Research Progress of Springback in Multi-Point Forming of Sheet Metal

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Abstract. In the manufacturing of sheet metal, multi-point forming replaces the traditional integral die with discrete basic body groups to adjust the height of each basic body and form the required three-dimensional curved surface, thereby facilitating flexible processing. Multi-point forming is the most common approaches for the manufacturing of sheet metal but can cause serious shape distortion due to springback phenomena. In this paper, key research on springback is categorized and analyzed from three aspects: springback theory, springback numerical simulation analysis, and springback control, followed by summary of the current research status and outlook on promising future research directions of springback in multi-point forming springback. And the conclusion is drawn: in the future, multi-point forming of sheet metal using high-frequency ultrasonic excitation for springback control during the forming process coupled with artificial intelligence for springback compensation control will be a promising research direction for controlling springback in the multi-point forming of sheet metal.

Keywords. Multi-point forming of sheet metal, springback, research progress.

1. Introduction
In the manufacturing of sheet metal, multi-point forming replaces the traditional integral die with discrete basic body groups to adjust the height of each basic body and form the required three-dimensional curved surface, thereby facilitating flexible processing [1-4]. Continuous multi-point forming is a forming technology developed based on multi-point forming. However, both multi-point forming and continuous multi-point forming have a general springback problem in the sheet forming process. Especially in the flexible multi-point forming process of the sheet, the springback phenomenon is more serious and decreases the dimensional accuracy and surface quality of the parts. Repeated multi-point forming can reduce the springback of the sheet, but the efficiency is too low. Therefore, in-depth research and effective control of the springback in multi-point forming of sheet metal are required.

The final springback shape of the part as the result of the cumulative effect of its entire forming history, and the sheet metal forming process is closely related to many factors, such as die geometry, material characteristics, and frictional contact. Flexible multi-point forming of sheet metal is determined by the basic body of the die. Discreteness and diversity of the frictional contact complicate the springback problem in multi-point forming of sheet metal. In the past 30 years, in-depth research and discussion on springback in multi-point forming has been reported, covering from bending forming to complex stretch forming, from theoretical analysis to numerical simulation, from springback prediction to springback control, as well as error compensation and other aspects. This paper reviews the work on
springback in multi-point forming in three aspects and predicts the development direction of springback in multi-point forming.

2. Bending Theory Research and Analysis Method of Springback

Springback is a phenomenon that occurs during the sheet forming and unloading process. The sheet deforms under the action of an external load, and this deformation is composed of two parts: plastic deformation and elastic deformation. When the external load is removed, plastic deformation is retained, while elastic deformation is restored. The reason for the recovery is that the residual stress after unloading overcomes the forming force generated by plastic deformation. In this way, during the unloading process, the shape and size of the formed part will change in the opposite direction of the deformation during the loading process, which is the reason for the elastic recovery of the plate.

The analytical method of springback analysis theory is mainly aimed at simplification of the appropriate mechanical model for typical forming processes or parts, and the nature of springback phenomena in the sheet metal forming process is analyzed by analytical, numerical, or incremental methods. Since sheet metal bending is a problem of small strain and large deformation, and the proportion of elastic deformation is relatively large, the springback of parts after unloading is relatively large. It is important to study the springback problem with sheet metal bending as a special case. Because sheet metal bending only involves simple die geometry and boundary conditions, the analysis is relatively simple, and an analytical expression for springback can be obtained. This expression is useful to reveal the mechanism of springback and understand the instructive main factors affecting springback. Bending generally only involves relatively simple geometric shapes and boundary conditions, so it can be studied in-depth by analytical methods. In the 1950s, the work of R.Hill, F.Proska, F.J.Gsrdiner, et al. [5] laid the theoretical foundation for sheet bending and springback analysis.

Springback is the reverse elastic deformation produced in the process of bending and unloading. The classic calculation formula for sheet springback is equation (1).

\[
\Delta k = \frac{1}{R_n} - \frac{1}{R'_n} = \frac{12M(1-\nu^2)}{Et^3}
\]  

(1)

where \(\Delta k\) is the change in curvature of the sheet before and after springback; \(R_n\) and \(R'_n\) are the curvature radii of the neutral layer before and after sheet springback, respectively; \(E\) and \(\nu\) are Young's modulus and Poisson's ratio of the sheet, respectively; and \(M\) and \(t\) are the inner bending moment and thickness of the cross section after the sheet is formed before springback, respectively.

