The International Journal of Advanced Manufacturing Technology (2019) 104:2739–2750
https://doi.org/10.1007/s00170-019-04144-9

ORIGINAL ARTICLE

Experimental and numerical study on deformation behavior of doubly curved metal plates during incremental bending process

Feifei Zhang [1,2] · Ji Zhang [1,2,3] · Qiyang Zuo [1,2] · Xiaobing Dang [4] · Kai He [1,2]

Received: 8 April 2019 / Accepted: 9 July 2019 / Published online: 23 July 2019

Abstract
Doubly curved metal plates are widely used in various industrial fields, so many efforts have been made to achieve the required doubly curved metal plates at reasonable quality and high efficiency in the last few decades. This paper presents a flexible forming process called incremental bending to achieve the doubly curved metal plates. The basic deformation behavior of the metal plates during the incremental bending process, including the loading force distribution and springback amount distribution along the whole surface of the metal plates, was investigated and analyzed based on experiments and numerical simulation. Results show that the maximum loading force and the springback amount of the metal plates are significantly influenced by the punching position while not by the incremental step. The results provide an important theoretical foundation for the practical application of the incremental bending process for achieving various doubly curved metal plates in the future.

Keywords Flexible forming · Springback · Numerical simulation · Incremental step

1 Introduction

Doubly curved metal plates are widely used in various industrial fields, including aerospace, vehicle, and shipbuilding. How to accurately manufacture the doubly curved metal plates in the industries has always been the focus of attention. In order to solve the problem, many efforts have been made in research institutes or enterprises in the last few decades.

The traditional method to manufacture sheet metal plates is die-stamping process, which is highly efficient and accurate. However, the expense of the die production is very huge, so it is mainly applicable to mass production. For some metal plates used in aerospace or shipbuilding fields, the dimension of the metal plate is large and the required amount is quite small. Using the die-stamping method to fabricate such metal plates, the corresponding die and machine tool with large size should be designed, which would greatly increase the machining cost.

In the last few decades, great efforts have been made to reduce the huge die fabrication cost in stamping. For example, hydroforming process [1] was proposed to apply fluid pressure replacing the solid punch or die to the blank to form various metal components. Electrohydraulic forming process [2] was developed to use electric arc discharge in liquid to make the metal plate contact with the die. Magnetic pulse forming process [3] was exploited to apply magnetic force generated from the magnetic pulse forming system to deform workpiece with good conductivity. Laser shock forming process [4] was presented to use shock wave induced by high-energy pulsed laser to produce plastic deformation. For those flexible forming processes mentioned above, only half die is used, so the specific half die should also be fabricated for each objective plate with specific shape. The cost for manufacturing various small-batch metal plates is still very high.

So far, many more flexible forming processes without integrated die have been developed to solve the machining problem for many small-batch metal plates. One of the widely used flexible forming methods is incremental sheet forming process (ISF), which forms the metal sheet into the final workpiece following the incremental movement of one round tipped tool. According to whether there is stable supporting tool,

✉ Kai He
kai.he@siat.ac.cn

1 Shenzhen Key Laboratory of Precision Engineering, Shenzhen, Guangdong, China

2 Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen, Guangdong, China

3 China University of Petroleum, Changping, Beijing, China

4 Chow Yuk Ho Technology Centre for Innovative Medicine, The Chinese University of Hong Kong, Sha Tin, Hong Kong

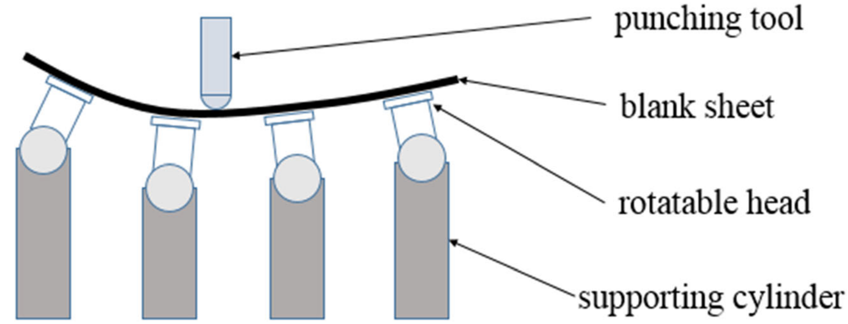

Fig. 1 Schematic diagram of the incremental bending process

incremental sheet forming process can be divided into single point incremental forming process (SPIF) [5] and two-point incremental forming process (TPIF) [6]. According to whether there is flexible supporting tool, incremental sheet forming process also can be divided into single point incremental forming process (SPIF) and double-sided incremental forming process (DSIF) [7]. ISF is proved to improve the materials' formability while the friction between the blank and the tools may result in poor surface quality of the deformed plates. Besides, ISF is generally regarded to be more suitable for machining the complicated thin metal plates. In addition, Li et al. proposed multi-point forming process (MPF) [8]. This flexible forming process uses a group of punch elements to reshape the surface of the integrated die. By controlling the height of each punch element, the required die shape can be obtained to deform the metal plates. MPF has been utilized to fabricate the distorted steel columns of Beijing Olympic Stadium. The main shortcoming of MPF is that its control system is really complex and the surface quality of the deformed metal plate is limited due to the unchanged globular tool pins. By combining the multi-point forming with stretch bending, Lee and Kim developed the multipoint stretch forming process (MSF) [9], and they succeeded in fabricating 45133 unique varying curved metal panels for Dongdaemun Park building in Seoul, South Korea. Compared with the traditional die casting method and hydroforming method, the fabrication cost based on MSF is reduced to 3.71% and 8.67%, respectively. Even though MPF and MSF realize die-less production, the expense of fabricating the whole equipment is huge and the loading force of the machine tools is quite large since the tool groups contact with the metal plates during the forming processes. In order to reduce the forming force and energy consumption, Luo et al. proposed cyclic multipoint incremental forming process (CMPIF) [10]. Similarly to MPF, this technique also uses two reconfigurable tool groups to replace the solid die, while each tool is cyclically controlled to move a small step until all tool groups are gradually moved to achieve the final shape of the part. So the forming force during CMPIF is decreased significantly.

