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ORIGINAL ARTICLE

Investigation of forming accuracy in multipoint forming with composite elastic pads

Erhu Qu [1,2,3] · Mingzhe Li [1,2] · Rui Li [3]

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Abstract
Defects in the form of dimples, straight edges, and wrinkles can easily appear when a multipoint die is used to directly form sheet metal. The main methods currently used to address this issue are to add polyurethane elastic pads between the punch units and the blank or to use a blank holder device. However, the use of polyurethane elastic pads or a blank holder device may reduce the accuracy of the formed die surface or the material utilization ratio, respectively. To improve the outcome, a composite elastic pad for multipoint forming is proposed. Taking a spherical surface of radius R400 as the target surface, numerical simulations and forming experiments using three different forming conditions, namely, without any cushion, with polyurethane elastic pads, and with composite steel pads, were conducted using the finite element analysis software Abaqus and a YAM-200 multipoint forming press, which was independently developed by the Jilin University. The results show that compared with the forming conditions without any cushion and with polyurethane elastic pads, when the proposed composite steel pads are used in multipoint forming, the forming accuracy is effectively improved, and defects in the form of dimples, straight edges, and wrinkles are effectively suppressed. Further research revealed that varying the thickness of polyurethane sheet A or polyurethane sheet B in the composite elastic pad design will result in different effects on forming accuracy and quality improvement. When the thicknesses of polyurethane board A and polyurethane board B are 5 mm and 10 mm, respectively, the forming effect is the best. Compared with forming without a cushion, the maximum error and average error of the formed parts are reduced by 68.3% and 66.1%, respectively.

Keywords Multipoint forming · Forming accuracy · Numerical simulation · Composite elastic pad

1 Introduction

Multipoint forming (MPF) technology has been utilized in various industries, including construction, high-speed rail, shipbuilding, aircraft manufacturing, and skull repair. This technology has received much attention due to its die-less nature, short mold adjustment period, low manufacturing cost, die surface reconfigurability, and reusability in different small-batch part-forming processes.

✉ Mingzhe Li
limz@jlu.deu.cn

1 College of Materials Science and Engineering, Jilin University, Changchun 130025, China

2 Roll Forging Institute, Jilin University, Changchun 130025, China

3 Changchun Ruiguang Technology Co. Ltd, Changchun 130025, China

Dimpling, straight edges, spring-back, and wrinkling are common defects that occur in MPF and can seriously affect the forming accuracy, forming quality, and subsequent assembly. To improve the forming accuracy of MPF, scholars have conducted research on novel forming processes and mechanisms and have proposed various effective methods. To reduce the spring-back of a formed part, Li et al. [1] of the Jilin University proposed the concept of repetitive forming, through which the forming accuracy is greatly improved. For the method of using a variable blank-holding force (BHF) in MPF, Yagami et al. [2] found that when a suitable BHF curve is selected, the stress state of the blank becomes more uniform and the forming accuracy can be greatly improved. Mustafa Yasar et al. [3] found that the deformation distribution of a workpiece becomes more uniform when a suitable punch unit size is used. A new MPF method with a wrinkle resistance function, which provides a new option for anti-wrinkle measures in MPF, was developed by Liu et al. [4] in 2012. Through forming tests and numerical simulations of a

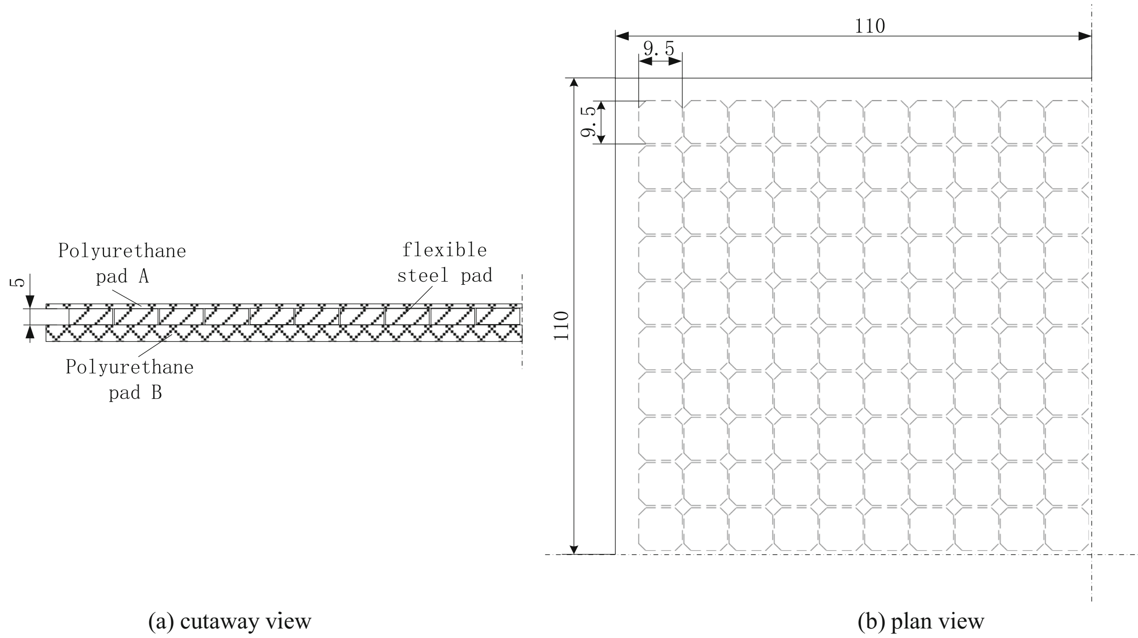


Fig. 1 Structure of the composite elastic pad. **a** Cutaway view. **b** Plan view

rectangular box part, Li et al. [5] found that flexible blank holder (FBH) forming technology has the great advantage of inhibiting wrinkles and spring-back in MPF. Research on forming accuracy in MPF with polyurethane pads of different properties was conducted by Fakhri et al. [6]. It was demonstrated by Abebe et al. [7] that kriging surrogate modeling can be used to easily determine the optimal forming parameters for MPF to improve the forming quality. Luo et al. [8] proposed the cyclic multipoint incremental forming process and studied its effect on improving the forming accuracy. Liu et al. [9] proposed the concept of using a multilayer flexible blank holder in MPF to suppress wrinkling and improve the forming accuracy.

At the same time, Cai et al. [10] deduced the criteria for wrinkling and studied the inhibitory effect on wrinkling of varying the deforming path in MPF. Through a study on the mechanisms of wrinkling and dimpling in an automobile outer panel during stamping, Li et al. [11] found some effective solutions for improving the forming accuracy. Zareh-Desari et al. [12] studied the effects of the elastic pad thickness and the friction coefficient on the forming quality and accuracy in MPF. Abebe et al. [13] predicted the optimal process

