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ORIGINAL ARTICLE

# Experimental and numerical study on one flexible incremental bending process

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**Abstract**
In the shipbuilding industry, the traditional manufacturing method for the complicated ship hull metal plates is line heating method, which is not only labor intensive but also inefficient. Considerable efforts have been taken to develop the new automated manufacturing processes at a reasonable quality, efficiency and price during the last few decades. This paper presents a novel flexible forming process called incremental bending to achieve complicated plates. In this method, the initial metal plate is supported by some rotatable hydraulic cylinders and the punches move according to the given path, which is decided by minimum energy method and springback compensation method, to achieve the final plate. Taking one variable curved metal plate as one example, this paper investigates the formability of this novel process based on experiment and numerical simulation. During the numerical simulation, the implicit method is used and the gravity of the plate is considered mainly for the automatic positioning of the plate during each springback process. Results show that the incremental bending process can achieve variable curved metal plates with good accuracy, high efficiency, and relatively small punch load. In comparison with the existing methods, the new process has greater potentiality in the ship hull manufacturing industry.

**Keywords** Incremental bending · Numerical simulation · Minimum energy method · Static implicit method

## 1 Introduction

Shipbuilding industry is an important part of advance equipped manufacturing industry for one contrary. The machining of the ship plate is one of the key links and its production with high efficiency and high precision would vastly improve the shipbuilding industry. However, the ship plates are usually manufactured in small batches and thus it is unrealistic to produce such components based on the traditional stamping process. Until now, it has always been a great challenge to manufacture such complex ship plate at reasonable quality and price.

The line heating process is one widely used forming method to manufacture ship-hull metal plates [1]. However, the working environment is really unpleasant and the product quality mainly depends upon the skilled worker's experience. Even though the line heating process has been automated in some countries, the accuracy of the deformed plate is limited. Therefore, other flexible forming techniques have been investigated to fabricate complex curved metal plates in the last few decades.

One of the widely used methods is incremental sheet forming process (ISF), which includes single point incremental forming process (SPIF) [2, 3] and double-sided incremental forming process (DSIF) [4]. ISF is generally proved to have low tooling cost and enhanced formability while the surface quality of the part deformed by ISF is poor due to the friction between the tool and the plate. So far, ISF is mainly used for forming the thin metal plates. In addition, Li et al. [5] proposed multi-point forming process (MPF), which employed two reconfigurable flexible forming tool groups to replace the traditional stamping dies. The huge expenses of fabricating specific dies are avoided, but on the surfaces of the pressed plates leaves obvious dents. Further, Wang et al. [6] adjusted the stable globular tool pins into rotatable square ones based

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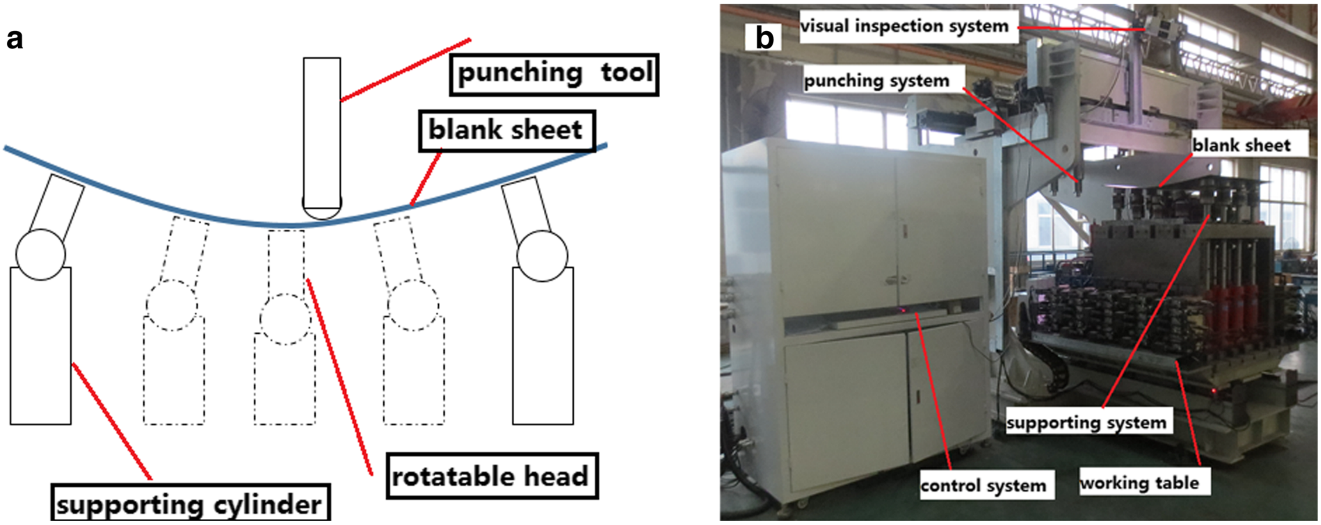


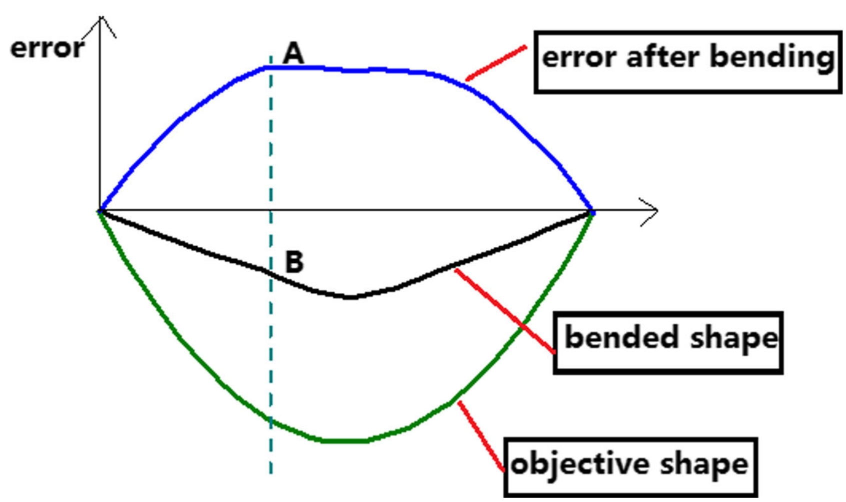

**Fig. 1** A schematic diagram of the incremental bending process. **a** Schematic diagram. **b** Experimental setup

on MPF. With the increase of the contact area between tools and the plate, the deformed surface of the objective part is much smoother. Besides, Lee and Kim [7] developed the multi-point stretch forming technique, which combined multi-point forming and stretch bending together. They succeeded in fabricating 45,133 unique varying curved metal panels for the Dongdaemun Park building in Seoul, South Korea. Compared to traditional stamping process, the work of Li, Wang, and Lee realized die less production, but the expense of fabricating the whole reconfigurable tool groups is very high and the forming force is quite big since the whole tool group contacts with the metal plates during the forming process.

