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ORIGINAL ARTICLE

Numerical simulation and experiment research on forming of two-step channel based on rubber pad pressing

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Abstract
Rubber pad pressing is one of advanced materials processing technologies. With the cooperation of both rubber pad and metal mold, the plate is accurately formed into the required shape. Not only the surface of the plate remains a good quality but also the springback is substantially reduced. In this paper, a new kind of two-step channel formed by the rubber pad pressing is researched. Both convex and concave metal molds are considered in the researches. All kinds of geometrical parameters like channel width, edge fillet, depth ratio, and second-step shape are discussed in this paper. In order to obtain a good two-step channel by rubber pad pressing, both FEM and real pressing experiments are done. Based on both FEM and experiment results, channel can be formed by rubber pad pressing with both convex and concave molds. The plate formed by convex mold can be better than that formed by the concave one.

Keywords Rubber pad forming · Tow-step channel · Convex and concave molds · FEM · Pressing experiment

1 Introduction

Traditional pressing with thin sheet is a complicated process. Peker et al. [1] proposed that lots of technological parameters needed to be considered together. Chen et al. [2] found that geometrical parameters of punch and die deeply impacted on the product. Different fillets and depths as well as widths were designed in male and female dies to form a punch-to-die clearance. Chen et al. [3] also obtained if the sheets were very thin or the precision of the product was required very high, both the heat treatment of tooling and lubricant of the dies could lead to the deviation of the sheets deformed. Beyond that during the pressing, movement of the punch should be controlled very precisely. Summing up the mentioned above, precision pressing in a traditional way is big economic costs of both tools and processing.

To solve these problems, an advanced pressing technology called rubber pad pressing was proposed by Browne et al. [4]. As it was shown in Fig. 1, during this processing, one of the concave and convex molds was replaced with rubber pad. With the cooperation of both rubber pad and metal mold, the plate could be formed into the required shape. Dirikolu et al. [5] used ANSYS to analyze the deformation of the rubber pad during the pressing and found the optimum parameters of rubber properties. Gau et al. [6] used aluminum sheet as experimental materials; the sheet was formed into simple channels by rubber pad forming. Comparing to traditional pressing, this new processing has a lot of advantages, which are listed below:

- Since only one rigid mold is needed, the cost of the tool is much reduced.
- The position of rubber pad is no need to be fixed, so a common moving control of rubber pad or metal mold is enough during pressing process.
- Various thicknesses and different metals can be pressed with the same tool, so there is no need to consider the punch-to-die clearance.
- Perfect surface quality can be remained, since there is no tool marks are created by flexible rubber.
- The rubber pressing is like hydraulic pressure or air pressure pressing; almost all surface of the plate is under the same pressure. The deformation is much uniform and the thinnest of the plate appears on everywhere of the plate surface.

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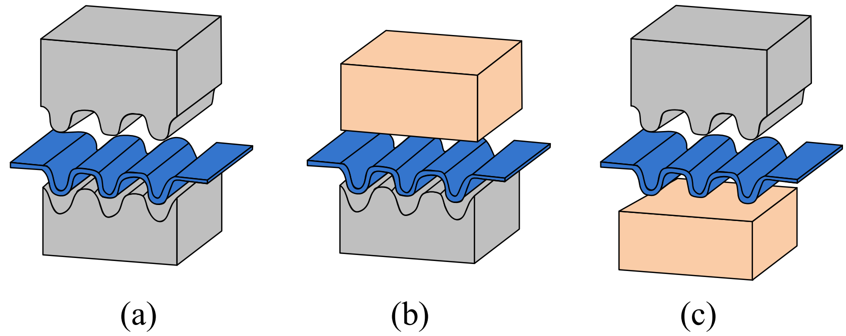

Fig. 1 Schematic diagrams of traditional pressing and rubber pad pressing

- After the deformation process is finished, less springback is shown.

After several years' researches of the rubber pad pressing, some scholars used this advance materials processing technology to form a bipolar plate in proton exchange membrane fuel cell. Peng et al. [7] used rubber pad pressing as a soft punch stamping process to form a simple straight channel. Liu et al. [8] also researched the deformation style of the rubber pad forming used for metallic bipolar plates. Peng et al. [9] used both numerical simulations and experiments to research the forming of metallic bipolar plates, but the modeling of the simulation was still a simple 2D model. Liu et al. [10] received a full plate with a fixed depth channel based on rubber pad forming. In that paper, a 2D model was proposed to research the simple channels. Also, the type of the mold was only a convex one. Peng et al. [11] summarized all kinds of feasible methods to produce the channels and provided the advantages of the rubber pad forming. Jin et al. [12] compared the properties of different materials like titanium nitride, chromium nitride, and multi-coated stainless steel 304. Then they used them to form bipolar plates based on rubber pad forming. Kolahdooz et al. [13] also proposed the critical factors about rubber pad forming, but the type of channel was only common channels and the simulation model was also only based on plane deformation.

Since the history of rubber pad pressing applied in BPP (bipolar plate) forming is short, the channel formed by this new technology is only some simple types. Most of them are single straight channel with a certain height or depth. This kind of channel is too simple to realize complicated functions. Now, there are some cyclic variable height or depth channels, which can be seen as Two-step channels. Yang et al. [14] provided this new channel through 2D simulation and analysis. Li et al. [15] also researched this new kind of channel based on simulation, but only the flow of gas was researched. The forming of this kind of channel was not proposed. Based on the cyclic variation of the height or depth in the channel, the reactant gas was forced to flow. Based on this force convection, the utilization of fuel and homogeneity of the reaction were both greatly improved in this kind of channel (Fig. 2).

In order to form this new kind of channel by rubber pad pressing, all of the geometrical parameters in two-step channel like channel width, depth, or height of the first and second channel, edge fillet and shape of the channel are researched. Since the plate can be formed by both convex and concave molds with the cooperation of rubber pad, two kinds of rigid molds are also considered in this paper. After rubber pad pressing is researched in

