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Study of forming process effects on the wrinkling and thinning percentage of micro-channels with a serpentine layout

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Abstract

The present study uses lubricated and non-lubricated stamping processes to fabricate metallic bipolar plates (MBPPs) with a thickness of 0.1 mm from SS3316 with a serpentine flow field. Then, experimental tests, together with the finite element (FE) model, were utilized to define the directional thickness distribution. According to the results, using a friction factor of 0.1 during the FE analysis can provide accurate results in terms of thickness prediction under lubricated conditions. Furthermore, the largest thinning percentages in the modified conditions were found to be 27.02%, 30.40%, and 26.00% in the longitudinal, diagonal, and transverse directions, respectively, indicating that the diagonal direction is the most critical one. Finally, the effect of the lubricating condition on the wrinkling of the sample was investigated. According to the results, using the lubricated condition during the stamping process augments the wrinkling of the bipolar plate, and the wrinkling of the bipolar plate's margin was not symmetrical.

1. Introduction

Due to the non-renewability of fossil fuels and the amount of pollutants caused by their use, the inclination to use fuel cells as clean and renewable resources has increased in recent years [1]. Fuel cells are a technology for energy production that produces electrical energy with high efficiency from the direct combination of fuel and oxidizer without causing en-

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vironmental and noise pollution. Fuel cells are divided into five main categories based on various variables such as the type of electrolyte used in the fuel cell, operating temperature and pressure, the type of ion exchanged through the electrolyte, the type of reactants, and the direct and indirect use of fuels [2]. Among the different fuel cells, polymer fuel cells have attracted special attention due to their higher power density, low operating temperature, and fast start-up. Of the components of fuel cells, the bipolar plates make up a high percentage of the weight and costs of the fuel cells; however, they contribute to the distribution of fuel and oxidant, transport of current outside the cell, and facilitate the water management making them one of the most important components of this stack [3]. Bipolar plates have channels with a specific dimension for the fuel distribution and exit of the reaction products. Among the different configurations of the flow field, the serpentine flow field has been proposed to solve the non-uniform distribution of the reactants [4]. Bipolar plates should have high corrosion resistance, low weight, low thickness, and suitable conductivity. Among the materials used to manufacture bipolar plates, metallic bipolar plates (MBPP) have advantages such as excellent mechanical resistance, gas impermeability, low cost, simple manufacturing, and the possibility of being formed into very thin sheets (a thickness of 0.1 mm or less). Metallic bipolar plates are manufactured by different methods such as electric discharge micro-machining, electrochemical micro-machining, stamping, vacuum casting, electromagnetic forming, rubber pad forming, and hydroforming. Among these production methods, stamping and rubber pad forming of metallic bipolar plates is more suitable for producing the metallic bipolar plates with low thickness and weight [5]. In the present study, the stamping process is used for the fabrication of metallic bipolar plates.

Several studies on metallic bipolar plate stamping have been conducted to improve the quality of the formed sample. The residual stress and thinning are the main parameters that could decrease the quality of the fabricated sample. Xu et al. [6] evaluated formed residual stress and bipolar plate thinning. Using a two-dimensional plane strain finite element model, they investigated the stress and deformation of 304 stainless steel with a thickness of 0.1 mm. Their results showed that by increasing the width and depth of the upper die, the peak of the residual stress increases and the formed thickness becomes less uniform, and as the curve radius increases, the residual stress decreases and the formed thickness becomes uniform.

Zhang et al. [7] used multi-stage forming of metallic sheets to fabricate bipolar plates with fine width and high aspect ratio in a proton exchange membrane fuel cell. They found that the forming depth can be increased with a larger second-stage punch stroke along a smaller clearance and radius. Also, increasing or decreasing the radius and the stroke of the second-stage punch simultaneously causes a larger draft angle. A small second-stage punch stroke and smaller radius are useful for larger rib width, and more uniform thickness distribution can be obtained using a smaller second-stage punch stroke and clearance. Finally, they introduced two-stage and three-stage forming for soft materials and relatively hard materials, respectively.

Talebi et al. [8] investigated the fracture behavior of the bipolar plate formed by the rubber pad method. They used three different damage criteria to predict failure. They constructed the failure surface using flexible failure criteria and reported the most accurate failure prediction through the normalized Cockroft-Latham failure criterion (9.14% failure prediction error). They found that the process parameters have no significant effect on the triaxial stress or the normalized Lode angle parameter. Therefore, they proposed the Cockroft-Latham normalized failure criterion to investigate the failure initiation.

Medanloo et al. [9] investigated the effect of forming parameters such as die clearance, stamping speed, die/sheet friction coefficient, and their optimal surface on the forming depth through the response surface method (RSM) in titanium bipolar plate forming. They used a strain-based damage model to investigate sheet failure during simulation. They found that the coefficient of friction and die clearance are the most significant parameters in the maximum filling depth, respectively, and that changing the stamping speed does not have a significant effect on the stamping of the titanium sheet. Lastly, they presented a regression model to estimate the maximum filling depth based on the input variables.

Barzegari and Ahmadi Khatir [10] studied the effect of forming force on the channel filling depth, channel width, rib width, uniformity in the depth of formed channels, and channel thickness distribution. They found that increasing the stamping force to the optimal level has almost no effect on the depth of the channels, but increasing the stamping force leads to an increase in the width of the channels and ribs. Hu et al. [11] used the finite element method to predict and prevent defects such as tearing, wrinkling, thinning, and spring back in the stamping process of metallic bipolar plates made of 304 stainless steel. They selected the flow channel dimensions, punch speed, punch radius and matrix, and draft angle as process parameters. Based on their results, the punch speed had an inverse effect on the peak thinning curve and the minimum thickness. Bayer et al. [12] fabricated bipolar plates made of 316 stainless steel with a thickness of 0.1 mm using the roll forming process. They presented a calibrated model to further improve the process with the aim of reducing wrinkling and distortion.