In order to decrease the forming force, Luo et al. [8] proposed the cyclic multi-point incremental forming process (CMPIF). Similar to MPF, CMPIF also employed two reconfigurable tool groups while only one tool pin moves a small step at each time until all tool pins gradually moves to achieve the objective part, so the forming force during the forming process is decreased significantly.

Besides stamping, rolling is another effective method to bend and achieve curved metal plates. Some scholars also conducted researches based on rolling to form complex curved metal plates. For example, Yoon and Yang [9, 10] developed two kinds of flexible rolling technologies. The double curved plates and the saddle curved plates can be achieved. In addition, Shim et al. [11, 12] proposed the line array roll set (LARS) process for fabrication of doubly curved plates. Similarly, Hu et al. [13] also presented a continuous flexible forming process (CFF) to form complex metal plates using three bendable rollers. More recently, Cai et al. [14] proposed a new continuous roll forming process (CRF) based on a pair of bendable rolls for swept surface components

**Fig. 2** Graphic illustration of the punching position according to the minimum energy method



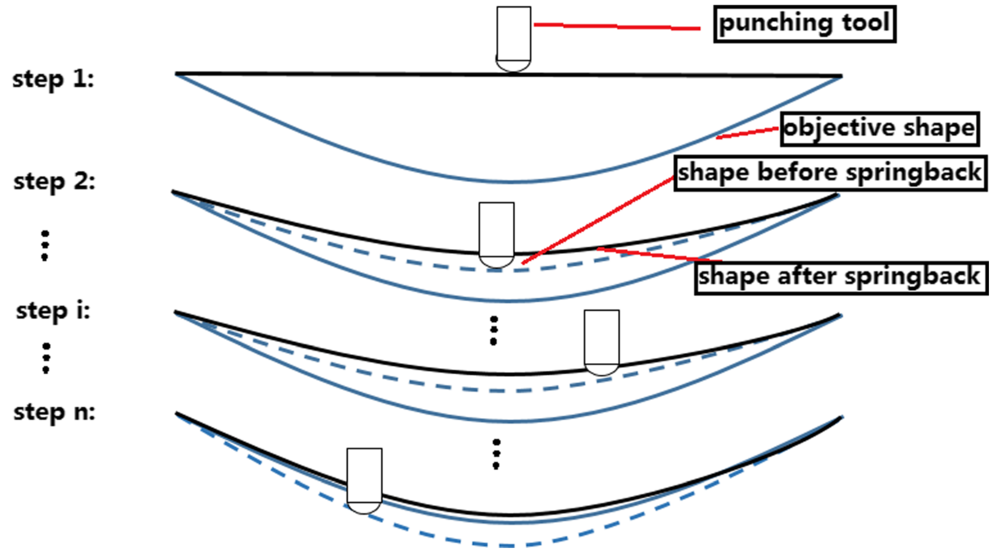



**Fig. 3** Schematic illustration of the incremental bending process

based on CFF. However, all the schemes mentioned above can only be used to form thin plates.

For the fabrication of the thick curved metal plates, Hwang et al. [15] designed a multi-point press forming (MPPF) device that only use a reconfigurable discrete die to form plates with large dimensions. The disadvantage of MPPF is that the forming force is relatively large since the edges of the plate are restricted by the rods.

Besides the flexible technologies mentioned previously, the laser shock forming (LSF) [16], which uses shock waves induced by high energy pulsed laser to produce plastic deformation, is another one effective method to achieve complicated metal plates. The disadvantage of LSF is that it is difficult to control its forming precision.

Review of the previous researches reflected that many new flexible forming processes have been proposed to save cost and improve forming accuracy or efficiency. However, most of them are still at the experimental research stage and they all have avoidable disadvantages. Recently, in order to reduce the forming force and energy consumption, a new technique called incremental bending process (as illustrated in Fig. 1a is proposed. During the incremental bending process, the punch tool moves down and presses the metal plate, which is supported by some hydraulic cylinders with rotatable heads, into some shape. The process may take several steps, and during each step, the punch's stamping positions and stamping depths are different according to the geometry of the objective part, and the process continues until the final shape is

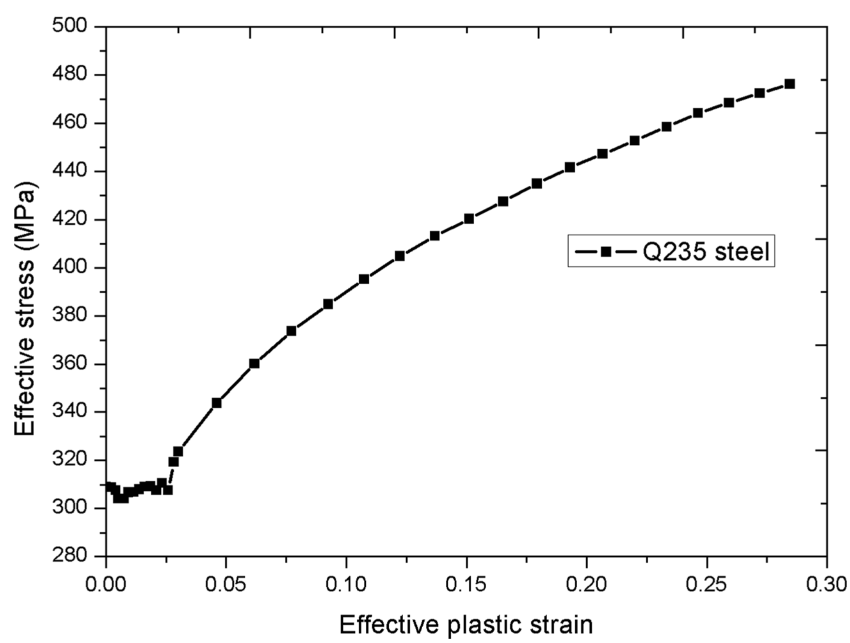



**Fig. 4** Stress-strain curve of the Q235 sheet

**Table 1** Mechanical properties of the Q235 sheet

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

achieved. Since the boundary of the metal plate is not restrained, the forming force is theoretically reduced.

In our previous study, some experiments were conducted to investigate the feasibility of incremental bending process. However, the information captured from the experiments is quite limited. So here, in this study, the numerical simulation method is also used to simulate the whole process and help us have a better understanding of this novel process. In order to give an overall understanding of the incremental bending process, the basic theory of the incremental bending process is introduced first and then one incremental bending experiment of a variable curved metal plate is carried out to verify the formability of this novel process. In addition, the corresponding numerical simulation is conducted to analyze the stress, strain, thickness, springback behavior, especially the stamping force distribution, during the incremental bending process.

## 2 Incremental bending theory

### 2.1 Incremental bending system-working principle

The deformation of the plate is usually not even during the bending process from a flat plate to a complicated plate, so it is not necessary to stamp the whole surface of the plate during the forming process. If some specific points of the plate get enough deformation, the whole objective shape can be obtained. From the previous idea, the incremental bending process is proposed. During the flexible forming process, the punch (or punches) gradually stamps some positions of the plate to specific depths until the objective shape is achieved. In this way, the energy loss is reduced significantly.