The cross section bending moment \(M\) is uniquely determined by the tangential stress distribution of the cross section. For the same bending process, different bending analysis models based on neutral plane movement, thickness change in the sheet metal forming process, material strengthening, Bauschinger effect, or anisotropy were applied, which resulted in different cross-sectional stress distributions. According to formula 1, the amount of springback of the sheet metal also varies. Therefore, in a theoretical analysis, the accuracy of the calculation of the cross-sectional stress distribution will directly affect the accuracy of sheet metal springback prediction.

Two basic theoretical models of bending springback in multi-point forming of sheet metal have been established: one model is the elementary theory of plastic bending, which is based on two basic assumptions of the elasto-plastic bending engineering theory: 1) Kirchhoff hypothesis (or straight-line method assumption); 2) the transverse shear stress of the sheet is neglected, causing a state of uniaxial tension or unidirectional compression of the fibers of each layer in the longitudinal plane of the sheet. This theoretical model neglects the transverse shear stress, neutral layer movement, and plate thickness changes during the sheet metal bending process, which affects the prediction accuracy of sheet metal springback. The other model is a more accurate theoretical model, which was first proposed by R. Hill [6]. This model considers the influence of lateral shear stress and the inward movement of the neutral layer: sheet bending is predicted to be neutral due to the effect of the lateral shear stress of the sheet. The layer is not always located in the middle of the plate and moves gradually to the inner layer of
the plate as the bending deformation of the plate progresses. The radius of the curvature of the curved neutral layer is calculated as equation (2).

\[ R_n = \sqrt{R_i R_o} \]  

where \( R_i \) and \( R_o \) are the radii of curvature of the innermost and outermost layers in the sheet bending process, respectively.

R. Hill [6] studied the pure bending of rigid and wide plastic plates, showing that the longitudinal deformation of the cross section can be divided into three zones when the wide plate is purely bent (figure 1).

Tensile zone A, compression zone B, and tension zone C after compression. Zone C is caused by the inward movement of the neutral layer (movement distance \( \delta \)). This zone undergoes reverse stretching, and the stress distribution is more complicated. Hill theory explains the influence of the inward movement of the neutral layer better and has better prediction accuracy for large curvature bending, which lays the foundation for future studies on sheet bending with improved accuracy.

Based on Hill theory, various in-depth studies on sheet metal bending have been reported. The main research progress is the use of reinforced material models, which describe the changes of various parameters during the bending process (such as plate thickness changes) more accurately. Yu et al. [5] published a monograph with a more detailed review on the research progress in this period. Since the 1980s, the research on bending and springback theory has been further refined to material models that consider various stress states (such as tensile bending) and complex loading history (such as cyclic loading).

Aiming at reducing the springback of multi-point forming plates, Li et al. [7] of Jilin University discussed the mechanism of springback reduction by repeated forming. Through repeated forming of several typical specimens, the effect of repeated forming on springback reduction, the effect of part springback, and the influence of sheet thickness on the effect of repeated forming in multi-point forming were demonstrated, showing that repeated forming could significantly reduce springback.

Z. Chen [8] used a force-displacement split-control multi-point forming method to study the more universal springback of the sail surface. In a numerical simulation study using the software ANSYS, the plate thickness, forming force, and curvature were obtained. Radius and sail surface parameters have different effects on the amount of springback in two different curvature directions. After sail surface formation, the springback of the sail surfaces of the two sail shapes mutually affect each other. Thereby, the springback in the direction of the curvature with large radius plays a leading role and affects the amount of springback in the direction of the curvature with small radius. In the direction of the curvature with large radius, the forming force increased with the plate thickness. The springback decreased when the radius of curvature decreased. In the direction of curvature with small radius, a smaller plate thickness associated with a greater forming force and smaller springback. However, the radius had little effect on the springback; in both directions, the amount of springback first increased and then decreased as the sail surface parameter increased.
Zheng et al. [9] of Harbin Institute of technology designed and manufactured an experimental device using the force-displacement split-control multi-point forming principle and applied this device to form a cylindrical surface. They compared the formed parts obtained under different forming modes, adopted theoretical analysis and numerical simulation to analyze and compare the stress and deformation conditions of different forming modes, and discussed the characteristics and laws of deformation under different forming modes. It is theoretically predicted that force-displacement split-control multi-point forming can effectively reduce springback and eliminate the straight edge effect. Force-displacement split-control multi-point forming technology reduces springback due to the effect of the normal restraining force, and the reduction of springback is proportional to the magnitude of the normal restraining force, which was verified by numerical simulation of the stress and strain distribution and the change of the support reaction force. Force-displacement sub-control multi-point forming essentially changes the stress and deformation conditions of the plate, which can effectively improve the forming quality.

