Springback law study and application in incremental bending process

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Abstract. One incremental bending process has been proposed for manufacturing the complex and thick ship-hull plates. The accuracy and efficiency for this novel process is mainly dependent on the loading path and thus the unavoidable springback behavior should be considered in the loading path determination. In this paper, firstly, the numerical simulation method is verified by the corresponding experiment, and then the springback law during the incremental bending process is investigated based on numerical simulation, and later the loading path based on the springback law and the minimum energy method is achieved for specific machining shape. Comparison between the designed curve based on springback law and the new simulation results verifies that the springback law obtained by numerical simulation is believable, so this study provides a new perspective for the further research on incremental bending process.

1. Introduction
Recently, one novel incremental bending process has been proposed for manufacturing the thick plates with much smaller loading force [1]. One of the most important issues to guarantee a good part with this method is to have a proper loading path. In our former study, minimum energy method and Euler-Bernoulli beam theory [2] were used to achieve the loading path. However, the whole incremental bending process is finished step by step while after each step there is huge springback phenomenon caused by stress relief. The loading path obtained based on minimum energy method and Euler-Bernoulli beam theory without considering springback would induce huge error in the final shape of the deformed part. So springback after each bending process should be considered carefully.

In recent years, many scholars have done researches on the factors that influence the springback phenomenon during bending process. For example, Ozgu et al. (2014) [3] conducted bending experiments for some steel materials and they found springback reduces with large bending angle. Michael et al. (2016) [4] investigated the springback behavior of two steels based on free bending experiments. Results show that bigger punch velocity can reduce springback while flat length has little influence on springback. Wiriyakorn and Sutasn (2017) [5] discussed the influence of channel width on springback characteristics in the U-bending process and they found that for the case without pressure pad, bigger channel width could induce bigger springback. Besides, Botros (1967) [6] proved that springback increases as the thickness of the blank decreases. Ma (2015) [7] verified that grain size could influence the stress distribution and thus effect the springback angle.

Review of the previous researches showed that many experimental conditions can influence the springback behavior, so efforts can be made to improve the springback prediction. However, most of
the research just qualitatively analysed the changing regularity of springback behavior. For the novel incremental bending process, the quantitative relationship between the springback amount and the initial bending shape should better be obtained to get the proper loading path. So far, some researchers have done such studies. For example, Gardiner (1957) [8] developed one generalized mathematical formula to describe the relationship of the final bending radius and the initial bending radius. But this analysis can only be used to predict the springback of the elastic-perfectly plastic materials. Hosford and Caddell [9] proposed another classic springback model for strain hardening materials. Besides, Zhang et al. (2007) [10] calculated the angular change during springback for U-bending process. The disadvantage of those springback models mentioned above is that it is hard to get the accurate shape directly after each springback process. Some new and complicated constitutive models have also been proposed to predict the springback behavior accurately [11, 12] while they are impossible to obtain the springback amount directly. Wang et al. (2008) [13] obtained the relationship between the unload angle and punch displacement for air bending process when the punch stamps only at the mid-span of the sheet metals. Their study provided a good air bending angle control system while the springback behavior is still unknown when the punch stamps at other positions of the sheet metals. Generally speaking, it is really difficult to obtain an intuitive theoretical model to describe the springback behavior in our incremental bending process. So in this paper, the numerical simulation method is used instead to find the springback law in the incremental bending process and to guide the loading path determination.

2. Basic theory of incremental bending process

2.1 Incremental bending process
Incremental bending process is one gradual forming process for manufacturing complex and thick ship-hull plates. Figure 1 (a) shows the schematic diagram of the incremental bending process. During the novel process, the plate is firstly supported by some rotatable and movable supports. Then the punch (or punches) moves down to press the blank. The process may take several steps and during each step the stamping depth and position may different according to the objective part. The process continues until the final shape is achieved. It should be noted that since the boundary of the plate is free, the forming force is significantly reduced compared with the traditional stamping process, which is one obvious advantage of this novel process. So far our group has designed one testing machine to realize the incremental bending process and the experimental setup is shown in Figure 1 (b).