So far, an incremental bending machine has been designed as shown in Fig. 1b. The machine includes a punching system, a supporting system, a working table, a control system, and a visual inspection system. The dimension of the machine is 3352 mm × 2461 mm × 3023 mm. At the beginning of the incremental bending process, the flat plate is supported by an array of flexible hydraulic cylinders, each of which has one rotatable flat head to enlarge the contact area between the metal plate and the hydraulic cylinder and then guarantee a smooth forming surface. With the help of the control system, the working table can move along the *X* direction with the moving stroke of 2000 mm and the three punches can move along the *Z* direction with the moving stroke of 600 mm. Besides, the three punches can also rotate along the *Z* direction. As a result, the punches can move along *X*, *Y*, and *Z*

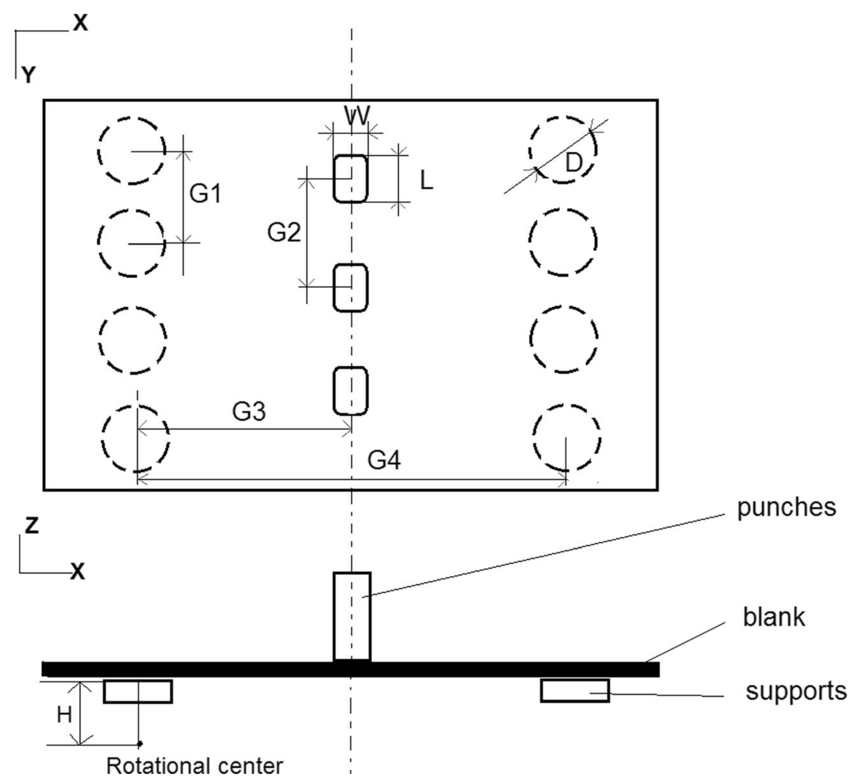



**Fig. 5** Schematic diagram of the experimental setup

**Table 2** Geometrical parameters of the experimental tools

| G1 (mm) | G2 (mm) | G3 (mm) | G4 (mm) | *L* (mm) | *W* (mm) | *D* (mm) | *H* (mm) |
|---|---|---|---|---|---|---|---|
| 200 | 300 | 400 | 800 | 50 | 35 | 100 | 70 |

directions to achieve the specific shape after several bending steps. Finally, the visual inspection system is used to get the geometric data of the deformed part. If there is some difference between the measured shape and the objective one, the incremental bending experiments can be conducted again to compensate and correct the forming shape.

## 2.2 Loading path generation

As mentioned in the literature [17], the punch path has a direct effect on the dimensional accuracy, surface finish, formability, thickness variation, and processing time. In the previous study, the punch position and bending depth are defined artificially by our intuition and the forming shape can be obtained by bending incrementally in several layers [18]. However, the accuracy of the deformed metal plate is still limited. Now, to get a better metal plate with high efficiency, the minimum energy method is used to generate the punch path. The detailed calculation process of the minimum energy method can be found in our previous paper [19]. According to the minimum energy method, the metal plate always deforms to the shape that drives the plate to the minimum energy, so the punch position should be at where the error between the current shape and objective shape is maximum. In our study, the metal plate is assumed to be series of discrete strips connected by virtual spring. When the strips deform to the specific shapes, the objective plate is regarded to be achieved.

During the incremental bending process, the shape errors of the strips are regarded as the error of plates. Taking one strip as an example (as displayed in Fig. 2), assuming the green line is the objective shape and the black line is the deformed shape after several incremental bending steps, which can be calculated based on Ruler-Bernoulli beam theory. The error between the objective shape and the deformed shape is calculated as follows,

$$E(x) = w_o(x) - w_b(x) \tag{1}$$

Where $x$ is the position of the point on the strip, $E(x)$ is the shape error, $w_o$ is the objective shape, and $w_b$ is the current bended shape.

The curve of $E(x)$ is marked in blue, where the maximum value is shown as point A. According to the minimum energy method, the corresponding point B in the deformed shape should be the next punch-pressuring position.

## 2.3 Springback consideration

Springback, which is caused by the release of residual stress when the applied forming force is unloaded, is an inevitable phenomenon in bending process. For this incremental bending process, it usually takes several steps to form a specific part. Springback phenomenon occurs after each bending step, so there would be a big error if neglecting the entire springback phenomenon. Thus, in order to achieve components with good dimensional accuracy, the deformed shape in Fig. 2 should be the shape after each springback. Figure 3 shows the punch path based on minimum energy method with consideration of springback phenomenon. We can see that the curvature radius changes greatly after springback, so the key point here is to correct the loading path to consider the

