP, extrusion, and combined ECAP-extrusion procedures in creating UFG-structured composites using Al-1080 materials. The numerical simulation results match the experimental findings, indicating that the workpiece produced utilizing the

ECAP approach achieves the highest level of uniform deformation.

The research mentioned above concentrated on the assessment of strain for bar workpieces with square or circular cross-sections. The best strain, according to these findings, is obtained while pressing along the B<sub>C</sub> route. However, there have been several research on plate blanks, which are used for producing sheet products. This study focuses on the ECAP method applied to the four main routes of the copper M1 plate, which is extensively utilized in the manufacturing, aerospace, and military industries. The Qform software simulates and assesses the deformation characteristics and uniformity of plastic strain in M1 copper. This provides the foundation for evaluating the potential to achieve ultra-fine grain structures using the ECAP method.

## 2. FINITE ELEMENT METHOD

### 2.1. Simulation model

The simulation model includes a punch, die, and workpiece with angle  $\Phi = 90^\circ$ ,  $\psi = 0^\circ$ , as shown in Fig. 2a. The study utilized M1 copper, which is considered isotropic. The composition of M1 copper is detailed in Table 1 [10], while the stress-strain relationship at a temperature of 20°C was obtained from the Qform library, as shown in Fig. 2b. The workpiece utilized in the research method is a rectangular plate with dimensions of 50 x 50 x 10mm.

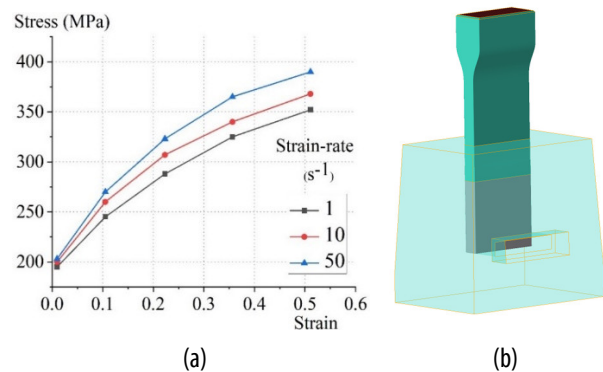


Fig. 2. Stress-strain relationship of M1 copper at 20°C (a) and 3D modelling (b)

During the simulation, the friction coefficient ( $\mu$ ) between the workpiece and the tools, as well as the velocity of the punch ( $v = 15\text{mm/s}$ ), 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 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 workpiece undergoes

six passes in four routes, as depicted in Fig. 2b. Because of the rise in temperature during the deformation process, it is necessary to cool the workpiece back to its original temperature after each pass before proceeding with further pressing. In the actual process, a portion of the workpiece must be lost because, after each pressing, a piece of the length has to be cut off, and burrs have to be ground away.

Table 1. Chemical composition of copper M1

Chemical element	Cu	Fe	Zn	O
Content, %	99.94	0.005	0.004	0.051

2.2. Assessment method

Fig. 3 illustrates the sample following the initial ECAP pass. The unequal distribution of plastic strain is evident, particularly at the head and end of the workpiece. Hence, in addition to considering the deformation and distribution across the entire workpiece, it is necessary to evaluate the distribution in both the head and center areas. To assess the strain distribution uniformity, choose two cross-sections, A and B, positioned approximately 5mm and 20mm away from the head of the workpiece, as indicated in Fig. 3. These cross-sections will represent the deformation at the ends and middle of the workpiece, respectively.

