



## Investigation on Forming of Titanium Bipolar Plates Using Micro-stamping Process

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## A B S T R A C T

Micro-stamping process is one of the most cost-effective methods to manufacture metallic bipolar plates (BPPs). This research investigates the forming of titanium thin sheet as a potential candidate for BPPs in proton exchange membrane fuel cell (PEMFC). In this regard, the process was first simulated using finite element (FE) code Abaqus. Afterward, experimental tests were implemented and the validation of the FE model was confirmed using the experimental results. In the simulations, the corner radius of the die, draft angle, and friction coefficient at die/sheet interface were selected as variable factors. Forming force and thickness reduction as response functions were evaluated. It is demonstrated that the die corner radius has more influence on the maximum punch force compared to the draft angle and friction coefficient. The maximum punch force decreases with increasing the die corner radius. On the other hand, in order to have a lower thickness reduction, a high die corner radius, higher draft angle, and low friction coefficient are required.

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## 1. INTRODUCTION

A fuel cell is an electrochemical system that directly converts the chemical energy to electricity. There are different types of fuel cells such as alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), solid oxide fuel cell (SOFC), molten carbonate fuel cells (MCFC), direct methanol fuel cell (DMFC), and proton exchange membrane fuel cell (PEMFC). Among the mentioned full cells, PEMFC has been widely used in automotive and aerospace industries as a sustainable source of energy. The performance of a PEMFC is depicted in Figure 1. As can be seen, at the anode side of BPP the reaction is carried out and hydrogen decomposes to electron and proton (positive ion). The produced electron pass through the external circuit and then reach to the cathode side. Also, proton passes the membrane and moves to the cathode. At the cathode side, a reaction comprises proton, electron, oxygen, and catalyst is performed. The formed water is left through the microchannels of the BPP [1-6].

Microchannels help better distribution of the hydrogen and oxygen on the BPPs, transmission of the produced electrons and water, and cooling the fuel cell to increase the efficiency. In addition, BPPs are the key component of a fuel cell from weight and price points of view [7]. Hence, it necessitates the forming of the metallic BPPs due to their advantages including proper mechanical, electrical, thermal properties and also ease of production [8]. Nowadays, several applicable

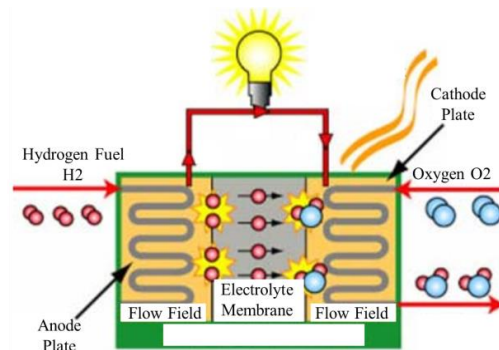


Figure 1. Operation principle of a PEMFC [1]

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methods have been introduced by researchers to fabricate metallic BPPs such as rubber pad forming [9], hydroforming [10] and micro-stamping [11]. Due to the reduction of the manufacturing time and cost, the micro-stamping process has been gained the capability of mass production [12]. Although there are many interesting works regarding the micro-stamping of metallic BPPs [13-15], none of them are connected with the forming of titanium thin sheet. Due to its excellent corrosion resistance and low density, titanium has been raised as a prominent candidate for manufacturing metallic BPPs [16]. Nevertheless, low formability of the titanium at room temperature necessitates the precise control of the forming process in terms of proper levels of the input parameters. In this study, the forming of titanium BPPs with the higher channel depth is numerically and experimentally investigated using the micro-stamping process. A titanium sheet with an initial thickness of 100  $\mu\text{m}$  (0.1 mm) was used. After validation of FE simulation by experimental results, process parameters including corner radius, draft angle, and friction coefficient were evaluated. Results showed that FE simulation could be considered as a powerful tool for predicting the optimal forming condition in the micro-stamping process.

## 2. FE SIMULATION

The explicit FE code ABAQUS 6.14 was used to investigate the forming of titanium BPP using the micro-stamping process. A 3D model was applied for die set (punch and matrix) and sheet as is shown in Figure 2. The die set was meshed via R3D4 (four nodes 3D bilinear rigid quadrilateral) element due to discrete rigid assumption. On the other hand, the sheet was considered as deformable and C3D8R (eight nodes linear brick, reduced integration, hourglass control) element was used for its meshing. The number of mesh in the thickness direction was considered as three convergence of the maximum punch forces [17].