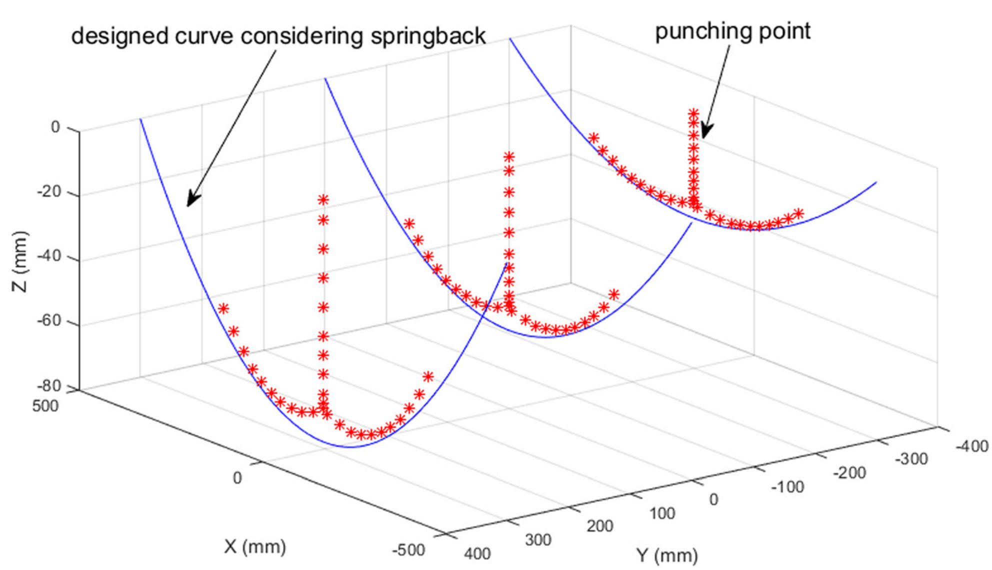



**Fig. 6** Loading path for variable curvature plate

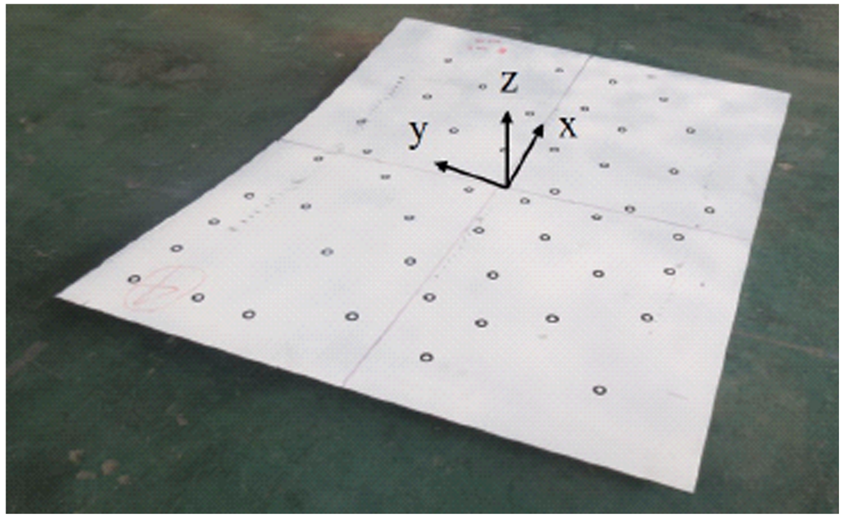



**Fig. 7** The experimental result of the variable curvature plate

springback compensation during the incremental bending process.

In this study, the punches make concentrated load on the plate during the incremental bending process, so the plate is actually under three-dimensional deformation state. It is really hard to obtain an intuitive theoretical model to describe the springback behavior after this bending process. By far, many scholars have been working on the springback study [20, 21], still these researches cannot be used directly here to guide us to accurately obtain the shape of the plate after each springback process.

The incremental bending process can be affected by many factors, including springback, friction, and material properties. The vision-based model-less control method is used here to ensure the bending accuracy. The model-less control is a computational method that only needs input and output data. For our incremental bending process, the input data is the objective shape of the beam that can be described by $W_{\text{objective}}(x,z)$, while the output data is the measured shape of the beam which can be defined by $W_{\text{measured}}(x,z)$. The control objective is to find the bending $W(x,z)$ to minimize the error between $W_{\text{measured}}(x,z)$ and $W_{\text{objective}}(x,z)$. According to the abovementioned vision-based model-less method, the shape change of the beam caused by springback can be compensated. Combining the minimum energy method and the springback compensation method, the punch-pressing loading path for one specific objective plate shape can be obtained and thus be used to guide the incremental bending process.

## 3 Experimental procedure

### 3.1 Working material

The material used in this study is carbon steel Q235. The mechanical behavior of Q235 is assumed elasto-