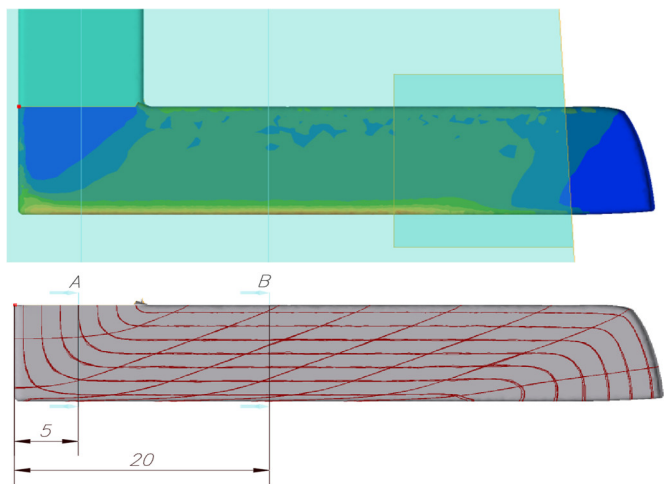


Fig. 3. Plastic strain after the first ECAP pressing

To assess the uniformity of strain distribution, utilize the inhomogeneity index ( $C_i$ ) [7, 11, 12]:

$$C_i = \frac{\epsilon_{max} - \epsilon_{min}}{\epsilon_{avg}} \quad (2)$$

$\epsilon_{max}$ ,  $\epsilon_{min}$ , and  $\epsilon_{avg}$  denote the plastic strain's maximum, minimum, and mean, respectively. A smaller value of this index indicates a higher level of uniformity in strain distribution.

3. RESULT AND DISCUSSION

Fig. 4 illustrates the relationship between force and displacement during the initial pressing. During the initial stage, the force undergoes a rapid promotion, reaching at around 3 - 5mm from the beginning of the stroke. And then, the force diminishes in a straight line because the area of contact between the workpiece and the die reduces as more material escapes through the outlet channel. The maximum value achieved is about 33 tons, suitable for most hydraulic presses used in laboratories.

Fig. 5 illustrates the simulation results obtained after six pressing passes following four routes. Due to the mechanical machining, a workpiece section is removed after each pass, so the sample is changed from its original square to a rectangular one. Following routes  $B_A$  and  $B_C$ , the workpiece undergoes a 90° rotation after each pressing. Because the shape of the workpiece is changed to rectangular, when pushing through the  $B_C$  and  $B_A$  routes, the workpiece performs the upsetting process in the inlet channel to reach the width size first and then passes through the outlet channel. As a result, the product will have an irregular shape when pressed using these two routes compared to routes A and C. The finished product must eliminate significant material to achieve a uniform shape.

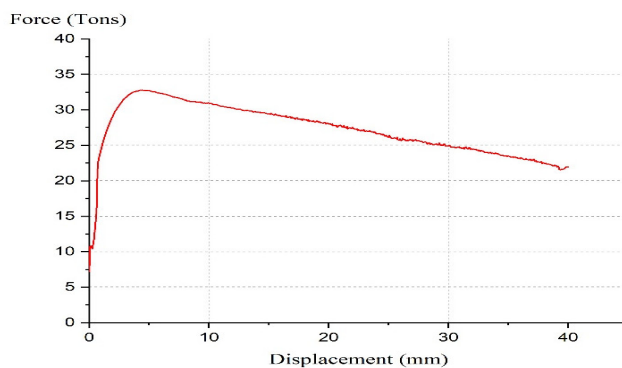
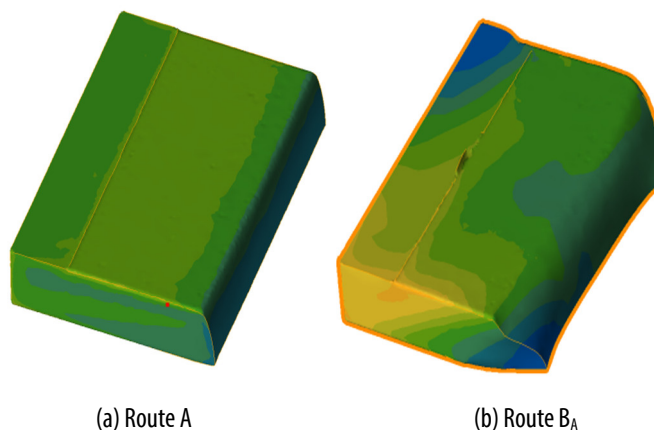


