The establishment of a newly modified numerical global springback compensation method

Wei Xiong 1, Wenfeng Zhang 1, 2*, Yong Lv 1, Chuan Li 1, Xiaohui Song 1 and Yushan Xia 3

1 School of Mechanical Engineering, Gulin University of Aerospace Technology, Guilin 541004 China
2 Guangxi Colleges and Universities Key Laboratory of Robot & Welding, Guilin University of Aerospace Technology, Guilin 541004, China
3 Key Laboratory of Contemporary Design and Integrated Manufacturing Technology, Ministry of Education, Northwestern Polytechnical University, Xi’an 710072 China

*Corresponding author’s e-mail: zwf@guat.edu.cn

Abstract. Part shape deviation caused by spring back is a quality problem in sheet metal forming. There are two major approaches, adjusting tooling shapes and adopting process control. This paper focused on tooling contour design. A new die design approach, called global compensation method (GC), has been proposed and it possesses following advantages. Compensation factor in displacement adjustment method (DA) is extended to a compensation matrix, thus every node has its own compensation magnitude and compensation direction, which are related to the global forming error.

1. Introduction
Springback during the unloading phase of sheet metal forming leads to deviation from design part shape. It affects products’ geometrical acceptability. There are several means to reduce the dimensional error caused by springback. One of them is trying to eliminate springback by modifying forming processes. Another instance is increasing blank holder pressure or using inverse approach in deep drawing process. These methods possess the benefits of convenience in die design, but their application may be restricted by parts’ materials and shapes. Stretch-warp bending is not quite suitable for parts with internal ribs like integral panels. As blank holder pressure increases the chance of excessive thinning augments too.

Although iterative die design can be carried out with actual dies and parts, trail-and-error method will not be included in this paper. Since it consumes too much time and money, interest is attracted by new measures based on numerical simulation. Initially, Karafillis and Boyce [1][2][3] suggested what is called “spring forward” method to design the tooling and the blinder shape with a finite element (FE) program. Opposite section moments or tractions are applied on the desired part shape, which was mistaken for the initial unbending part in Ref.[4], to generate new trial for tooling shape. Besides arguments of lacking convergence in asymmetric cases[5][6], a few more works have to be done in applying loads to the desired shape. Webb and Hardt[7] viewed the iterative die design process as a close loop control system and introduced deformation transfer function to relate changes of die shapes to that of part shapes. Attempts have also been made using optimization algorithm[8][9][10][11]. These methods involve considerable complexity in formulation and implementation as part of a
special-purpose finite element program[5]. GAN and WAGONER [5][6] proposed displacement adjustment (DA) method, whose concept is to move the die surface nodes in the direction opposite to the springback error. To remedy this issue, a natural solution is to include abscissa and/or z direction in compensation, such as the three dimensional smooth displacement field in Ref.[12]. Although the RD approach reflects the tendency of rotation during springback to some extent, it deviates a lot from the right direction in V-bending [12]. However, far more work is needed to put it into practice. Because not only calculating distinction of normal directions but also an angle factor for an optimal compensation direction are necessary in the approach.

In this paper, endeavor has been made to improve DA method by extending the compensation factor to a compensation matrix. By doing so, not only both compensation magnitude and direction, but the global issue of spring back is taken into account.

2. The establishment of the modified global springback compensation method

2.1. The compensation matrix
The compensation matrix can be introduced from the traditional DA method. The principle of DA can be described as follows:

\[ C = D - \alpha (S - D) \]  (1)

where, C, D and S are topological identical sets of points in the compensated geometry, desired geometry and springback part geometry, respectively. They represent shape of the three geometries. \( \alpha \) is the compensation factor. When the DA is performed iteratively, it can be represented by Eq.(2).