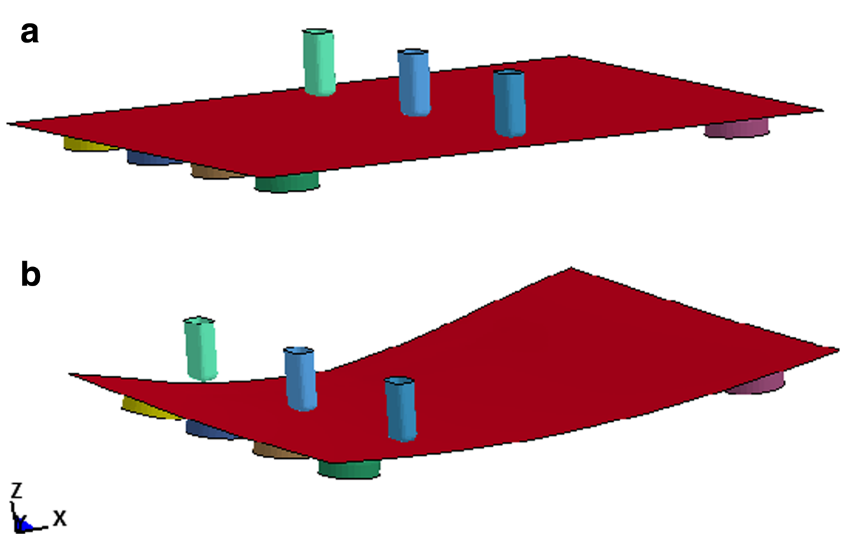



**Fig. 8** FEM model. **a** Initial state. **b** Final state

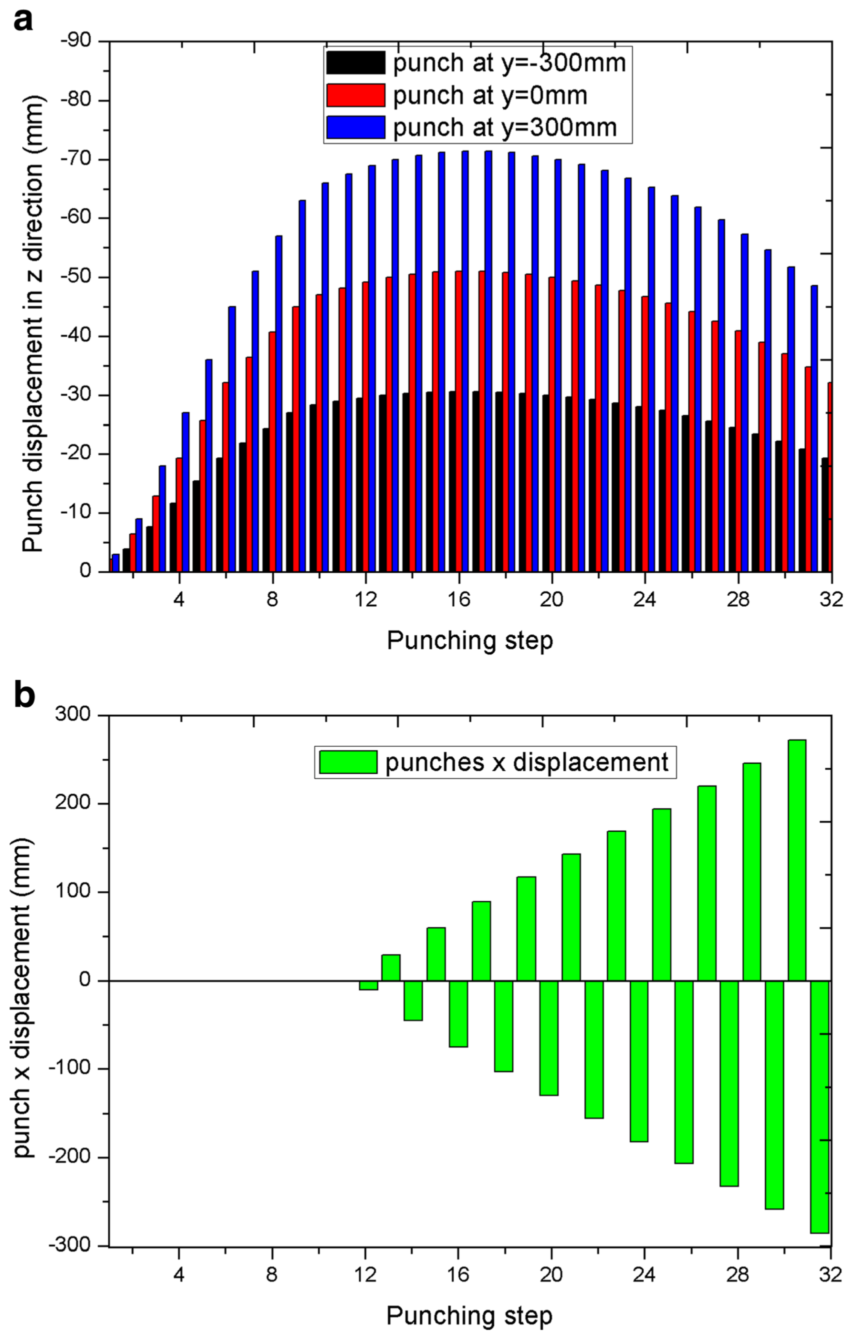



**Fig. 9** Loading paths of three punches **a** along *z*-axis and **b** along *x*-axis

plastic and its stress-strain curve obtained by uniaxial tensile experiment is presented in Fig. 4. Other mechanical properties of this material is listed in Table 1. The dimension of the metal plate used in this study is 1000 mm × 800 mm × 5 mm.

### 3.2 Test procedure

The objective of the experiment is to achieve a metal plate with variable curvature. During the incremental bending experiment, only eight rotatable cylinders and three punches are

**Table 3** Simulation parameters of FEM

| Mesh size of the plate/ (mm × mm) | Integration points | Terminal time/(s) | Friction coefficient | Computational time with eight CPU |
|---|---|---|---|---|
| 5 × 5 | 5 | 0.85 | 0.2 | 5 h 51 min |

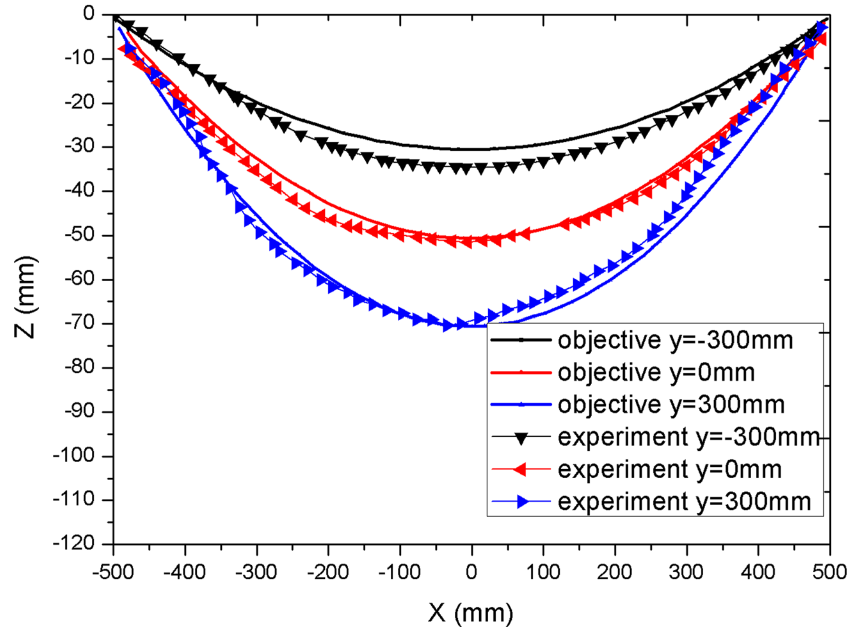



**Fig. 10** Comparison of experimental and objective shape at different positions

used to deform the metal plate. The schematic diagram for this experiment is presented in Fig. 5, and the corresponding geometrical information of the tools is given in Table 2. During the incremental bending process, the punches move relatively slowly (about 200 mm/min while the stamping speeds are a bit different for the three punches), so the bending operation can be regarded as a quasi-static deformation. The loading paths of the three punches generated by minimum energy method and springback compensation method are displayed in Fig. 6. It takes about 22 min to achieve the variable curvature plate based on 32 incremental bending steps, so the forming efficiency is significantly improved compared with that of the traditional line heating process. The final bended part is shown in Fig. 7. It is clear that the change of curvature of the metal plate is apparent and its surface is smooth without obvious dimples or indentations.

## 4 Finite element simulation

### 4.1 Determination of the algorithm in the simulation

Since we can only obtain limited information about the incremental bending process from the experiment, it is essential to