The geometrical dimensions of the die set are given in Table 1. In order to introduce the plastic behavior of

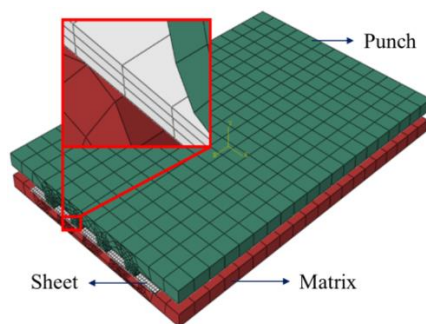


Figure 2. 3D FE model

the sheet to the software, a uniaxial tensile test was performed according to ASTM E8M standard. Coulomb model was used to define friction conditions between the sheet and die set with a friction coefficient of 0.1. The matrix was fully constrained and the punch speed was fixed at 0.6 mm/min.

## 3. EXPERIMENTS

The chemical composition of the titanium sheet is presented in Table 2. Titanium blanks were prepared with a dimension of 35×20 mm and 100  $\mu\text{m}$  thickness to conduct micro-stamping experiments by using a 20 tons testing machine. The upper and lower dies were made of St37, but H13 material was used for upper and lower cores because of its great wear characteristics.

Figure 3 shows the experimental components of the die set. SAE 10 oil was used as a lubricant. A constant crosshead speed of 0.6 mm/min was applied to perform the experiments. After that, the formed BPPs were prepared (mounting, polishing, and so on) to be observed under an optical microscope with 40 times magnification. Then, the amount of thickness reduction of the final plate was measured using Equation (1) in which  $t_0$  and  $t_f$  are the thickness of the initial sheet and the formed BPP's thickness, respectively [18]. Moreover, the forming force curve was obtained using a computer system connected to the press machine.

$$\text{Thickness reduction (\%)} = \frac{t_0 - t_f}{t_0} \times 100 \quad (1)$$

TABLE 1. Geometrical dimensions of the die set

Channel depth	Channel width	Rib width	Corner radius	Draft angle
0.75 mm	1.1 mm	1.5 mm	0.2 mm	20 °

TABLE 2. The chemical composition of the sheet (wt%)

Fe	Si	Sb	Mn	Sn	Ti
0.12	0.09	0.04	0.03	0.02	Balance



Figure 3. Experimental components of the die set

4. RESULTS AND DISCUSSION

**4. 1. Validation of Simulation Results** In order to verify simulation results, the curve of punch force (versus displacement) obtained from the FE simulation was compared with the experimental one [19]. This comparison is shown in Figure 4. As can be seen, there is a good agreement between the results, hence the FE model was used for further simulations.

Figure 5 demonstrates the stamped BPP by simulation and experiment. As is depicted, the final thickness ( $t_f$ ) occurs at the corner radius of the formed plate which implies this area is a critical zone for the thinning phenomenon. It should be noted that the equivalent strain at the onset of localized necking ( $\epsilon_{LN}$ ) was used for evaluating the stamped plate from the tearing point of view using Equation (2). In this equation,  $n$  and  $R$  denote strain hardening exponent and Lankford coefficient, obtained from the tensile test, respectively. The  $\epsilon_{LN}$  was computed; which was equal to 0.27. Figure 6 represents a typical sample with tearing (high rate thinning). The enlarged image of the successful final plate is shown in Figure 7. As is depicted, the forming depth was obtained equal to 0.353 mm. Compared to the highest channel depth reported so far for the titanium BPPs i.e. 0.27 mm [9], an improvement of 31% in forming depth is obtained using the proposed micro-stamping process in this research.

$$\epsilon_{LN} = \frac{n\sqrt{2}}{2} \sqrt{1+R} \sqrt{1 + \frac{1}{1+2R}} \quad (2)$$

**4. 2. Effect of Die Corner Radius** In order to understand the effect of the die corner radius, several radiuses were considered changing from 0.1 to 0.3 mm. It should be noted that the draft angle and friction coefficient were kept constant at 20° and 0.1, respectively. Also, both punch and matrix have the same corner radius. Figures 8 and 9 show the effect of the die

