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COMPENSATION FACTOR METHOD FOR MODELING SPRINGBACK OF AUTO PARTS CONSTRUCTED WITH HIGH-STRENGTH STEEL

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ABSTRACT−To more accurately manufacture an auto-body workpiece, a predictive compensation factor method was used to predict the workpiece's springback, and the factors influencing springback are introduced. Based on this method, a numerical simulation was produced to simulate the springback compensation after distortion of the workpiece. After analyzing the simulation results, a compensation method was introduced to reduce the springback influence on an actual workpiece. Here, we used a fortified B-pillar, which is a kind of longitudinal stand-frame workpiece, made with a high-strength steel material (TRIP700). The simulation results indicated that the proposed method is feasible and can be efficiently used for predicting the distortion of springback compensation of an auto-body workpiece.

KEY WORDS : Auto-body workpiece, High-strength steel, Springback, Compensation factor

1. INTRODUCTION

Since the mid-1960s, high-strength steel (HSS) has been increasingly used as a new material in the production of automobile components. The recent development of high-strength steel sheets has depended upon the large amount of technical information available in this field. Currently, the automobile industry is more urgently demanding reductions in overall vehicle weight (for fuel-economy reasons), and it is also demanding materials that can satisfy safety and crash-worthiness requirements. To meet these demands, the utilization of HSS materials is necessary. However, the amount of springback of formed HSS parts after unloading is generally much larger than that of common steel materials. Such springback is also difficult to restrain or to eliminate. Therefore, the study of springback compensation methods for auto-body workpieces is increasingly important. Today, there are some car components typically made from HSS; such materials include the A-, B- and C-pillars, the inner-door workpieces, the cross-rail bumpers, the wheel housings, and the inner-workpiece tail gates.

In this work, a fortified B-pillar made with an HSS material (TRIP700) was chosen to illustrate the predictive compensation-factor method for drawing auto body workpieces after unloading. First, some important influence factors impacting springback are introduced. Then the predictive compensation-factor method is derived by analyzing the factors influencing springback of HSS. Finally, a compensation-factor method for reducing springback is proposed and verified by examining the fortified B-pillar.

2. IMPORTANT PARAMETERS INFLUENCING SPRINGBACK

In the deep drawing of auto-body workpieces, springback of the workpieces is inevitable; however, springback can be reduced by modifying and optimizing a procedure's parameters during the loading and unloading processes. Modifying these parameters should be done carefully, however, because such changes can cause difficulties associated with the workpiece.

Generally, the main procedure parameters (Huette, 2001) affecting the springback distortion of drawn workpieces are one of three types:

2.1. Die Geometry

The primary die-geometry parameters that influence springback are the edge radius, the drawing clearance, and other similar parameters. By reducing the drawing clearance and by modifying edge radius, the die geometry can be changed, thus reducing the piece's springback.

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2.2. Plastic Deformation of the Drawn Workpiece

In this category, the important parameters are the initial surface pressure, the height of the drawing groove, and the like. By increasing the surface pressure and enlarging the height of the drawing groove, it is possible to decrease plastic deformation, which consequently reduces springback. To generate a finite element analysis (FEA) simulation and to form a comparison between the simulated and experimental results, the material properties of the TRIP700 drawn workpiece were given as the following:

Young' modulus, E=210000 N/mm^2;
Blank thickness, h=1.46 mm;
Friction coefficient, m=0.15; and
Yield stress, σ_s=700 MPa.

The stress-strain curve during flow obeys $\sigma = K\varepsilon^n$, where n=0.26 and ε is the logarithm of strain. Hill's 1948 yield function was used in the FEA, and the anisotropy coefficients were experimentally determined as the following:

$r_0 = 0.76$;
$r_{45} = 0.71$; and
$r_{90} = 0.77$.

2.3. Workpiece Geometry

In this category, the important parameters include the thickness of the workpiece and the surface section of the workpiece. In general, enlarging the stamped surface and increasing the thickness of the workpiece can reduce springback.

However, although the above operations tend to reduce the springback, they generally result in other adverse effects. For example, changing the die geometry also correspondingly transforms the final geometry of the stamped workpiece. such changes are not desirable.

As a rule, the die-face geometry is accurately designed according to a Computer-Aided Design (CAD) model provided by the product designer, and it cannot be modified easily. Moreover, increasing the plastic deformation of the stamped workpiece increases manufacturing difficulties. Large plastic deformations will increase the possibility of fracturing, wrinkling and local necking during the manufacturing process. Furthermore, increasing the thickness of the workpiece will negatively impact the ability to generate a lightweight auto body. Especially for HSS materials, it is more difficult to reduce the springback by adjusting the above process parameters.