Besides die-stamping method, rolling is another effective bending method to achieve curved metal plates. Yoon and Yang developed incremental roll forming process (IRF) [11], which achieved continuous bending deformation based on the movement of one upper center roll and two pairs of lower support rolls. Based on two reconfigurable rollers, Yoon et al. and Cai et al. proposed flexibly reconfigurable roll forming process (FRRF) [12] and continuous roll forming process (CRF) [13], respectively. In addition, Hu et al. presented a continuous flexible forming process (CFF) [14] based on three reconfigurable rollers. The convex parts and saddle-

Fig. 2 Experimental setup of incremental bending process

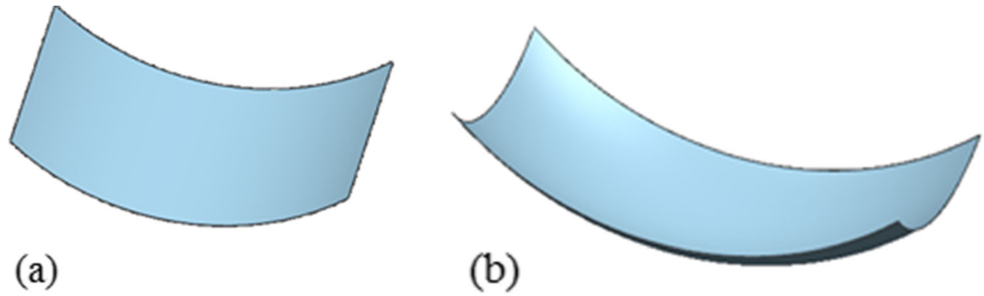

Fig. 3 Classification of the bending parts **a** singly curved bending parts and **b** doubly curved bending parts

shaped parts with small size can be achieved based on the schemes mentioned above. In order to achieve a doubly curved plate with larger size, Shim et al. [15] developed line array roll set process (LARS), which was composed of a pair of upper and lower symmetric roll assemblies. The objective plate of 1000 mm × 1000 mm can be bended successfully based on LARS.

The flexible forming processes mentioned above are developed to reduce the manufacturing cost, improve the forming precision, or enhance the forming efficiency. But most of them are still at the stage of experimental study, so there is still long time to be industrialized. Recently, one novel flexible forming process called incremental bending process has also been developed to reduce the deformation force and minimize the energy consumption during the manufacturing process for variable 3D curved metal plates with relatively larger thickness [16]. Some singly curved metal plates were successfully obtained based on this incremental bending process [17]. However, it should be noted that the deformation behaviors of the singly curved plates and that of the doubly curved plates are quite different; the minimum energy method based on beam deformation theory cannot be used directly to guide the deformation process of the doubly curved metal plates. So it is necessary to first investigate the basic deformation behavior of the doubly curved plates during this novel flexible forming process. And then, based on the basic research results, the proper mathematical models or some novel control scheme [18, 19] can be chosen to obtain the optimized loading path for the specific doubly curved metal plates in the future.

Here, in this paper, the basic deformation behavior of the doubly curved metal plates, including the loading force and springback amount distribution, during the incremental bending process is studied based on experiments and numerical simulations. The rest of the paper is organized as follows: the theory of the incremental bending process, the experimental procedure, and the corresponding numerical simulation are presented in Section 2. The experimental results, the validation of the numerical simulation, and more numerical simulation results are discussed and analyzed in Section 3 for better understanding the deformation behavior of the doubly curved metal plates. Finally, Section 4 contains the conclusion.

2 Experimental and numerical simulation study

2.1 Incremental bending theory introduction

The schematic diagram of the incremental bending process is shown in Fig. 1. During the incremental bending process, the metal plate is supported by several supporting cylinders with rotatable heads. When the punch (or punches) moves down to press the metal plate, the metal plate is deformed to a certain shape under the action of both punch (or punches) and supporting cylinders. The punching action can be operated several times and during each time, the punching position and the punching depth are different to finally achieve the objective metal part with specific shape. From Fig. 1, we

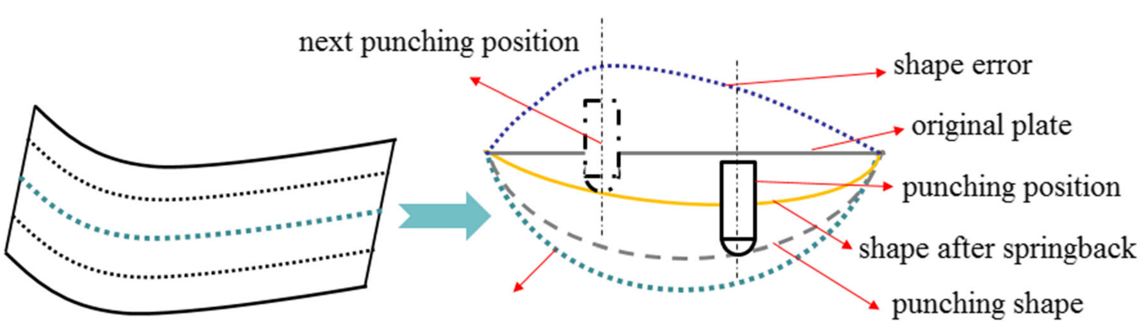

Fig. 4 Loading path determination for singly curved metal plate during incremental bending process

Table 1 Mechanical properties of carbon steel Q235 sheet

Density (kg/ mm^3)	Elastic modulus (GPa)	Yield stress (MPa)	Poisson's ratio
7800	207	311.3	0.3

can see this is a bending-dominated deformation process, so the forming force is reduced significantly.

Based on the deformation theory of the incremental bending process, the corresponding machine tool is established as shown in Fig. 2. Compared with the machine tool mentioned in our previous study [17], the experimental setup is also composed of a punching system, a supporting system, a computer-control system, and a 3D optical scanning system. However, the dimension of the machine tool and the corresponding plate used in literature [17] are very large, so three punches are used to make sure the in-plane deformation only occurs in one direction. While in this study as shown in Fig. 2, the machine tool and the blank are relatively much smaller, one punch is used to deform the plate and thus, it takes longer time than the case with more punches. The maximum loading force for the punch is 20 kN and its working stroke along z-axis is 500 mm. There are totally 12 supporting cylinders arranged as 4 × 3 for this machine tool. The diameter of each supporting cylinder is 80 mm and the distance between each supporting cylinder is 120 mm. The supporting system can move along x-axis and y-axis and the corresponding working stroke is 400 mm and 300 mm, respectively. It should be noted that different from the bigger plate used in our previous study [17], the dimension of the plate used for this machine tool is too small to keep stable during the whole bending processes if it is placed on top of the supporting cylinders directly, so screws or fixtures are used to help constrain the plate partially. During the incremental bending experiments, the computer-control system shown in Fig. 2 is used to control the movement of the punch and the supports, and the 3D optional scanning system is used to scan the metal plate and compare the shape of the deformed plate with that of the objective one.

In general, the bending parts used in manufacturing industry can be divided into two types. If the curvature changes only or mainly in one direction as shown in Fig. 3a, the bending type is called singly curved bending part, while if the curvature changes in two directions and neither change can be neglected as shown in Fig. 3b, the bending type is called doubly curved bending part. To be honest, there is a huge difference between the deformation behavior of the singly curved bending parts and that of the doubly curved bending parts. For singly curved bending parts, the metal plate can be simply assumed to be series of discrete strip, and it is believed the objective plate is achieved when the strips are deformed to the specific shapes. So we only need to figure out the deformation behavior of the strips. In our earlier research, the minimum energy method is proposed to determine the punching path. As shown in Fig. 4, the next punching position can be determined by the position that has the maximum error between the current shape and the objective shape. Based on the minimum energy method and the springback rule of the strips, the singly curvature metal plate and variable curvature metal plate can be experimentally obtained. The detailed research results can be found in the published papers [16, 17, 20]. However, the current theory is hard to guide the manufacturing process for the doubly curved bending parts (such as the saddle-shaped metal plates and bowl-shaped metal plates that are commonly seen in ship industry) for their complex deformation behavior. So here in this study, the deformation behavior of the doubly curved metal parts, including the loading force and springback amount distribution, is investigated in detail based on experiment and numerical simulation.