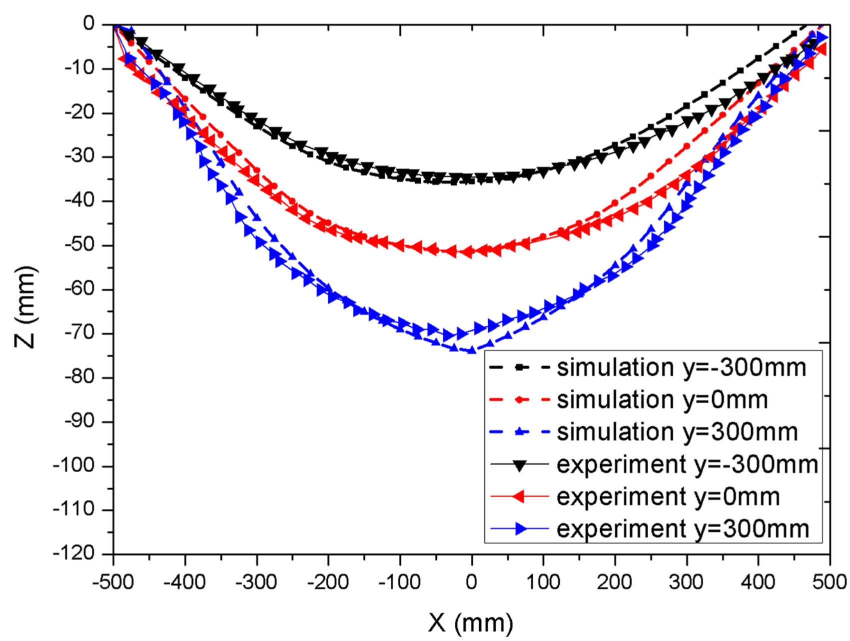



**Fig. 11** Comparison of experimental and simulation shape at different positions

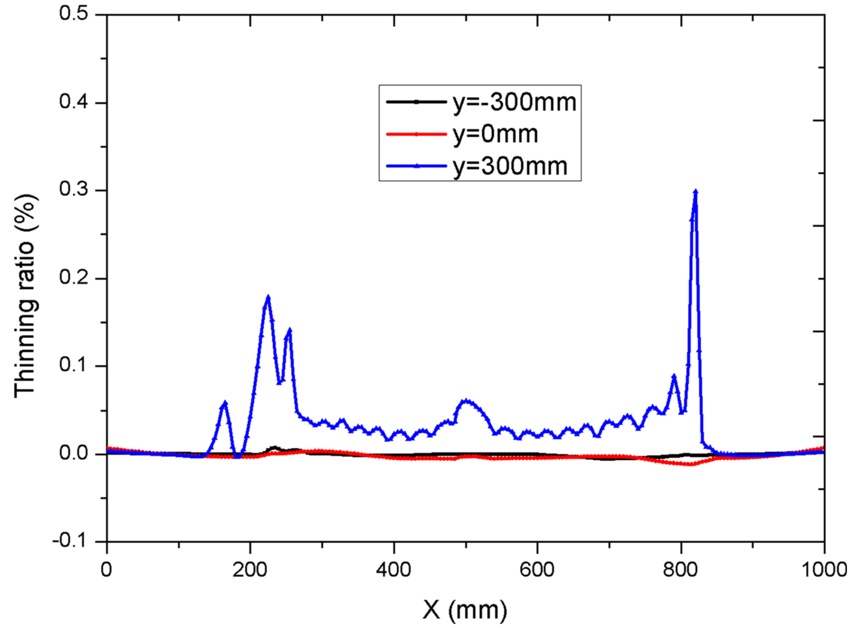



**Fig. 12** Thickness distribution of the bended plate

use numerical simulation method to get the stress, strain, and thickness trend, etc., especially the information of the stamping force during the whole process. Here in this section, the numerical method is introduced to simulate this flexible forming process.

Normally, there are two widely used finite element methods to analyze the elastic-plastic forming or bending process of sheet metals, namely, the dynamic explicit method and the static implicit method. The dynamic explicit method has been successful in solving the complex contact or constraint problems in sheet metal forming process with high efficiency. However, the prediction accuracy of dynamic explicit method is limited [22]. On the contrary, the static implicit method is more accurate than the dynamic explicit method but it may be difficult in handling the complicated contact problem. Usually, for the multi-operation numerical simulation, dynamic explicit method is used to analyze the forming or bending process while the static implicit method is used to analyze the springback process. During the incremental bending process, the plate is supported by some hydraulic cylinders and pressed by one or three punches. Beyond that, there is no more constraint conditions. Regarding this case, obvious dynamic effect occurs in the simulation if using the dynamic explicit method, which results in unbelievable tool force prediction. Meanwhile, there is no complex contact problem during the incremental bending process. So for the whole incremental bending (bending-springback-…-bending –springback) process, the static implicit method is selected for this simulation study.

## 4.2 Finite element procedure

In this study, the numerical model is composed of three punches, eight rotatable supports, and one plate. The initial state and the final state of the finite element model are shown in Fig. 8a, b, respectively. The geometrical dimensions of all the tools and the

