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ORIGINAL ARTICLE

Inhibitory effects of a flexible steel pad on wrinkling in multi-point die forming

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Abstract
A flexible steel pad was applied in multi-point die forming to inhibit wrinkling from occurring in sheet metal, which is based on the idea of sheet metal flexible forming method. In numerical simulations, three multi-point die forming processes, namely without a polyurethane cushion, with a cushion, and with a flexible steel pad, were carried out for a complex three-dimensional part. Comparison of simulation results indicates that adding the flexible steel pad could effectively improve the stress and strain distribution, forming precision, and surface quality as well as effectively suppressed the occurrence of wrinkles and dimples. Experimental results of the three forming processes are consistent with the simulations, which proves the inhibitory effect of the flexible steel pad on wrinkling and the accuracy of the numerical simulations.

Keywords Multi-point die forming · Wrinkle · Numerical simulation · Flexible steel pad

1 Introduction

A multi-point die surface is enveloped by a matrix consisting of regularly arranged punch elements that can be independently adjusted in the vertical direction [1]. Since a die surface can be changed rapidly according to CAD parameters through a computer controlling system, different parts can be produced by applying a set of multi-point equipment to realize die-less, fast, and flexible production [2].

Wrinkling, a common defect of stamping, generates wrinkles and waves on surface of a panel that causes size deviation and shape change [3, 4]. Although a blank holder is widely adopted to deal with wrinkles, it increases the size of the blank and equipment costs. In addition, a trimming process is also used to cut the addendum, but it increases manufacturing charge and prolongs production cycles [5, 6].

Herein, a novel forming process that applies the flexible steel pad in multi-point die forming (MPDF) is proposed to manage the wrinkling of sheet metals, based on the sheet metal flexible forming method. The use of a flexible steel pad could produce a normal pressing effect in the part area, thus avoiding material waste problems caused by the addition of a blank holder device [7, 8].

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2 Forming principle

Figure 1 shows that the target part is symmetrical and bent upward. The arc lengths of the four edges changed during deformation (contracted inside, expanded outside), leading to the occurrence of material staking near the center of the four edges [9]. Obviously, the largest curvature appeared in the lower boundary (Fig. 1a), which is more prone to wrinkling [10, 11].

2.1 Sheet wrinkling mechanism

Wrinkling is caused by plastic instability under the action of external force [12]. Because the out-of-plane deformation energy is smaller than the in-plane energy, when the panel is subjected to a large tangential compressive stress and there is not enough constraint, then the deformation path changes from in-plane to out-of-plane and wrinkling occurs [13].

As shown in Fig. 2a, the panel was placed on top of the lower die and supported by four points (A, B, C, and D). When the upper punches moved down, the panel first extruded at point O and then bended. The mechanical state of edge AD is illustrated in Fig. 2 b (the other three edges were also subjected to the same situation). The panel was supported on

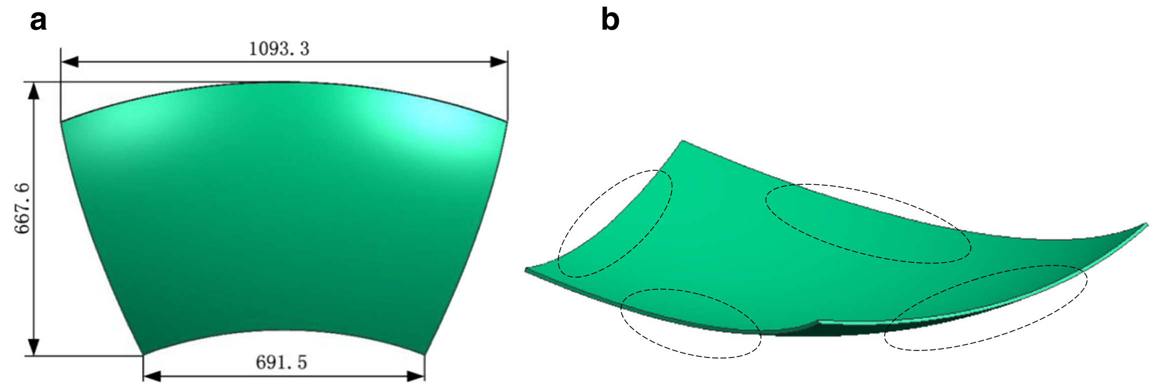

Fig. 1 Product illustration and size. **a** Top view. **b** Axonometric

the left and right ends, while all other parts were suspended. When the upper punches descended, the elements near the point O1 were compressed in the tangent direction and led to the trend of out-of-plane deformation. When compressive press was large enough, the material became unstable and wrinkled.