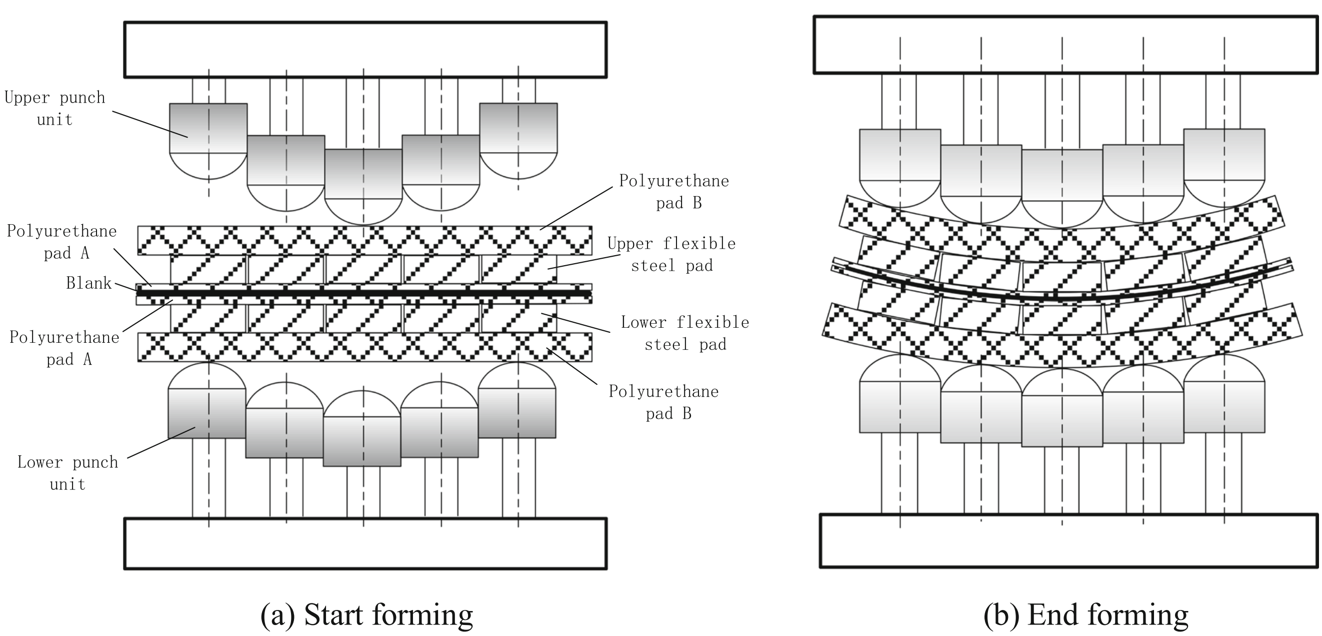


Fig. 2 Forming process. **a** Start of forming. **b** End of forming

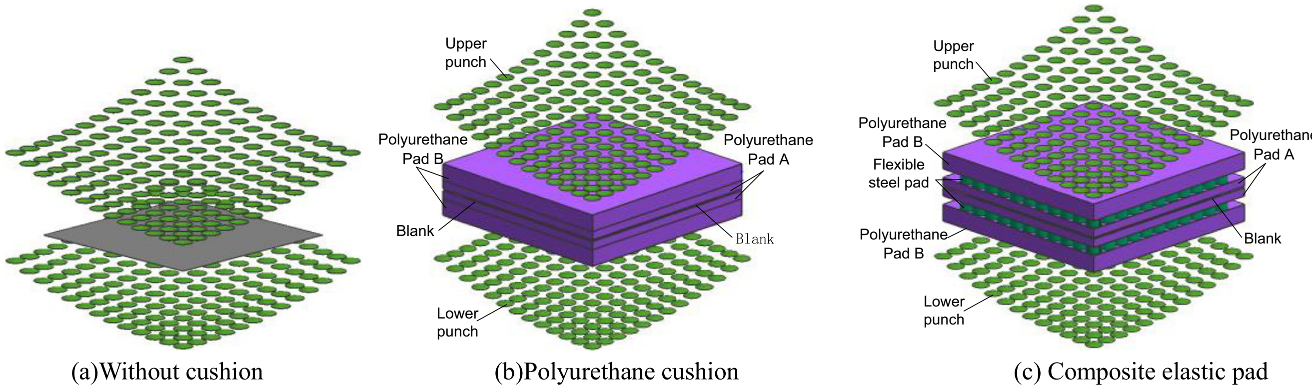


Fig. 3 Finite element model of MPF. **a** Without any cushion. **b** Polyurethane pads. **c** Composite elastic pads

parameters through CAE simulations for saddle part forming and experimentally verified the influences of the various parameters on the forming quality. Abosaf et al. [14] proposed the method of orthogonal experiments to determine the optimal process parameters to improve the forming accuracy.

The forming processes and theory of MPF have been improved to a certain extent by the above research results. However, most of the techniques and theories proposed by the above scholars still require theoretical verification or analysis via engineering experiments. Many of these schemes cannot be applied in actual production due to the difficulty of equipment development and the high costs incurred. In this paper, to improve the forming accuracy and suppress forming defects, a novel forming condition involving the use of composite elastic pads in multipoint die forming (MPDF) is proposed. The proposed composite steel pad design has a simple structure and a low manufacturing cost, which will facilitate its widespread implementation in MPF. It is different from the traditional sandwich structure used in MPF because the composite steel pads are able to conform to the blank during the forming process and compress the blank inside the mold, thus serving the function of a blank holder. The influences of the forming conditions and the thicknesses of polyurethane pad A and polyurethane pad B in the composite elastic pad design on the shape accuracy of the formed part were investigated. The results of simulations and experiments reveal that using composite elastic pads in MPF can effectively improve the forming accuracy and inhibit wrinkles and dimples. It has also been determined that the effect on the forming accuracy will differ when using composite elastic pads with different thicknesses of polyurethane pads A and B and that the most suitable thicknesses can be predicted via numerical simulations and experimental methods.

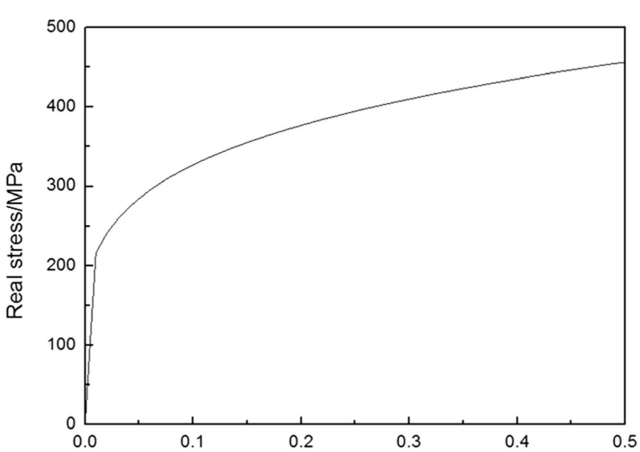


Fig. 4 Stress–strain curve of 08Al

2 Forming principle

2.1 Multipoint forming

MPF is a flexible, digital sheet forming technology based on a structure composed of an upper die and lower die, which is similar to a conventional mold. The sheet metal is deformed by a multipoint die driven by a mechanical press. The die faces of both the upper and lower dies are discrete, composed of a number of regularly arranged, highly adjustable punch units. By adjusting the heights of the punch units, the mold surface can be quickly modified for different production processes or for the production of different parts with the same set of equipment, thus enabling die-less, fast, and flexible production.

2.2 Structure and forming principle of the composite elastic pad

The proposed composite elastic pad has a sandwich structure and consists of a layer of ordered steel gaskets and two polyurethane pads, A and B, which are located on the upper and lower sides of the composite pad, as shown in Fig. 1. The steel pad can be made of spring steel, stainless steel, or another elastic material, and its cross-sectional shape can be round, square, octagonal, hexagonal, or triangular. Figure 1 shows the dimensions of 1/4 of the entire part (the thicknesses of polyurethane pads A and

Table 1 Main mechanical parameters of the blank

Material	Density (kg/m3)	Poisson's ratio	Young's modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)	Maximum elongation
08AL	7850	0.3	205	185	325	33%

B, which need to be determined by means of numerical simulations and tests, are not marked).

By introducing such composite elastic pads between the blank and the lower and upper punch units, the strain distribution of the part being formed can be effectively improved. The composite pads can also eliminate the concentrated loads induced by the point contacts of the punch units with the material, resulting in a uniform compressive stress load on the blank. Consequently, wrinkles and dimples are effectively inhibited, and high-quality parts can be formed.