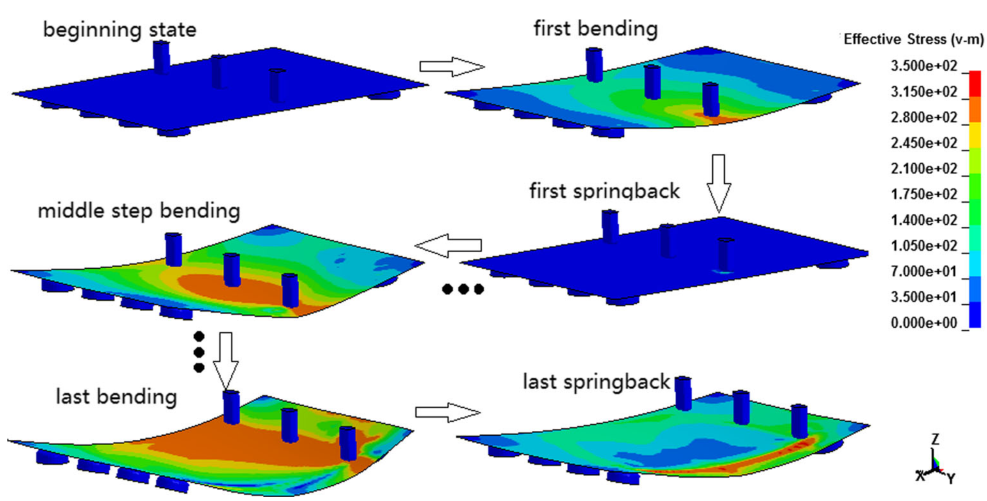



**Fig. 13** Effective stress distribution during the whole incremental bending process

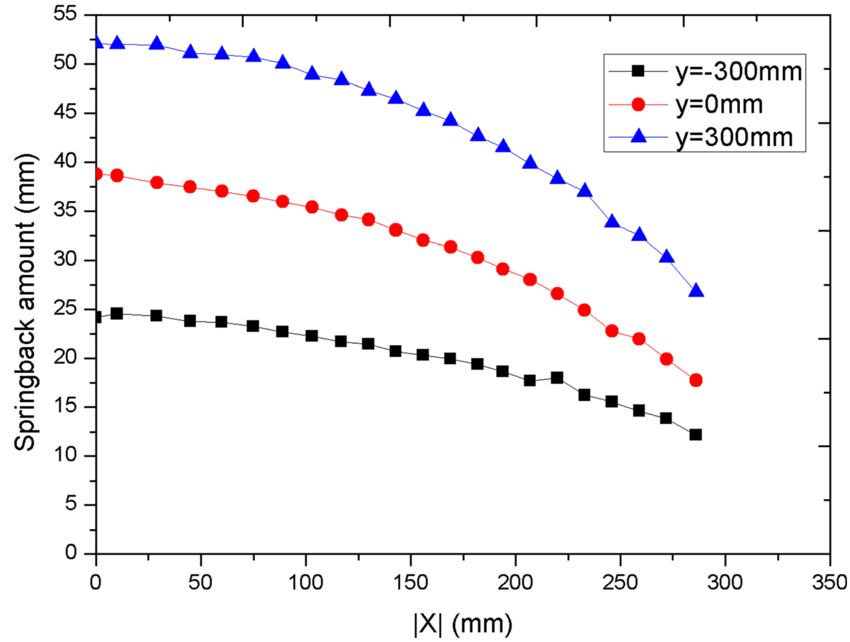



**Fig. 14** Springback amount of the plate at the punching positions during the whole incremental bending process

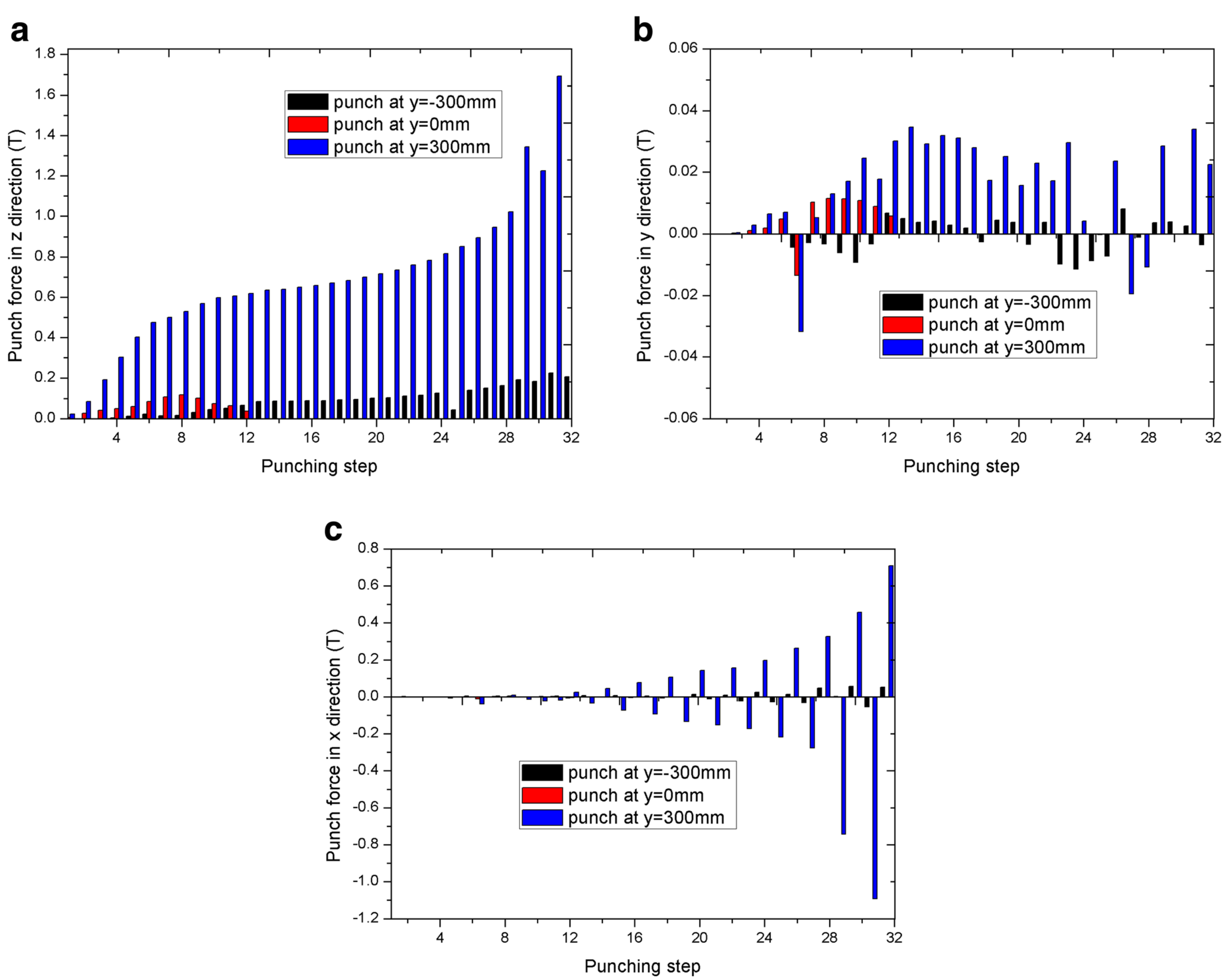



**Fig. 15** Punch force distribution during incremental bending process. **a** *z*-axis. **b** *y*-axis. **c** *x*-axis

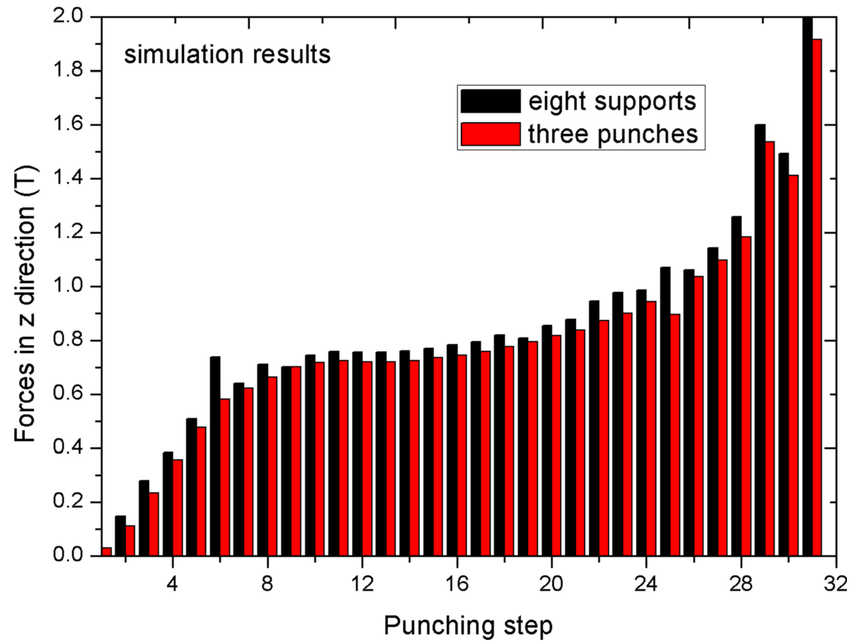



**Fig. 16** Resultant forces along $z$-axis for punches and supports during incremental bending process

plate are similar as used in the experiments. Since the dimension of the plate is very big (1000 mm × 800 mm × 5 mm), it would consume more time if solid element is used. Actually, the computational results for a smaller model by using solid element and shell element are compared and it is found that the predicted punch forces and stress distribution are quite close to each other while the computational time is much less for the case with shell element than that with solid element. So here in this finite element simulation, the full integrated shell element is used to mesh the plate. In addition, von Mises yield function is used to represent the yielding behavior of the plate and coulomb friction law is used to describe the frictional behavior between the tools and the plate. For the incremental bending simulation, the effect of the metal plate's gravity during the whole process is considered mainly for the automatic positioning of the plate during each springback process. Since the boundary of the metal plate is free, some uncontrollable behavior can be seen during each springback step and thus can lead to invalid simulation results if the gravity is not considered. The loading paths for the three punches used in numerical simulation are presented in Fig. 9, and other simulation parameters are displayed in Table 3.