Elyasi et al. [13] fabricated the 316 stainless steel bipolar plates with a serpentine flow field using rubber pad forming. They used polyurethane rubbers with different hardnesses (Shore A40, A55, A65, and A90) and 10, 20, and 30 mm thicknesses. They further investigated the effect of applied force, hardness, and rubber thickness on the filling percentage, thickness distribution, and dimensional accuracy. Their results showed that the filling percentage increased as the applied force increased, but the channel depth was not equal in different directions. Also, increasing the rubber hardness improved the uniformity in the channel depth. In addition, reducing the rubber hardness and increasing the rubber thickness increased the filling volume. However, in the end, they used the semi-stamp rubber forming method to improve the maximum filling percentage, dimensional accuracy, and thickness distribution. Their results indicated an improvement of 11.7, 9, and 1.075% in the modified method's filling percentage, thinning percentage, and dimensional accuracy.

Talebi et al. [14] studied the effect of punch load, thickness, and hardness of rubber on the channel depth (before failure) in order to determine the maximum channel depth. They prevented the failure by machining the rubber pad, increasing the channel depth. Their results showed that increasing the rubber hardness reduces the channel depth and increasing the applied force and the rubber thickness increases the channel depth. Further, they reported that the maximum filling percentage (before failure) was 76%, achieved with a rubber pad Shore A40 and a thickness of 30 mm; the maximum thinning percentage before failure was about 30%. Finally, they increased the filling percentage to 88% by machining the rubber pad.

Ahmadi Khatir et al. [15] investigated the effect of using a lubricant in the manufacture of metallic bipolar plates made of 316 stainless steel with a thickness of 0.1 mm using the stamping process. Their results showed that using lubricant can improve the thickness reduction, uniformity of channels, depth of flow channels, and thickness distribution.

Elyasi et al. [16] investigated the dimensional accuracy of 316 stainless steel metallic bipolar plates in the diagonal, longitudinal, and transverse directions. Their results showed that the dimensional accuracy increases with the increase of the applied force, rubber hardness, and rubber thickness. According to their results, the central channels have a lower channel depth than the lateral channels, and as the applied force increases, the difference between the central and lateral channel depth decreases. They report that the most accurate bipolar plate is made with an applied force of 450 kN and rubber with a 90 shore A and a thickness of 30 mm. Ultimately, they improved the dimensional accuracy by using the semi-stamp rubber pad forming method instead of the standard rubber forming.

Madanloo et al. [17] predicted the onset of failure using three ductile failure criteria, including Rice-Tacey, Brozzo, Ayada, and a developed forming limit criterion considering the effect of material size. According to their results, the most accurate failure prediction during the process is obtained through the Brozzo failure criterion, with an error rate of 3.68%, compared to experiments.

Ahmadi Khatir et al. [18] investigated the effect of geometrical parameters of the metallic bipolar plates, including channel width, rib width, channel depth, draft angle, and corner radius, on the thinning percentage and filling depth of bipolar plates by using the design of experiments and finite element methods. Their results showed that the channel depth, draft angle, and corner radius are the parameters with the greatest influence on the bipolar plates thinning, and the corner radius and draft angle are the parameters with the greatest influence on the maximum depth of the channel.

Talebi et al. [19] investigated the effect of the forming force and rubber hardness on the channel depth in metallic bipolar plates forming using a rubber pad. Their results indicated a direct relationship between the channel depth and applied force. Also, they reported that the maximum channel depth decreases as the rubber hardness increases. However, more reduction in rubber hardness causes reduces the pressure required to form microchannels.

Talebi et al. [20] studied the plastic deformation of straight and curved microchannels, forming limit criteria, and deformation mechanics in the stamping process of metallic bipolar plates and provided a reliable model to estimate fracture initiation. They developed a fracture model based on thinning percentage and equivalent strain to predict the instability of metallic bipolar plates. Their results showed that both equivalent strain and thinning percentage criteria with critical limits of 0.56 and 33.45% are considered the permissible range of plastic deformation during the process. In the end, they showed that the maximum thinning in all directions is less than 33.45% by modifying the process.

Jin et al. [21] formed bipolar plates using stamping and indirect squeeze casting and investigated the formability of these processes. They found that the filling rate increases by increasing the punch pressure in indirect squeeze casting.

Jung et al. [22] investigated the effects of the process parameters, such as punch speed and plate pressure, on the stamping depth using rubber pad forming to manufacture MBPs. Their results show that the channel depth increases with an increase in the punch speed and plate pressure. They also discovered that the draft angle affects the depth and can be set between 20° and 30° to provide optimal effectiveness.

Talebi et al23] .] studied the plastic deformation of the metallic bipolar plate with a serpentine flow field using the stamping process. Their results showed that the percentage of reduction in the thickness of the central channel is higher than the lateral channel in all longitudinal, diagonal, and transverse directions. In addition, the maximum thickness reduction in the central channels was reported in the longitudinal direction, while the diagonal direction was considered a critical direction for the lateral channels. In the end, they used a lubricant to reduce the thickness reduction percentage.

Medanloo et al. [24] manufactured a titanium bipolar plate using a hot stamping method. They reported that this method obtained a maximum channel depth of 0.494 mm, which is about 40% improved compared to stamping at room temperature. Also, this method reduced the dimensional accuracy error caused by spring back.