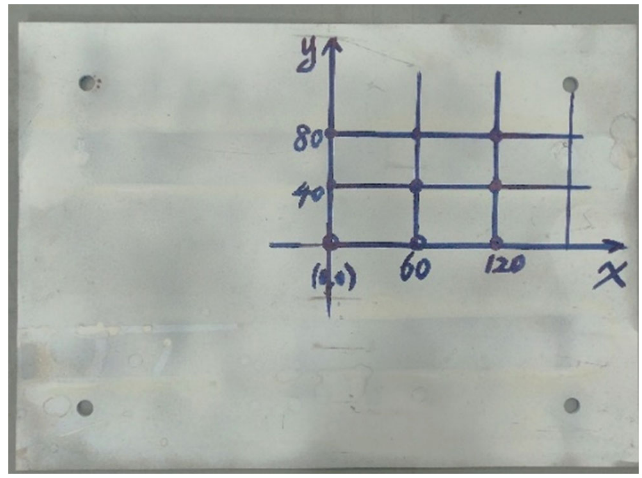

Fig. 5 Experimental punching position

2.2 Experimental procedure

For this incremental bending process, the punching force at various positions should be taken into consideration. If the required punching force is larger than the nominal force for the machine tool, the objective shape cannot be achieved. Besides, the springback law of the doubly curved bending parts should also be investigated because the springback behavior of the metal plate is huge since the boundary of the

Table 2 True stress-strain hardening data for carbon steel Q235 sheet

Plastic strain (%)	0.0	3.02	6.18	9.27	13.64	16.55	19.32	23.33	27.30
Plastic stress (MPa)	309.2	323.3	360.1	384.6	412.7	427.45	441.2	457.7	472.3

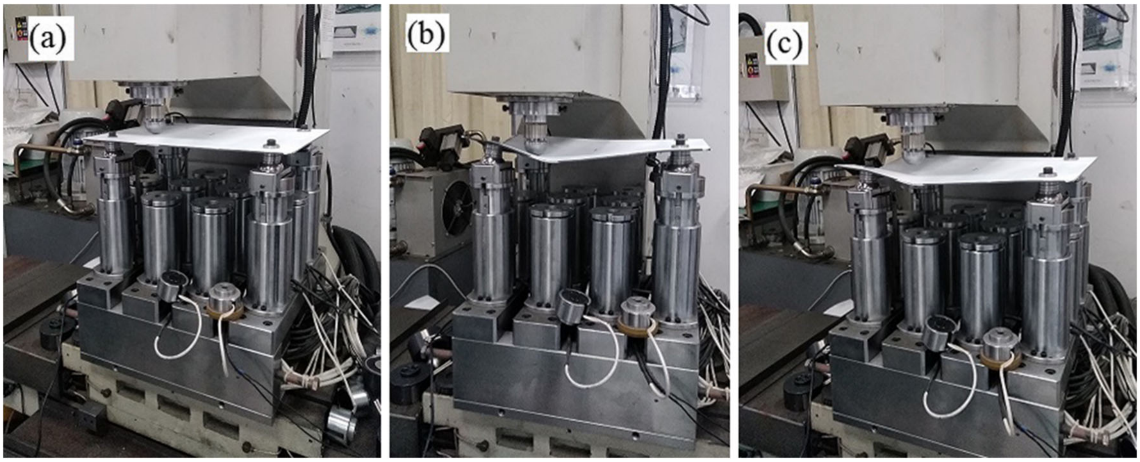

Fig. 6 Experimental plates at various states. **a** Initial state. **b** Punching state. **c** Springback state

metal plates during the incremental bending process is not constrained strictly, which can directly influence the final shape of the deformed metal plate. So the objective for this study is to find out the deformation rule (including the loading force distribution and springback amount distribution) along the metal plates' whole surface during the incremental bending process.

The material used in this experiment is carbon steel Q235 sheet. The mechanical behavior of Q235 and its corresponding true stress-true strain hardening data obtained by uniaxial tensile experiments are listed in Tables 1 and 2, respectively. The dimension of the metal plate used in this study is 460 mm × 330 mm × 3 mm as shown in Fig. 5. During the experiments, four screws were used to partially constrain the metal plate and make it rotate with the supporting cylinders. Four corresponding circular holes were also machined on the metal plate and the distance between each hole was 360 mm (along x-axis) or 240 mm (along y-axis).

Figure 5 also shows the message of the punching position on the experimental metal plate. By carrying out one-step punching experiments at different positions, the influence of punching positions on the loading force and springback behavior of the metal plates will be investigated. While by carrying out the punching experiments with the same maximum punching depth and different incremental steps at one specific position, the influence of incremental bending step on the loading force and springback behavior of the metal plates will be investigated.

Figure 6 shows the actual experimental condition. First, the metal plate was put on top of the four supporting cylinders and was partially constrained by the screws. Then, the punch moved down to press the metal plate to a certain depth at the specific position. Last, the punch moved back and springback phenomenon occurred to make the metal plate change its shape secondly. For each state, the 3D optical scanning system was adopted to obtain the metal plates' shape to analyze its springback behavior during the incremental bending process.

2.3 Numerical simulation study

At present finite element simulation is regarded to be an essential method to investigate the deformation behavior of metal plates during the sheet metal forming process in a much more efficient way. Here, in this section, the numerical simulation method based on the general finite element analysis software is used to analyze the incremental bending process for carbon steel Q235 sheet.

To obtain accurate simulation results, it is necessary to define both the mechanical properties of the metal plates and the constraint and movement of the tools precisely. For this

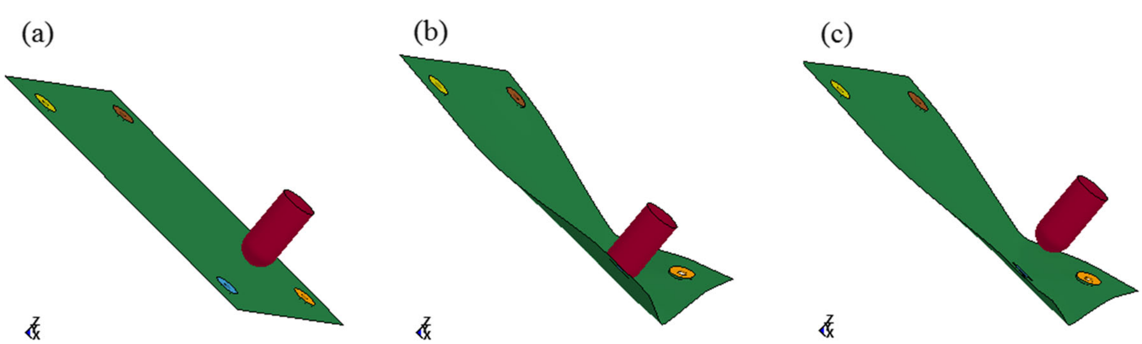

Fig. 7 Numerical simulation models at various states. **a** Initial state. **b** Punching state. **c** Springback state