Zhang [10] studied the springback compensation of complex curved surfaces in multi-point forming using a combination of theoretical analysis, numerical simulation, and experimental verification to establish a springback compensation method. By calculating the springback compensation surface, one complex curved surface was formed, which exhibited the target shape. This method was applied for the precise forming of curved parts and showed a good prediction effect. Moreover, this method has a good practical application value.

3. Application of FEM in the Analysis of Complex Springback Problems

In addition to bending parts, springback also has a great influence on the dimensional accuracy and production efficiency of shallow drawn parts, such as car cover parts as a typical example. With the continuous improvement of the market requirements for car body appearance quality and the wide application of high-strength steel and aluminum plates in the car body, the negative impact of springback on the manufacture of panels and dies has attracted more and more attention of engineers and researchers. Especially multi-point forming involves complex geometric shapes and boundary conditions. These problems must be solved with numerical simulation technology, mainly finite element method (FEM), while general analytical methods are no longer used.

FEM simulation technology of sheet metal forming has been first used in the 1990s. In the past 30 years, great development in material models, element types, contact friction processing, and nonlinear algorithms has been achieved. Liu et al. [11] proposed an analytical method to predict springback and residual stress distribution of a multi-point formed cylindrical workpiece. Considering the loading model of the multi-point forming process, the bending moment could be obtained by superimposing the bending moment generated by each punch, which was calculated through the stress in the thickness direction.

The springback value and residual stress in tangential direction were obtained theoretically, and the strain and stress variation in the thickness direction during the loading and unloading processes were also analyzed. Finite element simulation and the bending experiment were conducted for comparison with the analytical results. The results showed that the proposed method could effectively predict the springback value and residual stress distribution in the multi-point forming of acylindrical workpiece. Zhang [10] established a multi-point forming finite element model based on the Abaqus software to describe the processing of the boundary conditions, such as element selection, contact definition, friction coefficient, constraint, displacement, and explicit-implicit combined algorithm, during the simulation process. Springback in multi-point forming was simulated, and the handling of constraints in springback simulation was explained. The use of elastic pads in multi-point forming and the effects of sheet thickness, material, and radius of curvature on springback were studied. Selection of an elastic pad with appropriate thickness, compression rate, and elastic modulus was important for achieving a good surface forming quality and effectively reducing the amount of springback. As the plate thickness increased, the amount of springback decreased gradually. The amount of springback after unloading of
the workpiece decreased when the elastic modulus of the material increased. In addition, the radius of curvature decreased with the decrease of the amount of springback.

The whole process of sheet metal stamping includes forming and springback, which are both related but relatively independent processes. In general, the forming process does not include springback. The springback and forming processes are different in the stress and strain changes, so the numerical simulation technology used in the analysis of the springback problem is also different from that used in the forming process. From the perspective of the element model, since springback simulation should consider the bending effect, shell elements, such as solid and degenerated shell elements, are generally used for calculation. Modified die elements are also used for calculation, and the so-called modified die unit uses bending stress to correct the die stress. This method does not only meet the requirements of bending calculation, but also significantly reduce the calculation cost. In the past, the same algorithm used for the forming problem was mostly used to solve the springback problem. Thereby, the same algorithm was used for the whole process of forming and springback, and the most commonly used algorithms were the dynamic explicit algorithm and the static implicit algorithm. The dynamic explicit algorithm has high efficiency and good stability and is suitable for calculating various complex forming problems. However, its efficiency in springback calculation is extremely low, and the used machine time is often several times higher than that of the forming calculation. The static implicit algorithm is used for solving large-scale forming problems. The time efficiency is low, and the convergence is poor, but it is extremely efficient in solving the springback problem and often provides good results after one or several iterations. In view of this, the dynamic/static algorithm is generally used to solve the springback problem. The basic process of the dynamic/static algorithm is as follows: the dynamic explicit algorithm is used to solve the forming process, and the obtained result is used as the input for the static implicit algorithm for springback calculation. This method gives full play to the advantages of both algorithms and greatly improves the calculation effectiveness.