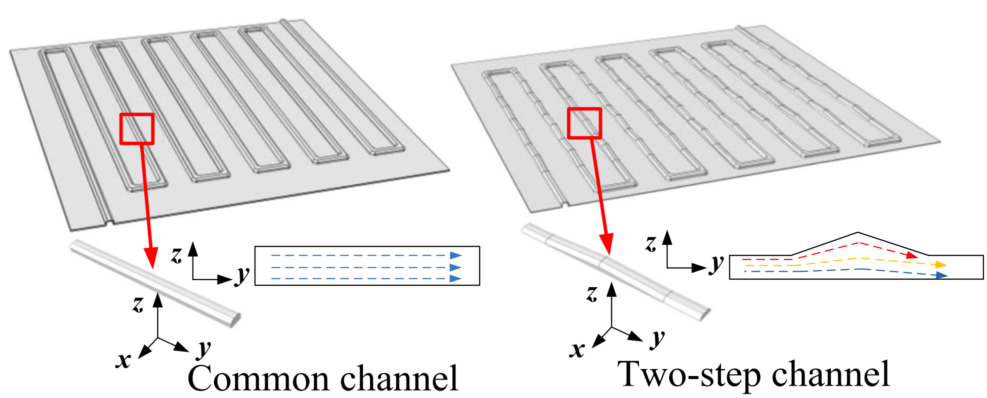

Fig. 2 Common serpentine flow field and two-step serpentine flow field

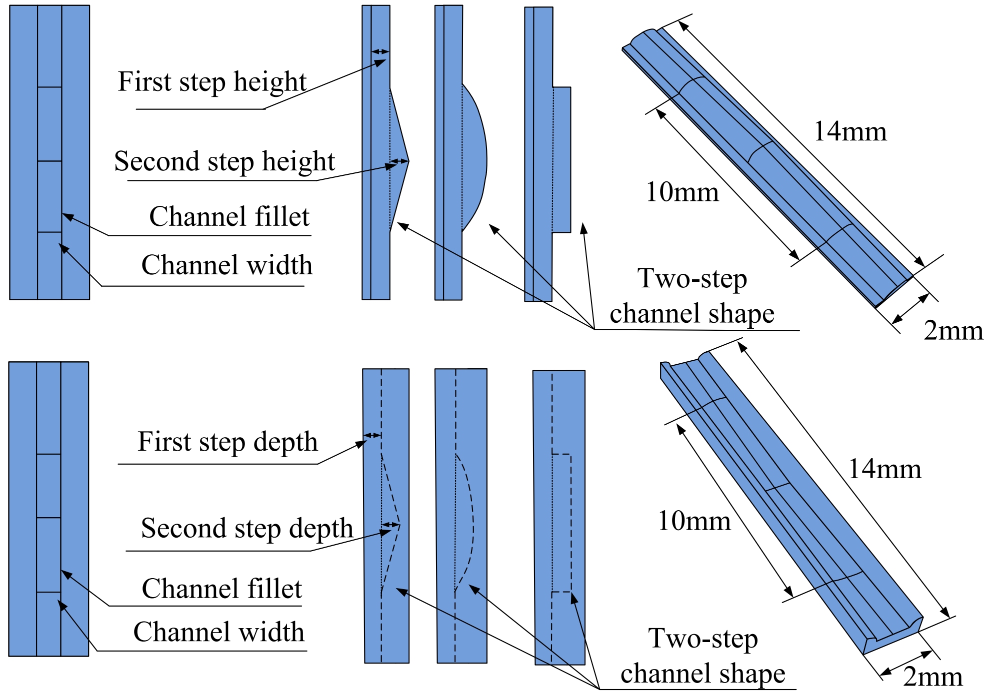

Fig. 3 Schematic diagrams of the convex and concave molds

ABAQUS, FEM experiments results are discussed. At last, the real rubber pad pressing experiments are conducted, and the results obtained based on the real pressing experiments are used to prove those received from the FEM experiments (Fig. 2).

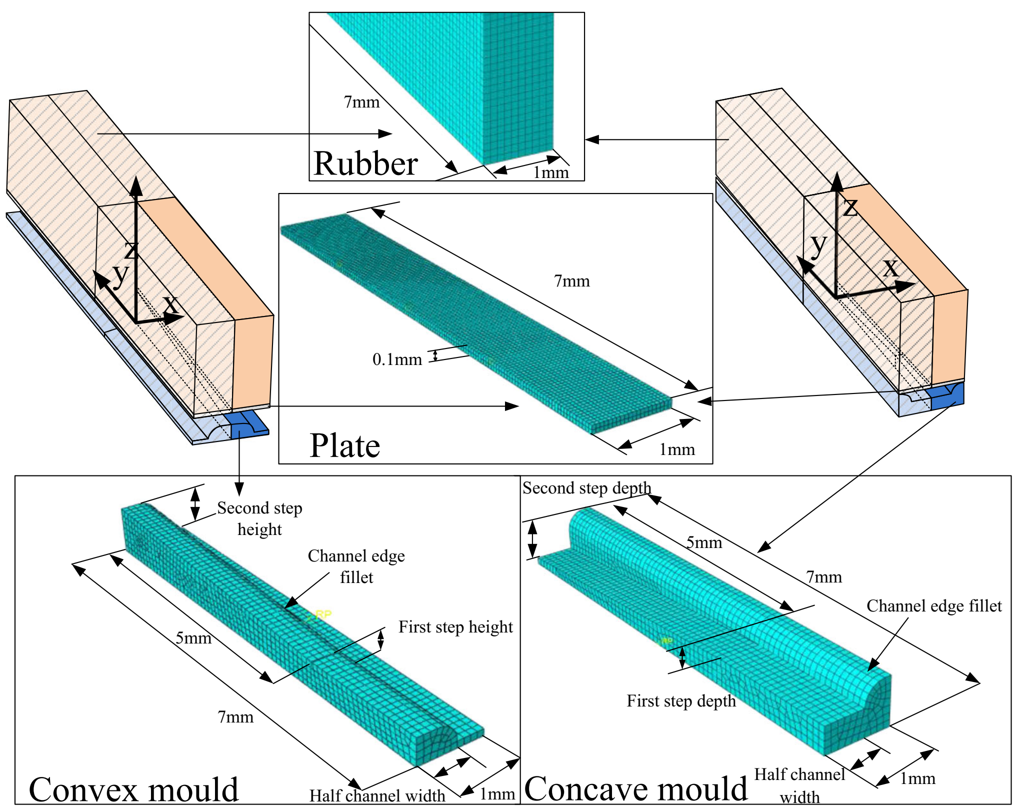

Fig. 4 Quarter of modeling and meshing as well as assembling of the rubber pad pressing simulation

Table 1 Parameters of the convex and concave molds

Mold number	Mold type	Channel width mm	First-step height (depth) mm	Second-step height (depth) mm	Edge fillet mm	Two-step channel shape
1	Convex	1.2	0.3	0.3	0.3	Triangle
2		1	0.3	0.3	0.3	Triangle
3		0.8	0.3	0.3	0.3	Triangle
4		0.6	0.3	0.3	0.3	Triangle
5		1	0.2	0.4	0.3	Triangle
6		1	0.2	0.4	0.3	Arc
7		1	0.1	0.5	0.3	Triangle
8		1	0.1	0.5	0.3	Arc
9		1	0.3	0.3	0.2	Triangle
10		1	0.3	0.3	0.1	Triangle
11		1	0.3	0.3	0.3	Arc
12		1	0.3	0.3	0.3	Rectangle
13	Concave	1.2	0.3	0.3	0.3	Triangle
14		1	0.3	0.3	0.3	Triangle
15		0.8	0.3	0.3	0.3	Triangle
16		0.6	0.3	0.3	0.3	Triangle
17		1	0.2	0.4	0.3	Triangle
18		1	0.2	0.4	0.3	Arc
19		1	0.1	0.5	0.3	Triangle
20		1	0.1	0.5	0.3	Arc
21		1	0.3	0.3	0.2	Triangle
22		1	0.3	0.3	0.1	Triangle
23		1	0.3	0.3	0.3	Arc
24		1	0.3	0.3	0.3	Rectangle

After the three parts are assembled together in the space, the load is applied in the rigid mold and the plate is formed into the required shape

2 Modeling

The geometrical parameters of the metal mold are significant to the results of rubber pad pressing. As it is shown in Fig. 3, in order to compare the formabilities of the plates formed with different molds, both convex and concave molds are cooperated with rubber pad in pressing process. All the important parameters are considered in modeling of both concave and convex metal molds.

According to the symmetry, a quarter of the model is imported into ABAQUS. Both convex and concave molds are used in the finite element modeling, respectively. The geometrical parameters of the molds and plate as well as rubber pad are described in Fig. 4. From Fig. 4, the modeling and meshing as well as assembling in the simulations are shown.

The rubber pad is put in the top of the model, and the hexahedron mesh is applied in this part. The mesh type is C3D8RH (8-node linear brick, hybrid, constant pressure, reduced integration, hourglass control). The material

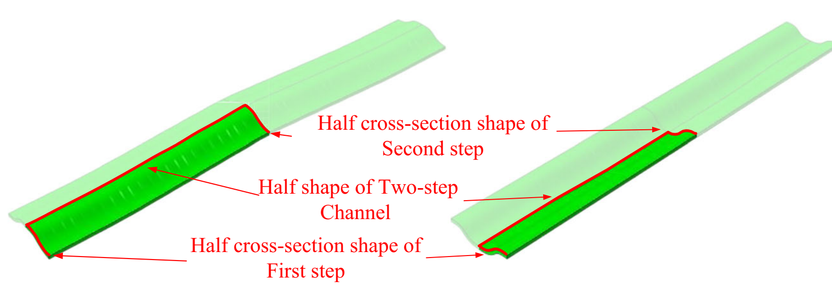

Fig. 5 Whole of the channel in simulation result based on mirror symmetry, half shape of two-step channel, and half cross-section shapes of the first and second steps