The MPF process using the composite elastic pads is shown in Fig. 2. At the beginning of forming, the punch units of the lower and upper dies are adjusted to the positions indicated by the CAD data, and a composite elastic pad is added between the blank and the punch units of both the lower and upper dies. During the forming process, the upper die gradually moves downwards, which causes the upper polyurethane pad B to deform and produce an elastic force. Then, the flexible steel pad unit follows the deformation of polyurethane pad B and converts the elastic force into normal compressive stress on the blank, suppressing the wrinkling of the sheet metal. Due to the friction between polyurethane pad A and the blank, the wrinkling suppression will be significantly increased as the composite elastic pad converts the vertical pressure from the upper punch units into normal compressive stress. Then, the blank will deform with tensile stress in the tangential direction, thereby inhibiting the generation of wrinkles and spring-back. In addition, since the sandwich structure formed by the steel pad and polyurethane pads A and B endows the composite elastic pad with high rigidity, the point-to-face contact state between each punch unit and the sheet material can be converted into a face-to-surface contact. Therefore, the composite elastic pads can effectively disperse the concentrated loads generated by the point contacts of the punch units on the blank, thus suppressing the formation of dimples.

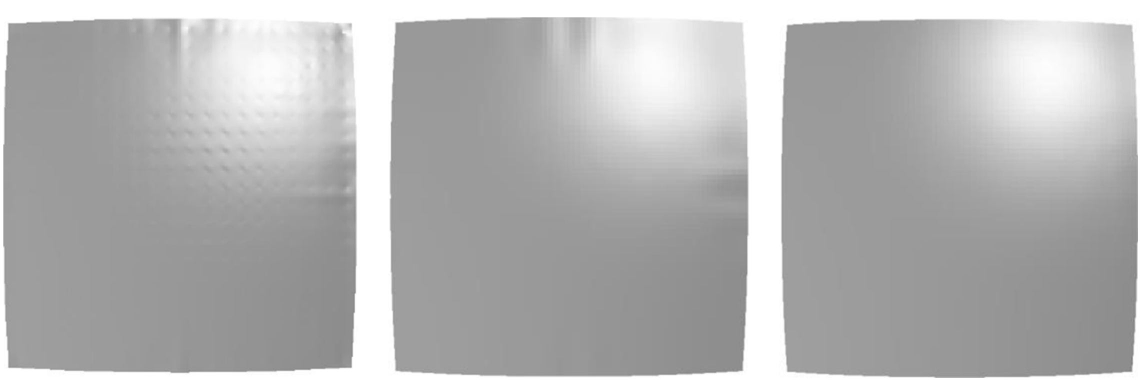
2.3 Principle of using composite elastic pads to improve the forming accuracy in multipoint forming

The main factors affecting the forming accuracy of the formed part include spring-back, wrinkling, dimpling, and straight edges. From Section 2.2, it can be seen that using the proposed composite elastic pads in the MPF process can generate a normal compressive stress on the blank, which results in the blank being deformed under tensile stress. In this way, the degree of plastic deformation of the blank is increased, and spring-back and wrinkling are suppressed. In addition, the steel pad layer of the composite elastic pad has a high hardness and thus can effectively mitigate uneven deformation of the polyurethane pad; consequently, the curvature of the formed die surface can be more easily controlled, thereby improving the forming accuracy of the blank.

To analyze the accuracy of a formed part, the difference between the actual shape of the formed part and the target surface can be calculated in terms of the Z-direction error and the average error of the part:

$$Z_{\mathrm{err}} = Z_t - Z_O \tag{1}$$

$$E_{\mathrm{err}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Z_t - Z_o)^2} \tag{2}$$



(a)Without cushion (b)Polyurethane cushion (c) Composite elastic pad

Fig. 5 Illumination maps of the formed parts. **a** Without any cushion. **b** Polyurethane pads. **c** Composite elastic pads

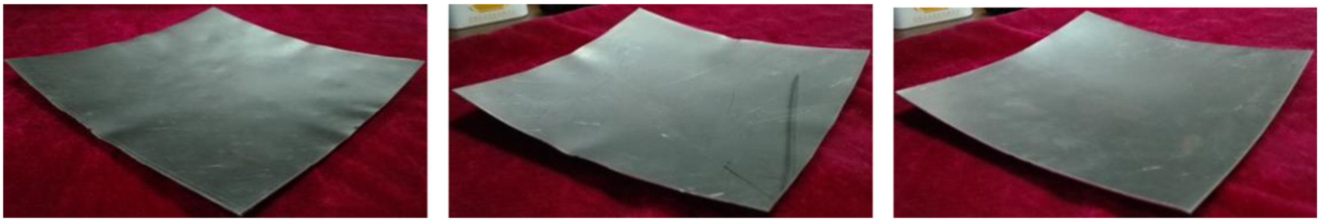


Fig. 6 Experimental parts. **a** Without any cushion. **b** Polyurethane pads. **c** Composite elastic pads

where Z_{err} is the forming error in the Z-direction, Z_O is the node height of the target product surface, Z_t is the node height of the formed part, E_{err} is the average error, and n is the total number of points considered in the calculation.

3 Establishment of the finite element model

In this paper, a spherical object with a radius of R400 is considered as the object of study. Finite element numerical simulations and analyses of the three different forming conditions, namely, without any cushion, with polyurethane pads, and with composite elastic pads, were performed using the software Abaqus Figs. 3. To improve the calculation efficiency, the three models were simplified to a quarter of the whole model with symmetrical constraints applied in the horizontal and vertical directions, considering that spherically curved parts have complete symmetrical geometries [15]. The forming pressure for all three conditions was set to 3 MPa.

The multipoint molds for the three different forming conditions were composed of 13 × 13 punch units with cross-sectional shaping unit dimensions of 10 × 10 mm and a crown radius of R10. Each punch unit was simplified to a crown surface represented by a shell element rigid body model of mesh-type S4R. The dimensions of the steel pad unit were set to φ 9.5 mm and a thickness of 5 mm, with 65 Mn as the material and mesh-type C3D8R, and a solid elastic model was applied.

The material of the blank was 08AL, which was assumed to be isotropic and to obey the von Mises yield criterion and the plastic flow law, and the stress–strain relationship was assumed to obey an exponential reinforcement relation. The blank size was 200 × 200 mm, the thickness was 1 mm, and the mesh type was S4R with a shell element deformation model. The tensile test data of the material were translated from the nominal stress–strain relationship into the true stress–strain relationship; the true stress–strain curve is shown in Fig. 4. The relevant mechanical properties are presented in Table 1. Each polyurethane pad had a Shore A hardness of 79° and dimensions of 250 × 250 mm, and the mesh type used for the polyurethane pads was C3D8R with a hyperelastic model.

General-type contact was applied between the punch units and the polyurethane pads, the blank and the polyurethane pads, and the steel pads and the polyurethane pads. The friction coefficient was set to 0.25, and the upper die was driven by the force method with a loading time of 0.2 s [16].