Fig. 4. Plastic strain of the workpieces after six passes



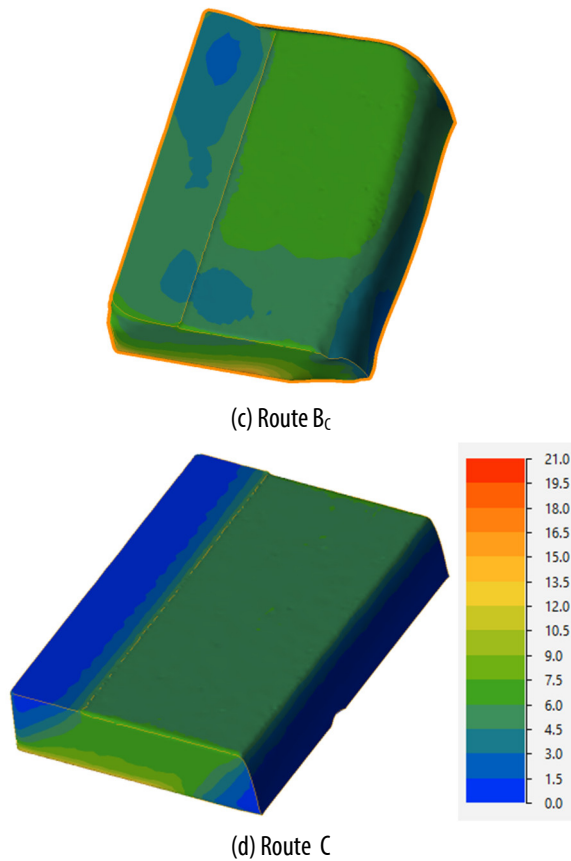
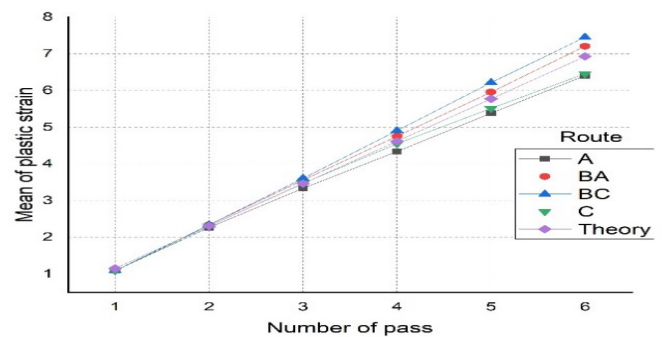


Fig. 5. Plastic strain of the workpieces after six passes

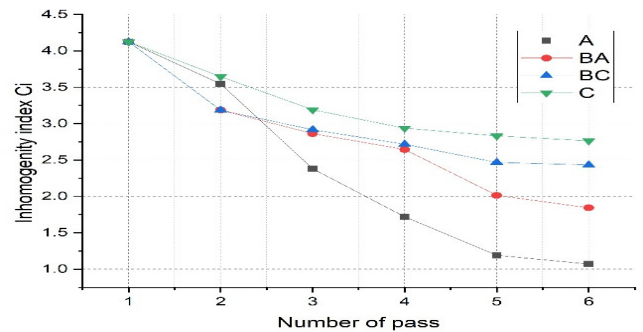
Fig. 6 illustrates the mean plastic strain on the workpiece and the inhomogeneity index during the pressing process across four different routes. The mean strain values are compared with those obtained after calculating theoretical formula 1. The mean plastic strain obtained after six passes varied between 6.4 and 7.5. This value is within the range for severe plastic deformation (6-8) [13]. The graph in Figure 6a demonstrates that the results obtained from simulation calculations exhibit a significant degree of closeness to the theoretical formula 1. After six pressing passes, the mean strain value exhibited a linear increase, and there was a considerable improvement in homogeneity across all four routes. The mean strain value increases in the following order: route A, route C, route B<sub>A</sub>, and finally, route B<sub>C</sub>. When assessing the uniformity throughout the total volume of the workpiece, route A shows the highest level of uniformity, followed by routes B<sub>A</sub>, B<sub>C</sub>, and finally, route C. When examining the total volume of the workpiece, it is evident that the 90° rotation routes (B<sub>A</sub>, B<sub>C</sub>) result in a higher degree of accumulated strain and a moderate level of homogeneity.