However, the effect of lubrication on the thickness distribution in different directions and the wrinkling of the bipolar plate margin in stamping the metallic bipolar plates process has not been investigated in previous studies. It is worth noting that these items would significantly affect the quality of the final sample (fracture onset) and could also be effective on the complementary processes needed to fabricate the final sample, including the welding and coating processes. Therefore, this study investigates the effect of the forming process on wrinkling and thinning percentages in detail.

2. Experimental setup and methodology

2.1. Material properties and metal forming die

Uniaxial tensile test results (AStM E08) were used to determine the mechanical properties of 316 stainless steel sheet metal. First, the force-displacement values from the experimental test were converted to real stress-strain values. Next, the Swift equation (Eq. 1) was used to estimate the plastic behavior of the plate at strain values higher than the experimental values from the uniaxial tensile test.

$$\sigma = k\,(\varepsilon_0 + \varepsilon_p)^n \tag{1}$$

Where k , ε_0 , ε_p , and represent the strength coefficient, pre-strain, plastic strain, and strain-hardening exponent. The specified values for the swift equation coefficients and other mechanical properties of the sheet, such as density, yield stress, and Young's modulus, are shown in Table 1.

Table 1. Swift law Equation Coefficient Values

Mechanical properties	Symbol	Value
Strength coefficient, Mpa	k	1576
Pre-strain	ε_0	0.0315
Hardening exponent	n	0.51
Young's modulus, Gpa	E	200
Density, $\frac{gr}{cm^3}$	ρ	7.8

The stamping process was used to fabricate metallic bipolar plates from SS316 with a thickness of 0.1 mm. The stamping consisted of two parts, punch and matrix. The forming die and experimental equipment are shown in Fig. 1. The microchannel layout (serpentine flow field) was machined on the punch and matrix. The rib width, channel width, inner corner radius, and outer corner radius were considered equal to 1.1, 0.5, 0.3, and 0.1 mm, respectively. The process was performed under lubricated and non-lubricated conditions. A fracture was observed in the samples fabricated under non-lubricated conditions. The maximum thinning reduction was measured from the fracture site and used as the critical value of the forming limit. Also, the samples were successfully fabricated under lubricated conditions. These samples were used to verify the finite element model and investigate the thickness distribution and wrinkling in detail.

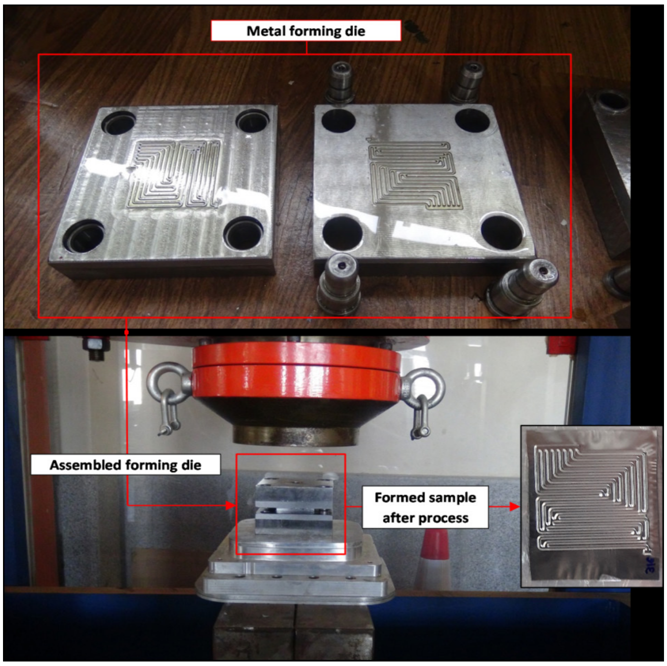

Fig. 1. The experimental equipment of the stamping process.

2.2. Finite element method

The ABAQUS finite element software was used to simulate the process. The punch and matrix were modeled as a rigid and metallic sheet as a deformable shell. Using the mesh convergency method and checking the changes of the maximum equivalent strain at the end of the process, elements with dimensions of 0.065 and 0.15 mm were used for meshing the sheet and die geometry, respectively. The coefficients in Table 1 were used to apply the mechanical properties of the sheet metal. The matrix was constrained in all directions, and displacement boundary conditions were applied to the punch to apply the force to the sheet. The contact conditions between the die components were considered surface-to-surface with a friction coefficient of 0.2 and 0.1 for non-lubricated and lubricated conditions, respectively. The friction coefficient was determined by comparing the experimentally measured and numerically predicted thickness distribution and thinning percentage. To minimize the simulation time, an explicit numerical method was used with a time scale such that the ratio of kinetic energy to internal energy during the process is always less than 1% to maintain the quasi-static state of the problem.

3. Results

3.1. Determining the friction coefficient

The friction coefficient is the effective parameter in defining the contact behavior between process components in finite element simulation. Hence, the friction coefficient of the lubricated stamping process is calibrated by comparing the experimentally measured and numerically predicted results of the thickness distribution and thinning percentage in the longitudinal direction to present a validated model for predicting the process status in the presence of a lubricant. For this reason, the finite element simulation was examined by considering the friction coefficients of 0.2, 0.1, and 0.05. The experimental and numerical results of the thickness distribution are presented in Fig. 2. According to the results, a friction factor of 0.1 leads to the most accurate results in predicting the experimentally measured thickness distribution and thinning percentage. Therefore, the friction factor of 0.1 was applied to determine the thickness distribution in other directions using finite element simulations.