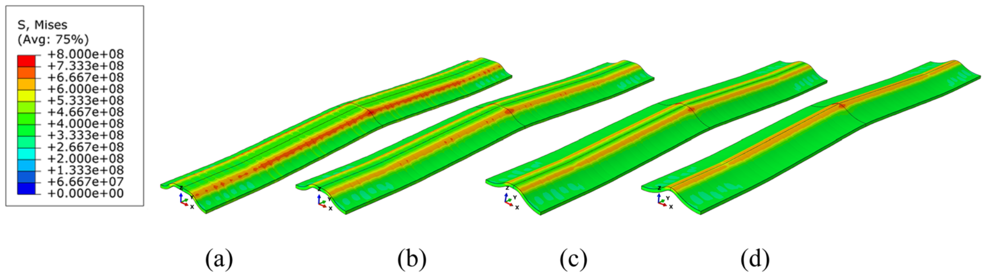

Fig. 6 Stress distribution on the plates formed by the convex molds with different channel widths (groups 1, 2, 3, and 4)

properties of the rubber are significant to the final results in this model. This is not only because that huge deformation will appear in the rubber but also the plate will be formed into the required shape under the pressures from the rubber. Since the deformation of the rubber pad has following characteristics like: incompressible and hyperelastic as well as nonlinear, Mooney-Rivlin model is set in materials behavior. Since in this model, the rubber is polyurethane rubber with shore A hardness of 70 (HD 70), the parameters C_{10} and C_{01} in Mooney-Rivlin model are chosen as 0.736 and 0.184 [7, 9, 13]. The density of the rubber is 1.2 g/cm^3 and the friction between the rubber and plate is selected as 0.2 [8, 13]. In addition to the above, since deformation in this model is huge, the grid will be changed severely. During the deformation, there may be zero energy deformation mode in the element. This mode is so-called hourglassing mode, and the hourglass control should be also set in the model.

Between rubber pad and mold, there is the plate. In this model, the plate is also seen as a deformable part. The hexahedron mesh is also used in the plate, but the mesh type is different. The common C3D8R (an 8-node linear brick, reduced integration, hourglass control) is selected. Stainless steel sheets SS304 are chosen as the blank material. Its Young's module is 162.5 GPa. The Poisson's ratio is selected as 0.3. The yield stress and plastic strain satisfy the following relationship: $\sigma = 1421(0.047 + \varepsilon)^{0.561}$. The density of the plate is 7.833 g/cm^3. Since the contact surface between plate and mold is smoother than that between rubber and plate, the contact interaction property between plate and mold is set as 0.1 [8, 13].

In bottom of the model, there is the mold, which is edited as a rigid part. Different geometrical parameters are all considered in this part. The details of the parameters are shown in Table 1.

3 Results

After the plate is pressed with rubber pad and metal mold, both thicknesses and shapes of the plate are recorded. Not only the stress distribution contours are shown in the results but also several lines of shapes are received in the figures.

During the modeling and simulating, a quarter of the channel is pressed. Based on the mirror symmetry, whole of the channel can be shown as Fig. 5. From this figure, half cross-section shape of the second step can be used to show the height or depth of second-step channel. Also, this shape will show the limit of the rubber pad forming in vertical direction. Half cross-section shape of the first step can be used to describe the height or depth of the first-step channel. Also, it can be used to compare with the second one. Based on the comparing with the shapes of two steps, the formability of this two-step channel can be obtained. The last one is half shape

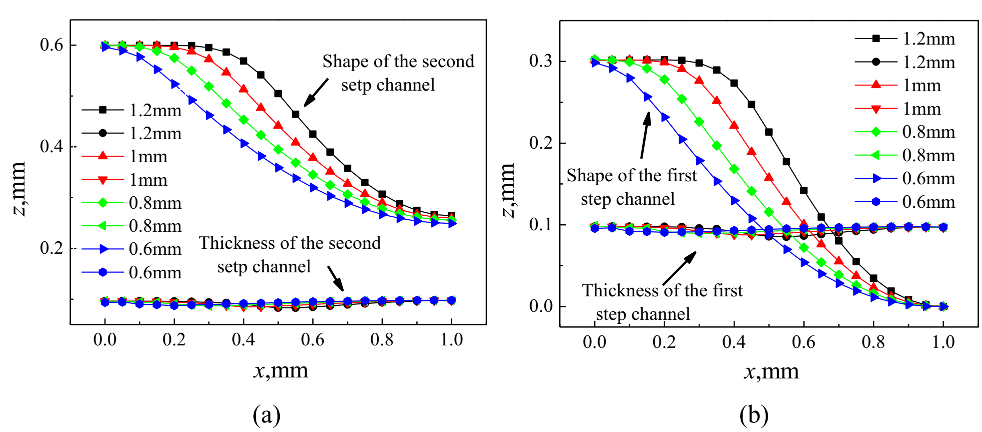

Fig. 7 **a** Half cross-section shape of the second-step channel and its thickness. **b** Half cross-section shape of the first-step channel and its thickness (groups 1, 2, 3, and 4)

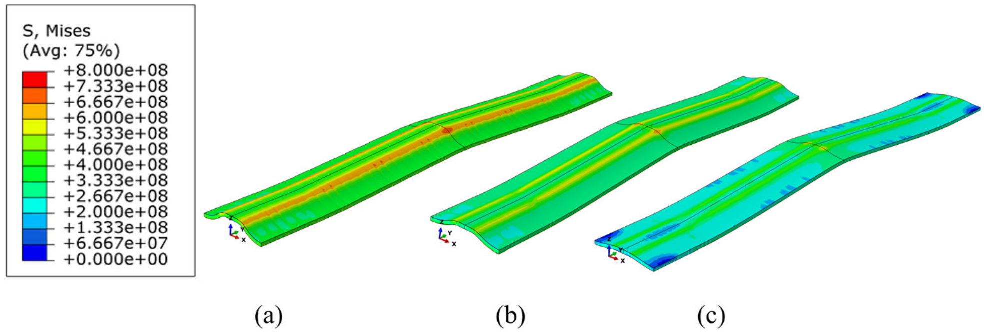

Fig. 8 Stress distribution on the plates formed by the convex molds with different heights of two steps (groups 2, 5, and 7 triangle)

of two-step channel; this line can be used to show the ridge shape of the channel.

As it is shown in Fig. 6, plates are pressed into different shapes by convex molds with different channel widths. From the stress distributions along the edges of the channels, larger stress will appear when there is a wider channel in the convex mold. The maximum of the stress will be focused along the edge of the channel. It is different from the common pressing with male and female molds, there is only one stress concentration position, and the deformation will be more uniform.

From Fig. 7, both the second and first-step channels with different channel widths are researched. In Fig. 7a, when the width is decreasing, the heights of the second-step channel are almost the same. But since the total widths of the channels are different, the top widths of the channels are also different. The thicknesses of the channels are shown in the figures. Since the plates are pressed under the rubber pad, the thicknesses are reduced almost uniform. The thinnest thickness appears in the edge of the channel. This can be explained by the stress distribution; since the maximum stresses are shown near the edges, the more deformation means the more reduction of the thickness. In Fig. 7b, the first-step channels are similar with the second ones. When the widths of the convex molds are increasing, the widths of the channels are also increasing. Only difference between the second and first steps is the maximum height of the channel, but both these two steps can be formed well based on the convex mold and rubber pad.

As it is shown in Fig. 8, different heights of two steps are selected in the convex molds. The height ratios of first to second step are 1:1 (0.3 and 0.3 mm) and 1:2 (0.2 and 0.4 mm), as well as 1:5 (0.1 and 0.5 mm). When the ratio is 1:1, the deformation appears along the whole channels. But if the ratio is reduced to 1:2 and 1:5, the deformation and stress almost disappear in the first-step channels. This means when the height of the second step is too much larger than the first one, the channel will be more difficultly pressed. These figures show the limits of the two-step channels. Only when the heights of second step are not too large, the channel can be formed well.

