Shape and Position Design of Two-Step Micro-Channel on Plate During Rubber Pad Forming Process Based on Simulation

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Abstract

Rubber pad forming is an advanced processing technology. The micro-channel is formed on the plate by both rubber pad and the metal mold. With the development of micro-channel, a two-step micro-channel has been applied in more and more fields. However, little attention was given to the geometric design and forming process of this unique channel. In this paper, the process of forming multi-row two-step micro-channels on plate by rubber pad forming is studied. At the same time, the length, width, height ratio and the edge chamfer of two-step micro-channel are discussed as the main parameters of geometry. The number and distance of the second-step structures are also studied in this paper. The influence of these geometric parameters on the forming results is analyzed in the finite element simulation. The plates are designed according to these geometric parameters and structures. Moreover, a novel shape and position design of two-step micro-channel are provided. In addition, forming experiments are also carried out for further study. Finally, a design strategy is provided by forming results in conclusions.

1. Introduction

Rubber pad forming is a new forming process with only a few years of history. Browne et al. [1] and Belhassen et al. [2] proposed that aluminum plates could be formed into the designed shapes through the cooperation of rubber and metal mold. Because only elastic deformation was produced on rubber. Rubber can be used repeatedly. At the same time, the steel mold on one side was replaced by rubber. Forming cost was reduced greatly. In the research of Peng [3, 4] and Chen [5–7], polyurethane and punch were used to process micro-channels on thin plates. Thiruvardhelvan [8] reviewed several rubber pad forming technologies and found that polyurethane played an important role in the forming process. As it is shown in Fig. 1, not only polyurethane, stainless steel 304 is also used in the study of Chen et al. [9]. Since Wang et al. [10] found the formability of convex mold was much better than that of concave one, polyurethane is chosen to replace the concave mold in much more researches.

As shown in Fig. 2, micro-channels are mainly used to guide fluids. And then, industrial and livelihood applications such as heat dissipation [11], gas reaction [12, 13], and drag reduction [14] are developed. However, It should be clear that the channeling of fluids by micro-channels should be divided into two categories. One is the horizontal direction, it is mainly based on the corner channel and the spatial distribution of straight channel. The other one is the vertical direction. It mainly depends on three-dimensional two-step micro-channel.

As it is recorded above, many scholars have studied the process of forming micro-channel by rubber pad forming [15] on the horizontal direction. As shown in Fig. 3(a), a serpentine micro-channel was researched by Ghadikolaei et al. [16] and Wang et al. [17]. Based on the reciprocating of the gases, the reaction efficiency of these micro-channels was significantly improved. In Fig. 3(b), two concentric spiral micro-channels were proposed by Juarez-Robles et al. [18]. As shown in Fig. 3(c), a new flow field design in horizontal direction was proposed based on the same design concept.

However, the flows fields shown above are not changed in vertical direction. Yang et al. [19] proposed a two-step micro-channel. Based on the cyclic variation of the height and depth in the micro-channel, the fluid was forced to flow in three dimensions. This kind of micro-channel was also studied by Liu et al. [20] based on finite element simulation. The forced convection of gas, as a type of fluid, is more obvious in this channel.

The forming processes of the single two-step straight channel and single corner channel were studied by the authors, respectively [10, 21]. They found that the geometries of both straight and corner channel had particular significant effects on formability. When the parameters are suitable, the micro-channels can be well formed. However, it is worth mentioned that, only structural units like second-step structure and corner channel have been studied so far. The forming process of entire plate is still unknown. Since the entire plate should contain both two structures, a study focused on completed channels is studied in this paper.

In order to form this kind of flow field by rubber pad forming, all geometrical parameters are considered. Firstly, the geometric parameters of second-step structure like the length, width, height ratio and edge chamfer are studied, these parameters have mainly effects on the final shapes of second-step structures.

Secondly, the distribution of second-step structures like the number and distance of second-step structures are also discussed, also these parameters influence the final positions of second-step structures a lot.