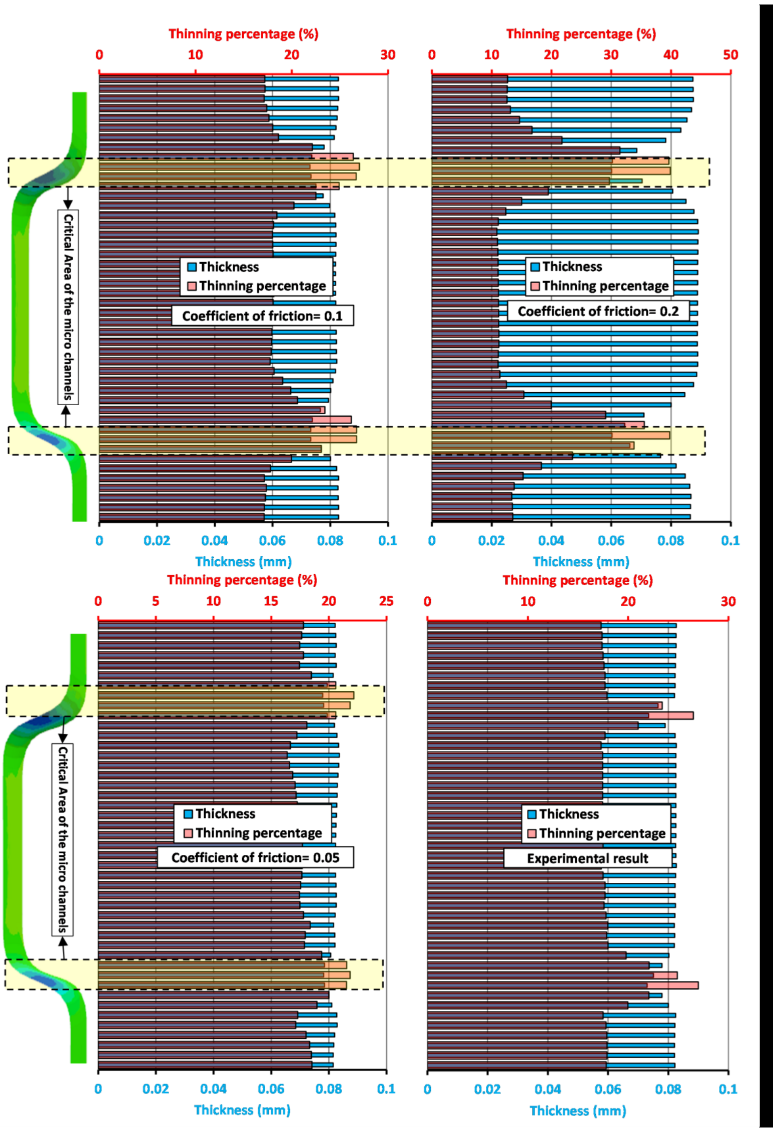

Fig. 2. Determination of the friction coefficient for the simulation of the SS316 bipolar plate forming process using a lubricant.

3.2. The lubricant effect on the thickness distribution

The thickness distribution in different directions of the fabricated MBPPs in the presence of lubricant is examined using the results of finite element analysis. The results of thickness distribution (thinning percentage) in the elements located in the longitudinal, diagonal, and transverse directions are presented in Fig. 3. According to the results, the maximum thinning percentage was created in the longitudinal direction. The maximum value of the thinning percentage in the longitudinal direction is 27.02%, and the corresponding values in the diagonal and transverse directions are equal to 30.4% and 26%, respectively. According to the results, the diagonal direction is the critical area under lubricated conditions despite the conventional stamping process. It is worth noting that the thinning percentage in all directions of the sample fabricated under lubricated conditions is lower than the critical value (maximum thinning percentage before fracture of the experimental sample in non-lubricated conditions), indicating that the modified process using the lubricant prevented form fracture onset on the formed sample which means that the modified process could be utilized as a feasible technique for the manufacturing process of high-quality MBPPs. The critical value of the thinning percentage is 33.45% based on the data-driven form of the formed sample under non-lubricated conditions.