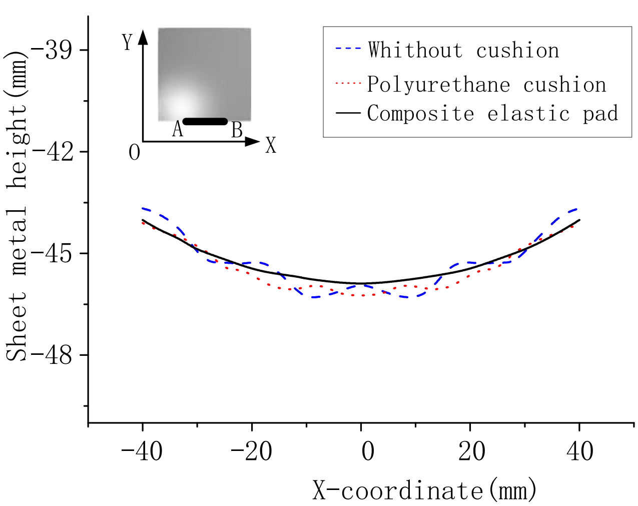


Fig. 7 Node height analysis for the different forming processes

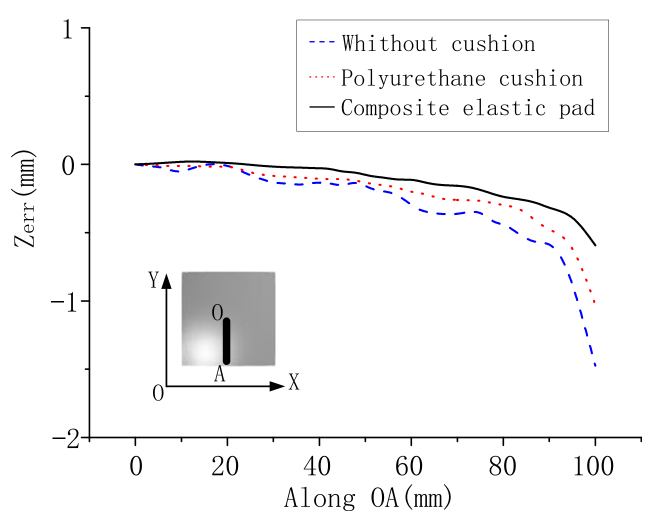


Fig. 8 Accuracy analysis for three different forming conditions

Table 2 Maximum and average errors under three different forming conditions

	Forming conditions		
	Without any cushion	Polyurethane pads	Composite elastic pads
Maximum error	1.475	1.036	0.468
Average error	0.833	0.589	0.283

4 Comparison and analysis of simulation results

4.1 Influences of the three forming conditions on the forming quality and forming accuracy

Figures 5 and 6 show the illumination maps and experimental photographs of the parts formed using the three different conditions (no cushion, polyurethane pads, and composite elastic pads). It can be seen from Figs. 5a and 6a that wrinkling occurred at the four edges of the part formed without any pads, while dimpling appeared in the center area. Figures 5 b and 6 b display the illumination map and experimental photograph for the MPF process using polyurethane pads. It can be seen from these figures that the use of the polyurethane pads led to a significant reduction in the wrinkling area and a decrease in the corrugation height. However, the wrinkles did not disappear completely. Figures 5c and 6c show the illumination map and experimental photograph of the part formed using the composite elastic pads, which show that the wrinkling and dimpling completely disappeared and that the part had a smooth surface and a regular contour. These findings reveal that the use of the composite elastic pads can effectively inhibit wrinkles.

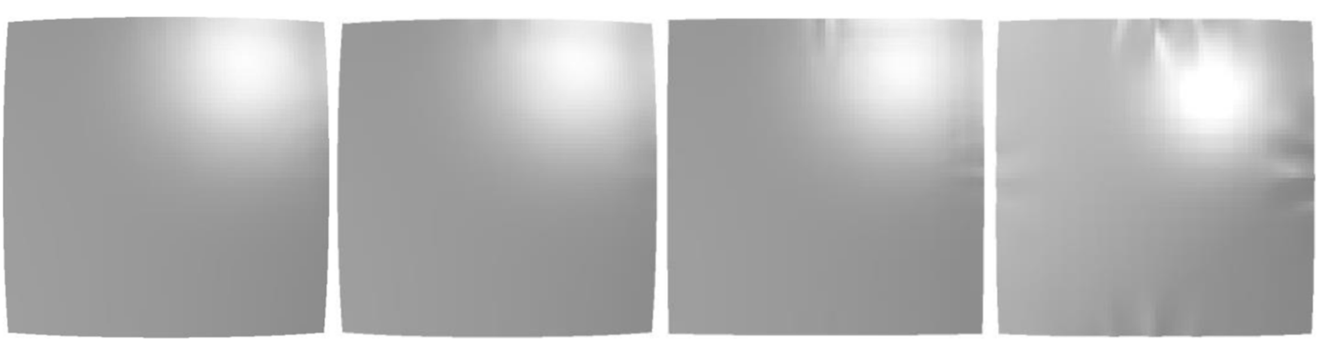
Furthermore, a section along one edge of each formed part, with a length of 80 mm and centered on the midpoint of the edge (labeled AB in Fig. 7), was considered to analyze the contour height. The node heights for profile AB are shown in Fig. 7. The curve fluctuations of profile AB are completely different among the three forming conditions. For the part formed without any cushion, the profile undulates from − 40 to 40 mm, and the maximum wrinkle height reaches 1.253, indicating severe wrinkling of the blank. For the part formed using polyurethane pads, the region of undulation is reduced to − 20 to 20 mm, and the maximum wrinkle height is reduced to 0.885. For the part formed using the composite steel pads, the profile is smooth, and there is no undulation.

Figure 8 shows the error diagram for the symmetric centerline (OA) for each of the three forming conditions. From this figure, it can be seen that for the part formed without any cushion, the error curve exhibits serious undulations, and the maximum error reaches 1.475 mm. For the part formed using polyurethane pads, the amount of undulation is decreased, and the maximum error is reduced to 1.036 mm. For the part formed using the composite elastic pads, the maximum error is reduced to 0.468 mm, and the curve is smooth and flat, indicating that the strain state became more uniform and that the forming quality and precision were greatly improved. The detailed statistical data on the errors resulting from the three different forming conditions are shown in Table 2.

4.2 Influence of the thickness of polyurethane pad A on the forming quality and forming accuracy

The roles of polyurethane pads A and B are different. Polyurethane pad A is mainly used to fill in the gaps between the steel pad units and the blank to prevent the edge of the steel pad from scratching the sheet metal and producing dimples. Polyurethane pad B is primarily used to convert the vertical stress into normal stress to achieve blank tightening during forming. To study the influence of different thicknesses of the polyurethane pads on the forming accuracy, all other parameters of the composite elastic pad were kept unchanged.

Since polyurethane pad A acts as a backing plate, the thickness of this plate should be as thin as possible while ensuring that the hardness and toughness are sufficiently high. Figure 9 shows the illumination maps of the forming simulation results obtained with polyurethane pad A thicknesses of 5, 10, 15, and 20 mm. (Based on empirical



(a) 5mm (b) 10mm (c) 15mm (d) 20mm

Fig. 9 Inhibitory effect on wrinkling with various thicknesses of polyurethane pad A. **a** 5 mm. **b** 10 mm. **c** 15 mm. **d** 20 mm data, the thickness of elastic pad B was provisionally set to 10 mm in these simulations.) This figure reveals that as the thickness of polyurethane pad A increases, the amount of wrinkling at the four edges of the formed part gradually increases. When polyurethane pad A has a larger thickness, such as 15 or 20 mm, it absorbs most of the compressive stress converted by the steel pad and weakens the effect of normal pressing on the blank, leading to more severe wrinkling on the part surface. Therefore, the thickness of polyurethane pad A was set to 5 mm in subsequent simulations and experiments.

Figure 10 shows the node heights of profile AB with the different thicknesses of polyurethane pad A. As the thickness of elastic pad A increases, the degree and range of the fluctuations gradually increase. When the thickness of elastic pad A is 20 mm, the maximum wrinkle height reaches 0.898 mm, and the undulations extend over the entire range of − 20 to 20 mm.

Figure 11 shows the error curves for the symmetric centerline OA. For the part formed with a polyurethane pad A thickness of 5 mm, the error curve is smooth, with a maximum error of 0.468 mm. As the thickness of polyurethane pad A gradually increases, fluctuations and local mutations appear in the curve. For a thickness of 20 mm, the maximum fluctuation height reaches 1.239 mm. Therefore, it can be concluded that the greater the thickness of polyurethane pad A is, the worse the surface quality and accuracy of the formed part. The detailed statistical data on the errors achieved with various thicknesses of polyurethane pad A are shown in Table 3.