Based on these parameters, different molds are manufactured. In the rubber pad forming process, the plates are formed through these molds. Finite element simulations and pressing experiment are established to study this process. Flow fields with different parameters are compared based on their forming results and stress patterns. Finally, a well-formed design strategy can be obtained.

2. Modeling

In this paper, ABAQUS6.14.3 is used to simulate the whole forming process. In order to ensure the accuracy of the simulation, the rubber pad forming model of the whole plate is established. As shown in the Fig. 4, the geometric parameters in molds are shown.

In order to obtain a comprehensive understanding on forming of two-step micro-channel with different shapes based on rubber pad forming. There are 11 groups with different geometric parameters. Molds are discussed separately based on their types. As shown in Table 1, the details of parameters are displayed.

Table.1 Parameters of micro-channel in different groups

No.	Second-step structure length(mm)	Channel width(mm)	Height ratio of first to second step channel(mm)	Edge chamfer $D_1:D_2$ (mm)
1	5	1	0.30:0.30	0
2	6	1	0.30:0.30	0
3	7	1	0.30:0.30	0
4	7	1	0.30:0.30	0.125:0.30
5	7	1	0.30:0.30	0.25:0.30
6	7	1	0.30:0.30	0.375:0.30
7	7	1	0.30:0.30	0.50:0.30
8	7	1	0.35:0.25	0.50:0.30
9	7	1	0.40:0.20	0.50:0.30
10	7	1.1	0.30:0.30	0.55:0.30
11	7	1.2	0.30:0.30	0.60:0.30

It is not only the parameter of the second-step structure, but also the distribution of these structures have important influences on the forming of the plate. As shown in Fig. 5, The rectangular coordinate system is established with the center of the plate as the original point O. The length and width of the plate are represented by l_1 and w_1 , respectively. The width of the channel is defined as w_2 . The distance between two channels is set to d_1 . The distance between the outermost channel and the edge of the plate is indicated by d_2 . Therefore, Eq. (2.1) can be used to determine the width of the channel and the distance between the channels. n_1 is the number of channels in the x-axis.

$$w_1 = 2d_2 + n_1w_2 + (n_1 - 1)d_1$$

(2.1)

As shown in figure, the corner area is shown in red. Similarly, the straight channel and second-step structure are shown in blue and white, respectively. The length of the second-step structure is shown as l_2 . l_3 is the length of the straight channel. The distance between second-step structures is called d_3 . d_4 is the distance between the second-step structures and the corner area. ϑ is the angle of the corner area of the plate. It can be clearly seen from the figure, when d_4 is increased (decreased), ϑ is also increased (decreased). The number of two-step channels are also changed. And then, the following formula can be obtained. n_2 is the number of second-step structures.

$$d_4 = \frac{l_3 - n_2 l_2 - (n_2 - 1) d_3}{2}$$

(2.2)

According to the Eq. (2.1) and Eq. (2.2), MATLAB is used to find the best parameter combination. As shown in Fig. 6, the 3D surface diagram of Eq. (2.1) is shown. The relationship between the parameters can be visually displayed. As it can be seen from the figure, the number of channels (n_1) is easily affected by the width (w_2) and distance (d_1) of the channels. As the value of d_1 goes up, the value of n_1 gets smaller and smaller. In addition, the value of n_1 is decreased with the increase of parameter w_2 . According to the MATLAB surface diagram, the appropriate width and distance of channels can be found.

The relationship between the parameters of Eq. (2.2) is shown in Fig. 7. As shown in the figure, the number of second-step structure is directly affected by the length and distance of the second-step structure. When the length of second-step structure increases, the number of second-step structure is decreased. The number of second-step structure is also limited by the distance of second-step structure. Only when the parameters are appropriate, the suitable structural design can be obtained.

As shown in the figures above, when the size of the plate and the parameters of the two-step channel change, based on the Eq. (2.1), Eq. (2.2) and MATLAB, the best parameter group can be found. The best design strategy can be provided by these parameters.