From Fig. 9a, different heights of two steps are selected in convex molds. When the height ratio of first to second steps is decreasing from 1:1 to 1:5, the shape of second-step channel is worse. The thickness of the second step also can be used to show this phenomenon. When it is 1:5, the thickness along the cross-section almost remains the initial value. However, when it is 1:1, the thickness is reduced seriously near the edge of the channel. From Fig. 9b, the shape and thickness of the first-step channel are shown with different height ratios. Since the heights of the first-step channel are different, the curves are

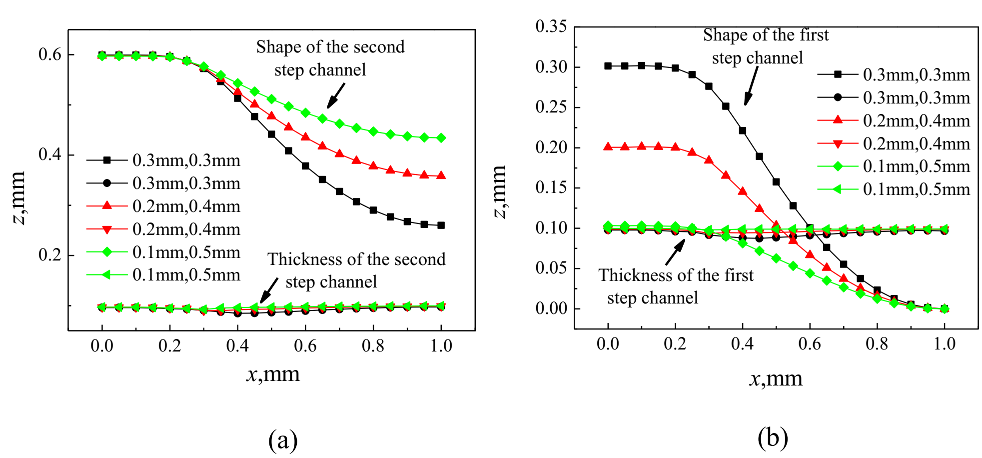

Fig. 9 **a** Half cross-section shape of the second-step channel and its thickness. **b** Half cross-section shape of the first-step channel and its thickness (groups 2, 5, and 7 triangle)

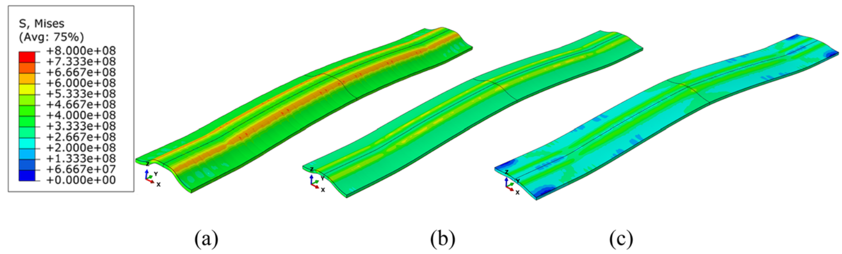

Fig. 10 Stress distribution of the plates formed by the convex molds with different heights of two steps (groups 11, 6, 8 arc)

decreasing with the decreasing of the first-step channel height. The thicknesses are all reduced obviously near the edge because of the deformation, but with the decreasing of the first-step channel height, the deformation appears less.

When the shape of two-step channel is changed from triangle to arc, different height ratios of first to second step are also studied. Comparing with the results in Fig. 8, the stress distribution in Fig. 10 is approximately the same. These figures can be used to prove that if the height ratios of first to second step are changed, the stress distributions are also changed even though the shapes of channels are different. Comparing with the shapes, the stress is more deeply influenced by the height ratios.

From both Fig. 11a, b, the same results are shown in the figures. When the difference between heights of first and second step is larger, the shape of second step can be worse, and the thickness of the plate is almost equal to the initial one. For the first-step channel, when the height of convex mold is increasing, the height of the final channel is also increased. Based on the mentioned above, when the shape of the two-step channel is changed from triangle to arc, the shapes of the first and second channel are almost the same. The height ratio is more significant to the shapes of first and second channels.

From Fig. 12, when the edge fillet is decreasing from 0.3 to 0.1 mm, the stress is increased. The edge of metal mold takes part in the deformation directly, and the plastic deformation here is the most serious one. When the fillet is decreasing, the deformation will be more focused.

Based on Fig. 13a, b, the cross-section shapes of the second- and first-step channels are shown. When the edge fillet is decreasing from 0.3 to 0.1 mm, the heights of the channel are almost the same. The only difference among different plates formed by molds with different fillet is the width. So, the fillet of the convex mold only has an influence on the stress distribution and the width of the channel. The depth of the channel is independent of the edge fillets.

From Fig. 14, different shapes of the second-step channel will very deeply impact on the final plate forming. When the convex mold is a triangle or an arc, the plate can be pressed into the required shapes. But when it is a rectangle, the plate is very difficult to be formed based on the requirement. Since the second step is suddenly raised up from the first one, the plate cannot be easily pressed. Based on these results, the conclusion can be drawn that the heights of second and first channels should be changed gradually. Suddenly changing of height will make the plate difficultly formed by the convex mold.

As it is shown in Fig. 15, the plates are formed by molds with different shapes. Not only cross section shapes of the first and second steps but also the longitudinal section shape of the two-step channel can be found. From both Fig. 15a, b, the second and first steps cannot be formed well, when the mold is a rectangle. When the molds are triangle and arc, the channel can be pressed into the required shape in cross section. This may be explained by the angle between first and second step. If the angle is close to 180°, the channel can be raised up gradually and a better plate can be formed. When it is the

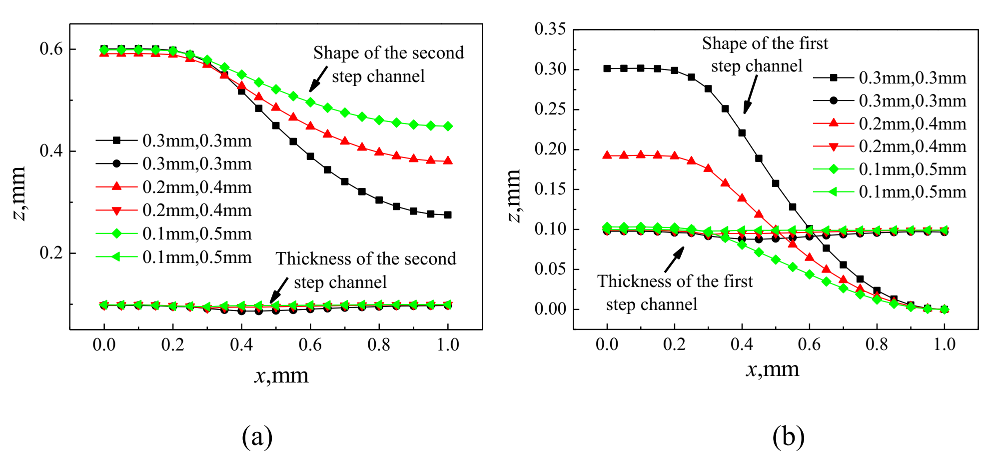

Fig. 11 **a** Half cross-section shape of the second-step channel and its thickness. **b** Half cross-section shape of the first-step channel and its thickness (groups 11, 6, and 8 arc)

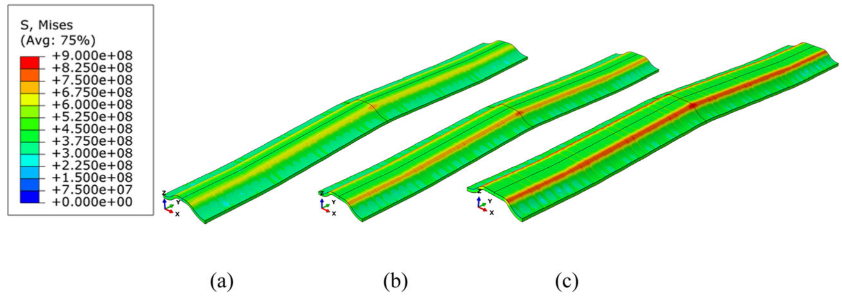

Fig. 12 Stress distribution on the plates formed by the convex molds with different edge fillets (groups 2, 9, and 10)

longitudinal section, the results showed that the height of the channel is suddenly reduced from the second step to the first one. This changing makes the plate cannot be easily pressed into the required shapes.

From Fig. 16, the stress distributions on the plates formed by four kinds of concave molds are shown. The only difference among these molds is the width. When the widths are reduced from 1.2 to 0.6 mm, the stresses along the edge are increasing obviously. But from the figures, the plates are deformed uniformly, and the differences between the first and second steps are not so many.

From both Fig. 17a, b, the second and first steps of the channel are shown along the cross section. When the width of the channel is decreasing, the depths of channels are all decreased. When it is the second channel, the deepest depth does not reach 0.6 mm. This means the plate cannot be formed well by the concave mold as those formed by the convex one. When it is the first-step channel, the deepest depth is 0.3 mm. This means the first step can be pressed into the required shape by the concave molds.