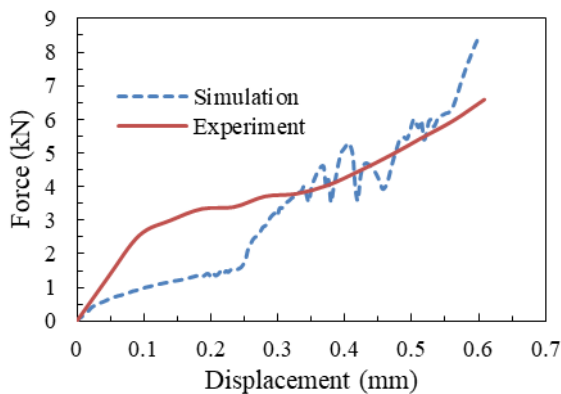


Figure 4. Punch force-displacement curve

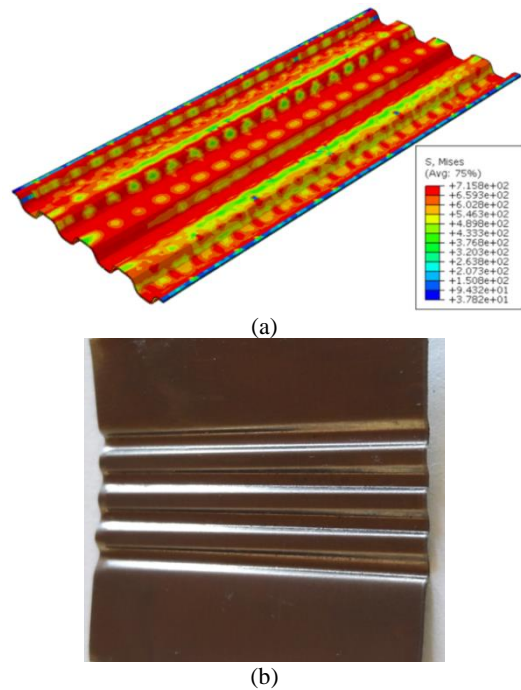


Figure 5. The stamped BPP, (a) Simulation (b) Experiment

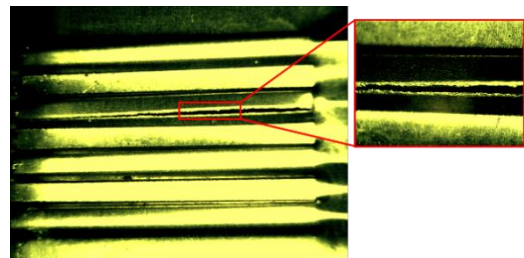


Figure 6. The formed plate with tearing

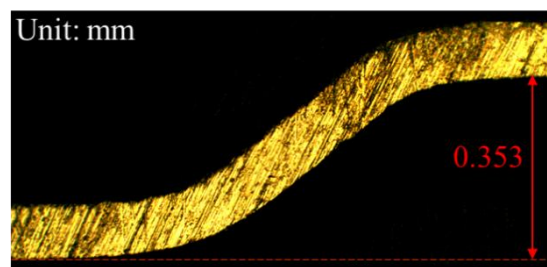


Figure 7. The enlarged image of the successful plate

corner radius on maximum punch force and thickness reduction, respectively. As it is depicted, when the die corner radius increases from 0.1 to 0.15 mm, the maximum punch force increases as well. Afterward, the maximum punch force dramatically decreases with increasing the die corner radius from 0.15 to 0.3 mm. On the other hand, by increasing the die corner radius from 0.1 to 0.15 mm, the thickness reduction increases.

But, from 0.15 to 0.2 mm of radius, the thickness reduction drastically decreases by 74%. After 0.2 mm, the change in the thickness reduction is not so sensible. When the corner radius is increased, the sheet deforms more easily and material flow is more uniform on the die surface and subsequently, the forming force is decreased.

**4. 3. Effect of Draft Angle** First, die corner radius and friction coefficient were kept constant at 0.2 mm and 0.1, respectively. Then, the draft angle was assumed to be variable from 0 to 20°. The maximum punch force and thickness reduction of the analysis are shown in Figures 10 and 11, respectively. As can be seen, the maximum punch force is first increased and then is decreased from a draft angle of 0 to 10° and 10 to 20°, respectively. For the thickness reduction, it should be pointed out that from the angle of 0 to 10°, its changing is not so tangible. From 10 to 20°, the thickness reduction extremely decreases by 81%. Increasing the draft angle leads to a better sliding of the sheet on the surface of the die, hence a decrease in thickness reduction is expected.

**4. 4. Effect of Friction Coefficient** With the aim of investigation of the lubrication effect on forming force and thickness reduction, different coefficients of friction were evaluated changing from 0.05 to 0.25 while the die corner radius and the draft angle were kept as constants (0.2 mm and 20°, respectively). Figures 12 and 13 illustrate the effect of the friction coefficient on maximum punch force and thickness reduction, respectively. It can be inferred that increasing friction coefficient causes an increase in the maximum forming force. By increasing the friction between the sheet and die interfaces, sheet sticks onto the die and sheet material flows tightly. As a result, the punch needs more force to overcome this phenomenon. Increasing the friction coefficient from 0.1 to 0.2 gives rise to an impressive increase in thickness reduction of 85%. In addition, the effect of friction coefficient before and