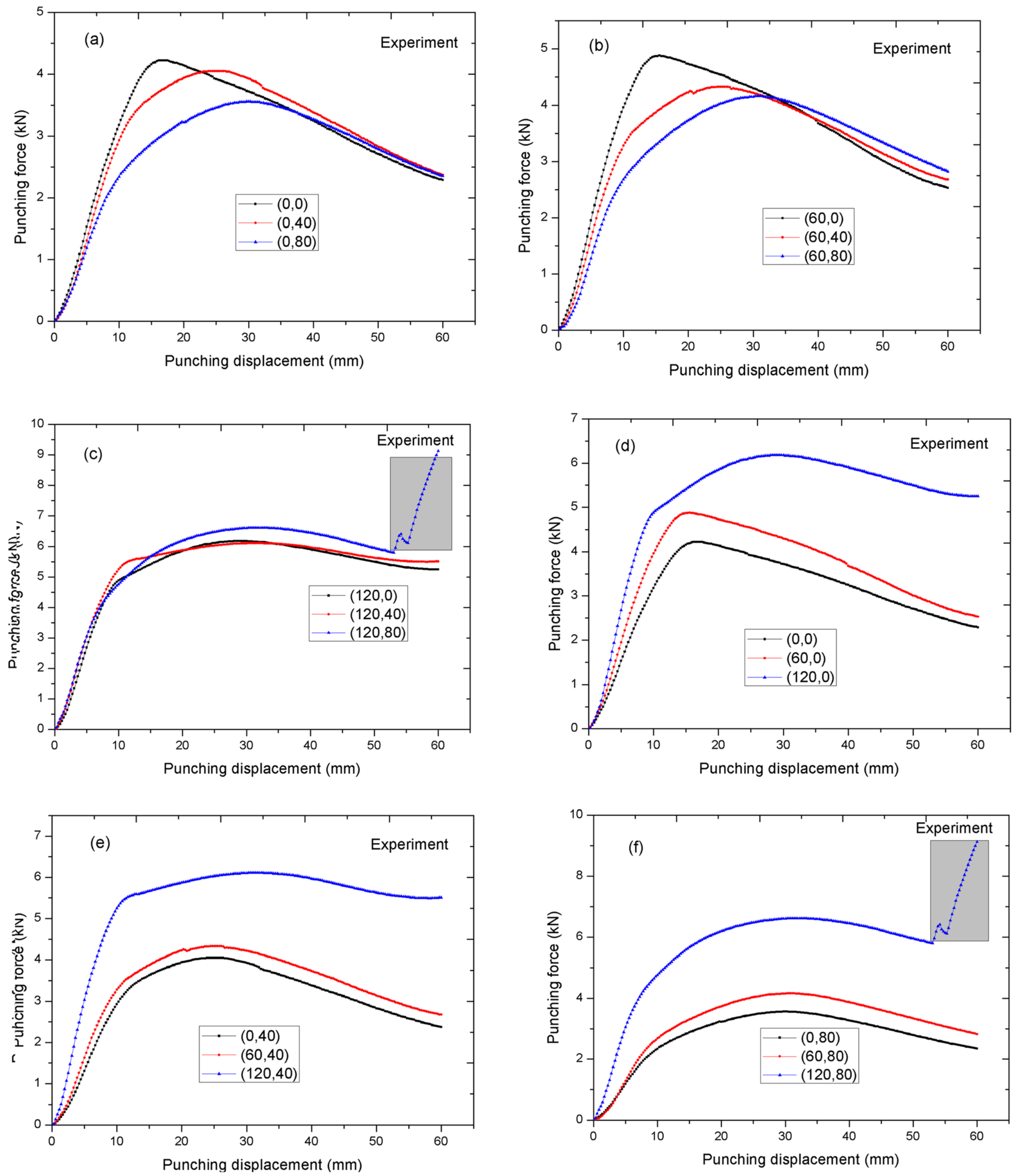

Fig. 8 Punching force distribution during one-step bending process **a** along $x = 0$ mm; **b** along $x = 60$ mm; **c** along $x = 120$ mm; **d** along $y = 0$ mm; **e** along $y = 40$ mm; and **f** along $y = 80$ mm

simulation study, first, select the proper finite element analysis method. Normally, there are two widely used methods: dynamic explicit method and static implicit method. The dynamic explicit method is usually used to analyze the punching process since it is successful in solving the complex contact or constraint problem, while the static implicit method is usually used to analyze the springback process due to its better accuracy. For the experimental cases with several incremental steps, successive punching-springback processes are conducted; thus, it is not convenient to change the finite analysis methods over and over again. Besides, there is significant dynamic effect if using the dynamic explicit method to simulate the incremental bending process since the constraint condition is quite limited. So considering the simulation precision, the static implicit method is selected for both punching process and springback process during the whole simulation.

In this study, the numerical simulation model is composed of 1 blank sheet, 1 punch, and 4 rotatable supports, and the

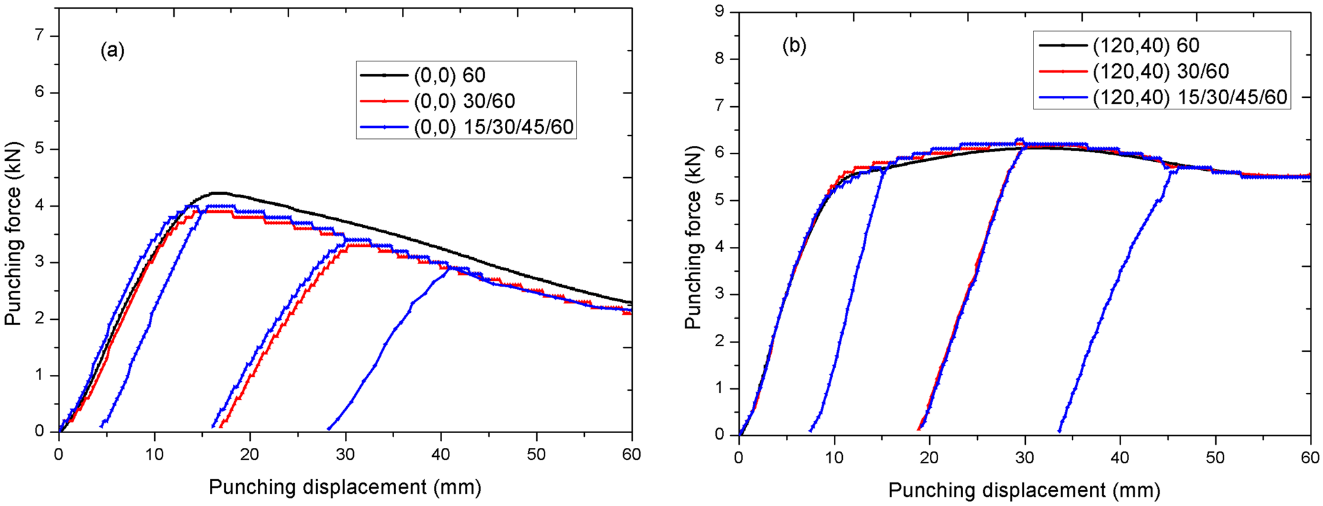

Fig. 9 Punching force distribution for three loading paths. **a**Punching position is (0, 0). **b** Punching position is (120, 40)

geometrical dimensions of all the parts are the same as that used in the experiments. In finite element simulations, the blank was meshed with 5.0 mm × 5.0 mm in the plane with 5 integrated nodes along the thickness direction. The elastic-plastic material model and the rigid model are used to describe the mechanical properties of the carbon steel Q235 plate and the tools, respectively. During the simulations, the punch moves down along *z*-axis with specific velocity and the supporting system rotates with the deformed blank. It should be noted that, since the blank is constrained by the screws connecting the rotatable supports, the screws and the rotatable supports are integrated as four rigid simulation models for simplicity. Each integrated supporting simulation model can rotate along some specific central point while the displacement of the integrated model is fully constrained along *x*-axis, *y*-axis, and *z*-axis. The initial state, punching state, and the springback state of the finite element numerical model can be seen from Fig. 7a, b, and c, respectively.