2.2 Judgment of sheet metal wrinkling

According to the energy balance principle, if all elements are in a state of balance, their displacement potential energy should reach the extreme value:

$$\delta^2 E = 0$$

In order to further judge the balance state, the potential energy changes should be surveyed at nearby areas. It is assumed that when a force is applied on one balanced element, the potential energy will be changed from E to E', which can be presented by the following Taylor series:

$$E' = E + \delta E + \frac{1}{2!}\delta^2 E + \dots$$

Since $\delta E = 0$, then:

$$\Delta E = E' - E = \frac{1}{2!}\delta^2 E + \dots$$

When the second order and higher differential terms are ignored, the following formula can be obtained:

$$\Delta E = E' - E \approx \frac{1}{2!}\delta^2 E$$

Based on this equation, it can be assumed that:when $\delta^2 E$ is > 0, potential energy is in a stable balanced state and no wrinkling occurs;

when $\delta^2 E$is < 0, it is an unstable balanced state and wrinkling occurs; and

when $\delta^2 E$ is = 0, it is a critical balance state.

3 Structure of die with a flexible steel pad

3.1 Multi-point die forming

MPDF is the most commonly used multi-point forming method due to its simple structure and short adjustment cycle. It is very suitable for workpieces with small curvature and large thickness. As shown in the schematic of structure and motion process in Fig. 3, MPDF is a combination of two parts from both the upper and lower dies, which are composed of regularly arranged punch units that can be adjusted vertically. According to the input information of the product, the adjustment system will automatically adjust the heights of punch units, which envelope the upper and lower die surfaces. When the upper die moved down, the panel was deformed

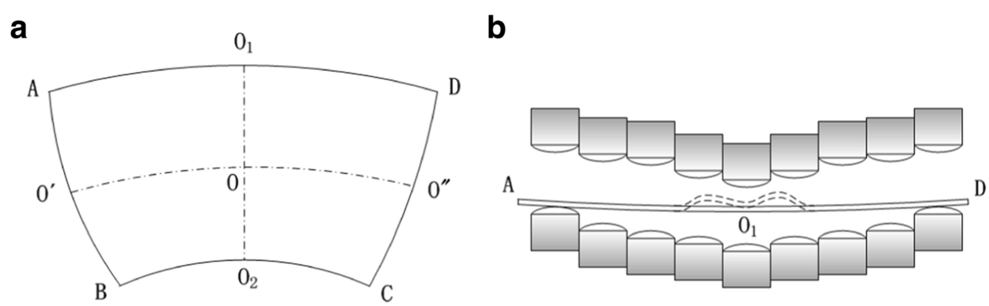

Fig. 2 Wrinkle schematic. **a** Top view. **b** Partial wrinkle

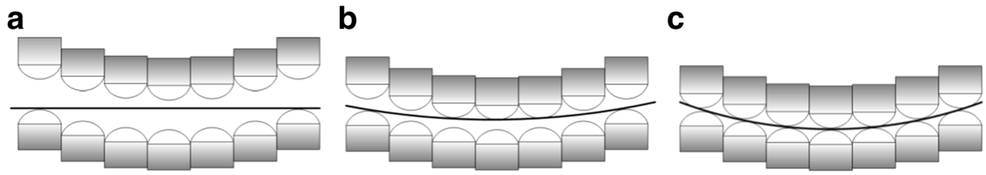

Fig. 3 Multi-point die. **a** Start forming. **b** Partial forming. **c** End forming

by the support of the lower die and the extrusion of the upper die. When the two dies were completely closed, forming was completed and the upper die began to move up.

3.2 Flexible steel pad

Based on multi-point die, the adjustment pad (a 10-mm-thick polyurethane pad), flexible steel pad (structure shown in Fig. 4a), and elastic pad (a 5-mm-thick polyurethane pad) were separately added into the upper and lower dies. At the beginning, the upper die gradually moved down, which caused the upper adjustment pad to deform and produce elastic potential energy. Then, the flexible steel pad and the blank started to bend. Through the whole forming process, the centerline of each flexible steel pad unit always stayed in line with the normal direction of the panel. The elastic potential energy from the compression of the upper adjustment pad was translated to the panel, thus transforming the vertical pressure from the upper punch unit into normal pressure on the panel. The normal pressure on the panel was realized by this process and led to an inhibitory effect that prevented wrinkling.