![Figure 1. Incremental bending process (a) schematic diagram (b) testing machine.](image)

2.2 Determination of the proper loading path
In order to obtain a ship-hull plate with good quality and high efficiency, the proper stamping loading path should be used, otherwise the bending process may take a much longer time or the deformed shape is not accurate as we expected. Minimum energy method could be used as one principle to
design our loading path. The detailed explanation of the minimum energy method can be found in our published paper [14]. According to minimum energy method, the stamping point should be at where the error between the current shape and objective shape is maximum. It should be noted that, after each bending process, there is huge inevitable springback phenomenon caused by relief of residual stress in sheet metal forming process. So the error mentioned in minimum energy method should be the one between the objective shape and the shape after each springback process. So how to get the shape correctly after each springback process is very essential for the loading path determination, and that is the key research topic in this study.

3. Verification of numerical simulation analysis
Since it is difficult to get the theoretical model directly for this incremental bending process, the numerical method is used instead to investigate the springback law, so the first issue here is to verify the reliability of the numerical simulation method.

The basic numerical simulation model is shown in Figure 2(a). During the incremental bending process, eight supports can be used to support the plate, and the three punches can move along y-axis and z-axis to make the plate deform. The corresponding experiment was also carried out on our testing machine and the final variable curved plate is shown in Figure 2(b).

![Figure 2. FEM and experimental Models](image)
(a) FEM model; (b) experimental result.

Figure 3 shows the bending shape along y-axis of the deformed plate. It can be found that the predicted z-axis displacement of the plate coincides well with the experimental data, which validates the numerical simulation model in the application of this incremental bending process. The maximum difference between the experimental data and numerical ones are about 10mm. Compared to the dimension of the plate (1000mm*800mm*5mm), the numerical results are quite acceptable. The errors are considered to be caused by neglecting the Bauschinger effect and anisotropy of the steel plate. Considering the good results shown in Figure 3, the numerical model used in this study can help us analyze the springback behavior during the incremental bending process.

![Figure 3. Comparison of experimental and simulation results at different positions.](image)

![Figure 4. numerical model for springback study.](image)
4. Springback law analysis based on numerical simulation
Here in this section, the numerical simulation method is used to analysis the springback behavior in incremental bending process. The basic numerical model is shown in Figure 4, where L is the distance from punch center to the middle of the two supports, and S is the spacing between two supports. We will change the value of L and S separately to investigate how the springback changes. It should be noted that during one simulation, the punch only moves up and down along z direction to realize different bending depths while it doesn’t change along the length direction of the blank (or y-axis).

4.1 Springback study for the case with constant L=0mm
In this section, the springback of the plate is investigated for the situation that the spacing of the two supports changes while the punch always stamps at the middle position of the supports (that is, L=0mm).

Figure 5 shows the geometry of the plate after each bending process and after each springback process, where ‘first-before spbk’ means the shape of the blank after the first bending process, ‘first-after spbk’ means the shape of the blank after first springback process. From the results, we can get some interesting phenomenon.

![Figure 5](image)

**Figure 5.** The geometry of the plate before springback and after springback for various bending steps for L=0 mm.

First, results show that when the stamping depth is smaller, the geometry of the plate after bending process is a smooth curve. However, when the stamping depth is larger (bigger than 50mm), the geometry of the plate is more inclined to two intersecting straight lines. This phenomenon can be explained as follows: When the stamping depth is smaller, the deformation of the stamping position of the blank is mostly elastic. According to classic Euler-Bernoulli Beam theory, the deflection for the beam can be described by a simple cubic equation. However, when the stamping depth is larger, the deformation of the stamping position of the blank is mostly plastic, so the deformation is only concentrated on the loading area.
Second, when the spacing of the two supports are smaller, the geometry of the plate after each bending process is more inclined to two intersecting straight lines, which is caused by the truth that the deformation of the stamping position of the blank is more prone to plastic. Third, the geometry of the plate after each springback process is two intersecting straight lines. That’s because after springback, the elastic deformation of the plate is recovered and only the plastic deformation is left. So only the stamping point (or area, depends on the shape and dimension of the punch) has obvious geometry change.

Generally speaking, it is not easy to describe the geometry of the plate after each bending process and each springback process using the same equation, so in the following study, we try to figure out the springback distribution law after each stamping step. Figure 6 shows the springback amount of the plate for various bending steps. It is clear that the springback curve for the first bending stage in Figure 6(a) (or Figure 6(b)) is different from other cases. From Figure 5(a) (or Figure 5(b)) we can see that the geometry of the plate (shown in red in Figure 5(a) or Figure 5(b)) is one horizontal line after springback, that means during the first stamping process, only elastic deformation occurs in the blank, so the springback curve for the first bending stage is equal to the stamping curve. For other stamping steps, there is plastic deformation, and results show that all the other springback curves after different stamping depths are close to each other when the spacing of the supports are constant. Besides, when the spacing of the supports are smaller, the maximum springback amount is smaller due to the bigger plastic deformation.