3 Results and discussion

3.1 Experimental results analysis

During the incremental bending process, one pressure sensor was mounted on the punch to record the history of the punching force as shown in Fig. 2. The experimental punching force distribution results for different punching positions are obtained and shown in Fig. 8. Results show that the punching forces at all punching positions increase first and then decrease with the punching depth. That is because at first only, the elastic deformation occurs; when the punching depth increases, the bending moment increases so the required punching force increases accordingly. However, when the punching depth is bigger enough, the plastic deformation also occurs; the bending moment does not increase much while the distance is larger, so the required punching force is reduced. For some cases (as shown in the gray marked section in Fig.

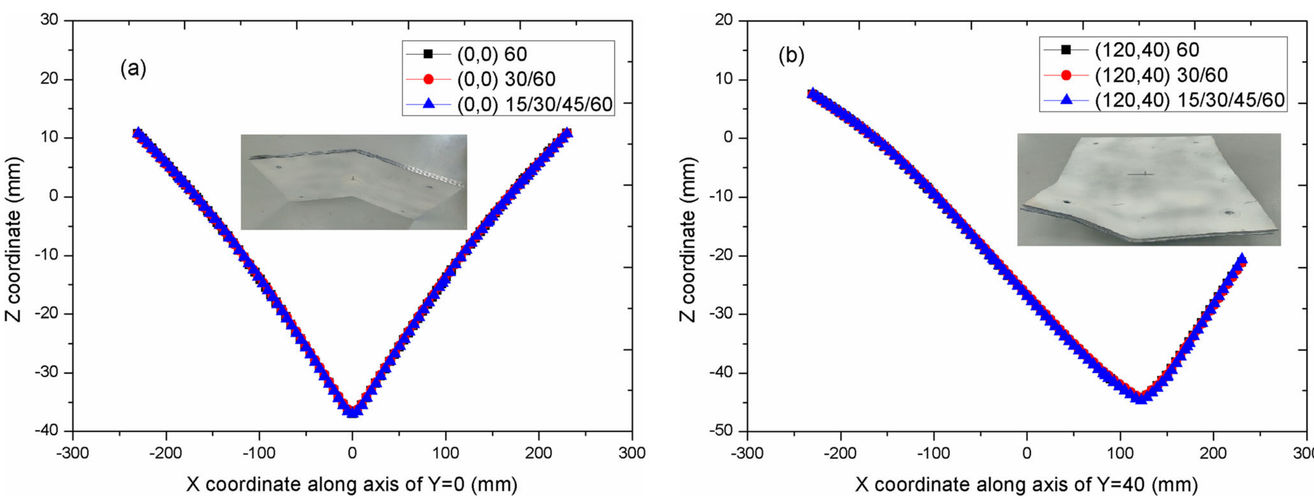

Fig. 10 Finial shape of the deformed plate for three loading paths. **a** Punching position is (0, 0). **b** Punching position is (120, 40)

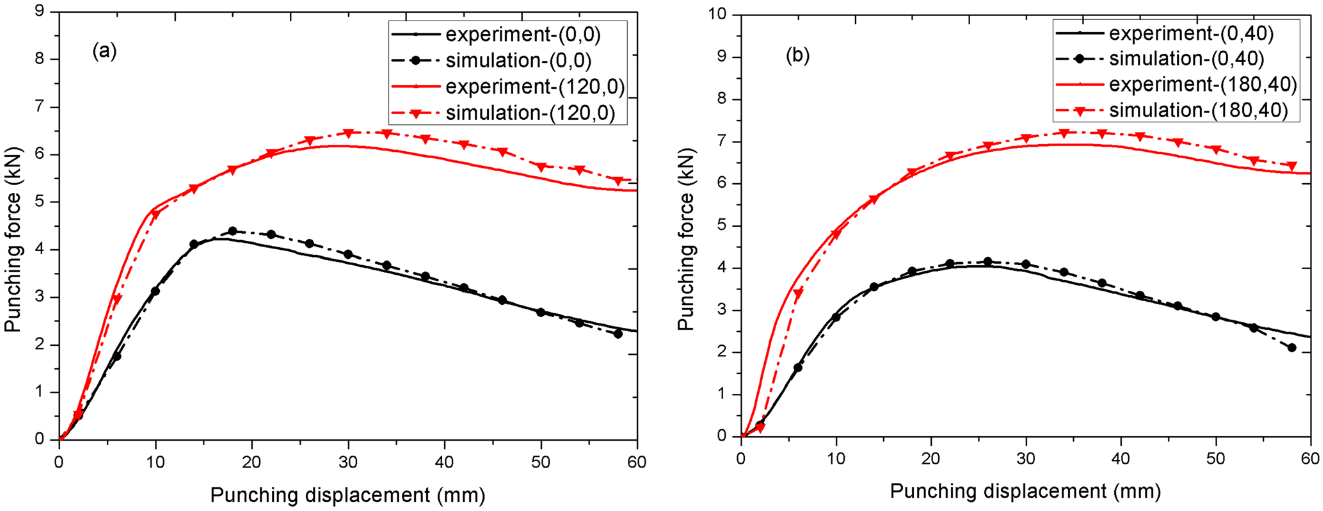

Fig. 11 Comparison of experimental and numerical punching force distribution for one-step punching process. **a** Punching position are (0,0) and (120,0). **b** Punching position are (0,40) and (180,40)

8c), the punching force increases greatly again at the end of the punching process, that is because the rotatable screw has moved to the limit position. After that, obvious stretching occurs, so the corresponding punching force increases. Actually, what we care about in this study is the bending-dominated deformation stage, so no more explanation on the stretching phenomenon is introduced in the following sections.

Even though the trends in punching force distribution for different punching positions are similar, the maximum punching force varies and follows different rules along different sections. For example, along the axis of x = 0 mm (as shown in Fig. 8a), the maximum punching force decreases with bigger y-coordinate (the punching position is closer to the longer edge of the metal plate). However, along the axis of x = 120 mm (as shown in Fig. 8c), the maximum punching forces are similar to each other wherever the punching position is. Besides, along the y-axis with various values, the maximum punching force increases with bigger x-coordinate (as shown in Fig. 8d–f).