From Fig. 18, the plates are pressed with different molds. The only difference among the molds is the depth ratios of the two steps. When the ratios are decreasing from 1:1 (0.3 and 0.3 mm), 1:2 (0.2 and 0.4 mm) to 1:5 (0.1 and 0.5 mm), the shapes of the channels are gradually vague. The stresses are also decreasing based on this changing.

From Fig. 19, the cross section shapes of the second- and first-step channels are researched. When the depth ratios of the two steps are decreasing from 1:1 to 1:5, the depths of the both second- and first-step channels are decreased. From Fig. 19a, even the ratio is 1:1, the second-step depth is still far from 0.6 mm. This means

The ratios of the steps can affect the final depths of the channel. But when the depth difference between the first and second step is larger, the channel cannot be formed well. The plate cannot be pressed very well into the shape by concave mold even the ratio is 1:1.

When the shape of the concave mold is changed from triangle to arc, the plates are still cannot be formed well into the required shapes. From Fig. 20a, b, c, when the depth ratio of the first to second steps is decreased, the shape of channel is more unobvious.

Based on Fig. 21a, b, the cross sections of both second and first steps are shown. When the depth difference is small, the plate can be formed better. However, when the depth difference is larger, the plate can be hardly formed. Comparing to the triangle ones, the second-step depth is much less when the mold is an arc. This can be explained by the angle between the first and second-step channels. If the angle is too large than 180°, the plate cannot be formed well. Also based on the shape of the first-step channel, the deepest depth is about 0.3 mm and this is equal to the deepest depth of first step formed by the triangle molds.

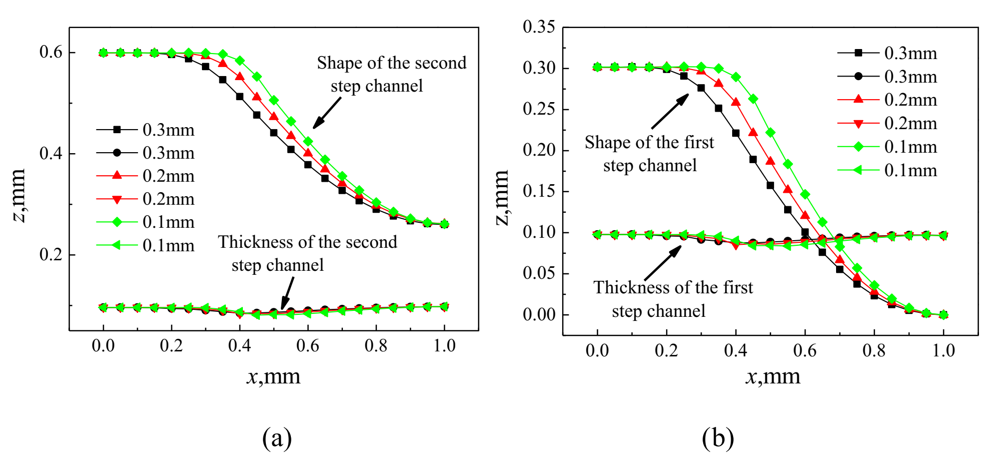

Fig. 13 **a** Half cross-section shape of the second-step channel and its thickness. **b** Half cross-section shape of the first-step channel and its thickness (groups 2, 9, and 10)

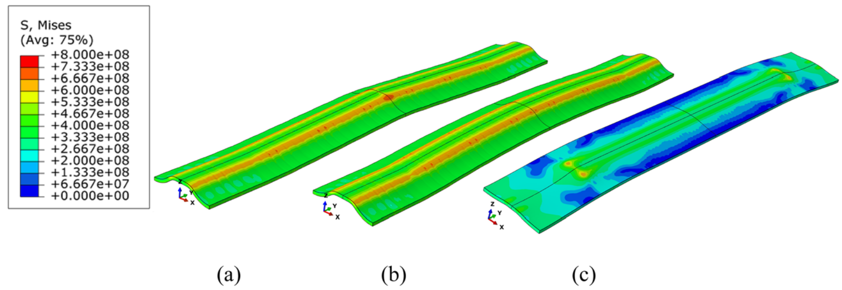

Fig. 14 Stress distribution on the plates formed by the convex molds with different shapes (groups 2, 11, and 12)

As it is shown in Fig. 22, when the edge fillet is reducing from 0.3 to 0.1 mm, the channel becomes more difficultly to be formed. The deformation will be focused along the edge. If the edge fillet is decreased, the plate is more difficultly pressed into the required shapes.

From the cross-section figures, the same conclusions can be drawn. In Fig. 23, though the deepest depth still does not reach 0.6 mm which is the designed depth, the second-step channel is a little deeper than the first one. When edge fillet is reduced to 0.2 and 0.1 mm, the depth of second step is reduced obviously. The depth of the second step is almost equal to the first one at these situations. So, when the edge fillet is less than 0.3 mm, the channel will be very difficult to be formed by rubber pad and concave mold.

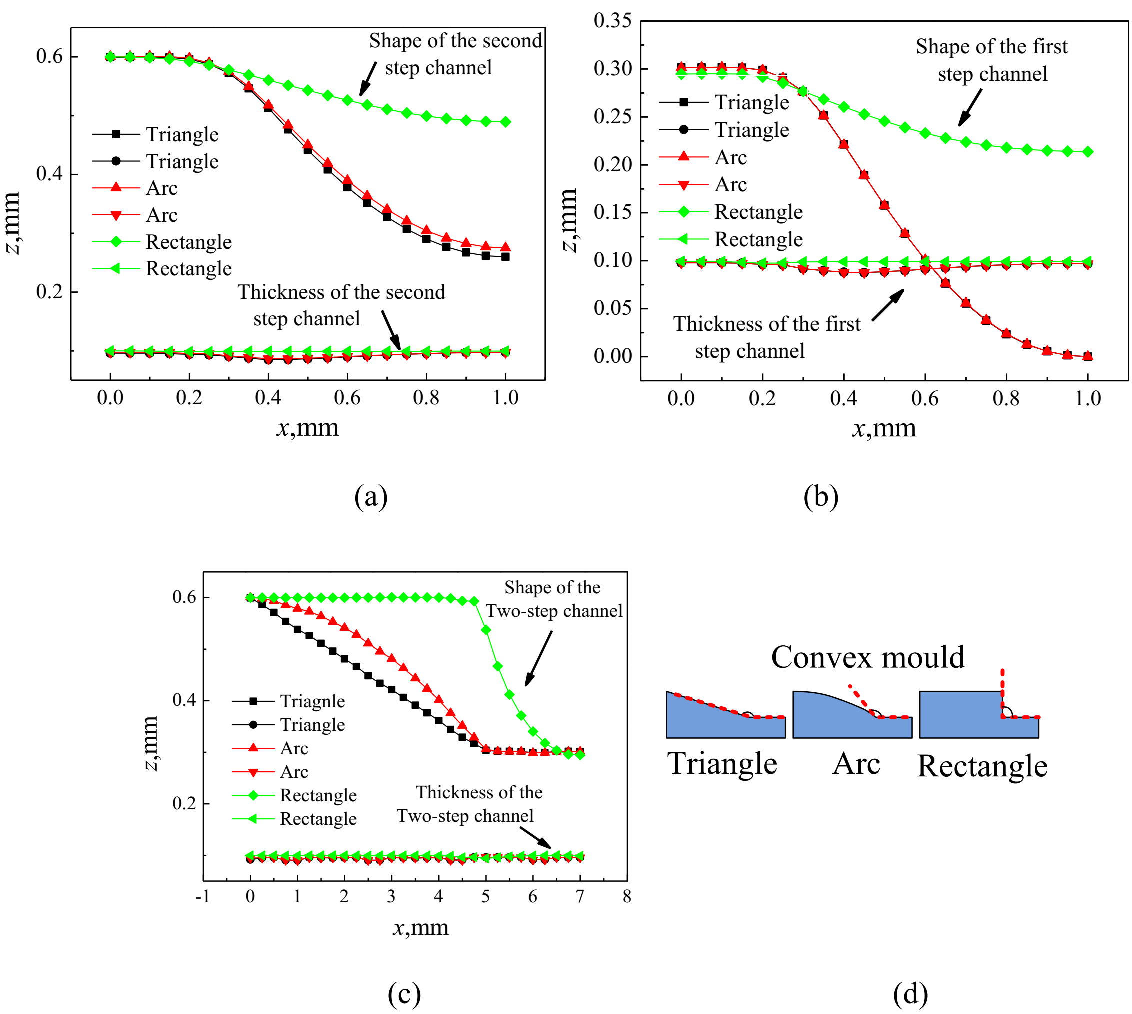

Fig. 15 **a** Half cross-section shape of the second-step channel and its thickness. **b** Half cross-section shape of the first-step channel and its thickness. **c** Half longitudinal section shape of the two-step channel. **d** Schematic diagram of the convex molds with different shapes (groups 2, 11, and 12)