The die surface was formed by the envelope surface, which was either composed of punch units or flexible steel pad (shown in Fig. 5), with both envelope surfaces displaying the same size and shape. However, the punch units of the traditional model are wavy continuous and contact the panel by points, which may lead to a stress concentration phenomenon and dimples. On the other hand, the flexible steel pad units are connected to each other in a straight segment and contact with the panel by surface, which could easily scatter the concentrated stress and inhibit dimples. Furthermore, the smaller the gap between the flexible steel pad units and a more continuous die surface will result in uniform stress and strain on the panel, which could effectively reduce the trend of wrinkling and dimpling.

According to the structure and working principle of the flexible steel pad, the pad units rotate with panel deformation and induce a normal pressure on the panel to suppress wrinkling, which is very similar to the swing unit in the forming principle and motion process. Moreover, the flexible steel pad is superior due to its simpler structure, operation flexibility, and a larger scope of application.

As shown in the plan view of the flexible steel pad in Fig. 6a, all pad units were ideally and completely discrete and had no constraints among them. On this basis, the units will rotate automatically under the pressure of the adjustment pad and induce a normal pressure on the panel. However, when the pad units are discrete to each other, the following problems may be encountered during testing:

1. Due to the large thickness, an uneven deformation will occur around the adjustment pad during the bending, which causes the flexible steel pads to move and overlap each other.
2. At the beginning of forming, a large gap exists between the adjustment pad and the elastic pad in the area far from the center, which produces a small friction on the flexible steel pad. Since the friction is not large enough to overcome the gravity impaction and other external forces, it may cause the flexible steel pad unit move.

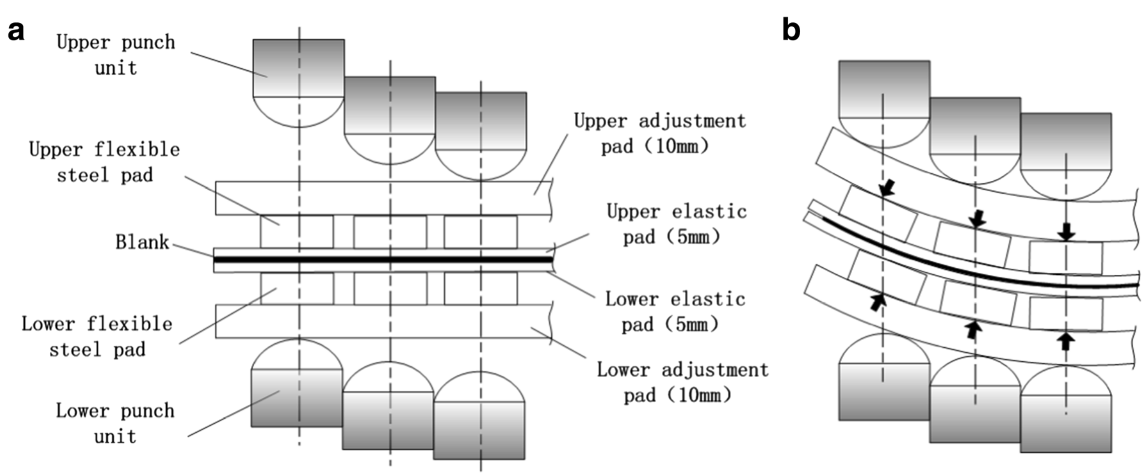

Fig. 4 Flexible steel pad. **a** Start forming. **b** End forming

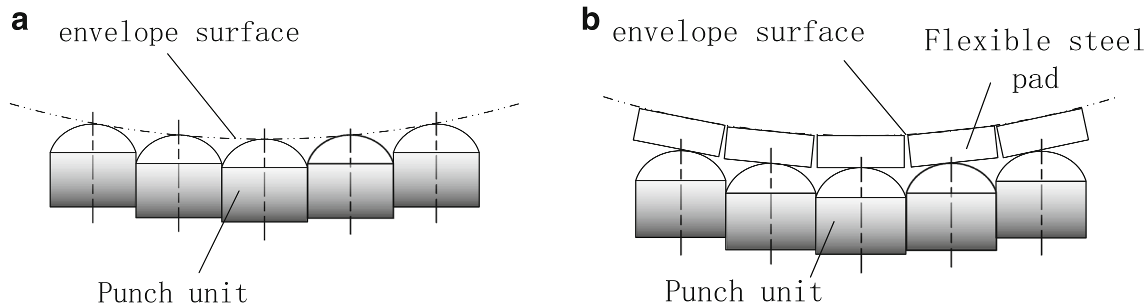

Fig. 5 Flexible steel pad. **a** No flexible steel pad. **b** With flexible steel pad