## 5 Results and discussion

### 5.1 Validation of the simulation

After the experiment, the 3D scanner installed on the machine tool is used to collect the data on the deformed plate's shape, which is then used to construct the digital 3D models. Figure 10 shows the experimental results of the deformed plate in comparison with the objective results. As we can see, the experimental results match well with the objective results. The maximum error between the experimental and the objective results is 6.4 mm, which demonstrates that the incremental bending process based on minimum energy method and springback compensation method is quite effective. The difference between these results may be caused by neglecting the slip phenomenon.

Figure 11 reflects the numerical and experimental bending shape along $x$-axis for the deformed plate. It can be found that the predicted bending depth (or the contour of the plate) coincides well with the experimental data, which validates the static implicit computation method in the application of this incremental bending process. The maximum difference between the experimental data and numerical ones is less than 10 mm. Compared to the dimension of the plate (1000 mm × 800 mm × 5 mm), the numerical results are quite acceptable. Normally, it is difficult to get the accurate springback during the numerical simulation. For this incremental bending process, the springback occurs after each bending step. Therefore, together, there are maybe dozens of springback before achieving the final part. The error caused by inaccurate springback prediction can accumulate, which makes big error between the final numerical and the experimental results. Here in this study, the gravity is considered during each bending and springback process, which helps to locate the plate accurately and reduce the positional error during the springback simulation.

### 5.2 Thickness, stress, and springback analysis

The numerical model can be used to analyze the general deformation behavior during the incremental bending process, including thickness distribution, strain and stress distribution, and loading force changes.

Figure 12 displays the final thinning ratio along $x$-axis of the deformed plate. As we can see from this picture, the maximum thickness reduction of the deformed plate is less than 0.50%, which means the deformed plate is relatively uniform and it meets the qualification with limited thickness reduction, so the curved plate manufactured by the incremental bending process is qualified.

Figure 13 shows the effective stress distribution of the plate during the whole incremental forming process. After each bending process, there is a huge springback phenomenon, so the stress distribution and the plate's shape are totally changed after each springback. The numerical results also manifest that the stress mainly focuses on the moving region of the punch which has the largest bending depth.

The springback behavior is one inevitable phenomenon for the bending process of metal sheets. Usually, the bending angle is investigated to check the magnitude of springback. In this incremental bending process, it is not proper to describe the springback behavior with the change of bending angle since the punches stamp at different positions during the whole process. Here in this study, the change of the plates' position in the punching direction is used to describe the springback behavior. Figure 14 shows the measured springback amount of the plate at the punching positions after each bending process. It can be seen that the springback amount is related to the punching position. When the punching position is closer to the support ($|x|$ is bigger), the springback amount is smaller. Besides, when the punching depth is bigger, the springback amount is bigger.

### 5.3 Loading force analysis

Hydraulic cylinders are used to supply punching force and supporting force during the incremental bending process. Fixed machine tool structure and technical parameters of the hydraulic cylinders limit the bearing capacity for each punch and support in different loading directions. For example, if the punching force or the supporting force in the $X$ direction is larger than the limited value, the loading path could be unexpectedly changed or the machine tool could be damaged during the incremental bending process. Therefore, the forming force is one important element in this study of incremental bending process.

Figure 15 presents the punch force in different directions during the incremental bending simulation process. Results show that for a specific punch, the maximum force is applied in $z$-axis, which is the bending direction. The force in $x$-axis is caused by the bending curvature. The force in $y$-axis is much smaller than that in $x$-axis and $z$-axis. That is because the three punches move along $x$-axis and $z$-axis simultaneously while there is relatively little deformation in $y$-axis, since the supports are arranged in two lines along the $Y$ direction (as shown in Fig. 8). In general, to form such a variable curvature plate, the bearing capacity of the punches in $x$-axis and $z$-axis should be attached to make sure the objective plate can be achieved without exceeding the bearing capacity of the punches.

As can be seen from Fig. 15a, the force of the punch at $Y = 300$ mm, which has the largest bending depth, is much bigger than that of the other two punches since the deformation resistance of the plate increases with larger deformation. However, the relatively larger force for the punch at $Y = -300$ mm than that of the punch at $Y = 0$ mm is mainly caused by reversible deformation of the plate at position of $Y = -300$ mm. The residual stress distribution shown in Fig. 13 also exhibits the similar loading condition. In addition, simulation results prove that the force in $z$-axis of the punch at $Y = 300$ mm increases with bigger punching depth and smaller punching distance from the punch to the supports.

From the simulation results, the bearing load for each punch and support in various directions can be obtain, which helps to judge whether the curved plate can be formed by the machine tool or not.

The resultant forces along $z$-axis for three punches and eight supports are displayed in Fig. 16. Results show that the resultant forces of punches and that of the supports are very similar to each other, and the slight difference is caused by the gravity of the plates. If the periphery of the plate is restrained, the simulated resultant force along $z$-axis for three punches is about 20 t. It is clear that the largest resultant force along $z$-axis to form one variable curved plate based on the incremental bending process is about 2 t, so the largest working load of the machine tools is reduced to 10%, which can be regarded as one great advantage of this new flexible incremental bending process.

From the previous discussion, it is clear that incremental bending process has great potential in manufacturing complicated ship hull plates. But to be objective, the presented system is still at the beginning of the development stage. This current study provides a fundamental interpretation of this novel process and it helps to guide the fabrication of more complicated metal plates with better machine control based on experiments and numerical simulation. In general, the future work could be done from the following three aspects:

- In theory: to further improve the accuracy of the predicted punch path by considering the slip phenomenon of the plate.
- In numerical simulation: to adopt more appropriate material model that can describe the springback phenomenon accurately.
- In experiments: to manufacture doubly curved ship-hull metal plate and saddle-shaped ship-hull metal plate.

## 6 Conclusions

Incremental bending is one novel flexible metal forming process to fabricate the complicated ship-hull metal plates. This paper investigates the forming performance of incremental bending process based on experiment and numerical simulation. One variable curved plate is fabricated on the incremental bending device and corresponding numerical simulation is conducted to investigate the different parameters during the incremental bending process. The main conclusions can be drawn as follows:

1. The incremental bending process can achieve variable curved metal plates with good accuracy and high efficiency.
2. The implicit method is applicable for the simulation of incremental bending process while the gravity of the plate should be considered to help position the metal plate during springback.
3. The springback amount of the plate after each bending process is related to the bending depth and bending position.
4. The forming load during the incremental bending process is significantly reduced since the periphery of the plate is free, so smaller bearing capacity of machine tools can be used to achieve a required part.

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