To clearly understand the effects of the incremental step on the deformation behavior of the metal plates during the incremental bending process, the multi-step bending processes with the same maximum punching depth and different incremental steps are investigated. Figure 9 shows the loading force curves for three different cases at punching position of (0, 0) and (120, 40), respectively. It should be noted that in Fig. 9a, the label "(0, 0) 15/30/45/60" means the coordinate of the punching position is (0, 0) and the punch moves down to press the blank four times, and the punching depths are 15 mm, 30 mm, 45 mm, and 60 mm, respectively. For Fig. 9a, the maximum punching depths for these three cases are all 60 mm, and the black line, red line, and blue line represent the incremental punching depths are 60 mm, 30 mm, and 15 mm, respectively. Results show that the incremental

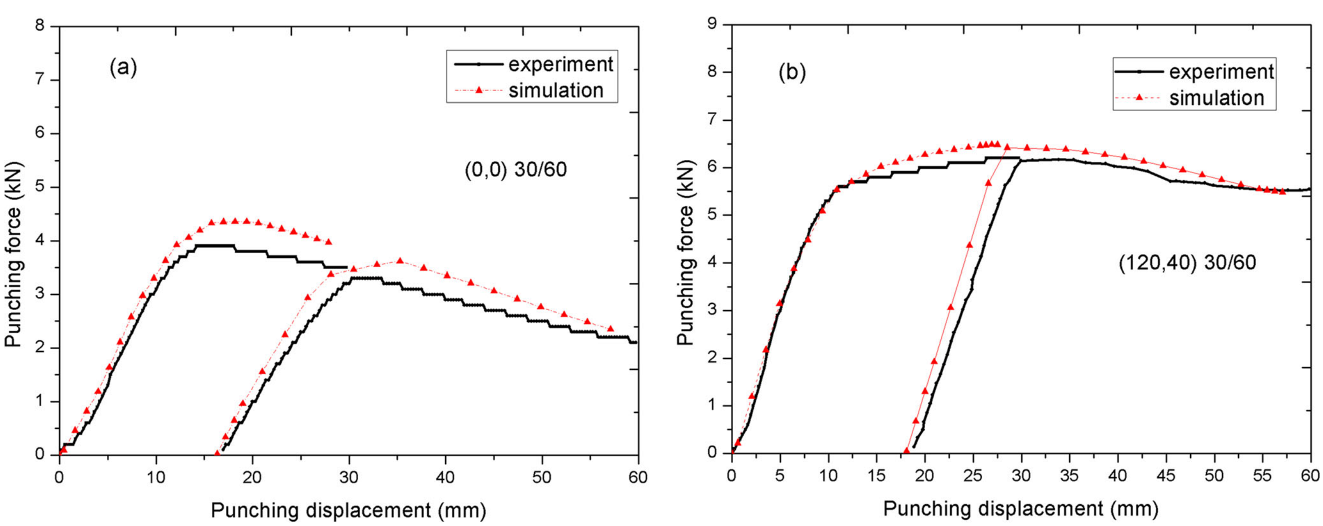

Fig. 12 Comparison of experimental and numerical punching force distributions for two-step punching process. **a** Punching position is (0, 0). **b** Punching position is (120, 40)

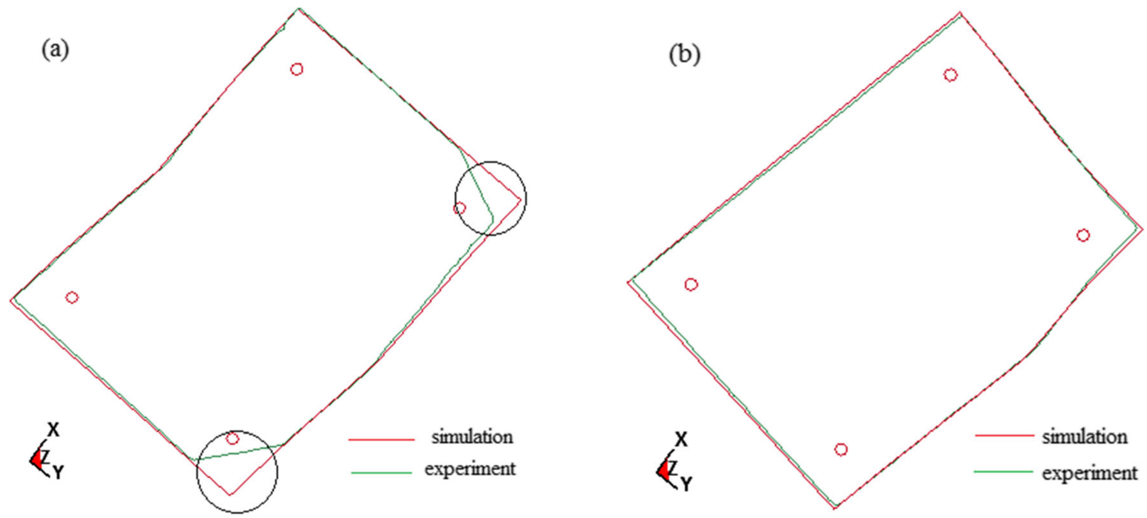

Fig. 13 Comparison of experimental and numerical contour of the deformed metal plates. **a** Punching position is (0, 80). **b** Punching position is (120, 80)

step has no significant influence on the loading force distribution if the punching position and the maximum punching depth are the same. Figure 10 also shows the final shape of the metal plates under these three loading paths for two punching positions. The incremental step does not change the final shape of the plates if the maximum punching depths are the same, so from the efficient point of view, there is no need to punch one position several times.

3.2 Validation of the numerical simulation results

After the numerical simulation, the predicted loading force curves during the incremental bending process are obtained and are used to compare with the experimental results. Figure 11 shows the numerical and experimental one-step punching force curves at four punching positions. As we can see, the numerical simulation results coincide well with the experimental data. The slight difference between the experimental data and numerical ones may be caused by the rough description of the supports' inertia during the finite element numerical simulation. In addition, Fig. 12 shows the comparison of experimental and numerical punching force distribution for two-step punching process at punching positions of (0, 0) and (120, 40). The predicted two-step punching force curves also agree well with that of the experimental ones. So the accuracy of the numerical simulation method is validated.