3. When large dimensional parts are deformed, the flexible steel pad maybe composed of thousands of discrete steel pad units, which can result in difficulties with positioning and assembly.

In order to overcome these problems, we wholly cut the flexible steel pad via wire cutting. The pad units were then connected following the fishbone connection method to effectively prevent panel movement and maintain discreteness of each unit to the largest degree.

4 Establishment of finite element model

To better analyze the blank forming result after adding the flexible steel pad, we simulated three models with and without a polyurethane cushion and with a flexible steel pad on the finite element software Abaqus. The forming results, shape errors, and stress and strain state of the three models were comparatively analyzed [14, 15].

Figure 7 shows the structure diagrams of the three models. The model without the polyurethane cushion was composed of three parts, including the blank and upper and lower punch units (Fig. 7a). The finite element model consisted of two different layers (a 10-mm-thick layer and 5-mm layer) of polyurethane cushions lying on or below the blank (Fig. 7b). The third model required inserting a flexible steel pad into the two polyurethane cushions on both sides of the blank (Fig. 7c). In addition, to decrease simulation time, one half of the models of the three different models were established by applying the left and right symmetry constraints [16].

The cross-sectional dimension of both upper and lower punch units was 40 × 40 mm; the top radius of the punch unit was 40 mm; and the pressure was 100 tons. The diameter and thickness of the flexible steel unit (304 stainless steels) were 36 and 3 mm, respectively. AL2219 was used as the forming material, which was meshed with C3D8R, assumed to be isotropic, and was 6-mm-thick (Table 1) [17]. The material used for the elastic and adjustment pad was polyurethane with a Shore A hardness of 79. All punch units were meshed with a R3D4 shell element and assumed to be discrete rigid bodies. The contact type between parts was global automatic; the friction coefficient was 0.25, and the model running time was 0.2 s [18].

5 Results and discussion

5.1 Effect of forming methods on wrinkling

Figure 8a shows the illumination maps of forming parts without the cushion. Clearly, a large area of dimples appeared in the center of the panel. Since the blank was in direct contact with the punch units during the forming and the curvature of punch units surpassed that of the panel, a large partial pressure was applied on the panel and caused local deformation and dimpling. Meanwhile, wrinkles appeared in areas I, II, and