2.4. Boundary Conditions in the Stamping and Springback Analysis

Figure 1 shows the constraints for the boundary conditions used in the stamping and springback analysis. During the stamping stage, two drawbeads are put on the die surface, and three constrained points ("RPS points") are considered during the springback analysis. A single-action press was used for testing the die. The punch force was determined to be 840 T, and the press force of blank holder on the panel was 140 T.

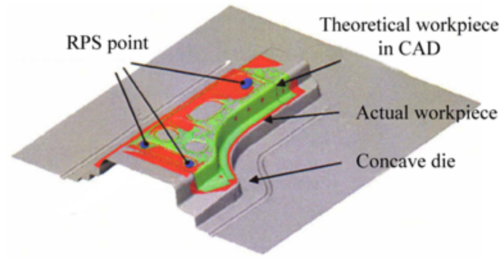

Figure 1. Constraints for boundary conditions and the reference points for positioning the workpiece.

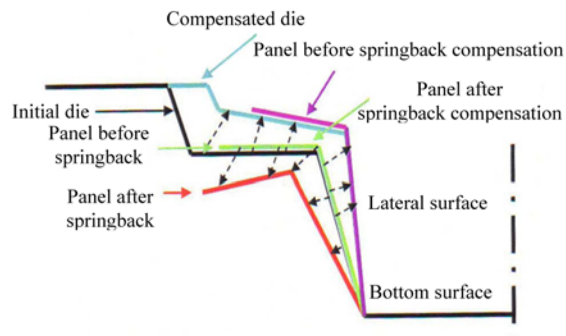

Figure 2. Geometric compensation principle for the stamping section.

3. COMPENSATION PRINCIPLE OF SPRINGBACK

Due to the ineluctability of springback and for the reasons clarified above, die surface compensation should be an effective option for addressing springback. The geometric compensation principle is shown in Figure 2.

It was assumed that the springback region before compensation can be described by a spatial polynomial equation, and the equation was mapped to the compensated die. That die was used for stamping the auto body workpiece, which had a geometry and size that coincided with the actual CAD model.

4. SEVERAL METHODS OF SPRINGBACK COMPENSATION

Recently, the study of springback compensation has attracted the attention of major automobile manufacturers. As a result of this work, some springback compensation methods have been developed.

4.1. Multi-compensation Methods Based on Springback Simulations

General Motors Corp. proposed a method of springback compensation based on a springback simulation (Geng and

Table 1. Parameters of a simulation model based on the multi-compensation method.

Material principle	Balart isotropy
Finite element	Shell element
Rigidification grade	3
Integrated point of the plate blank's thickness	7
Drawing speed	1000 mm/s

Zhao, 2003). The simulation results describing the die surface shape could be compared with the sizes of the actual workpiece. After the first compensation was performed, the compensated die surface shape was simulated and analyzed again. This process was repeated until the deviation between the simulation results and the sizes of the actual workpiece was minimized. The simulation parameters based on this method are shown in Table 1.

4.2. Anticipated Elasticity Method

Some automobile manufacturers applied the anticipated elasticity method (Zhang and Cheng, 1995) to perform springback compensation. In this method, the stress tensor in the workpiece is multiplied by a negative factor after the stamped workpiece is simulated. In other words, the workpiece is loaded in advance by an elastic deformation. Next, a new die surface was designed based on the workpiece shape after loading with an elastic deformation. By adjusting the negative factor, the deviation between the drawing simulation and the elastic deformation results can be minimized.

5. PREDICTIVE COMPENSATION FACTOR METHOD

5.1. General Description

The springback compensation method (Zhang and Wu, 2004) is based on the anticipated elasticity method, which is a global compensation method. The method is often based on simulation results within die, addendum and blankholder. However, it is generally difficult to compensate by simultaneously adjusting the addendum and the blankholder. In particular, it is undesirable to extend the compensation region to the blankholder because it is in the general plane. Additionally, there are many workpieces (e.g., the B-pillar, the bumper, etc.) with a length in one direction that is much larger than that its vertical dimension. The springback compensation of these workpieces can be efficiently described along its vertical section line by using a simple polynomial formula without compensation on the boundary profile connecting the piece with the blankholder. Moreover, after the iterative determination of the springback and the boundary profile, it is easy to choose a predictive compensation factor that modifies and adjusts the polynomial's extent. A detailed description of this process is described in the following sections via analysis of a B-pillar.