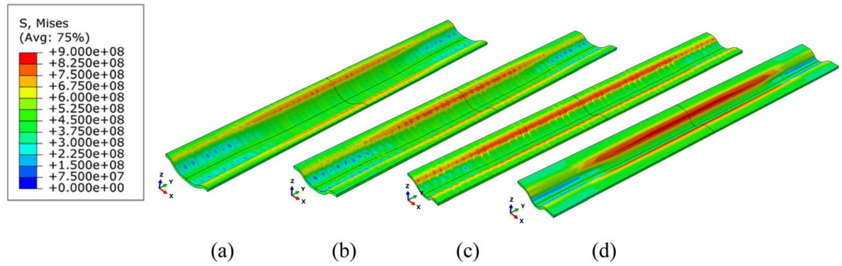

Fig. 16 Stress distribution on the plates formed by the concave molds with different width (groups 13, 14, 15, and 16)

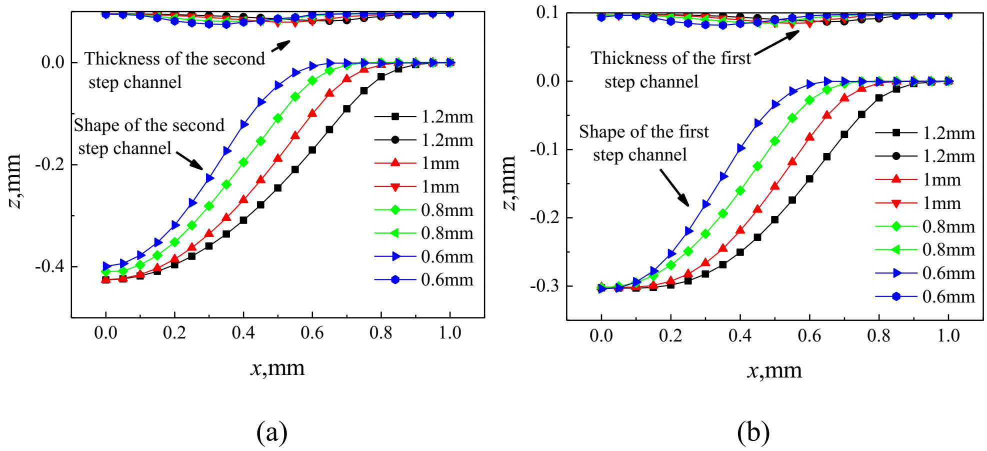

Fig. 17 **a** Half cross-section shape of the second-step channel and its thickness. **b** Half cross-section shape of the first-step channel and its thickness (groups 13, 14, 15, and 16)

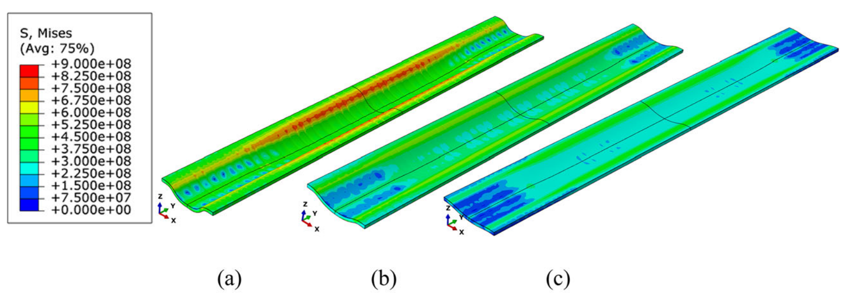

Fig. 18 Stress distribution on the plates formed by the concave molds with different depths of two steps (groups 14, 17, and 19, triangle)

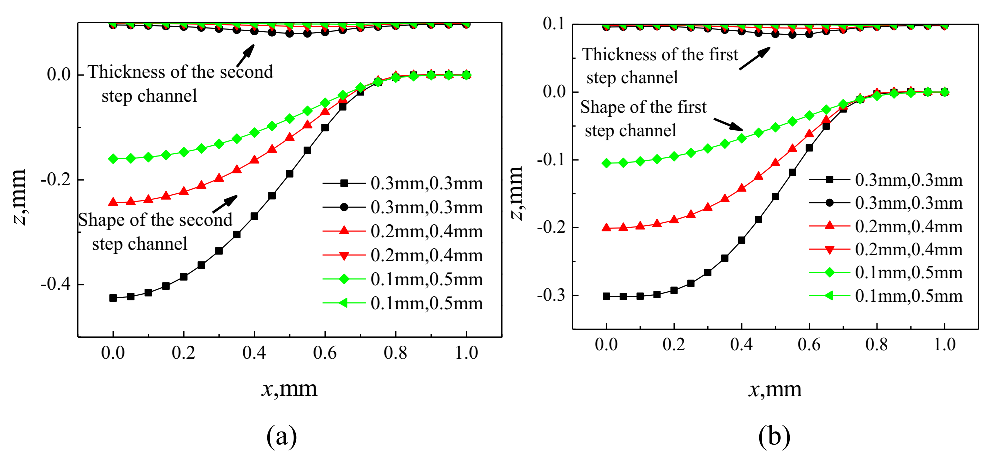

Fig. 19 **a** Half cross-section shape of the second-step channel and its thickness. **b** Half cross-section shape of the first-step channel and its thickness (groups 14, 17, and 19 triangle)

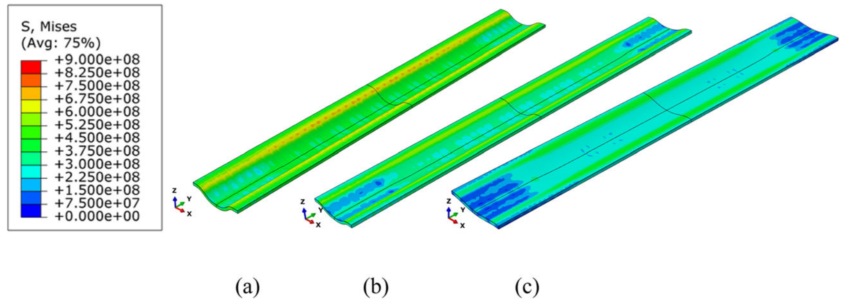

Fig. 20 Stress distribution on the plates formed by the concave molds with different depths of two steps (groups 23, 18, and 20, arc)

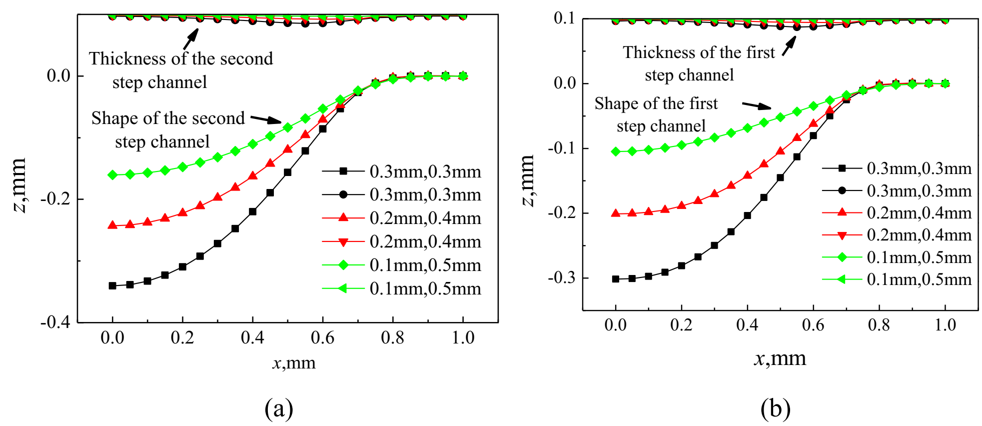

Fig. 21 **a** Half cross-section shape of the second-step channel and its thickness. **b** Half cross-section shape of the first-step channel and its thickness (groups 23, 18, and 20, arc)