Moreover, based on the above parameters, the molds shown in Table 2 are also designed.

Table.2 Parameters of micro-channel in different groups

No.	The distance between the second-step structures $d_3(\text{mm})$	No.	The number of second-step structures
12	0	15	134
13	1	16	112
14	2	17	100

The assembly and meshing of molds, plates and rubber pad in finite element experiments are shown in Fig.8.

To simplify the calculation, the following assumptions are proposed: The mold is assumed to be rigid in the simulation. Plate is considered to be rigid-plastic material without strain-hardening effect. The volume of rubber is considered as a constant value in deformation because of hyperelasticity.

In the rubber pad forming process, the entire model is in a frame. Deformation is allowed to occur only in the vertical direction because of frame. To simplify the simulation model, the role of the frame is replaced

by additional constraints. The only free surface in the rubber pad is the one contact to the plate. The rest of all surfaces are limited by loads. The top surface is limited with no displacement. The horizontal surfaces are locked at the x and z axes. Rigid mold is only allowed to move up in vertical surface to form the plate. With these loads, all deformation can be taken part into the forming of the groove.

In this model, the mold is defined as a rigid part. Moreover, it is placed at the bottom of the entire model.

The plates are placed between the mold and the rubber pad. It is seen as a deformable part. SS304 was selected as a plate material. The friction between the plate and the mold is less than that between the plate and the rubber pad. The contact interaction properties are entered as 0.1 and 0.2 [22, 23]. The thickness of the plate is selected as 0.1 mm. Density of plate is 7.833 g/cm³. The Poisson's ratio and Young's module are 0.3 and 162.5 GPa, respectively. The yield stress and plastic strain of the plate satisfy the following relationship: $\sigma = 1421(0.047 + \epsilon)^{0.561}$.

The rubber pad is installed at the top of the model. Same as the plate, the rubber pad is also regarded as a deformable part. Polyurethane with hyperelasticity is selected as rubber pad material. The hardness and Poisson's ratio of rubber are 70 Shore A and 0.4999, respectively. Because the nonlinear hyperelasticity and incompressible properties need to be defined on rubber material, the Mooney-Rivlin model is used. In addition, the parameters C10 and C01 in Mooney-Rivlin model were selected as 0.736 and 0.184 [3, 24].

As shown in Fig. 8, the rubber pad and plate are meshed with 0.5*0.5*0.5 mm elements. The mesh types of rubber pad and plate are C3D8RH (8-node linear brick, hybrid, constant pressure, reduced integration, hourglass control) and C3D8R (8-node linear brick, reduced integration, hourglass control) respectively.

3. Results

In order to study the effects of different geometric parameters on forming results, not only the stress contours are displayed on the deformed plate, but also the shapes of micro-channels are shown.

As it is shown in Fig. 9, stress contours and forming results are shown. When the length of the second-step structure is different, the stresses on the plate are described by contours. When the length is 5 mm, the deformation between channels is insufficient. If the length is increasing from 5 mm to 7 mm, the stress shown on the plate is increasing based on these comprehensive reasons. The forming results of the plate also become better based on this changing. This can be explained as the flow of rubber will be less restricted when the second-step structure is long enough. The channel can be formed more accurately with larger stresses.

However, as shown in Fig. 9, it is obvious that the ridge of two-step channel is not well formed. Actually, more stresses are needed, when the height of two-step channel is varied. Also, the shape of the second-step structure should be well adjusted to further improve the formability. As shown in Fig. 10, different edge chamfers of the second-step structure are researched to improve this situation.

As it can be seen in Fig.11, with the increasing of edge chamfer (D_1 , D_2), the forming results of the plate firstly become worse and then a better result can be shown. When , the plate is suffered to a smaller stress, and the first-step channel is barely formed. When $D_1 > 0.25$ mm, the stress shown on the plate is increased, the first and second step channels are obviously formed, and the forming results are better. When edge chamfer D_1 , D_2 are 0.5 mm and 0.3 mm, the shape of the top second-step structure is changed to straight line from rectangle. Since the edges of the second-step structure are accurately formed, the forming result can be better at this time.