Table 2. Data comparison for the springback compensation study.

Compensated data	Compensated data based on actual measured data	Compensated data based on simulated results
Theoretical geometry	CAD data	CAD data
Springback geometry	Measured data from the actual workpiece	Simulated results
Compensated geometry of the die	CAD data for the die	CAD data of die
	Measured data from the die	

5.2. Comparison between the Measured and the Simulated Results of a Workpiece

To calculate the springback compensation, the CAD geometry of the die face must be transformed into a mesh. The deviation between the CAD mesh data and those of the stamped workpiece after springback can be obtained by comparison between the measured data and the simulated results. However, actual measured data for the workpiece can be obtained only after it is stamped and unloaded from the actual die. For a springback simulation, the actual die is not necessary.

Theoretically, the compensated die geometry can be applied both to the measured data from the actual die and to the CAD geometry data. Table 2 summarizes the input data for the springback compensation derived from our Predictive Compensation Factor Method (PCFM).

Raster measurements were used to calculate the deviation region between the actual workpiece geometry and the theoretical workpiece geometry. Then, the compensation factor was applied to the raster grid of the die. The process of springback compensation is illustrated in Figure 3.

Compared with the Anticipated Elasticity Method (AEM), PCFM has the following advantages:

(1) PCFM carries out a variable and parametric factor-adjusted design for springback compensation; AEM requires predetermined and quantitative predictive springback compensations on the die face.

(2) PCFM can achieve an efficient combination of local and whole-body compensations; AEM executes only the whole-body compensation.

The choice of the variable and parametric factors is generally based on the experience of the die designer, but for simulations, PCFM has a wider practicability and adaptability and AEM.

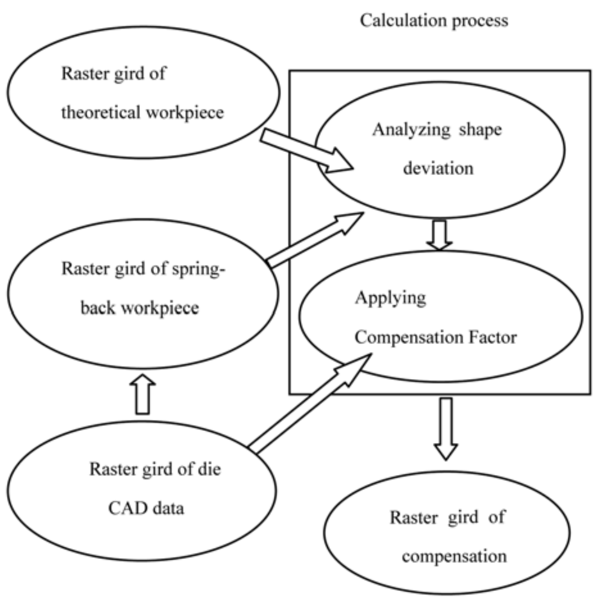

Figure 3. Process of springback compensation using PCFM.

5.3. Compensation Implementation Procedure

In this section, a fortified HSS B-pillar, a kind of longitudinal stand-frame workpiece, was chosen to demonstrate our methods for springback compensation of the workpiece and to illustrate the PCFM process.

The geometry of the concave die used for the fortified B-pillar was considered to be the reference data for the compensated die. The geometries of the concave die and the binding surface will be reproduced by the geometry of the compensated concave die. Figure 4 shows the input raster data.

5.3.1. Positioning of the workpiece

Effective springback compensation requires accurate positioning of the workpiece with respect to the concave die. The deviation region between the actual workpiece and workpiece data in the CAD drawings must be figured explicitly in three-dimensional space. These deviations can be fed back to the design of the corresponding concave die.

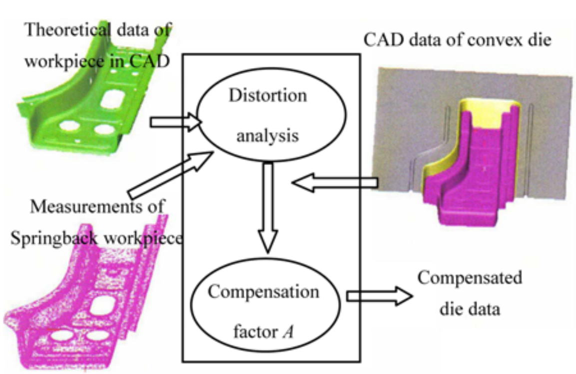

Figure 4. Input raster data.