\[ C^{i+1} = C^i - \alpha (S^i - D^i) \]  (2)

where, \( j \) represents the \( j \)-th iteration. In Eq.(2) and Eq.(1) \( \alpha \) is identical, which means every point in the die employs the same compensation magnitude. However, optimal compensation factors vary from one point to another. So, an intuitive solution is to utilize different compensation factor for different points. This can be represented by a matrix equation:

\[
\begin{bmatrix}
\bar{e}_1^{i+1} \\
\bar{e}_2^{i+1} \\
\vdots \\
\bar{e}_n^{i+1}
\end{bmatrix} = \begin{bmatrix}
\alpha_1 & 0 & \cdots & 0 \\
0 & \alpha_2 & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & \alpha_n
\end{bmatrix} \begin{bmatrix}
\bar{e}_1^i \\
\bar{e}_2^i \\
\vdots \\
\bar{e}_n^i
\end{bmatrix} - \begin{bmatrix}
\bar{d}_1 \\
\bar{d}_2 \\
\vdots \\
\bar{d}_n
\end{bmatrix}
\]  (3)

where, \( \bar{e}_i^i \), \( \bar{s}_i^i \) and \( \bar{d}_i^i \) are points in C, S and D. Here, only elements in the diagonal have non-zero value. So it still considers springback compensation in a local manner. However, if non-zero values are assigned to elements in upper and/or lower triangle as Eq.(4), a vector in the compensated die geometry is related to a set of forming errors in the entire part, thus springback compensation can be treated in a global approach.

\[
A = \begin{bmatrix}
\alpha_{11} & \alpha_{12} & \alpha_{13} & \cdots & \alpha_{1n} \\
\alpha_{21} & \alpha_{22} & \alpha_{23} & \cdots & \alpha_{2n} \\
\alpha_{31} & \alpha_{32} & \alpha_{33} & \cdots & \alpha_{3n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\alpha_{n1} & \alpha_{n2} & \alpha_{n3} & \cdots & \alpha_{nn}
\end{bmatrix}
\]  (4)

In the Eq.(4), A represents compensation matrix. Except its advantages in providing different compensation magnitudes and directions for different nodes in the die geometry, its evaluation is still needed to be solved when it is applied in compensation practice. This will be discussed in the following section.
2.2. Evaluation of the compensation matrix
Unlike most references mentioned above, where compensation factors are evaluated in a static manner, here the compensation matrix is related to the forming deviation. The evaluation of its elements is self-adapting. To achieve this, the problem of die design is studied from an unusual, macroscopic view to introduce the concept of forming function. And the details such as compensation magnitude and direction will be discussed later.

The process of employing finite element method (FEM) to calculate the forming deviation of a certain die can be summarized like this: First, a set of mesh node coordinates, which represents the contour of the die, is imputed. Then after computation a set of forming errors, which describes deviations between the part’s shape after stamping and that of designation, is outputted. In the case of die design, forming errors are usually converted to the form of deviations in every node of the die mesh. Therefore, the number of deviations is equal to that of die nodes, or coordinates of die nodes if deviations are decomposed to components in three coordinate’s directions. It can be represented by a set of equations:

\[
\left\{ 
\begin{array}{l}
 f_i(x_i, y_i, z_i, y_1, \ldots, y_k, z_1, \ldots, z_k) = \delta_i^k \\
 f_i(x_i, y_i, z_i, y_1, \ldots, y_k, z_1, \ldots, z_k) = \delta_i \\
 \vdots \\
 f_i(x_i, y_i, z_i, y_1, \ldots, y_k, z_1, \ldots, z_k) = \delta_i 
\end{array}
\right.
\]

(5)

where, \(x_i, y_i, z_i (i = 1, 2, \ldots, m)\) are mesh nodes’ coordinates in the die, \(\delta_i (i = 1, 2, \ldots, m)\) are forming errors. Die design is equal to search a group of coordinates that make \(\delta_i = 0\). This is the non-linear equation solving concept for die design presented in Ref.[4]. Eq.(5) is called forming function and its zero value, or zero values if multiple solutions exit, is the desired die contour.

By converting die contour design question to solving nonlinear equations, algorithm borrowing from numerical analysis can be used. However, not all numerical methods are suitable to solving these equations due to several characters of them. First, these equations cannot be written down analytically, so calculation of derivatives is not possible. Any method, which needs derivatives, cannot be employed. Second, these equations can only be work out as a whole, therefore, some methods requiring computation certain equations in them can be eliminated from consideration. In this paper, the following quasi Newton (QN) algorithm is used to evaluate the compensation matrix:

1. Set initial value \(y(0)\), permitted error \(\epsilon\) and initial Hessian matrix \(H_0 = I\), \(k = 0\);
2. Calculate \(F \left( x, y, z \right)^{(k+1)}\), if \(\left\| F \left( x, y, z \right)^{(k+1)} \right\| < \epsilon\), then let mold contour be \(y = y^{(k)}\), terminate program;
3. Calculate \(y^{(k+1)} = y^{(k)} - H_{(k)} F \left( x, y, z \right)^{(k+1)}\);
4. Calculate \(\delta^{(k)} = y^{(k+1)} - y^{(k)}\),
\[
H_{k+1} = H_k + \frac{1}{\delta^{(k')} \delta^{(k)}} \left( s^{(k)} - H_{k} \delta^{(k)} \right) \delta^{(k)};
\]
5. \(k + 1 \to k\), go to (2).

where, \(\left\{ x, y, z \right\}^{(k)}\) are die’s mesh node coordinates in \(k\) th FEM calculation, \(F \left( x, y, z \right)^{(k)}\) refers Eq.(5) for short. And the Hessian matrix in the algorithm is an evaluation of the compensation matrix \(A\).

2.3. Algorithm of springback compensation
The algorithm mentioned above can be used directly to design die contour. In certain cases, it converges faster than DA. However, the algorithm is sensitive to the initial guess of the die contour. To avoid its limit of local convergence, while to keep its advantages in regulating compensation magnitude for individual node based on the forming error on it and employing global compensation matrix, a homotopy algorithm is introduced to springback compensation.
Figure 1. Global compensation algorithm for MATLAB

The basic idea of homotopy method is creating serial equations and employing the solution of the last equation as the initial value for the current equation. Here Eq. (5) is referred as $F(x) = \delta$ for short, the equation needs to be work out is $F(x) = 0$. A serial homotopy equation can be constructed by embedding parameter $t_i$ as follows:

$$H(x, t_i) = 0$$

where, $0 = t_1 < t_2 < \cdots < t_N = 1$. Eq.(6) satisfies following requests:

$$H(x, t_i) = F(x)$$

$$H(x, t_0) = F_0(x)$$

where, $F_0(x)$ is an equation that its solution $x_0$ is already known. Assuming $x^i$ is the solution of the $i$th homotopy equation in Eq.(6), if $t_i - t_{i-1}$ is small enough, it can be expected that $x^{i-1}$ is enough close to $x^i$ and is capable of serving the initial value to solve the $i$th homotopy equation with a local convergence algorithm.

One form of homotopy equation that tally with the requests from Eq.(7) and Eq.(8) is

$$H(x, t) = H(x) + (1-t)A(x - x_0)$$

where, $F_0(x) = x - x_0$ and $x_0$ can take the design contour ($D_0$) of the part needs to be formed. Eq.(9) can be solved one after another through local convergence methods.
In this paper, the quasi Newton method described above is used to solve homotopy equation (Eq. (9)) and to evaluate the compensation matrix. However, another problem should be taken into consideration. The determinant of $\delta(x_1, x_2, x_3)$ in the fourth step of quasi Newton method might be close to zero, if so, it will be added with a damping parameter $\alpha I$ to avoid unfavorable effects.

The springback compensation method can be described with N-S flowchart as Fig. 1. This flowchart is design for realization with MATLAB, which does not support “until” type loop, therefore only “when” type loop type is used.

2.4. Realization of the method
There are several details needs to be coped with in the realization of GC for springback compensation. In the first place, deviations in the part’s mesh nodes must be defined and calculated. Because the part’s contour is described by a set of mesh nodes after FEM simulation of its forming. It is convenience to compare these points with the nodes that represent the part’s design shape, which is employed as the initial value for iterative springback compensations. And it is also expedient to adopt the mesh nodes, which is in the very moment that the part has completely contact with the die in the first FEM calculation, to represent the part’s design contour. Therefore, deviations in three dimensions in each and every part nodes can be work out. However not all distances of corresponding nodes represent forming deviation, they may be caused by global movements of node sets. Therefore, before these deviations actually are calculated in computer program, registration job must be done to minimize the effects of global motion. The registration scheme is similar to that in Ref. [4], except the initial registration. First, it calculates the maximum and minimum distances of the two set of nodes only in stamping direction. Then it moves the nodes in the contour after forming the average of the two extremums towards that represents the design contour. It is not only the program is simpler but its effect is better. In accurate registration, the scheme still use genetic algorithm and its parameters are same to that in Ref. [4].