Two methods are generally used to solve the springback problem [12]: in the first method, the die is removed at the end of forming and replaced with the contact reaction force, followed by iterative calculation until the contact force is zero; in the second method, the die is allowed to move in the reverse direction at the end of forming until the punch is completely separated from the sheet. Both methods provide very similar calculation results, but the second method is more efficient and has a wider range of applications, as it can calculate the trimming springback in contrast to the first method.

4. Springback Control

4.1. Springback Control in Bending

Traditional springback control methods in bending forming include the stretch bending method, pressure correction method, die compensation method, and over-bending method. Different methods can be used to control springback according to the shape of the part and the bending process.

Die compensation and over-bending methods are two basic springback control methods. The former is suitable for die bending (closed bending), and the latter is suitable for free bending (air bending). For bending parts with very small curvature, due to insufficient plastic deformation and large springback, it is difficult to implement simple die compensation. In general, the combined action of stretch bending and die compensation is used to control springback. For curved parts with large local curvatures, the theoretical prediction accuracy is poor. In the actual production, local compression correction methods are generally used to control springback. In addition, some new control methods have been reported, such as the secondary bending method proposed by Shu et al. [13], which can significantly reduce the springback of bending parts applying a relatively simple implementation process.

As basic springback control methods, the die compensation and over-bending methods have a strong theoretical basis, and various in-depth studies applying these methods have been reported. Oral et al. [14] discussed the die compensation algorithm for cylindrical bending springback. These studies were based on pure theoretical calculations and numerical simulations and achieved results in a short time with low cost. However, judging from the current situation, the theoretical prediction accuracy of springback is
relatively poor, and supplementation with appropriate process tests is necessary to obtain more satisfactory results. Yang et al. [15] combined the general theoretical prediction and process test methods and realized adaptive control of springback in free bending. The key point of their method was the real-time measurement of the bending force-punch displacement curve at the end of the bending of the part. This process essentially embed process tests into the production process, thereby basically eliminating the dispersion of material properties. This basically eliminates the springback prediction error caused by the dispersion of material properties.

After measurement of the real-time force-displacement curve, real-time control of the subsequent bending process can be realized in many ways. Yang et al. [15] compared the measured curve with the curve stored in the test database and applied the fuzzy inference mechanism for real-time control of bending. Kwok [16] obtained the curvature bending moment equation based on the real-time force-displacement curve and calculated the downward overbending position of the punch. In Kwok’s[16] work, a real-time image processing system was added to accurately display the bending shape, which resulted in a wider range of applications. The biggest advantage of the above-mentioned adaptive bending control is that it does not require special process tests and that it can bend and form sheets of different characteristics and thicknesses, which has a good application prospect.

4.2. Springback Control in Complex Drawing Forming

In the past, few studies on the springback control of complex drawn parts have been reported. In engineering practice, experience and trial and error are usually used to reduce and eliminate the impact of springback. Since the 1990s, with the gradual solution of wrinkling and cracking in drawing forming, the problem of springback control has gradually become the focus of research [17], and the continuous improvement of sheet metal stamping CAE simulation technology has also been used for springback control research. The stretching multi-point forming equipment was shown in figure 2.

Figure 2. Stretching multi-point forming equipment developed at the Massachusetts Institute of Technology [18].