As it is seen in Fig. 12, The channels height ratios of the first and second step are 0.3:0.3, 0.35:0.25 and 0.4:0.2, respectively. With the increase of the height ratio of the first and second step channel, the forming results are worse and worse. This may be explained by the flow of rubber is more restricted. As the height of the second-step structure is decreasing, the volume of the second-step structure will also be decreased. When the ratio is 0.3:0.3, the plate is suffered the maximum stress and the forming result is the best.

The length, edge chamfer and height ratio all have influence on the forming result, but the width of channel seems to play a most important role on the final result. This kind of influence has nothing to do with the forming ability of the plate, but it is the location of the interaction that most affects the result. As the width of the channel is increased, the distance between channels is decreased in this experiment. As shown in the Fig. 13, when the channel width is increased from 1 mm to 1.2 mm, the forming results of the plate become worse and worse. This can be explained by the stresses applied on the ridge of the channel. When the distance between channels is too small, the plate cannot be formed accurately and smoothly with less stress. As observed in the figure, the plates are well formed when the distance is 1.4 mm and 1.3 mm, respectively. Therefore, the distance between channels should be equal or greater than 1.3 mm.

The best forming results for the two-step micro channel were found according to the above experiments. The parameters with the best forming results were selected for the following study. Multiple two-step structures are designed in one micro channel. As shown in Fig. 14, finite element simulation results were obtained when the distance between the second-step structures was 0 mm, 1 mm and 2 mm, respectively. It can be observed that the stresses applied on the channel are the same with each other. Also the depths of micro-channel are the same as the design ones. Therefore, the distances between the second-step structures have a little influence on the forming results in No.12, 13 and 14.

As shown in Fig. 15, the two-step channels with the largest number are inserted in the straight line areas. The length of the second-step structure is 7 mm, 8 mm and 9 mm in No.15 No.16 and No.17, respectively. According to the Eq. (2.2), when parameter a is a constant value, parameters b and c are determined. It can be observed that the number of second-step structures is decreased as its length is increasing. When length of second step structure is 7 mm, there will be 134 ones. When the length is 8 mm and 9 mm, the quantities of this structure will be 112 and 100, respectively. As shown in the figure, the three plates are well formed. And it can be found that, the straight line areas are all formed well. There are no obvious evidences to find a relationship between number of second step structures and formability.

In conclusion, the formable structure is obtained based on the following conditions met by each parameter.

1. The length of the second-step structure should be long enough (longer than 7 mm).
2. Side chamfers should be as large as possible. The second-step structure can be minimized.
3. The height ratio of the first and second step structures is 1:1.
4. The width of micro-channel should not be too small (greater than 1 mm is appropriate). And the distance between micro-channels should not be too small (greater than 1.3 mm is appropriate).
5. Second-step structures can be spaced as close as possible. Through this, the number of second-step structures can be increased.

4. Forming Experiments

In order to further investigate the forming process of plate with two-step micro-channels, the rubber pad forming experiment was also conducted. Based on the finite element simulation results, the parameters with the best forming results were selected. [25] Different molds are manufactured according to the channel parameters numbered No.7 and No.10.

The experiment was carried out on a press machine with fixture. The stepping speed of the press machine is set as 0.5 mm/s. A frame is also used on the press machine to fix all the equipment. All deformation is limited in the vertical direction due to the frame. There are mold, plate and rubber pad in the frame. They are all in the same size 60 mm*60 mm. Their total height is slightly higher than that of the frame. So, when the press machine is turned on, the mold is pressed into the frame by the punch. Plate is also formed between the rubber pad and the mold. The mold is placed on top of these parts. It was placed upside down so that the channels can be formed on the plate as designed. SS304, which has been annealed to improve its deformation capacities, was selected as the material for the plates. And its chemical composition is shown in Table.4.