The thickness of polyurethane pad A will directly affect the quality and precision of the die surface formed by the composite elastic pad, so its thickness needs to be reasonably selected. If polyurethane pad A is too thick, the degree of unevenness of the deformation after compression will be sharply increased, reducing the accuracy of the formed die surface. In addition, a polyurethane pad is a superelastic body

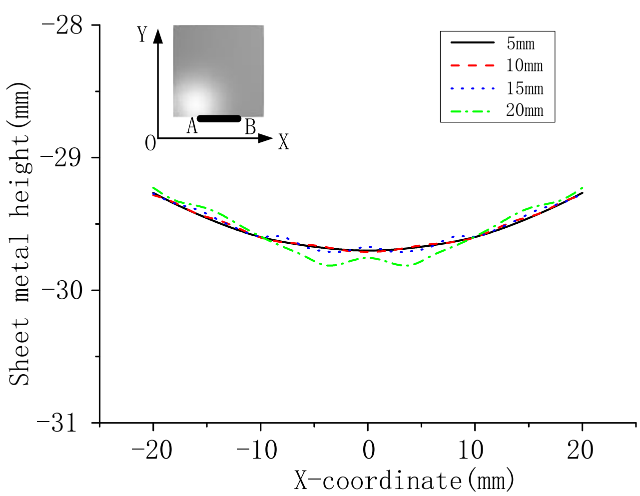


Fig. 10 Node height analysis for various thicknesses of polyurethane pad A

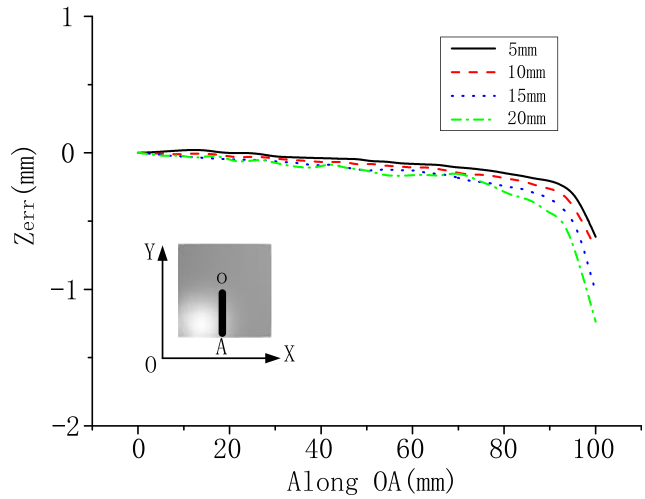


Fig. 11 Accuracy analysis for various thicknesses of polyurethane pad A

and thus may disperse compressive stress. Therefore, if the thickness of polyurethane pad A is too great, the blank holder effect of the discrete steel pad will be weakened. By contrast, if polyurethane pad A is too thin, dimple and scratching defects will not be effectively suppressed, and the toughness and strength of polyurethane pad A will also be greatly reduced.

In terms of the function of polyurethane pad A, as long as there are no scratches or dimple defects on the formed part, the thickness of this pad can be considered reasonable. It can be determined from the analysis of the MPF process with composite elastic pads that the selection of the thickness of polyurethane elastic pad A is related to the shape of the steel pad, the material of the blank, the curvature of the target surface to be formed, and the hardness of the polyurethane pad. Therefore, when selecting the thickness of polyurethane elastic pad A, it is necessary to comprehensively consider the parameters of the steel pad, the shape of the part to be formed, and the type of polyurethane material used, and finally, determine the optimal thickness through numerical simulations and forming tests.

4.3 Influence of the thickness of polyurethane pad B on the forming quality and forming accuracy

The thickness of polyurethane pad B will directly affect the compressive stress that the steel pad applies to the

Table 3 Maximum and average errors for various thicknesses of polyurethane pad A

	Polyurethane pad A thickness (mm)			
	5	10	15	20
Maximum error	0.468	0.701	1.021	1.239
Average error	0.283	0.369	0.505	0.619

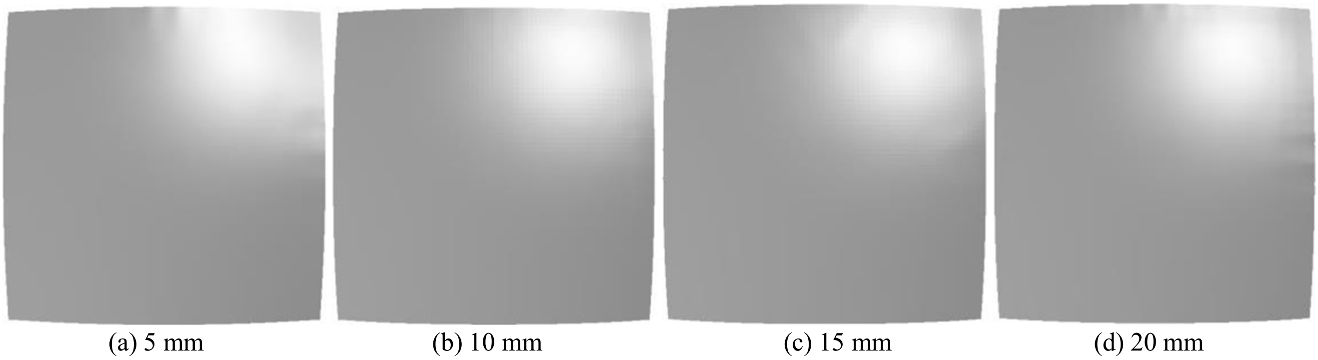


Fig. 12 Illumination maps for various thicknesses of polyurethane pad B. **a** 5 mm. **b** 10 mm. **c** 15 mm. **d** 20 mm

blank and will significantly influence the extent to which the composite elastic pad can suppress wrinkling during the forming process. Therefore, it is necessary to further study the selection of the thickness value for this pad.

Figure 12 displays the illumination maps of the parts formed using polyurethane pad B thicknesses of 5, 10, 15, and 20 mm. Figure 12a shows that for the part formed with a polyurethane pad B thickness of 5 mm, the wrinkle height is much smaller than that observed with no cushion or with only polyurethane pads between the blank and the punch units. For polyurethane plate B thickness of 10 mm (shown in Fig. 12b), it can be seen that the formed part has a smooth surface, a regular contour, and sufficient deformation without any dimples or wrinkles. These observations suggest that the frictional stress and normal compression stress imposed by the composite elastic pad are significantly increased when the thickness of polyurethane pad B is 10 mm, causing the blank to gradually deform in the tightened state. Consequently, dimpling and wrinkling defects are completely suppressed. With a polyurethane pad B thickness of 15 mm, wrinkles again begin to appear on the surface of the formed part, and when the thickness of polyurethane pad B is further increased to 20 mm, the wrinkling of the formed part is also further increased (as shown in Fig. 12c and d). These findings show that if the thickness of polyurethane pad B is too great, the ability of the composite elastic pad to suppress the wrinkling of the blank is decreased. This decreased suppression capability is mainly attributed to the adhesion of the steel pad to polyurethane pads B and A. If pad B is thicker than pad A, then the flowing displacement of microelements along their tangents when the composite elastic pad is squeezed by the upper die will be different. With a large differential displacement, the steel pad units will not remain perpendicular to the part surface after rotation, which will weaken the inhibitory effect on wrinkling.