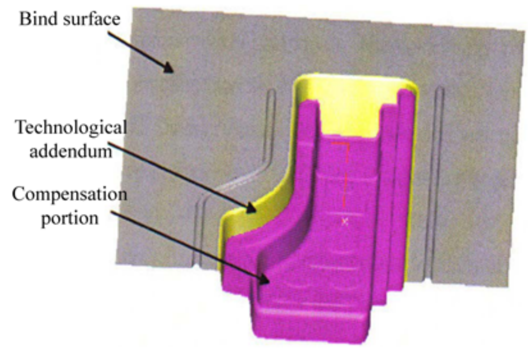

Figure 5. Frame of the concave die.

Generally, the geometry reference of the concave die must be between the theoretical geometry and actual measured geometry, unless there is an offset. Here, the geometry of the concave die was defined by the theoretical data in a CAD drawing. The geometry of the actual workpiece was detected by rastering; therefore, an offset was not necessary.

When positioning the workpiece and the die, it is convenient to choose the RPS point as the reference point (Lang, 1990), as shown in Figure 1.

5.3.2. Distribution of the compensated die

The compensatory function will directly influence the surface of the concave die. In other words, the bind surface will also be compensated, which is an undesired result. The reason for this compensation is that the bind surface is sometimes used as a plane in the usual drawing process. Thus, the bind surface should not be influenced by compensation. The frame of the concave die is shown in Figure 5.

The concave die region to be compensated is bigger than the actual workpiece region, and this difference generates the deviation region, as shown in Figure 5. The region between the bind surface and the compensation region is the technological addendum. After springback compensation, a new technological addendum part must be formed so that the region between the bind surface and the workpiece can be connected smoothly and easily.

5.3.3. Choice of compensation factor

The deviation region between the geometries of the theoretical and springback workpieces can be described using a polynomial. Compensation functions describing the die surface are generated using a compensation factor, which is a directly adjustable parameter. To optimize the parameter, the parameter region is defined between 0 and 3, and the compensation results are compared in this area. Figure 6 illustrates the same sectional views of workpiece formed using different compensation factors.

As shown in Figure 6, the compensation function changes quasi-linearly with the compensation factors. When the compensation factor is larger, the compensated size on the die surface is larger as well. On the bottom surface, a

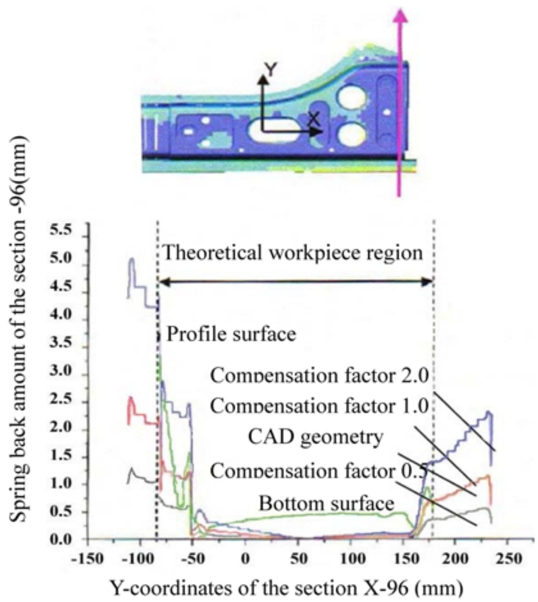

Figure 6. Sectional views of workpiece with different compensation factors.

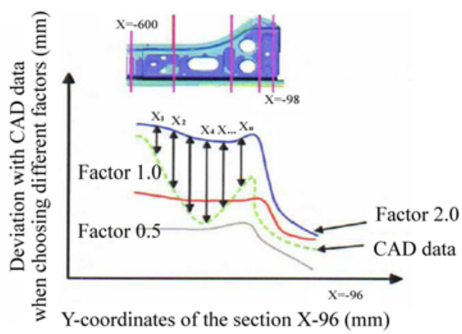

Figure 7. Deviations resulting from different compensation factors.

deviation between the theoretical and actual values is present for all compensation factors. However, this deviation appears only when the compensation factors are within 1.0 and 2.0 for the lateral surface. To choose an effective compensation factor, a mean deviation between the theoretical and actual values must be determined. The deviations from different compensation factors are shown in Figure 7.