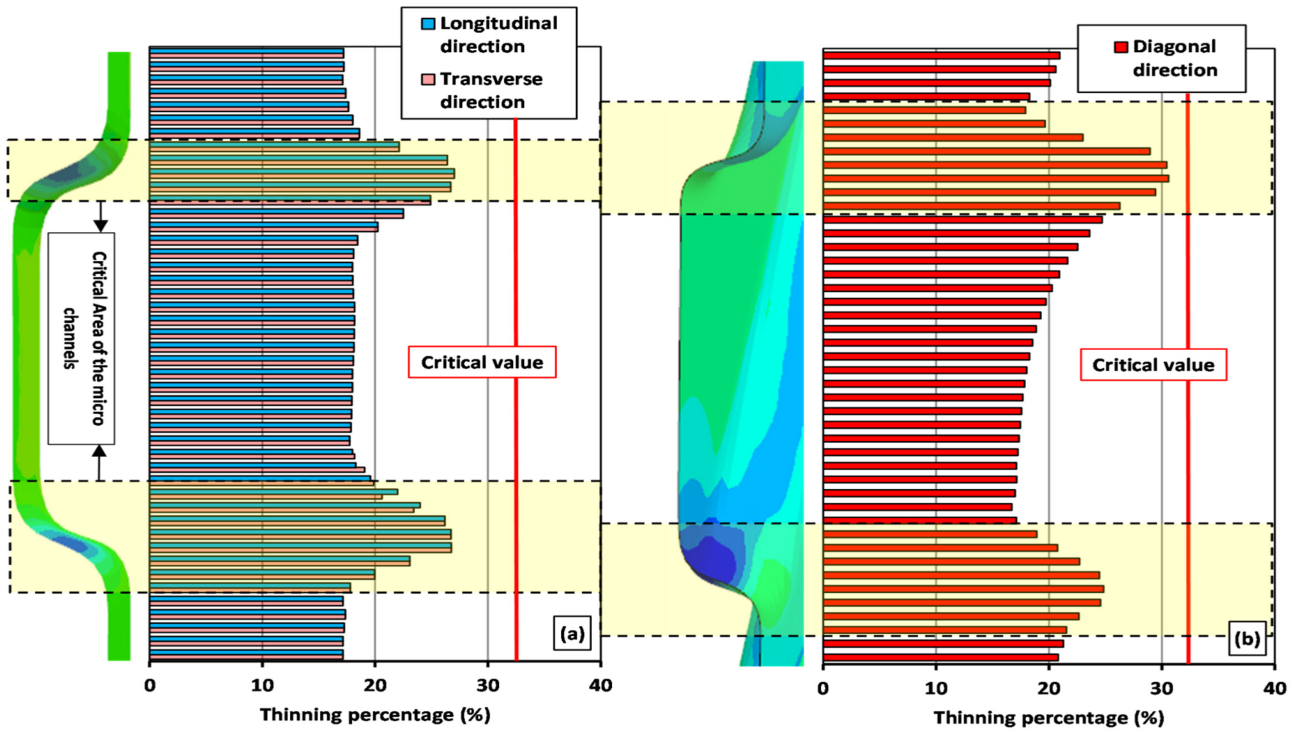

Fig. 3. Thickness distribution of MBPPs formed by the modified process together with the critical forming limit, a) transverse direction and longitudinal direction and b) diagonal direction.

3.3. The lubricant effect on the wrinkling

The lubrication effect on the thickness distribution and on the amount of the sheet plastic flow in different areas were investigated in previous sections. Due to the effectiveness of the forming conditions on the plastic deformation of various areas, it is necessary to investigate the effect of these conditions on the amount of the sheet wrinkling. Actually, the plate wrinkling is affected by the sheet plastic flow in different areas, which is affected by the lubrication conditions.

For this reason, the wrinkling of the fabricated samples under lubricated and non-lubricant conditions was investigated in two different areas. First, the sheet displacement value in different areas after unloading (raising the punch from the sheet surface) and the fluctuations of this quantity were taken as an index of the amount of wrinkling. Then, the changes in this quantity (displacement rate) were considered in six different paths, including three paths in the upper right corner (RU1, RU2, and RU3) and three paths in the lower left corner (LD1, LD2, LD3).

The results of the displacement changes and its distribution in the non-lubricant state are shown in Figs. 4 and 5. According to Fig. 4, the node displacement after unloading compared to the ideal state is located in the sheet's lower left corner (in the range of 0.05 mm), and the difference in the displacement of various nodes compared to the ideal state is observed in all three paths, indicating wrinkles occur in this area. Despite the fact that the maximum displacement is almost the same, the displacement fluctuation of different nodes increases as we get closer to the outer paths, path No. 3 (LD3, RU3), which indicates an increase in the wrinkling in path LD3 and RU3 compared to LD1, RU1 (Figs. 4 and 5). The maximum displacement is in the range of 0.05mm in this area. In this case, the node displacement fluctuations in the outer areas of path No. 3 (LD3, RU3) are more than the inner areas (LD1, RU1, LD2, and RU2).

In general, the results show that the displacement fluctuations from the ideal state in the group of paths LD1-3 (Fig. 4) and RU1-3 (Fig. 5) indicate that the displacement fluctuations occur in wider areas in the plate's lower left corner paths (LD1-3). This actually indicates the more critical wrinkling condition in the lower left corner of the plates, which is caused by increased changes in the shape of the bipolar plates' microchannels flow path in this area (in other words, the existence of a more complex flow channel compared to the upper areas) resulting in augmentation of the wrinkling.