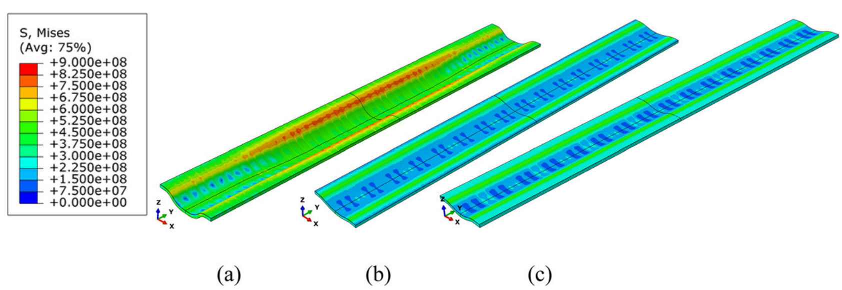

Fig. 22 Stress distribution on the plates formed by the concave molds with different edge fillet (groups 14, 21, and 22)

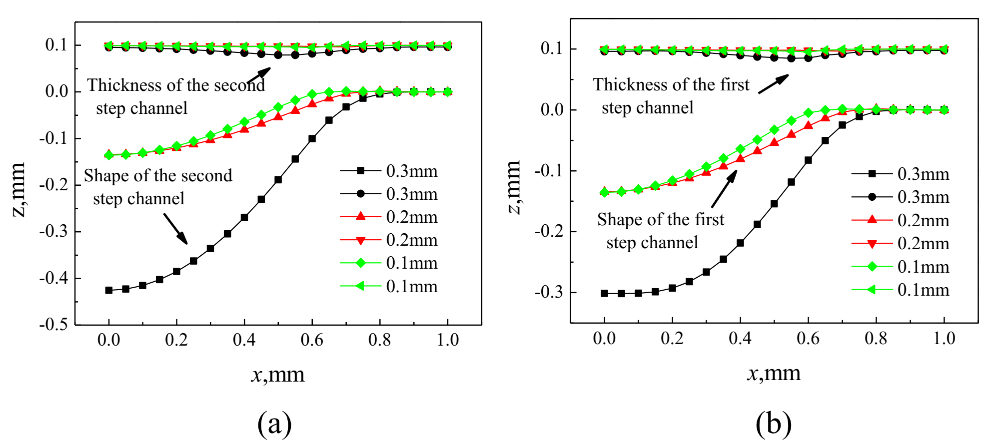

Fig. 23 **a** Half cross-section shape of the second-step channel and its thickness. **b** Half cross-section shape of the first-step channel and its thickness (groups 14, 21, and 22)

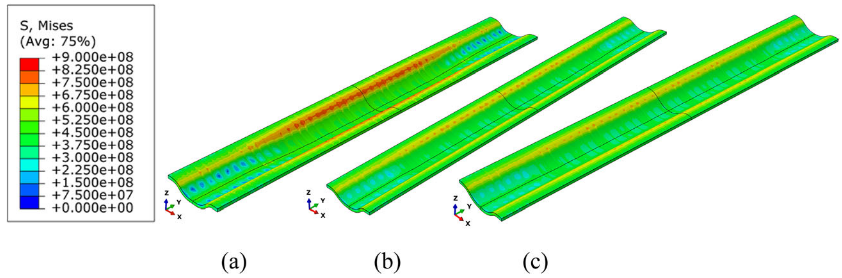

Fig. 24 Stress distribution on the plates formed by the concave molds with different shapes (groups 14, 23, and 24)

In groups 14 and 23 as well as 24, different concave molds with different shapes and rubber pad are used to press the channels. From Fig. 24, only if shape of the concave mold is a triangle, the channel can be formed obviously. When the shape of mold is an arc or a rectangle, the deformation on the plate is uniform. The stresses are only a little higher along the edges. The second-step channels cannot be easily told from the first-step channels when the shapes of the molds are arc and rectangle.

From Fig. 25a, b, the shapes of cross section in both first and second-step channels are shown. When it is a triangle concave mold, the second step can be a little deeper than the first one. When the shape of mold is changed into an arc or a rectangle, the depth of the second step is almost same with the

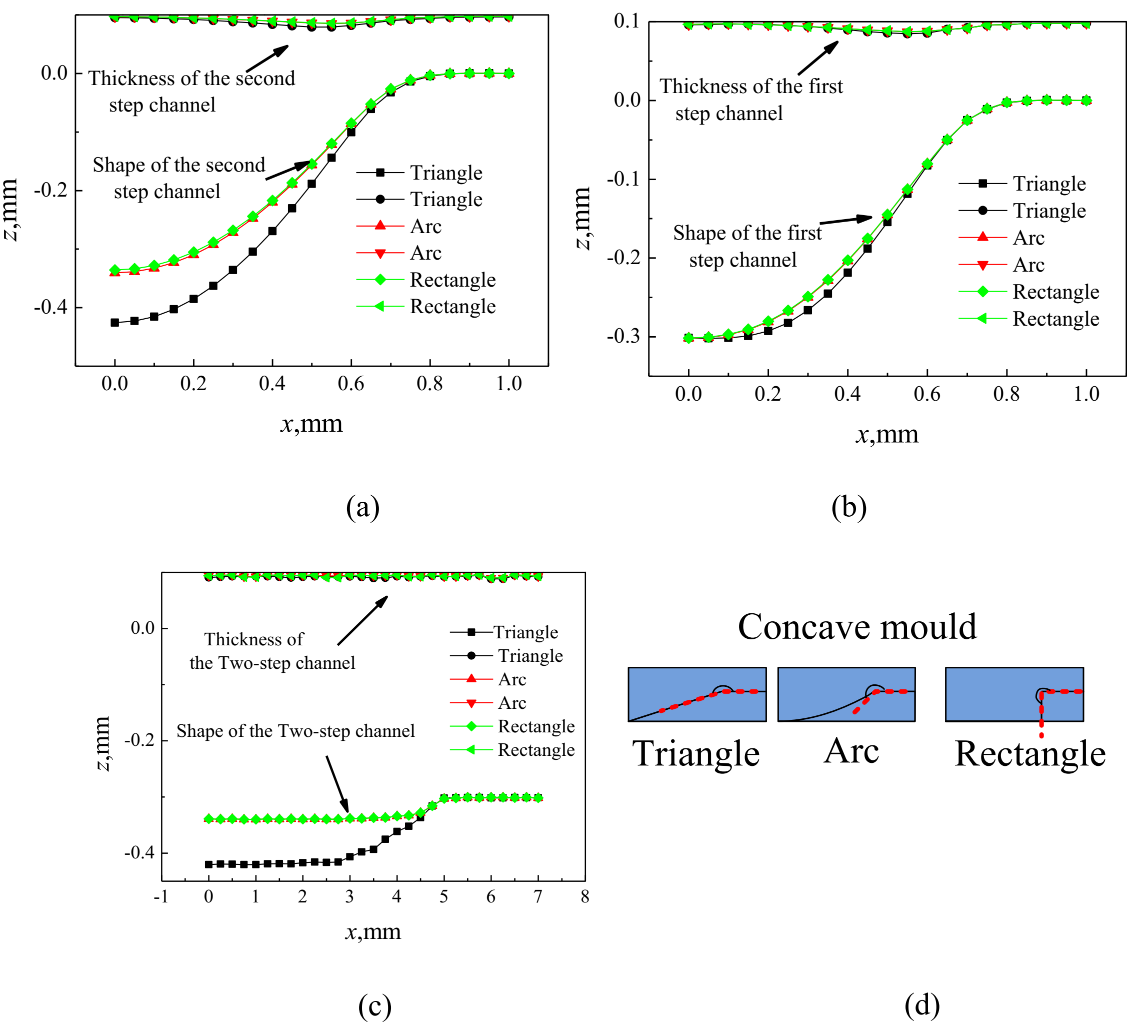

Fig. 25 **a** Half cross-section shape of the second-step channel and its thickness. **b** Half cross-section shape of the first-step channel and its thickness. **c** Half longitudinal section shape of the two-step channel. **d** Schematic diagram of the convex molds with different shapes (groups 14, 23, and 24)