Springback control of complex drawn forming parts is generally performed by two methods: 1) Process control method: springback is reduced by changing the boundary conditions of the forming process, such as the shape of the wool, the blank holder force, the die fillet, and the friction state. 2) Geometric compensation method: the size of springback is predicted or measured under a specific process part, and the shape of the die is modified to fit the shape of the springback to the design requirements. In engineering practice, both methods are generally applied jointly to achieve the best results. The direct relationship between the process conditions and springback is difficult to determine. In general, various process conditions are adjusted according to the principle of increasing tensile deformation to reduce springback. Research in this area is mostly focused on discussing the influence of blank holder force on the forming quality [19]. Adjusting the blank holder force can reduce the amount of springback to a certain extent. However, for shallow drawn parts, it is often necessary to modify the die to greatly reduce the impact of springback. In the past, die correction was basically achieved through trial and error, but the current development of numerical simulation technology provides a faster way. Many studies on the numerical simulation of springback die compensation and achieved good results. The basic idea is based on FEM simulation technology, and the shape of the die was continuously...
modified through an iterative algorithm so that the finally formed part just met the design shape requirements after springback. Zhang [20] has proposed an algorithm for springback compensation and modification for doubly curved plate, which is established by a combination method of theoretical analysis, numerical simulation and forming experiment.

5. Development Direction of Springback Research in Multi-Point Forming

In modern manufacturing, the products need to be designed to not cause any problems in the entire product life cycle. Obviously, the springback control method, which is based on experience and preceding repeated process tests, cannot meet such requirements. Exploring new control technology to study springback in multi-point forming is also a development direction. Cui et al. [21] used the finite element analysis software ANSYS/EMAG and ABAQUS/EXPLICIT to explore the influence of pulsed magnetic field force on the bending springback of sheet metal, and the springback angle obtained by simulation was consistent with the experimental results. They found that the springback angle of sheet metal decreased gradually when the discharge energy increased.

Our team have studied the multi-point plastic forming of 2024-O aluminum alloy sheet. By using ultrasonic vibration to assist forming in the stamping process and a combination of Abaqus numerical simulation and theory, the influence of ultrasonic vibration on the plastic deformation of sheet metal during the multi-point forming process was studied [22].

The punches are arranged regularly and the upper and lower heights are adjustable. Basic body group (Figure 3). In traditional integral mold forming, a set of molds can only form plates of a specific size and shape, while in multi-point forming, each basic body is independent and controlled by different control systems. It can be adjusted by computer to form different sizes and different shapes. The shape of the plate makes the forming die flexible and versatile.

![Figure 3. Multi-point forming model diagram.](image)

Under the same frequency and amplitude, the springback analysis of a 2 mm thick thin plate is carried out. Here, the sub-displacement cloud diagram of the displacement along the Z-axis direction under vibration and the sub-displacement cloud diagram along the Z-axis direction under the condition of no vibration are respectively made, and for comparison, as shown in the figure 4.

![Figure 4. Displacement cloud diagram along the Z axis with 20KHz, 9μm vibration applied.](image)
According to the data derived from the results, draw a dot-line diagram of the displacement along the Z axis in the two states.

As shown in figure 4 and figure 5, the maximum springback displacement occurs at the edge of the thin plate when there is no vibration, and the springback amount is 8.756 mm, when there is vibration, the maximum springback is 7.037mm, and the springback is reduced by 19.6% compared to the non-vibration model.

So the conclusion is that the sheet stress was effectively reduced after application of ultrasonic vibration, and the reduction of the internal stress had a great effect on the reduction of springback. Compared with the model without ultrasonic vibration, the model with ultrasonic vibration effectively reduced the springback, and this effect was more significant due to the shorter time of action.

Nowadays, the most common way to solve the springback problem is numerical simulation technology.

Most of the factors that affect multi-point forming of sheet metal have the characteristics of nonlinearity and large change and are difficult to measure. At the current research status, it is difficult to give an accurate mathematical expression. In recent years, artificial neural network methods have been successfully used in the study of multi-point forming processes and springback problems of sheet metal. For example, M.R. Jamli et al. [23] applied neural network theory to sheet metal forming, and the research on springback control of parts reduced the sensitivity of the process to material parameters and friction states. Springback is influenced by various factors in the sheet metal forming process. Neural network has the potential to solve finite element analysis complexity. Liu et al. [24] discussed springback prediction method for double-curved workpiece considering plate anisotropy in multi-point
Multi-compensation control will be springback control during the forming process coupled with artificial intelligence for springback compensation control will be a promising research direction for controlling springback in the multi-point forming of sheet metal.

6. Conclusion
In the future, multi-point forming of sheet metal using high-frequency ultrasonic excitation for springback control during the forming process coupled with artificial intelligence for springback compensation control will be a promising research direction for controlling springback in the multi-point forming of sheet metal.

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