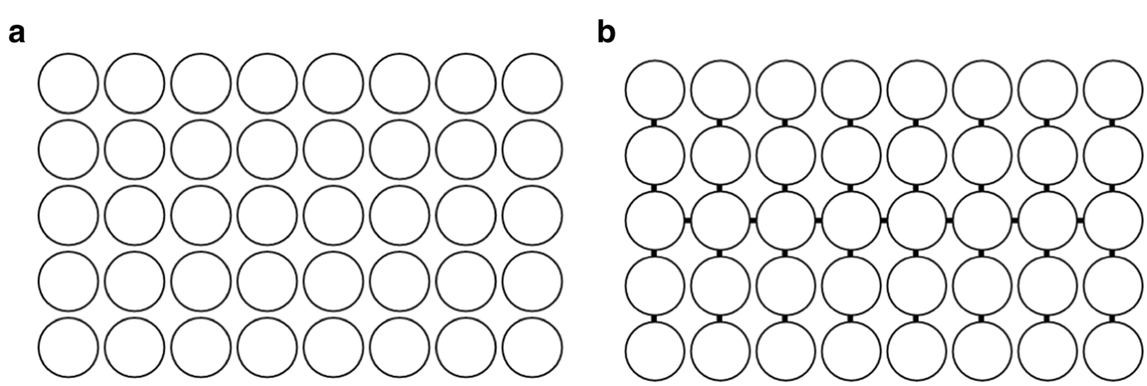

Fig. 6 Flexible steel pad plan. **a** No connection. **b** Fishbone connection

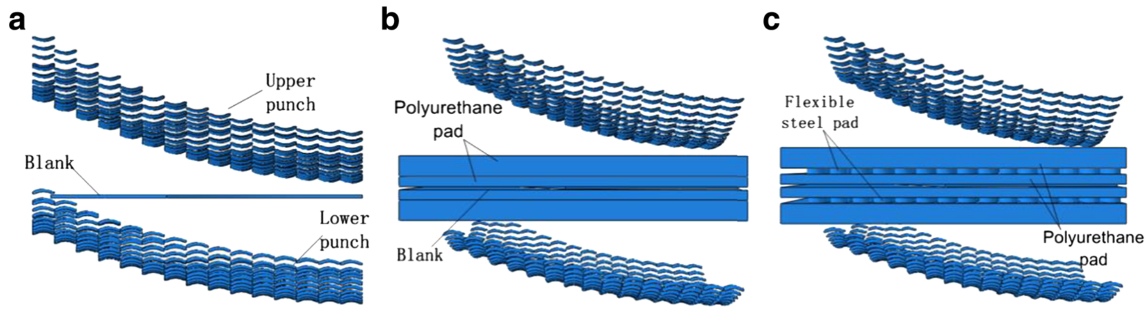

Fig. 7 Multi-point die forming finite element model. **a** Without cushion. **b** Polyurethane cushion. **c** Polyurethane cushion and flexible steel pad

significantly in III. In the model without the cushion, the panel lacked enough restraint, except the support around the corners from the lower die and the extrusion in the center from the upper die, while the other areas were under a suspended state. During bending, areas I, II, and III of the blank were subjected to tangential compressive stress. The partial element was compressed in the tangent direction and deformed out-of-plane, leading to the occurrence of wrinkling. According to the characteristics of sheet metal bending, a greater curvature would increase the probability of sheet wrinkling in sheets with the same thickness. The part in area III had the shortest arc length and largest curvature, so it wrinkled the most during the bending.

In order to eliminate the forming defects mentioned above, two layers of polyurethane pads were added to the upper and lower sides of the sheet, as shown in Fig. 8b. It is clear that the dimples completely disappeared, and wrinkling was also greatly inhibited. Because the polyurethane pad can effectively fill the gap between the punch units, the local pressure can be scattered on the sheet uniformly, which can effectively suppress dimples as a result. However, ripples still appeared in areas I and II of the light map. Although the height of the wrinkles was significantly reduced, they were not completely removed, demonstrating that the use of polyurethane pads cannot entirely eliminate wrinkles completely.

Figure 8c shows the results of forming parts after the addition of the flexible steel and polyurethane pads. The figure reveals that the forming part had smooth surfaces and regular contour, while the whole panel was free from any dimpling and wrinkling, indicating that the use of flexible steel pad and polyurethane pad can effectively inhibit dimples and wrinkles. Because the flexible steel pad units rotated automatically according to the bent sheet during the forming process, the vertical pressure from the upper punch unit was transformed into normal pressure on the panel, which tightened the blank and thus effectively inhibited wrinkles.

5.2 Analysis of forming strain

The strain distributions of the three forming models are shown in Fig. 9. The maximum strains of the models without the cushion, with the polyurethane cushion, and with the flexible steel pad were determined to be 4.48, 4.11, and 3.19%, respectively, while the corresponding minimum strains were 0.008, 0.008, and 0.007%. Compared to the model without the cushion, the maximum strain values of the model with the flexible steel pad were reduced by 1.29%. Generally, the model without the cushion presented the worst strain continuity as well as the most severe strain concentration and fluctuation, which is consistent with the illumination maps. On the contrary, the application of polyurethane cushions could improve the strain distribution uniformity, with a narrower range and higher continuity. However, local concentration at the edges of the panel still existed, which indicates that polyurethane cushions can effectively inhibit dimpling and relieve the fluctuation of wrinkling, but cannot eliminate wrinkles completely. In comparison, the use of the flexible steel pad greatly improved the strain state with no strain concentration and a much narrower distribution area. When the panel was subjected to the flexible steel pad, the area under tensile stress expanded and the strain distribution became more uniform.