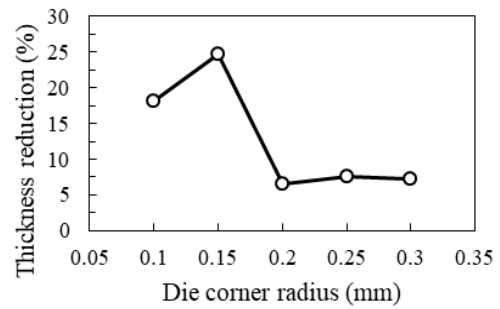


Figure 9. Effect of die corner radius on thickness reduction

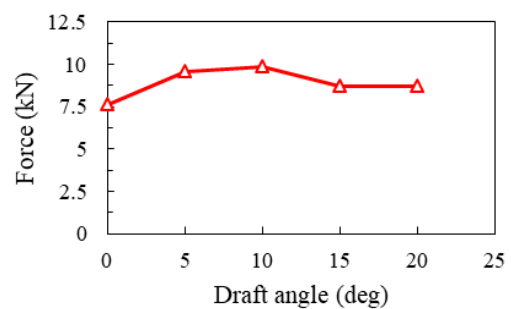


Figure 10. Effect of draft angle on maximum punch force

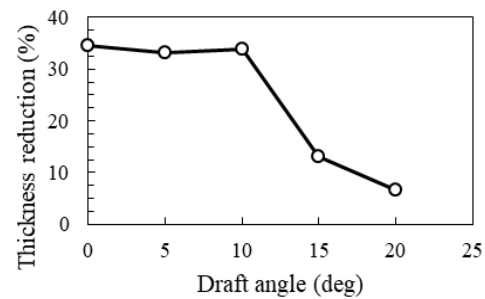


Figure 11. Effect of draft angle on thickness reduction

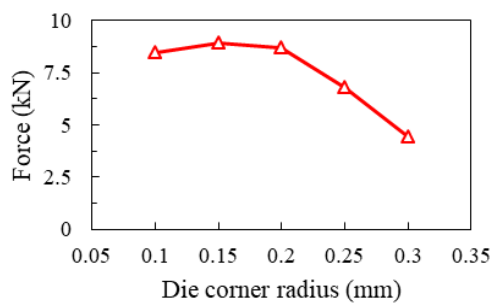


Figure 8. Effect of die corner radius on maximum punch force

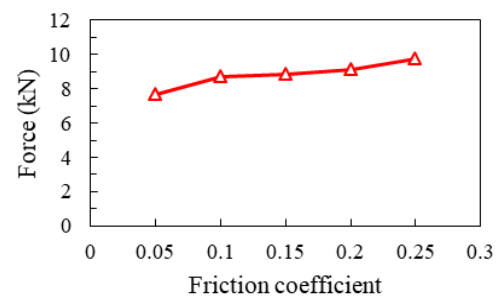
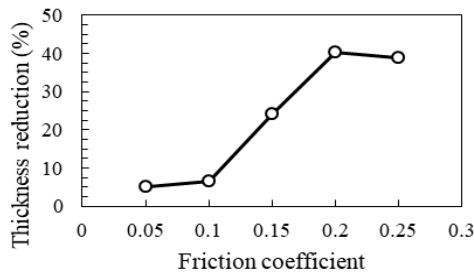


Figure 12. Effect of friction coefficient on maximum punch force



**Figure 13.** Effect of friction coefficient on thickness reduction

after the mentioned range is negligible. It can be deduced that the preparation of an appropriate forming condition from a lubrication point of view causes higher thickness reduction.

## 5. CONCLUSIONS

In this research, the forming of titanium bipolar plates using the micro-stamping process by simulation and experiment was investigated. Forming force and thickness reduction were evaluated; while, the effects of die corner radius, draft angle, and lubrication were considered. By using an experimentally verified finite element model, it was found that the die corner radius has more influence on the maximum punch force compared to the draft angle and friction coefficient. Moreover, increasing the die corner radius, increasing the draft angle, and decreasing the friction coefficient lead to decrease in thickness reduction.

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میکرواستمپینگ یکی از مقرون به صرفه ترین روش های ساخت صفحات دوقطبی فلزی می باشد. این تحقیق شکل دهی ورق نازک تیتانیومی به عنوان گزینه ای مناسب برای صفحات دوقطبی پیل سوختی غشاء پروتون را مورد بررسی قرار می دهد. در همین راستا، فرآیند در ابتدا با استفاده از نرم افزار اجزای محدود آباکوس شبیه سازی شد. در ادامه، آزمایش های تجربی اجرا و صحت سنجی مدل اجزای محدود با استفاده از نتایج تجربی تایید شد. در شبیه سازی ها، شعاع گوشه قالب، زاویه دیواره، و ضریب اصطکاک در سطح تماس ورق با قالب به عنوان پارامترهای متغیر در نظر گرفته شدند. نیروی شکل دهی و کاهش ضخامت به عنوان توابع پاسخ ارزیابی شدند. نتایج نشان می دهد که بیشینه نیروی سنبه با افزایش شعاع گوشه قالب افزایش می یابد. از سوی دیگر، جهت کاهش ضخامت کمتر به یک شعاع گوشه قالب بزرگتر، زاویه دیواره بزرگتر و ضریب اصطکاک کمتر نیاز است.

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