According to the observation from Figure 5 and Figure 6, we find that though it is difficult to describe the whole stamping process and springback process with the same equation, the maximum springback amount (the springback at the stamping position) only depends on the spacing of the supports if there is plastic deformation during the stamping process. So the geometry of the plate after each springback step can be predicted only if the maximum springback amount is given.

Figure 6. The springback amount of the plate for various bending steps for L=0 mm.
4.2 Springback study for the case with constant $S=700\text{mm}$

In the former section, the stamping point is only at the mid-span of the blank, here in this section, the springback of the plate is investigated for the situation that the spacing of the two supports is constant ($S=700\text{mm}$) while the punch stamps at different positions between the supports. Figure 7 shows the geometry of the plate after each bending process and after each springback process, and Figure 8 shows the springback amount of the plate for various bending steps. Similar to the phenomenon shown in Figure 5 and Figure 6, the maximum deformation occurs in the stamping point. Besides, since the springback is elastic process, the springback curves shown in Figure 8 satisfy the deflection equation of Euler-Bernoulli beam theory, which can be described by a simple cubic equation.

For each sub-figure of Figure 8, the horizontal distance of the stamping point to the support is the same (that is $L=\text{constant}$) and the springback amount for each bending steps are close to each other, so we can roughly regard that the springback amount is constant no matter how much the bending depth is. However, it is clear from Figure 8 that when the stamping point is more close to the support, the springback amount of the stamping point is smaller.

**Figure 7.** the geometry of the plate before springback and after springback for various bending steps for $S=700\text{ mm}$. 
4.3 Springback law summary

According to Figure 5- Figure 8 we can summary the springback law for the cases with different S and L. Figure 9 (a) shows the springback amount of the stamping point in the middle point of two supports when the spacing of the supports changes. According to the distribution disciplinarian of the springback amount, a quadratic equation can be used to fit the data and obtain other springback amount for different spacing of the supports (or S). Figure 9 (b) shows the springback amount of the stamping point at different positions when the spacing of the supports is 700 mm. Generally speaking, we can regard that the springback amount of the middle point varies linearly with the distance from the middle point to the punch stamping point. So based on the data of Figure 9, the springback amount for different positions when the spacing of two supports are different can be obtained, which will help to obtain the shape of the plate after each springback process and then achieve the proper loading path.

Figure 9. Springback law (a) for the case with S=700 mm (b) for different gaps.
5. Application of the springback law in loading path decision

Here in this section, the proper loading path of the incremental bending process can be obtained based on minimum energy method and the above springback law. Taking the objective shape \( y = x^2 \cdot 100/350^2 - 100 \) as an example, the green line in Figure 10 shows the objective shape, while the blue star points show the stamping positions and the blue curves show the achieved shapes of the blank after each stamping and springback process. Numerical simulation with the same loading path is also conducted. Actually, each step during the incremental bending process could be compared between the new simulation result and the designed curve based on the springback law. Figure 11 shows the comparison of some step between simulation results and the designed curve. Results show the new simulation results coincide well with the calculation results. The small error between them could be caused by neglecting the tool shape and the slight difference shown in each sub-figure for Figure 6 and Figure 8. However, the error shown in Figure 11 is quite acceptable, so the loading path determination method based on the springback law is validated.

![Figure 10](image1.png)

**Figure 10.** the loading path based on minimum energy method and springback law.

![Figure 11](image2.png)

**Figure 11.** the comparison of calculation curve and simulation result.

6. Conclusions

In incremental bending process, one important issue is to achieve a proper loading path. The unavoidable springback behaviour should be considered in the loading path determination. Here in this paper, the springback law is investigated based on numerical simulation, and the loading path based on the springback law and minimum energy method is used to guide the incremental bending process. Some key conclusions are summarized as follows:

- The maximum bending amount after each bending process is near the stamping position when there is plastic deformation.
- For the case that the spacing of the supports are constant, the springback amount for the same stamping position is the same no matter how many bending processes have been conducted. In other words, the springback amount for the same stamping position is independent with the loading path.
- When stamping the middle point of the two supports, the springback amount for the stamping position can be expressed as a quadratic function of the stamping point position.
- When the spacing of the two supports is constant, the springback amount for the stamping position varies linearly with the spacing from the middle point to the punch stamping point.

7. References

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