The strain distributions along AB, BC, and AD are shown in Fig. 10. Obviously, a large fluctuation occurred in the three-edge strain distribution in the model without the cushion. Moreover, the front edge of the panel had the largest amplitude (up to 3.59%) and the widest fluctuation range. When polyurethane cushions were applied, the strain concentration improved but was not eliminated completely. Using of the flexible steel pad, the fluctuation completely disappeared and the curve became smoother, indicating that wrinkling and dimpling of the sheet material were effectively suppressed. In addition, the maximum strain appeared in the center of the three edges and gradually declined from the middle

Table 1 Main mechanical parameters of blank

Material	density (kg/m^3)	Poisson's ratio	Young's modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)	Maximum elongation
AL2219	2700	0.3	71	115	168.7	26.26%

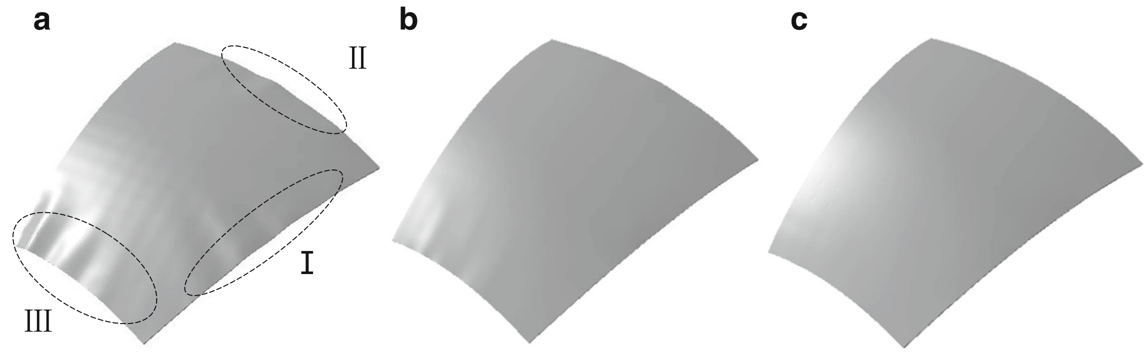

Fig. 8 Light map of forming parts. **a** Without cushion. **b** Polyurethane cushion. **c** Polyurethane cushion and flexible steel pad

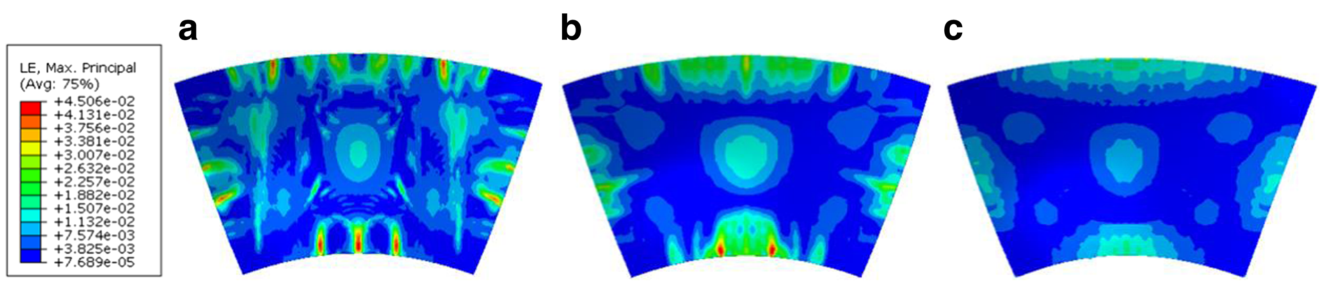

Fig. 9 Strain distribution of forming parts. **a** Without cushion. **b** Polyurethane cushion. **c** Polyurethane cushion and flexible steel pad

towards the corners. These results are in accordance with the previous analyses.

5.3 Comparison of forming accuracy

The node height of edge AB is shown in Fig. 11a. In the model without the cushion, large fluctuation occurred in the middle of AB, and wrinkling occurred in the area between 200 and 450 mm along the horizontal axis and reached a maximum height of 3.77 mm. The node height of the BC edge is displayed in Fig. 11b, which shows that wrinkles also appeared in the area between 200 and 375 mm with a maximum wrinkle height of 6.24 mm. As shown in Fig. 11c, fluctuation in the AB edge was relatively small, and the wrinkling area and maximum wrinkle height were 200–300 mm and 2.88 mm, respectively. In the model with the polyurethane cushion, the forming accuracy of the sheet was significantly improved based on a significant decrease in fluctuation of the three edges, which further demonstrates the cushion's inhibitory effect on wrinkling. With the use of the flexible steel pad, fluctuation completely disappeared and the curve became smoother, indicating that the increased normal restraint can better suppress wrinkling. Furthermore, the model with the flexible steel pad had a much larger curvature than the other two models, which means a more adequate plastic deformation and smaller deviation. This can be explained by the discrete steel pad that can effectively disperse concentrated loads generated by the punch during multi-point forming, thus increasing the uniformity of the forming force distribution and further completing plastic deformation.