After each experiment, the 3D optional scanning system is used to scan the metal plate and obtain the shape of the

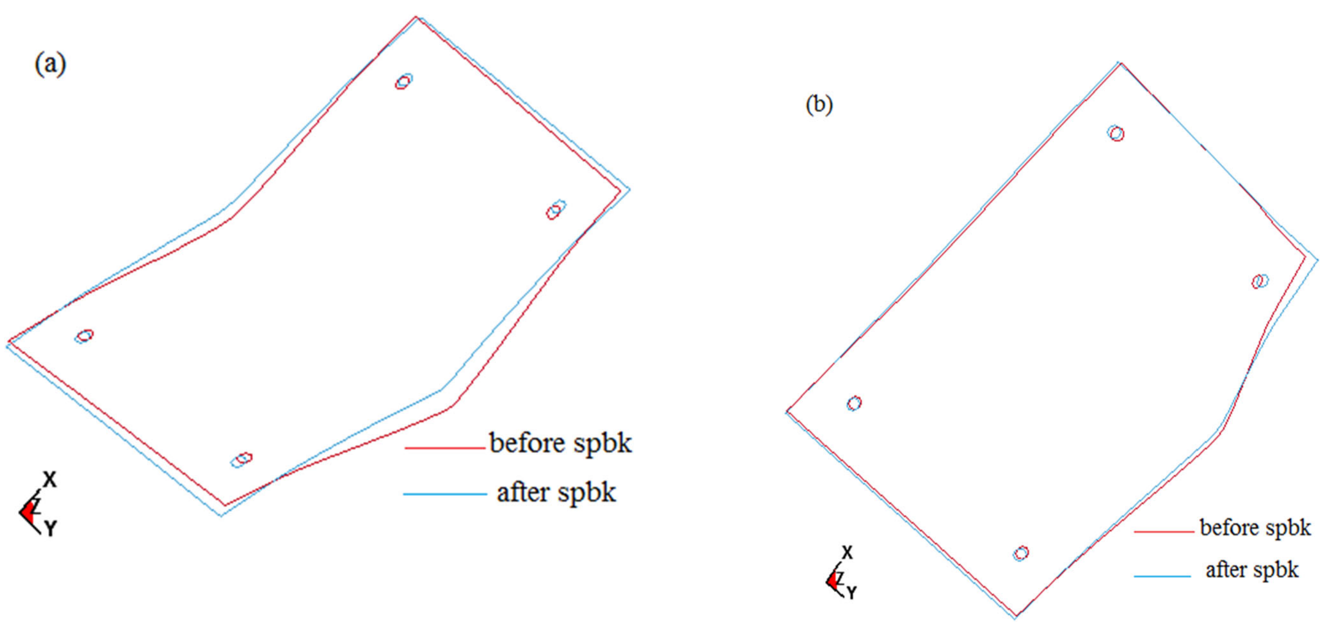

Fig. 14 Comparison of contour of the deformed metal plates before and after springback in simulation. **a** Punching position is (0, 80). **b** Punching position is (120, 80)

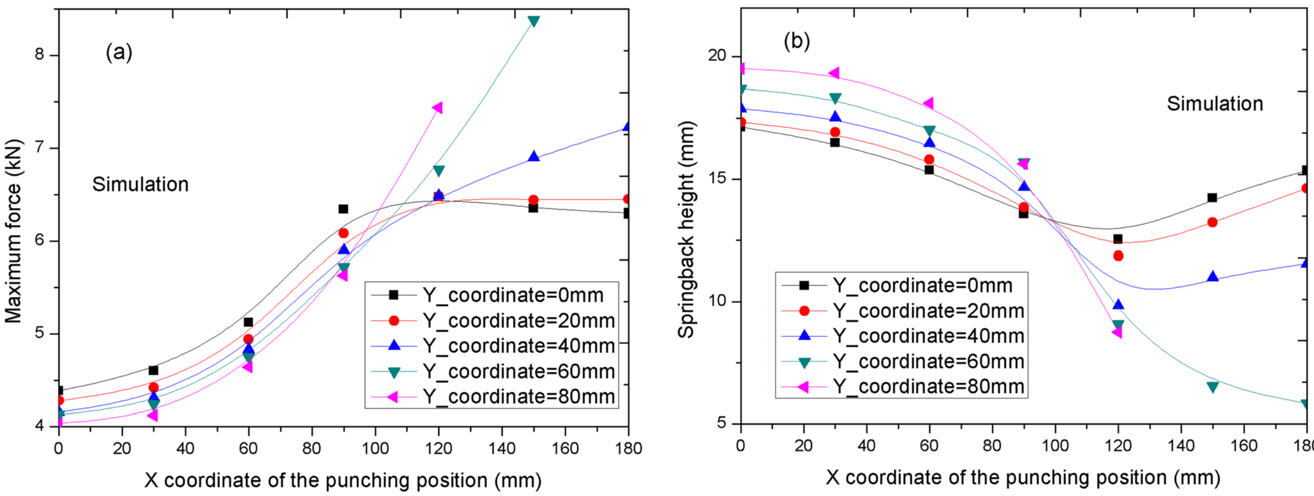

Fig. 15 Deformation behavior distribution along various sections of the doubly curved bending plate. **a** Maximum punching force. **b** Springback height

deformed plate. Figure 13 compares the contours of the deformed plates at two punching positions between experiment and simulation. The defection marked in circle for Fig. 13a is due to incomplete scanning. Except for the defective section, the maximum relative error of numerical simulation is less than 10%, so the final deformation shape of carbon steel Q235 in this simulation is also validated.

3.3 Deformation behavior of metal plates discussion

Figure 14 shows the contour of the deformed plates when the punch moves down to the depth of 60 mm and when the punch moves back for two punching positions. It is clear that there is huge springback, which could significantly influence the shape of the deformed plate. Actually, what we care most is the shape of the plate after each springback, so it is essential to investigate its springback rule during the incremental bending process. Usually, the springback amount is described by the change of bending angle; however, when using incremental bending process to deform 3D curved metal plates, the punching depth is commonly used in the loading path determination, so here in our study, the vertical displacement of the plate at the punching position before and after springback, called springback height, is used to describe the springback amount of the metal plates. The springback amount after the first punch (punching depth is 30 mm) can be found from Fig. 12. The springback height is 14 mm for the punching position of (0, 0), while the springback height is about 12 mm for the punching position of (120, 40). So the springback amount of the metal plate can also be influenced by the punching position. Here in this section, since the experiments are limited and the numerical simulation results are already validated by the corresponding experimental ones, more numerical simulations were conducted to find the deformation rule during the incremental bending process for doubly curved bending plates.

Figure 15 shows the maximum punching force and springback height distribution along various sections of the doubly curved bending plate. We can find some interesting phenomenon. First, let us focus on the deformation behavior of the metal plates along the y-axis. When the x-coordinate is smaller than 100 mm, the maximum punching force decreases while the springback height increases with bigger $|y$-coordinate$|$. However, when the x-coordinate is larger than 100 mm,

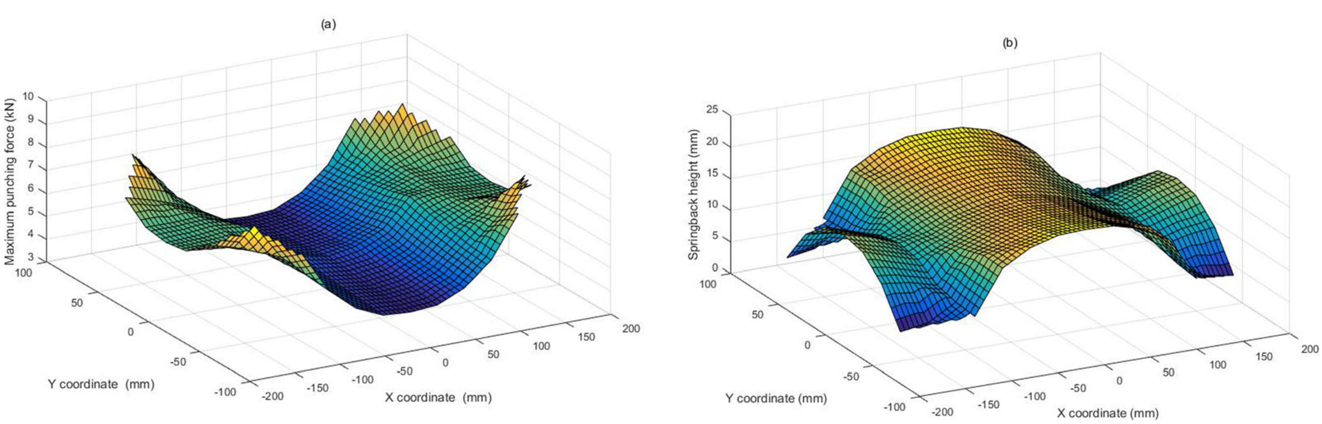

Fig. 16 Deformation behavior distribution along the whole surface of the doubly curved bending plate. **a** Maximum punching force. **b** Springback height