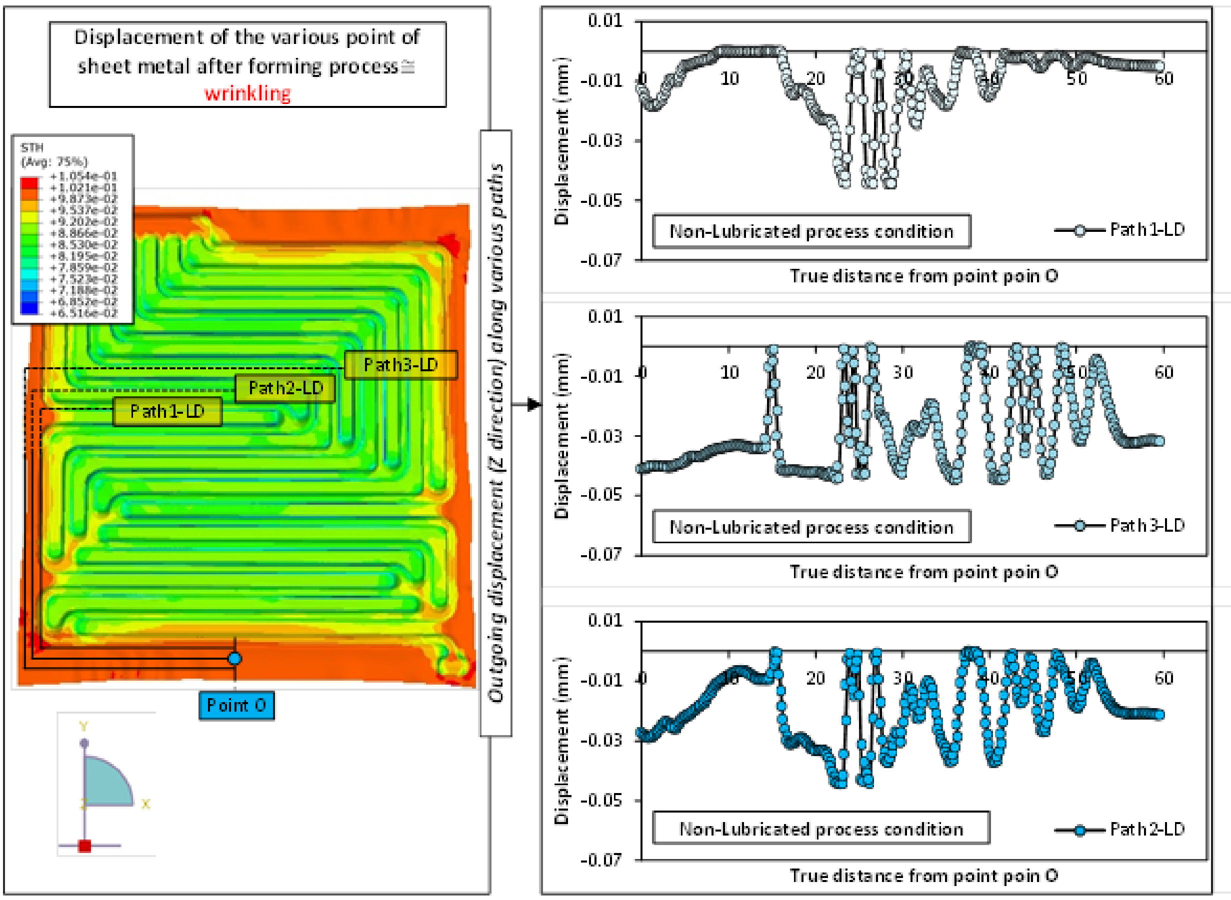

Fig. 4. The wrinkling of the left corner of the fabricated sample under non-lubricated conditions.

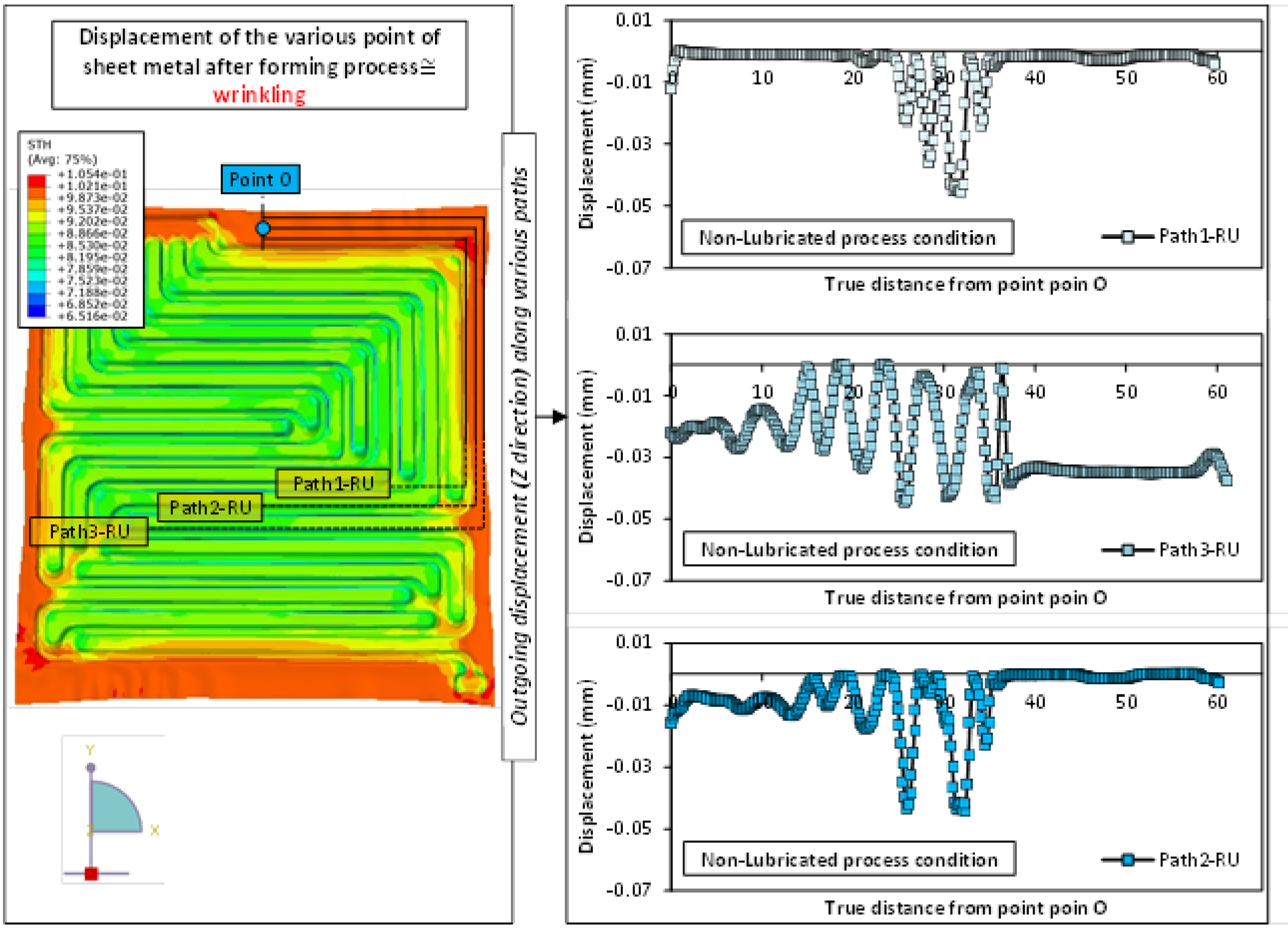

Fig. 5. The wrinkling of the right corner of the fabricated sample under non-lubricated conditions.