Table.4 Chemical composition list of SS304

	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Cr (%)	Ni (%)
SS304	≤ 0.08	≤ 0.1	≤ 0.2	≤ 0.045	≤ 0.03	18.00 ~ 20.00	8.00 ~ 10.50

At the bottom, there is the rubber pad. Polyurethane is chosen as the material of rubber pad. Due to the limiting effect of the frame, the moving and deformation of the polyurethane are limited in the desired direction. It is worth mentioning that the MoS₂ lubricant was used in the experiment in order to reduce the friction in the device.

As shown in the Fig. 17, after the pressing process, the plate was formed as it is designed. The channels of straight line and corner areas were easily seen on the plate. The second-step structure was obviously different from the first-step. As shown, the plates were cut along the red lines. The channels at the red

lines in each plate were divided into three groups that are shown in both macroscopic and microscopic photos. In order to prove the results obtained based on finite element method, the green lines representing the results of finite element method are also shown in the figure. The results of finite element method are in good agreement with the results of forming experiment. As shown in figure, by comparing the results of finite element simulation and forming experiment, the height and width of the second-step and first-step channels are basically the same. However, there is a little error in the area between the second-step structures. This may be due to the springback and the cutting method of the plate.

5. Conclusion

1. Based on the finite element method, the punch and the rubber pad are combined to form the two-step channel. The effect of channel width, length, height ratio, edge chamfer, the distance between second-step structure and the quantity of second-step structure on forming results were studied. The reasons for these results are discussed respectively.
2. A new flow field design based on serpentine flow field and two-step channel is proposed. Based on finite element analysis and pressing experiment, rubber pad forming process can be used to form this flow field.
3. Through finite element analysis and forming experiment, a large width and distance of micro-channels, a large edge chamfer and length of second-step structure, a small distance of second-step structures and a suitable first and second step height ratio are appropriate structural designs. Based on mathematical analysis and MATLAB, this structure design is still applicable in different plate sizes and channel parameters.

Declarations

Authors' Contributions

WHY, SJC and SJ were in charge of the whole trial; TF wrote the manuscript; WGD and JL assisted with finite element modeling; LJR and SSN assisted with forming experiment; All authors read and approved the final manuscript.

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Competing Interests

The authors declare that they have no competing interests.

Availability of Data and Materials

All data generated or analysed during this study are included in this manuscript.

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Figures

Figure 1

Schematic diagram of rubber pad forming

Figure 2

Common micro-channel and two-step micro-channel

Figure 3

Schematic diagrams of the flow fields

Figure 4

Schematic diagram of geometrical parameters of two-step micro channel

Figure 5

Schematic diagram of partial plate parameters

Figure 6

Schematic diagram of MATLAB of Eq (2.1) (d_1 : the distance between two channels, w_2 : The width of the channel, n_1 : the number of channels)

Figure 7

Schematic diagram of MATLAB of Eq (2.2) (d_3 : the distance between second-step structures, l_2 : the length of the second-step structure, n_2 : the number of second-step structures)

Figure 8

Modeling and meshing as well as assembling of rubber pad forming simulation

Figure 9

Stress acting and displacement diagram of deformed plate by molds with different channel lengths (No.1-No.3)

Figure 10

Schematic diagram of edge chamfers of molds with D1 and D2 (No.3-No.7)

Figure 11

Stress acting and displacement diagram of deformed plate by molds with different edge chamfers (No.3-No.7)

Figure 12

Stress acting and displacement diagram of deformed plate by molds with different height ratios (No.7-No.9)

Figure 13

Stress acting and displacement diagram of deformed plate by molds with different channel width (No.7, No.10, No.11)

Figure 14

Stress acting and displacement diagram of deformed plate by molds with different distance between the second-step structures (No.12-No.14)

Figure 15

Stress acting and displacement diagram of deformed plate by molds with different number of second step structures (No.15-No.17)

Figure 16

Forming experiment

Figure 17

Schematic diagram of forming results