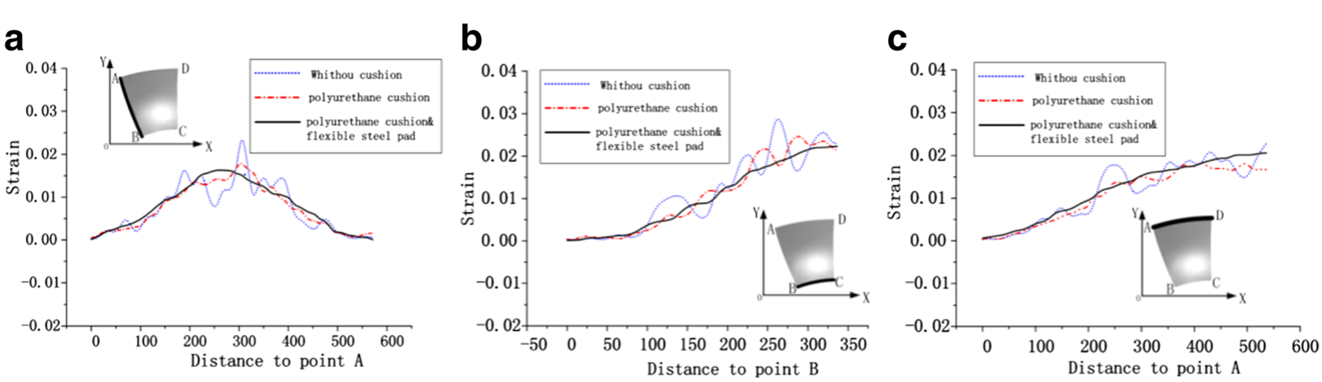

Fig. 10 Strain distribution of forming parts. **a** Along AB edge. **b** Along BC edge. **c** Along AD edge

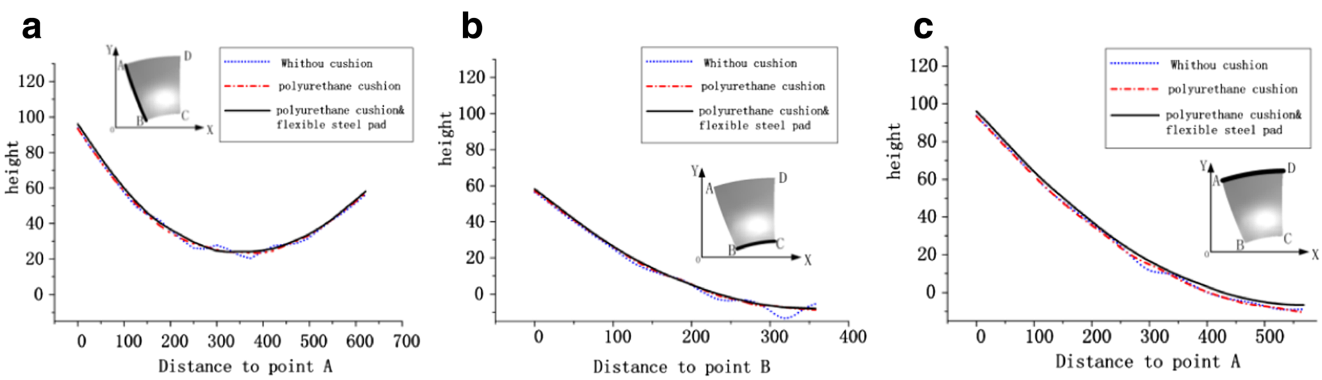

Fig. 11 Forming accuracy. **a** Along AB edge. **b** Along BC edge. **c** Along AD edge