Figure 13 shows the node heights of profile AB for various thicknesses of polyurethane pad B. It can be seen from the figure that when the thickness of polyurethane pad B is 5 mm, the form of the curve is altered between −20 and 20 mm, and the maximum wrinkle height reaches 0.658 mm. With a polyurethane pad B thickness of 10 mm, the curve becomes smooth and continuous, indicating uniform deformation of the blank with no defects. When the thickness of polyurethane pad B is increased

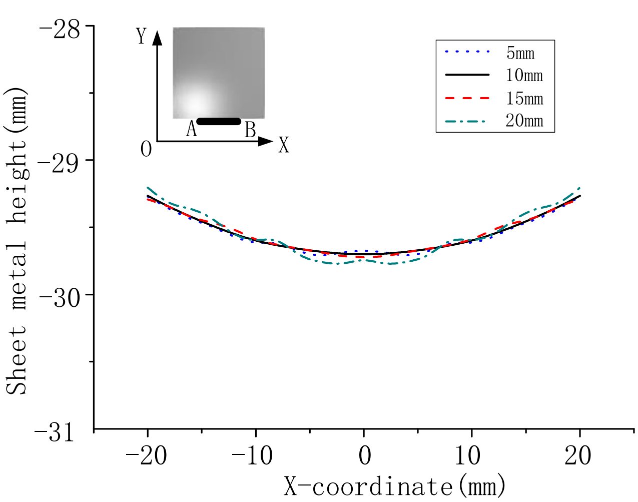


Fig. 13 Node height analysis for various thicknesses of polyurethane pad B

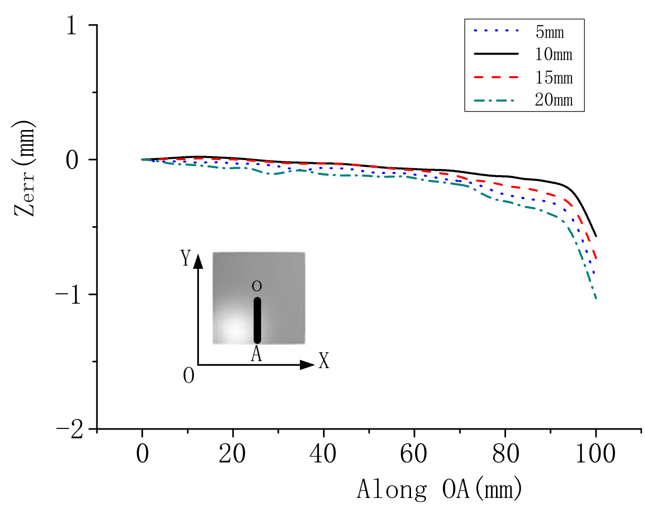


Fig. 14 Accuracy analysis for various thicknesses of polyurethane pad B

Table 4 Maximum and average errors with various thicknesses of polyurethane pad B

	Polyurethane pad B thickness (mm)			
	5	10	15	20
Maximum error	0.891	0.468	0.732	1.031
Average error	0.455	0.283	0.361	0.556

to 15 mm, the curve exhibits slight fluctuations near the center, in the range of − 10 to 10 mm, with a maximum wrinkle height of 0.365 mm. When the thickness of polyurethane pad B is further increased to 20 mm, the fluctuation amplitude of the curve is also further increased, the maximum wrinkle height reaches 0.457, and the fluctuation range is significantly wider.

Figure 14 shows the error curves of the symmetric centerline OA for various thicknesses of polyurethane pad B. It can be seen from this figure that when the thickness of polyurethane pad B is 10 mm, the OA error curve fluctuates minimally, with a maximum error of only 0.468. For polyurethane pad B thicknesses of 5, 15, and 20 mm, fluctuations are observed in the curve. For a thickness of 20 mm, the fluctuation reaches 1.031 mm. These findings demonstrate that a suitable thickness of polyurethane pad B can significantly improve the forming quality and forming accuracy when the proposed composite steel pads are used in MPF. The detailed statistical data on the errors achieved with various thicknesses of polyurethane pad B are shown in Table 4.

The main purpose of polyurethane pad B is to apply normal compressive stress to the discrete steel pad. Furthermore, the concentrated loads imposed by the point-surface contacts of the punch units with the discrete steel pad can be dispersed through polyurethane pad B, thus ensuring that the steel pad is subjected to a uniform and continuous compressive stress. However, if polyurethane pad B is too thin, it cannot completely eliminate the concentrated loads applied by the punch units. By contrast, if polyurethane pad B is too thick, the polyurethane pad will

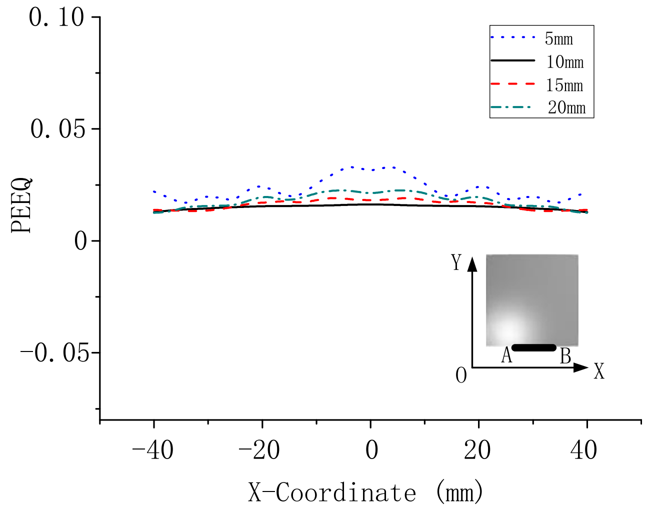


Fig. 16 Equivalent strain diagram for AB

undergo more uneven deformation under compression, with more severe deformation occurring near the edges of the mold. This will cause the compressive stress applied to the sheet metal by the discrete steel pad to be uneven (the center area is very large, and the edge area is very small); consequently, the compressive stress applied at the edges of the sheet will be insufficient, and the wrinkling of the sheet will not be completely suppressed.

In terms of the function of polyurethane pad B, as long as there are no wrinkles on the formed part, the thickness of this pad can be considered reasonable. The analysis of the MPF process reveals that the selection of the thickness of polyurethane elastic pad B is related to the deformation resistance of the sheet metal, the thickness of the blank, the hardness of the polyurethane material used, the section shape of the punch units, and the target curvature of the part, among other factors. Therefore, when selecting the thickness of polyurethane elastic pad B, it is necessary to comprehensively consider the shape of the part to be formed, the mold type, and the sheet metal parameters, among other factors, and the optimal thickness should ultimately be determined through numerical simulations and forming tests.

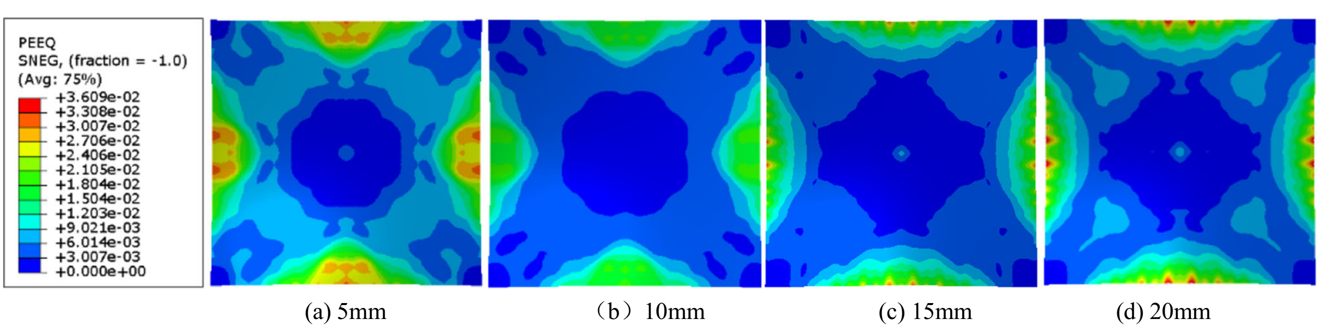
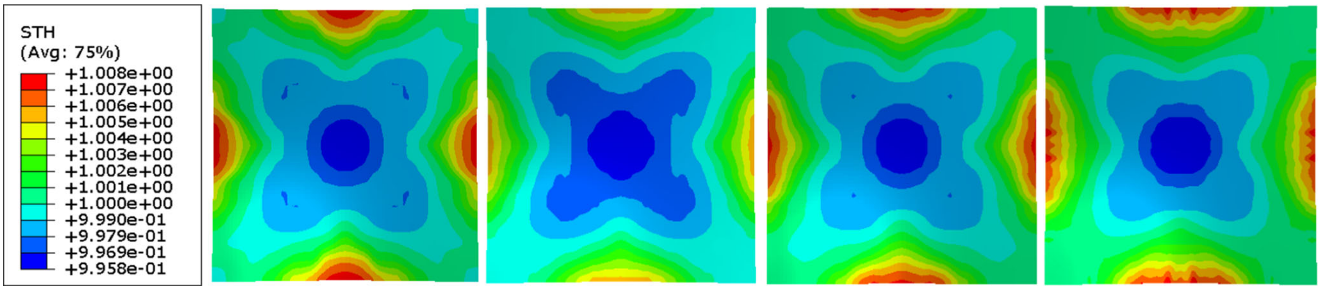