it comes to the opposite conclusion. Second, let us focus on the deformation behavior of the metal plate along the *x*-axis. The maximum punching force increases while the springback height decreases with bigger |*x*-coordinate|. In order to exhibit the deformation behavior of the metal plates more clearly, the maximum loading force and springback height along the whole surface of the metal plate are obtained as shown in Fig. 16. We can see that the maximum punching force and the minimum springhack height occurs at the position near the circle hole, which contacts with the rotatable supports. The minimum punching force and maximum springback height occurs at the position that is the center of the long side of the metal plate. So when using incremental bending process to deform one part with specific shape, the maximum punching force should be estimated first to make sure it can be achieved under the existing experimental conditions. Besides, the springback behavior should also be considered to define the proper loading path for the objective plate with specific shape.

4 Conclusions

Incremental bending process is one novel flexible forming process for objective parts with various 3D curved shapes. Here in this paper, the deformation behavior of the doubly curved bending plates under incremental bending process is investigated through experiments. In addition, the finite element simulation is performed to reproduce these tests and to analyze the deformation regular of the doubly curved bending plates more intuitively. The key conclusions are summarized as follows:

1. The incremental bending step has no significant influence on the maximum punching force and the springback behavior of the doubly curved bending plates. However, the punching position can greatly influence the punching force and springback behavior of the doubly curved bending plates.
2. The maximum punching force and minimum springhack height occur at the position that contacts with the rotatable supports, while the minimum punching force and maximum springback height occur at the center of the long side of the metal plate.

This study provides a fundamental understanding about the deformation properties of the doubly curved metal plate during the incremental bending process. Based on the study in this paper, the holistic deformation geometric shape of the doubly curved metal plates and its loading path optimization can be further investigated in the future. The results in this paper lay important foundation for the practical application of the incremental bending process for achieving various doubly curved metal plates in various industrial fields.

Funding information The authors received financial assistance from GRF/RGC with project No. 14204417 and Chinese Postdoctoral Science Foundation with project No. 2017M612779.

References

1. Alaswad A, Benyounis KY, Olabi AG (2012) Tube hydroforming process: a reference guide. Mater Des 33:328–339
2. Jenab A, Green DE, Alpas AT, Golovashchenko SF (2018) Experimental and numerical analyses of formability improvement of AA5182-O sheet during electro-hydraulic forming. J Mater Process Technol 255:914–926
3. Xu JR, Xie XY, Wen ZS, Cui JJ, Zhang X, Zhu DB, Liu Y (2019) Deformation behavior of AZ31 magnesium alloy sheet hybrid actuating with Al driver sheet and temperature in magnetic pulse forming. J Manuf Process 37:402–412
4. Jiang YF, Huang Y, Jin H, Gu YY, Ren AG, Huang LW, Qian XM (2013) Research on precision control of sheet metal forming by laser shock waves with semi-die. Opt Laser Technol 45:598–604
5. Iseki H, Kato K, Sakamoto S (1989) Flexible and incremental sheet metal forming using a spherical roller. Proceedings of 40th JJCTP, 41-44 (in Japanese)
6. Iseki H, Kato K, Sakamoto S (1992) Flexible and incremental sheet metal bulging using a path-controlled spherical roller. JSME Int J Ser C Mech Syst Mach Elem Manuf 5:3147–3155
7. Meier H, Smukala V, Dewald O, Zhang J (2007) Two point incremental forming with two moving forming tools. Key Eng Mater 344:599–605
8. Li MZ, Cai ZY, Sui Z, Yan QG (2002) Multi-point forming technology for sheet metal. J Mater Process Technol 129(1-3):333–338
9. Lee G, Kim S (2012) Case study of mass customization of double-curved metal façade panels using a new hybrid sheet metal processing technique. J Constr Eng Manag 138:1322–1330
10. Luo YX, Yang WM, Liu ZF, Wang YQ, Du RX (2016) Numerical simulation and experimental study on cyclic multi-point incremental forming process. Int J Adv Manuf Technol 85(5-8):1249–1259
11. Yoon SJ, Yang DY (2003) Development of a highly flexible incremental roll forming process for the manufacture of a doubly curved sheet metal. CIRP Ann Manuf Technol 52(1):201–204
12. Yoon SJ, Kim J, Kang BS (2016) Deformation analysis and shape prediction for sheet forming using flexibly reconfigurable roll forming. J Mater Process Technol 233:192–205
13. Cai ZY, Sui Z, Cai FX, Liu L (2013) Continuous flexible roll forming for three-dimensional surface part and the forming process control. Int J Mach Tools Manuf 66(1-4):393–400
14. Hu ZQ, Li MZ, Cai ZY, Gong XP (2009) Continuous flexible forming of three-dimensional surface parts using bendable rollers. Mater Sci Eng A 499(1-2):234–237
15. Shim DS, Yang DY, Kim KH, Chung SW, Han MS (2010) Investigation into forming sequences for the incremental forming of doubly curved plates using the line array roll set (LARS) process. Int J Mach Tool Manu 50(2):214–218
16. Dang XB, He K, Li W, Zuo QY, Du RX (2017) Incremental bending of three-dimensional free form metal plates using minimum energy principle and model-less control. J Manuf Sci E T ASME 51(5):493–506
17. Zhang FF, He K, Dang XB, Du RX (2018) Experimental and numerical study on flexible incremental bending process. Int J Adv Manuf Technol 96(5-8):2643–2655

18. Qiu JB, Sun KK, Wang T, Gao HJ (2019) Observer-based fuzzy adaptive event-triggered control for pure-feedback nonlinear systems with prescribed performance. IEEE Trans Fuzzy Syst:1. https://doi.org/10.1109/TFUZZ.2019.2895560
19. Sun KK, Mou SS, Qiu JB, Wang T, Gao HJ (2018) Adaptive fuzzy control for non-triangular structural stochastic switched nonlinear systems with full state constraints. IEEE Trans Fuzzy Syst:1. https://doi.org/10.1109/TFUZZ2018.2883374
20. Zhang FF, Ruan JB, Zhang J, He K, Du RX (2018) Experimental study of springback behavior in incremental bending process. Metal forming 2018, 16-19 September 2018, Toyohashi, Japan