Second, forming deviations in the part’s mesh nodes must be transferred to that in the die’s mesh nodes. Though the die’s contour can be represented by the part’s mesh nodes in the moment that the part makes fully contact with the die. The two groups of nodes have different configuration, which means there is no one to one relation between them. A remedy is numerical interpolation. Since the deviations are computed by comparing the design contour and the part’s contour after forming, and the part’s design contour has the same configuration of the shape in the contact moment in forming, every node’s deviation can be directly moved to the later node set, which has the same contour with the die but different meshes. Then deviations in three coordinate direction in a certain mesh node in the die can be interpolated with Shepard method like this:

$$\delta(x^i) = \frac{\sum_{i=1}^{N} W_i(x^i, x_1, x_2, x_3) f'_k}{\sum_{i=1}^{N} W_i(x^i, x_1, x_2, x_3)}, \quad i = 1, 2, 3$$

where, $x^i, (i = 1, 2, 3)$ are three Cartesian coordinates for the certain mesh node in the die, $\delta(x^i)$ are deviation in the same direction. And the number of $M$ nodes that are close to the certain mesh node are chosen from the set of the part’s mesh that taking on the die’s contour. $f'_k$ is the deviation of the $k$th node in $x^i$ direction. $W_i(x^i, x_1, x_2, x_3)$ are weights. They can be computed as follows:

$$W_i(x^i, x_1, x_2, x_3) = \left[ \sum_{i=1}^{N} (x^i - x'_k)^2 \right]^{-1}$$

Through using interpolation method, the deviations are expeditiously considering in all three dimensions. And the programming work is less than B Spline fitting employed in Ref. [4].

Last but not least, the FEM model’s robustness should be taken into consideration. Since iterative springback compensation methods are carried out by a computer program, which is realized with MATLAB here, stamping and springback simulation must be able to complete with a range of different die contours and part shapes. Unlike single simulation, boundary conditions, analysis steps,
mesh size and types and so on can be manually modified according to specific needs of the certain forming simulation. The FEM model used in the compensation program should be robust enough to accomplish forming simulation with different die contours that might appears in springback compensation. When ABAQUS is employed, as stamping commonly carried out with ABAQUS/Explicit, it has sufficient robustness. The problem usually occurs in springback simulation with Standard module in ABAQUS. Therefore, special treatment has to be down to ensure the FEM model’s robustness. Scripts that describe the springback FEM model are generated semi-automatically. First, a template of the springback script is created. It contains statements that import stamping results, material property design, and assembly and so on, but leaves any statement related to the part’s mesh, such as assigning material section to elements in the mesh, creating analysis steps and boundary conditions, empty. Then the MATLAB program reads stamping file and analyze its mesh. After that these mesh related statements are filled in the template in a way that allows the unloading processes from one set of nodes to another according to their distances to the final boundary condition.

3. Numerical Simulations

In order to test the effectiveness of the proposed compensation method, a series of cylinder, sphere and saddle parts were subjected to die design using GC, QN and DA. Three methods all compensate along three coordinate directions. The compensation factor for DA method is 1.0. For GC, \( t_i = 0.05(i - 1), i = 1, 2, \ldots, 21, A = 0.01 \) and \( \lambda = 0.1 \).

In all these shape cases, the modified methods successfully converge to ideal part shapes due to their simplicity.

4. Conclusion

In this paper, a new global method based on compensation matrix is proposed. In the method, homotopy algorithm is used to calculate die shapes iteratively and a damping parameter is also introduced into the method. The method converges faster and is not sensitive to the initial die contour. The new method has been compared with the displacement adjustment method and the quasi Newton method.

Compared with displacement adjustment method, in which compensation magnitude and compensation direction are important aspects, the compensation factor has been replaced by a compensation matrix. It enables different compensation magnitudes and directions for different nodes. And the compensation is not only based on the information of the very node but also information from other nodes in the entire part. This fits the global nature of the springback problem.

The new method also use a numerical approach to evaluate the compensation matrix based on forming shape deviations. Theoretical computation of the matrix will be included in the future work. And the method will be used in practical parts, such as creep age formed aircraft integral panels and automobile panels.

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