Fig. 15 Strain distributions for various thicknesses of polyurethane pad B. **a** 5 mm. **b** 10 mm. **c** 15 mm. **d** 20 mm



(a) 5 mm (b) 10 mm (c) 15 mm (d) 20 mm

Fig. 17 Thickness distributions for various thicknesses of polyurethane pad B. **a** 5 mm. **b** 10 mm. **c** 15 mm. **d** 20 mm

4.4 Analysis of the forming strain

Figure 15 displays the strain distributions of the parts formed with the thickness of polyurethane pad B set to 5, 10, 15, and 20 mm. When the thickness of polyurethane pad B is 10 mm, the strain distribution is the most uniform, and it is the least uniform with a polyurethane pad B thickness of 5 mm.

The equivalent strain curves within a scope of 40 mm on either side of the midpoint on one edge (AB) are displayed in Fig. 16. For a polyurethane pad B thickness of 5 mm, the curve displays extreme fluctuations. When the thickness of polyurethane pad B is increased to 10 mm, the strain curve becomes smooth, with no fluctuations. When the thickness of polyurethane pad B is adjusted to 15 mm, slight fluctuations in the curve again appear near the center, in the range of − 10 to 10 mm. When the thickness is further increased to 20 mm, the fluctuations in the curve also further increase, and the fluctuation range becomes wider. Considering that these changes in the curve are caused by increasing the thickness of polyurethane plate B, it can be concluded that the uniformity of the strain distribution shows a tendency to first increase and then decrease, with the best strain distribution corresponding to a pad thickness of 10 mm.

4.5 Analysis of sheet metal flow and thickness

Figure 17 shows the thickness distributions of the parts formed with the thickness of polyurethane pad B set to 5, 10, 15, and 20 mm. All formed parts exhibit symmetrical thinning in the center region and thickening at the midpoints of the four edges. These observations indicate that the sheet material flows from the outer edges towards the center during the forming process. In addition, the length of the blank decreases as the material flows towards the center, causing the material of the blank to aggregate near the midpoints of the four edges and readily leading to wrinkling when the restraining effect of the mold is insufficient.

For a polyurethane pad B thickness of 5 mm, the thickness of the blank near the midpoints of the four edges is significantly increased to a maximum thickness of 1.008 mm. This

(a) Press (b) Multi-point die

Fig. 18 YAM-200 MPF press. **a** Press. **b** Multipoint die

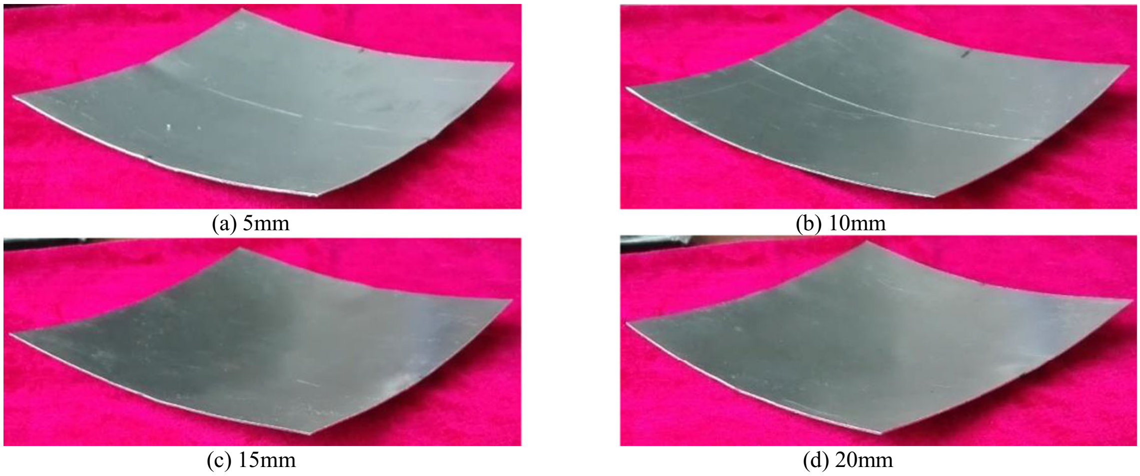


Fig. 19 Experiment parts formed with various thicknesses of polyurethane pad B. **a** 5 mm. **b** 10 mm. **c** 15 mm. **d** 20 mm

observation suggests that the tensile stress and compressive stress on the sheet are not sufficiently, resulting in an excessively high inflow speed of the sheet material and the accumulation of material near the midpoints of the edges. When the thickness of polyurethane pad B is 10 mm, the thinned region of the formed part is obviously larger, and the thickness distribution is more uniform (Fig. 17b). These results show that the thickening of the material near the midpoints of the four edges is well controlled. When the thickness of polyurethane pad B is increased to 15 mm, the central thinned area again begins to decrease, and the accumulation in the surrounding area becomes more serious. When the thickness is further increased to 20 mm, the accumulation near the midpoints of the edges is even more obvious, indicating that the

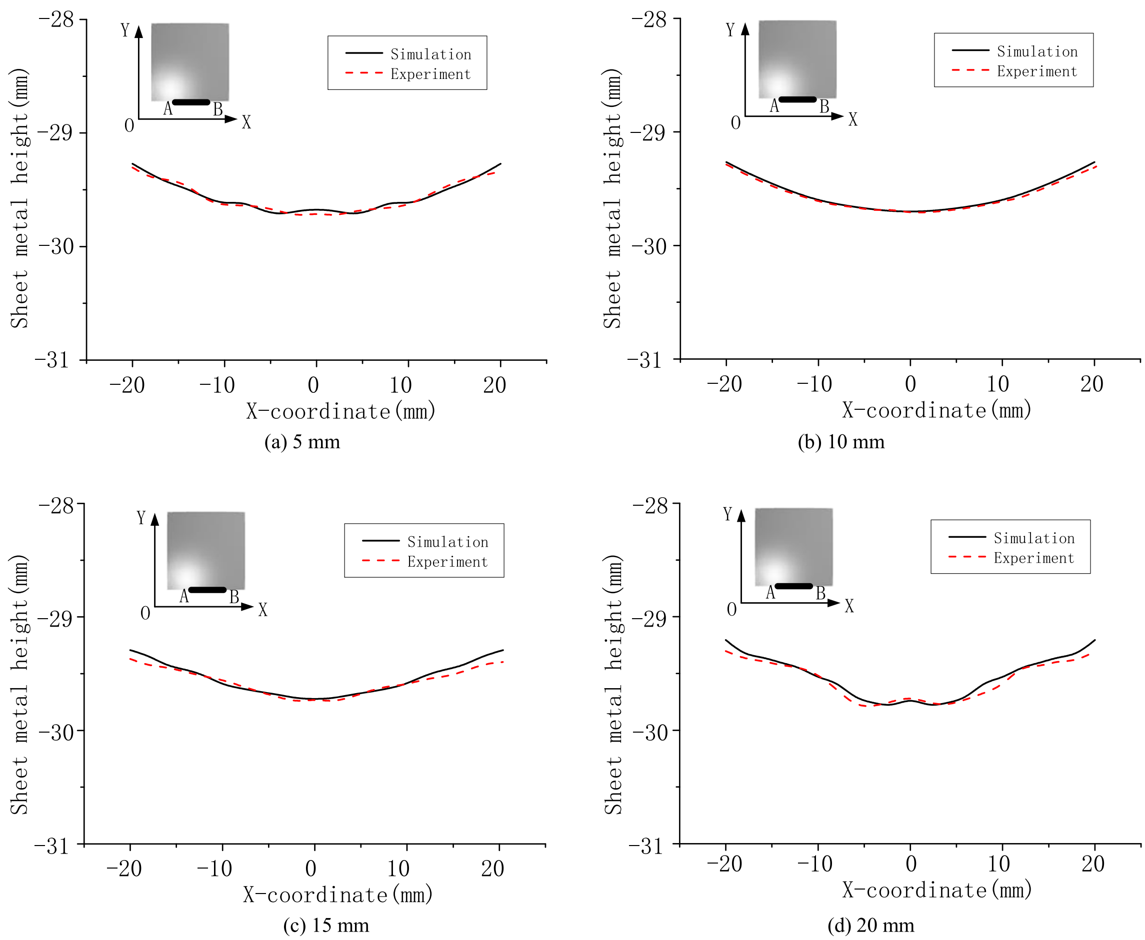


Fig. 20 Node heights along profile AB for various thicknesses of polyurethane pad B. **a** 5 mm. **b** 10 mm. **c** 15 mm. **d** 20 mm