The mean deviation is calculated with the following equation:

$$Y = \frac{x_1 + x_2 + x_3 + \ldots + x_n}{n} \tag{1}$$

where $x_1, \ldots, x_n$ are the deviations of each point and n represents the number of defined points.

To determine the mean deviation of the whole workpiece, five sections were chosen for evaluation. The calculated mean deviation, Y, of each section is shown in Figure 8.

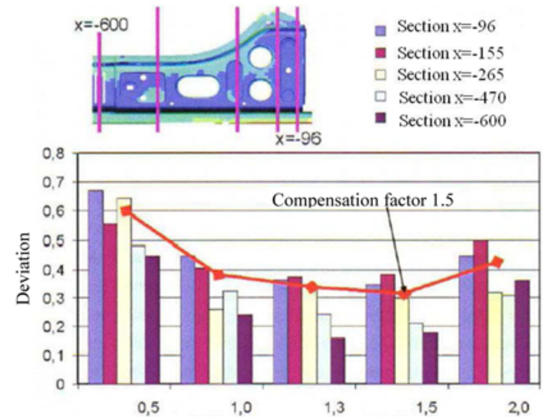

Figure 8. Choice of mean deviation.

5.3.4. Technological addendum

After the springback amount is compensated, it is necessary to produce a new technological addendum, which is automatically achieved with distortion simulation software (Hu and Li, 2003).

5.4. Verification of Springback Compensation

To verify the accuracy of the springback compensation via numerical simulation and to compare the experimentally measured data with the CAD data, it is necessary to simulate the springback process based on an actual compensated die. The objectives of this process are the following: 1) to check the die geometry; 2) to evaluate the manufacturability of the distortion; and 3) to track the springback behavior. The geometry distortion simulation of a die with compensation is shown in Figure 9. The drawbead was meshed to seal the geometry of the concave die. The convex die (the punch) and the bind surface were reproduced according to the geometry of the concave die and its offset, and the simulation parameters based on the actual workpiece were used. In the process of numerical simulation, friction effects were considered on two portions of the die; this consideration was consistent with the actual stamping and unloading processes.

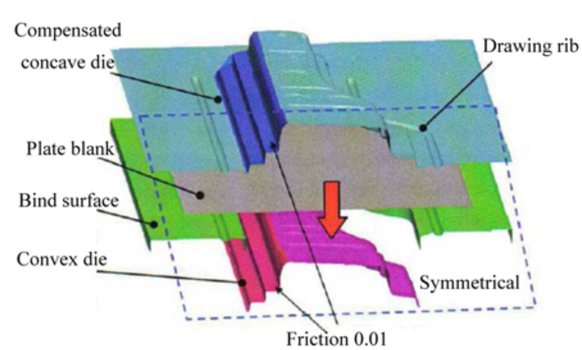

Figure 9. Geometry distortion simulation of a die with compensation.

5.4.1. Comparison of springback amounts from simulated and experimental results

First, the *PAM-STAMP* code was used to simulate stamping and springback. The simulation conditions, such as the constraint points (Figure 1), and various materials parameters were equal to those of the experimental workpiece. The *ATOS* system, made in Germany, was used to measure the springback amount, and the *ICEMSURF* software was used to measure and display the deviation between simulated and experimental springback amounts (relative to the CAD). The largest springback amount was about 12 mm at the inferior boundary of the workpiece, and simulation results showed relatively smaller springback amounts than those of the actual workpiece along its inferior boundary. The springback amounts were larger along its upper boundary, as shown in Figure 11. The largest deviation between the numerically simulated and the experimentally measured results was about 2.6 mm.

5.4.2. Springback compensation and comparison with CAD data

By utilizing PCFM with iterative calculations of the springback compensation, the actual die surface was modified.

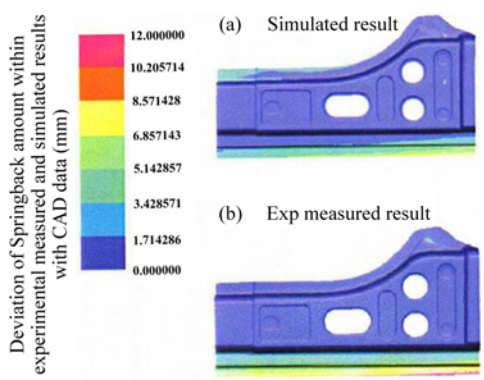

Figure 10. Springback amounts for the (a) Simulated workpiece before compensation (b) Actual workpiece before compensation.