In the following, the effect of a lubricant on the wrinkling and displacement deviation compared to the ideal condition was investigated. The results are shown in Fig. 6 and Fig. 7 for the upper right corner and lower left corner areas, respectively. According to the obtained results, the nodes deviation and displacement values have increased in all nodes compared to the condition without the use of lubricant. In fact, the maximum displacement deviation from the ideal state in this case is in the range of 0.065 mm, which indicates an increase the wrinkles compared to the state without using lubricant. Also, in both areas, the displacement fluctuations (compared to the ideal state) is more significant in outer path (RU3, LD3) indicating the increase in the areas that are wrinkled. Also, similar to the case without the use of lubricant, the displacement fluctuations intensity in the lower left corner is higher, which indicates an augmentation in the severity of wrinkling in lower are of the sample. Therefore, according to the results, despite the positive effect of lubrication process on the thickness distribution, it could lead to raising the wrinkling phenomenon. On the other hand, the wrinkling of the metallic bipolar plates could have destructive effect on welding process of metallic bipolar plate. Hence, the process parameters should be select such that the delicate balance being considered between the positive effect of lubrication condition on thickness distribution and their negative impact of wrinkling.

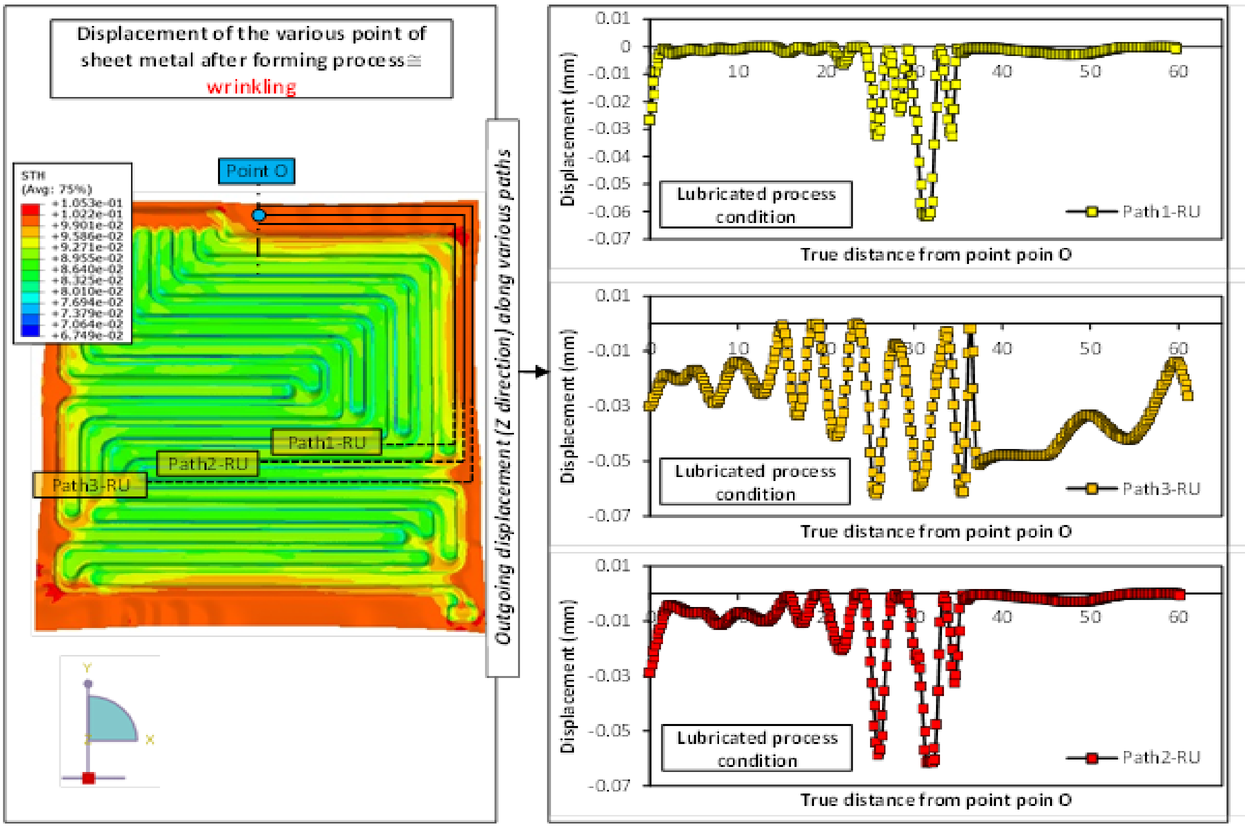

Fig.6 . The wrinkling of the right corner of fabricated sample under non-lubricated condition