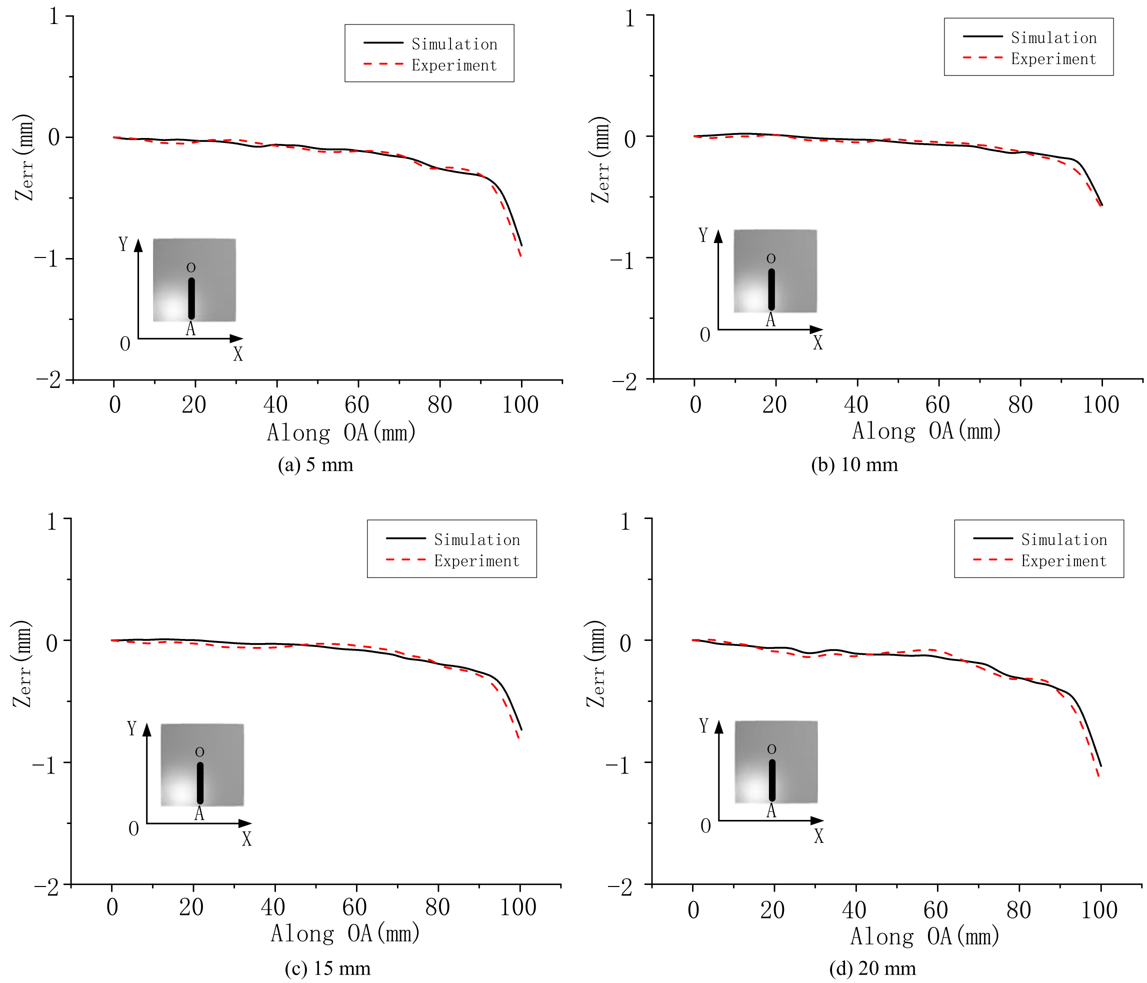


Fig. 21 OA errors with various thicknesses of polyurethane pad B. **a** 5 mm. **b** 10 mm. **c** 15 mm. **d** 20 mm

tensile and compressive stresses applied by the composite elastic pad are weaker and that wrinkles again form in the part.

5 Verification tests

To verify the effects of different thicknesses of polyurethane pad B on the forming accuracy as indicated by the simulations presented above, the YAM-200 MPF press developed by the Jilin University, which is shown in Fig. 18, was applied. The testing material was 08AL, the blank dimensions were 200 × 200 mm, and the target surface was a sphere of R400. The forming results are displayed in Fig. 19. When the thickness of polyurethane pad B was set to 5, 15, and 20 mm, significant forming defects were generated in the middles of the four edges of the formed parts. When the thickness of polyurethane pad B was 10 mm, the formed part was smooth without any defects. These results are consistent with the results of the numerical simulations.

The parts formed in the experiment were examined using a portable optical three-dimensional measuring instrument developed by Northern Digital Inc. (Canada). The comparisons of profile AB between the numerical simulation results and the experimental results are shown in Fig. 20. It can be seen from this figure that the experimental results are consistent with the numerical simulations. The fluctuations in profile AB varied with the thickness of polyurethane pad B. When the thickness of polyurethane pad B was set to 10 mm and 20 mm, the corresponding degrees of fluctuation of the curve were the minimum and maximum, respectively.

Comparisons of the forming errors along the symmetric centerline OA between the experimental results and the numerical simulation results are shown in Fig. 21. As seen from this figure, when the thickness of polyurethane pad B was 10 mm, the forming quality and precision of the plate were the best. By contrast, with pad B thicknesses of 5, 15, and 20 mm, the forming quality and precision of the plate were significantly reduced. Therefore, it can be concluded that the thickness of polyurethane pad B influences the ability of the proposed composite steel pads to improve the forming accuracy and forming quality achieved in MPF.

6 Conclusions

Numerical simulations and forming tests were performed under three different forming conditions. The results reveal that the use of composite elastic pads can effectively improve the achieved forming quality and accuracy. In addition, when the thicknesses of polyurethane pads A and B are 5 mm and 10 mm, respectively, the forming effect is the best. Compared with the forming condition without any cushion, the maximum error and average error of the formed part are reduced by 68.3% and 66.1%, respectively. In addition, the following conclusions are obtained:

1. The use of the proposed composite steel pads in MPF can facilitate control of the curvature of the formed die surface and improve the forming accuracy.
2. By comparing the simulated and experimental results for three MPF conditions (without any cushion, with polyurethane pads, and with composite elastic pads), it was found that composite elastic pads can effectively improve the strain distribution during the forming process, thereby inhibiting wrinkling and dimpling and improving the forming accuracy of the formed parts.
3. When composite steel pads are used in MPF, the thickness of polyurethane pad A should not be too great; the thicker polyurethane pad A is, the worse the surface quality and accuracy of the formed part.
4. The thickness of polyurethane pad B also affects the improvements in forming accuracy and forming quality achieved in MPF with composite steel pads.

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