The graphs in Figs. 6b and 7a demonstrate that the inhomogeneity index over the entire volume and at cross-section A is similar across all four routes. Therefore,

the level of uniformity at the initial and final positions of the workpiece significantly impacts the level of uniformity in deformation throughout the entire volume of the workpiece. In cross-section B (Fig. 7b), which is 20mm from the end face, representing the middle of the sample, route A still gives the best level of deformation uniformity. This is followed by route C, then route B<sub>A</sub>, and finally route B<sub>C</sub>. In contrast to the mean plastic strain value, the 90° rotation pressing methods result in less homogeneous deformation in the middle of the workpiece than the other two routes. Route C has better strain uniformity in the center area of the workpiece when compared to routes B<sub>A</sub> and B<sub>C</sub>. However, it has lower mean plastic strain and uniformity strain across the entire volume than the other routes.

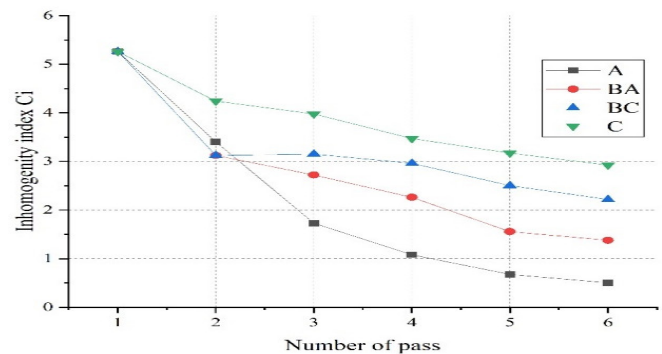


(a)



(b)

Fig. 6. Mean of plastic strain (a) and inhomogeneity index (b) over the entire workpiece



(a)

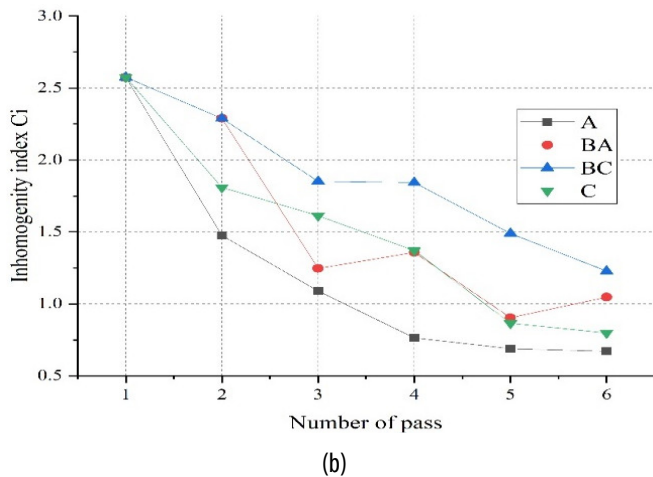


Fig. 7. Inhomogeneity index at cross-section A (a) and cross-section B (b)

#### 4. CONCLUSION

This study has demonstrated the plastic deformation and its distribution during the ECAP process of the M1 copper plate using four routes. The pressing route selection depends on the purpose and specifications of the pressing process, as shown by the results mentioned above. Route A provides excellent strain uniformity throughout the sample, particularly at the beginning and middle, but the cumulative strain level is the lowest. When conducting ECAP along route C, the uniformity of strain in the middle of the workpiece is very good. However, the overall workpiece exhibits the lowest level of strain uniformity, and the accumulated strain is also relatively low. Though the uniformity is average, routes B<sub>C</sub> and B<sub>A</sub> have a high mean plastic strain. Furthermore, a portion of the material needs to be removed following the ECAP process due to the unequal and distorted shape of the workpiece at the head.

Therefore, route A is recommended if the requirement for uniformity is well met and the mean strain value does not need to be too high. If a significant amount of strain is required and the level of homogeneity is not a primary concern, the options to consider are either B<sub>A</sub> or B<sub>C</sub>.

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#### THÔNG TIN TÁC GIẢ

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