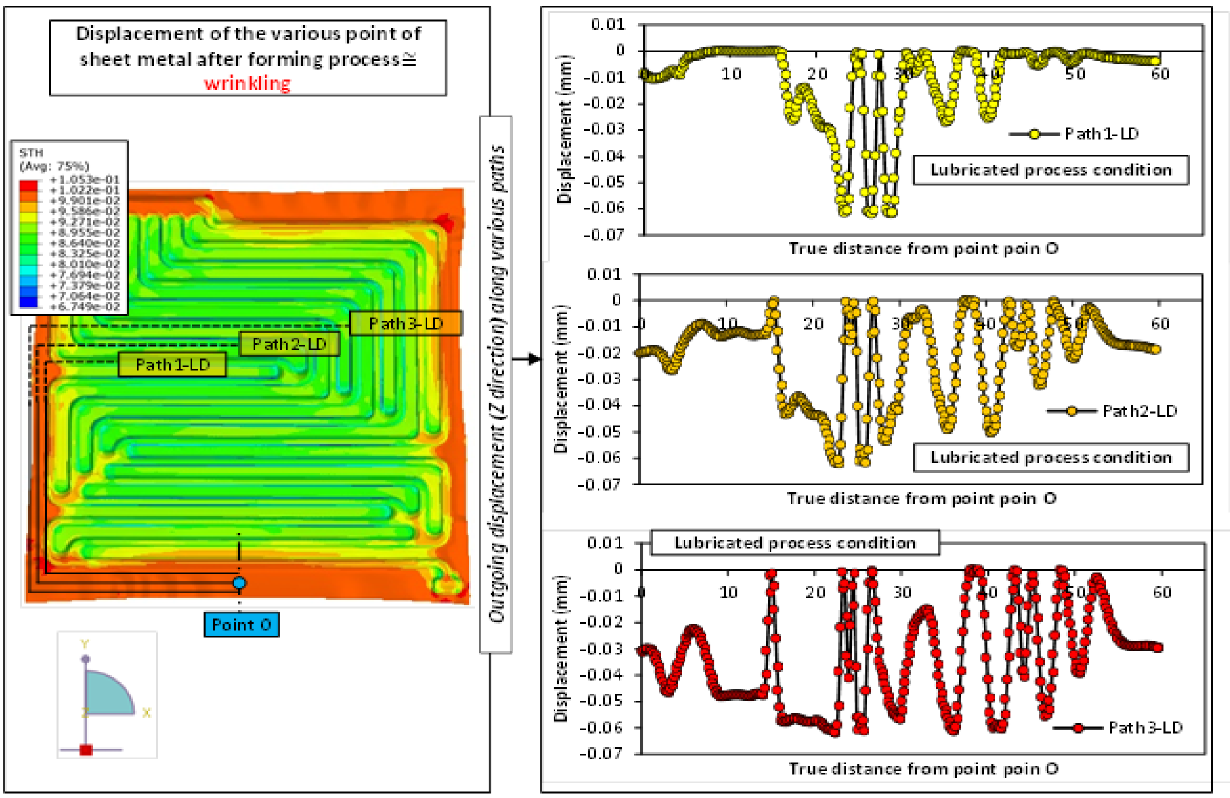

Fig.7 . The wrinkling of the right corner of the fabricated sample under non-lubricated conditions.

4. Conclusion

The present study evaluated the forming of the metallic bipolar plate using a lubricated stamping process. An appropriate finite element model is proposed. The results can be summarized as follows:
A friction factor of 0.1 leads to the most accurate results in determining the thickness distribution. Furthermore, the largest thinning percentages in the modified conditions were found to be 27.02%, 30.40%, and 26.00% in the longitudinal, diagonal, and transverse directions, respectively, indicating that the diagonal direction is the most critical one under lubricated conditions. Lastly, the effect of a lubricant on the wrinkling of metallic bipolar plates margin was investigated. According to the results, the deviation and displacement of the nodes from the ideal state in the lubricant condition increase compared to the non-lubricant condition in all nodes, indicating an increase in wrinkling when using a lubricant.

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Notes for Authors

Aims and Scope:

Iranian Journal of Hydrogen and Fuel Cell (IJHFC) is a research quarterly in Hydrogen and fuel cell fields. IJHFC publishes original research and reviews about the science and technologies of:

Production and purification and application of Hydrogen
Hydrogen reformers and catalysts
Fuel cells and their applications
Performance of fuel cells
Hydrogen storage
Modeling and simulations
Safety in Hydrogen and fuel cell technology
and related research works on Hydrogen and Fuel cells.

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Title: Should clearly and indicate the content of the article. No abbreviation should be used in the title.
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Keywords: Select up to five words should be provided on the title page.

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Tables and Figures: should be numbered consecutively with Arabic numerals (Table 1. and Figure 1.) Tables must have a brief descriptive title. Figures should have figure captions on a separate sheet. The content of figures and tables should not be duplicated.
References: References should be listed on a separate sheet in numerical order according to their order of appearance in the text. Typical citations are illustrated below:

1. Lindstrom B. and Pettersson L. J., "Hydrogen generation by steam reforming of methanol over copper-based catalysts for fuel cell applications", Int. J. Hydrogen Energy, 2001, 26: 923 [year of publication, Volume, number of the first page].

2. Brian W., US Patent 6 379 828, 2002.

3. Zhao T. S., 1st ed., Micro Fuel Cells, Academic Press, 2009.

4. Taghavi H., Shirazi M. M., Hooshmand N., Rahimpour M. R. and Jahanmiri A., "A Tubular Catalytic Plasma Reactor for Hydrogen-Rich Gas Production", Proceeding of the 2nd Conference on Hydrogen & Fuel Cell, Tehran, Iran, 2012: 7.