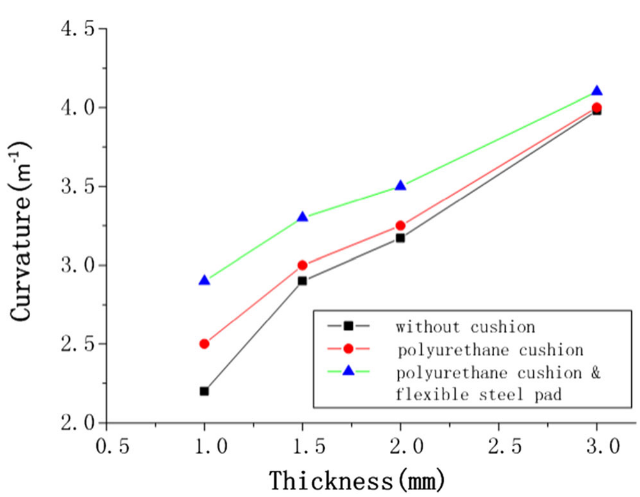

Fig. 12 Forming limit

5.4 The non-wrinkle forming limit

The spherical parts used for testing were formed in three different processes. The size of the parts was 200 × 200 mm, and 08AL was used as the material. The model was analyzed based on sheets of different thickness. The model was analyzed based on sheets of different thickness to test the assumption that the forming process reached its limit when waves or wrinkles occurred in the sheets. Comparison of the forming limit results of the three different forming processes is shown in Fig. 12. It was found that when the sheet thickness was small, the curvature was improved slightly after addition of the polyurethane cushion, where the inhibitory effect of wrinkling gradually weakened as the material thickened. Further, the forming limit of the panel was significantly improved when the flexible steel pad was used between the layers, where wrinkling was effectively restrained as the thickness of sheets became smaller.

6 Verification of test

To apply the available equipment for testing, the dimensions of the blank and model were compressed to a quarter of their original size, and YAM-200 multi-point forming press developed in Jilin University was used in the tests (as shown in Fig. 13). In Fig. 14, severe wrinkling occurred in the middle parts of the four edges of the model without cushions. Contrarily, the model with the flexible steel pad had the same parts with smooth surfaces and without any wrinkling. These

Fig. 13 YAM-200 multi-point forming press. **a** Punch and die of multi-point forming press. **b** Control system

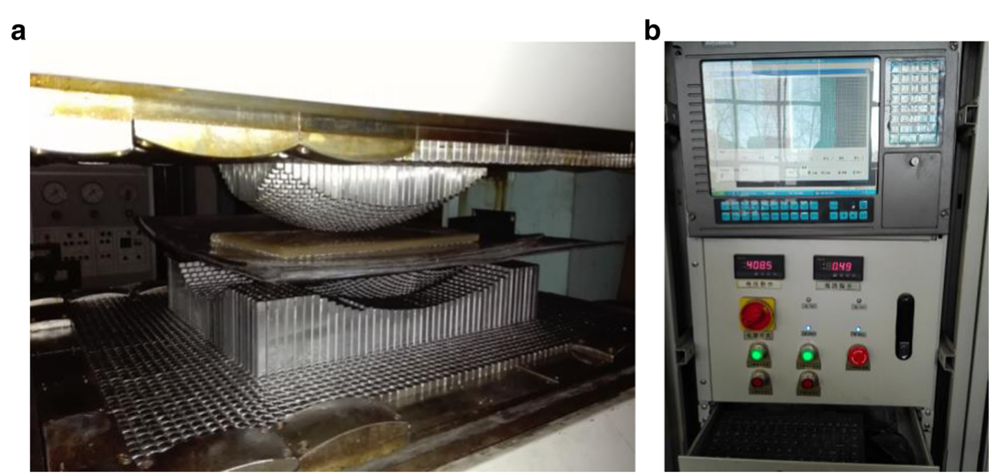

Fig. 14 Experiment parts. **a** Without cushion. **b** Polyurethane cushion. **c** Polyurethane cushion and flexible steel pad

results prove the inhibitory effect of the flexible steel pad on wrinkling and the accuracy of the numerical simulation.

7 Conclusions

1) In the multi-point forming process, the use of a flexible steel pad could produce a normal pressing effect in the part area, which can prevent material wastes caused by the application of a blank holder device.
2) During the multi-point forming process, the flexible steel pad unit rotated automatically according to the bent sheet, where the enveloped surface was more continuous and much closer to the desired surface.
3) The use of a polyurethane cushion in the multi-point forming can effectively scatter the concentration load of punch units and suppress dimples.
4) Applying a flexible steel pad in the multi-point forming model can further inhibit wrinkling and dimpling, increasing both the smoothness of part of the surface and the uniformity of strain distribution.

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