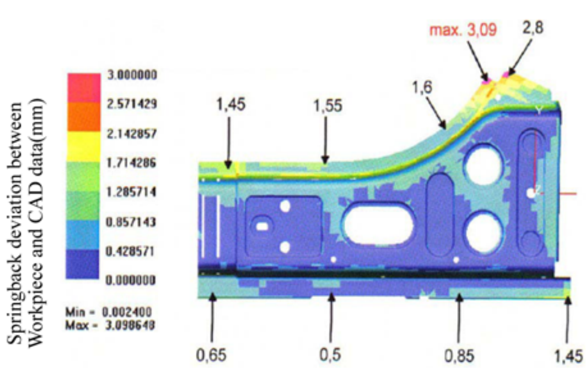

Figure 11. Deviation between workpiece springback and the CAD data after using PCFM with a compensation factor of 1.5.

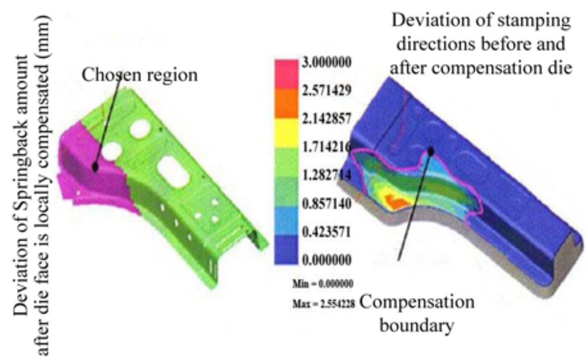

Figure 12. Illustration of Local compensation region.

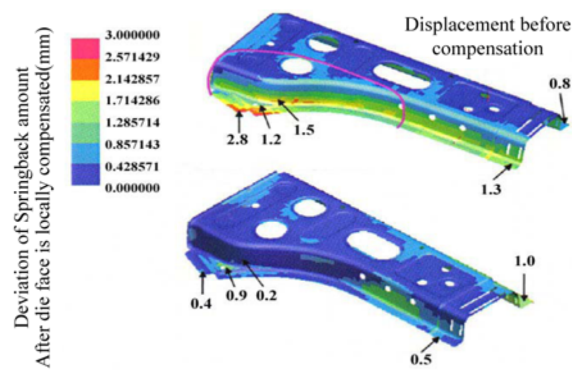

Figure 13. Locally compensated deviation.

Then, the actual workpiece blank was stamped and unloaded from the compensated die face. Finally, the deviation of the springback workpiece was compared with the CAD data to verify the validity of the PCFM.

According to the illustrations in section 5.3.3 and Figure 8, the ideal springback compensation factor was 1.5. After the die face was compensated, the measured deviations in the direction of principal strains were determined (Figure 11). The maximum deviation between the springback workpiece and the CAD data was 3.09 mm, and the springback deviation (Figure 10) had clearly decreased.

5.4.3. Local compensation

To further reduce the springback deviation, PCFM can also be used to perform local region compensation. First, the local region that must be compensated was chosen (Figure 12, left). Then PCFM was used on this region by selecting a new polynomial, re-calculating the mean deviation (Y) in equation (1), and determining new boundary constraints. For the local compensation scheme chosen, the compensation factor was determined to be 1.3.

The actual compensated region was larger than the chosen region, and the compensation region's boundary was smooth. An advantage of this situation is that the self-adaptive addendum is needed only if the side of the concave region is not formed. The local compensation scheme for die surface is also available for another round of reiterative simulation modification. The modified results are shown in Figure 13. By using the local compensation, the deviation in the chosen region was obviously decreased; however, the springback amount is only marginally changed out of the chosen region as a result of the stress-state change due to the springback compensation.

6. CONCLUSIONS

The PCFM was established for analyzing the springback process of auto body workpieces. It was then applied to the B-pillar drawing and associated springback to compensate for springback when using the TRIP700 material. The simulation results based on PAM-STAMP were quantitatively compared to experimentally measured results and CAD data to ensure the rationality of the present PCFM analysis. Using the present compensation method, the influence of springback on the drawing process can be effectively avoided. Moreover, optimized parameters determined from simulation of the HSS material were obtained and experimentally validated.

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