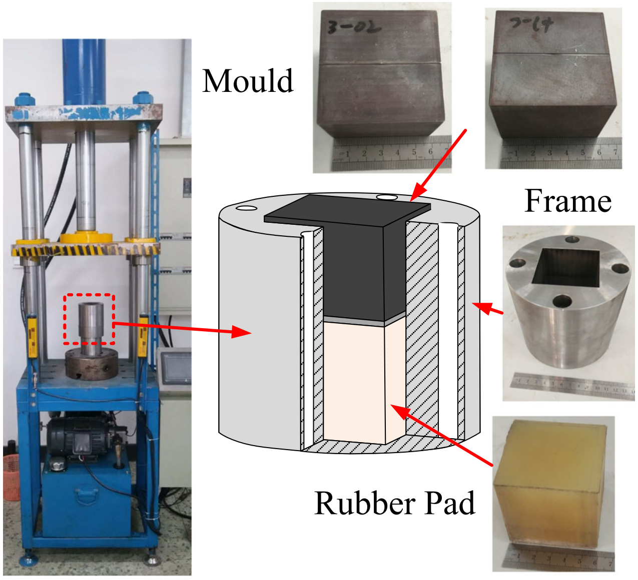

Fig. 26 Rubber pad pressing experiment

first ones. This can be explained by Fig. 25d, when the angle between the first and second steps is close to 180°, the second step can be formed and it will show two steps in the final channel clearly. But when it is a little lager, the second step will be hardly formed. These results can be used to compare with those shown in Fig. 15. If the mold is a triangle, no matter it is a convex or concave one can be used to form a two-step channel. If the shape is rectangle, neither convex nor concave mold can be applied to press a good two-step channel. If the shape of the mold is an arc, it will be a little complex. When there is a convex mold, even though the angle between first and second is a little larger, the channel still can be formed well, but when it is a concave mold, the channel cannot be shown very clearly.

4 Experiments

In order to prove the results shown in the FEM experiments, the rubber pad pressing experiment was conducted based on the real parameters [16, 17].

A press machine with fixture was used in these experiments. And a frame was fixed on the press machine. Its height was 90 mm. Inside the frame, there were molds and plate as well as rubber pad. The height of this pad was 60 mm. These parts were all in the same size 60 mm × 60 mm, so the frame could limit the horizontal deformation of the rubber pad, all its deformation could be along vertical direction and be used to take part in the forming of the plate. At the bottom, there was the rubber pad. All the moving and deforming of the rubber

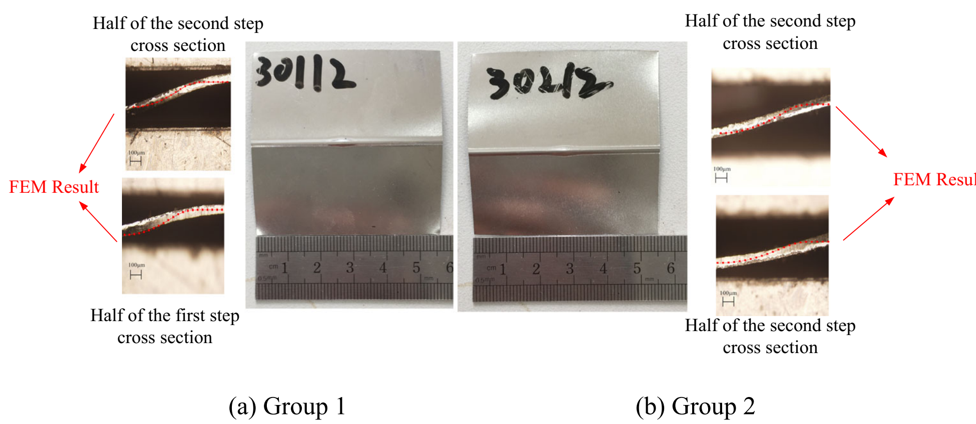

Fig. 27 Channel formed by the convex mold and the cross section of second and first steps under microscope

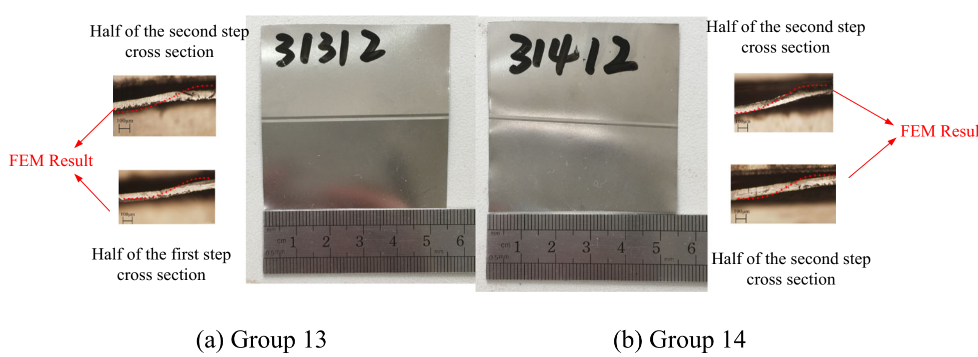

Fig. 28 Channel formed by the concave mold and the cross section of second and first steps under microscope

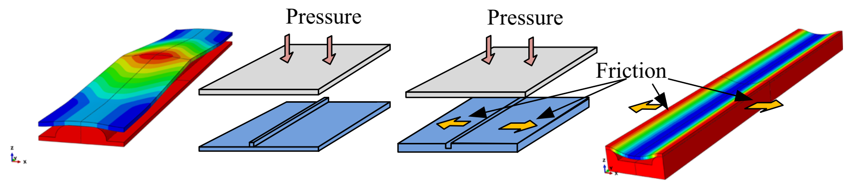

Fig. 29 Initial stage of the deformation with convex and concave molds

pad were limited based on this assembling. The SS304 plate was put between rubber pad and mold. At the top of these parts, there was the mold. Its height was 50 mm. The mold was put up-side-down, so the channel could be formed as it was designed. After assembly of these three parts, the height of the molds was a little higher than that of the frame. So, when the machine was turned on, the mold would be pressed into the frame by the punch. The plate between rubber pad and mold could be formed (Fig. 26).

After the pressing, the plate was formed as it was designed. From Fig. 27, after deformation, the two-step channel can be easily seen from the plate. If the mold is convex, the second-step channel is obviously different from the first one. In order to prove the results obtained based on FEM, the red lines which is on behalf of the FEM results are also shown in the figures. Through the comparing with the results received from pressing experiments, the FEM results can be used to prove well agreement with those shown in experiments.

From Fig. 28, the channels formed by concave molds are also shown in both macroscopic and microscopic photos. In the figures, the difference between second and first steps is not so obvious. Comparing with the results obtained in the pressing experiments, these obtained with FEM which are described as the red lines can be proved. From both Figs. 27 and 28, the channel formed by convex mold is much better than that formed by concave one.

The results mentioned above may be explained by the friction between the plate and mold, which is shown in Fig. 29. When the mold is a convex one, before the plate is contact with the mold completely, the deformation has already appeared in the edge of the channel. So, the friction has an influence on the deformation very slightly. However if the mold is a concave one, only if the plate is totally contact with the mold, the deformation will appear along the channel. At that time, the friction will be huge and the channel is not that easy to be formed.

5 Conclusions

1. Based on FEM, both convex and concave molds are cooperated with rubber pad to press a two-step channel. The effects of channel width, height or depth ratio, edge fillets, and shape of second step on the forming results are researched. The reasons for the results are discussed respectively.
2. In total, the channel can be formed easily and much better with cooperation of rubber pad and convex mold. If the mold is a concave one, the second-step channel will be not so obvious.
3. The conclusions drawn in this paper can be a strong theory support to the forming of the full cyclic variable height or depth channels. Based on these results, a novel waved flow field can be formed with rubber pad, which is an advanced material processing.
4. Using a concave mold in the rim of the mold like a blank holder, so the rim of the plate can be flat because of the huge pressing and friction stresses. At the same time, using a convex mold in the middle of the mold can be very benefit to the forming results. These can be design strategies of the metal mold.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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