A novel approach of springback analysis using a drawbead and a die shoulder database in sheet metal forming simulation

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Abstract

Springback in sheet metal forming is a deformation that occurs when a workpiece is released from dies after forming. Prediction of springback using the finite element method (FEM) has been used in the design of stamping dies. The present paper describes an effective approach by which to improve the accuracy of springback analysis, which can also suppress the increase in the calculation time. In general, FEM using the analysis condition to decrease discretization errors greatly increases the computation time. The proposed procedure is as follows: (1) Quick analysis using a large mesh size is performed. (2) Data mapping and morphology mapping for the forming results are then performed using the database based on a detailed partial analysis of the drawbead and the die shoulder. (3) Springback analysis is performed using the forming results modified by the data mapping and morphology mapping. A forming experiment was conducted to confirm that the proposed method using the database greatly improves the prediction accuracy of the shape after springback and also suppresses the increase in calculation time.

Keywords Sheet metal forming simulation · Springback prediction · Finite element method · Drawing process

1 Introduction

Springback in sheet metal forming is a deformation that occurs when a workpiece is released from dies after forming. Prediction of springback using the finite element method (FEM) has been used in the design of stamping dies [1, 2]. A number of studies involving material models describing the Bauschinger effect have been conducted in an attempt to improve springback prediction [3, 4]. On the other hand, it is also important to accurately simulate the history of the contact state in which the workpiece slides while undergoing tensile bending deformation by the die shoulder radius. In other words, since the stress distribution at bottom dead center determines the deformation of the product after stress release. For accurate simulation of the contact state, it is effective to reduce the space discretization error due to the finite element (FE) and to select an appropriate contact model [5, 6]. However, in general, calculation using the analysis condition to decrease

discretization errors increases the computation time. In particular, when the dynamic explicit method is adopted for analysis of the forming process, the small mesh increases the number of calculation cycles according to the Courant condition [7]. If the small mesh is set to calculate forming process highly accurately, the calculation time increases. The combination of calculation accuracy and calculation time has remained an unsolved issue.

On the other hand, a static implicit method with a large time increment can be used for springback analysis, which releases the stress at bottom dead center after the forming process. This is because the analysis releasing the stress is a static equilibrium problem without contact. Therefore, even if the number of FE meshes is large, the calculation time of the springback analysis is extremely short at the calculation time, as compared with the analysis of the forming process. The increase in calculation time for the springback analysis will not be an issue.

Based on the above background, the longer springback compensation period remains an unsolved issue when performing springback compensation for the drawing process of large automotive parts, such as side outer panels. This is because of the increase in the calculation time required for the analysis using the small mesh in the forming process. For example, we consider the situation in which the average mesh

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size of the workpiece is set to 3 mm or more in order to shorten the calculation time. The bending deformation of the workpiece by the drawbead and a small die shoulder radius, e.g., 1 or 2 mm, cannot be sufficiently represented by FE meshes. On the other hand, if the average mesh size of the workpiece is subdivided into areas having a mesh size of 1 mm, the calculation time using the dynamic explicit method is approximately 27 times that for the case in which the mesh size is 3 mm. This estimation includes an increase in the number of calculation cycles according to the Courant condition. It is obvious that the calculation time will be significantly increased.

Therefore, in general, the equivalent drawbead model is applied for performing the analysis of the large-scale forming process [8, 9]. The equivalent drawbead model is a model in which alternative forces are applied to the workpiece instead of the shape of the drawbead in the FE model of dies. There are two types of alternative force: a restraining force applied in the direction opposite the material flow and an up-lift force applied in the direction of the blank holder. The calculation time can be shortened using the equivalent drawbead model. This is because the shape of the small radius in the drawbead in the FE model of the dies can be omitted, and the smallest mesh size can be larger than that for the case of not using the equivalent drawbead model. According to the Courant condition, the time increment can be larger than that for the case of not using the equivalent drawbead model, and the calculation time can be shortened further. The equivalent drawbead is defined as curves connected at the center of the concave shape on the flange surface in the drawbead. The curves are discretized as line elements, each of which indicates the area to which the restraining force and the up-lift force are applied in the forming analysis.

The calculation time for the forming analysis using the equivalent drawbead model is short. However, when the equivalent drawbead model is used, the accuracy of the springback analysis decreases. This is because the stress distribution in the thickness direction due to bending deformation in the drawbead is different from that in the actual drawing process. Moreover, the stress distribution in the thickness direction of each FE mesh on the workpiece after passing through the drawbead is different from that in the actual drawing process.

On the other hand, the die shoulder radius must be changed according to the mesh size of the workpiece in order to reasonably analyze the bending by the small die shoulder radius. For example, when the mesh size of the workpiece is set to 3 mm and the die shoulder radius is set to 1 mm, the FE meshes on the workpiece will slide while being vertically deformed. In this case, the FE meshes cannot be drawn over the die shoulder radius, and the analysis fails. As such, the deformation by the original die shoulder radius cannot be represented using FE meshes. When the die shoulder radius is changed, the stresses on all of the meshes passing over the die shoulder are different from the actual stresses. In other

words, the stress distribution is also different from the actual stress distribution of the vertical wall on the workpiece at bottom dead center. The decrease in accuracy of the springback analysis caused by the discretization error of the drawbead and the die shoulder is an important issue in using sheet metal forming simulation in actual production.

For the above reasons, a method to improve the prediction accuracy of the shape after springback, which can also suppress the increase in calculation time of the forming analysis, is required. An adaptive method [10] is generally used to shorten the calculation time without increasing the discretization error. However, in the case of sheet metal forming simulation using the dynamic explicit method, the mesh size of the drawbead and the die shoulder becomes smaller at the beginning of the forming simulation. As a result, the time increment becomes smaller, and the number of calculation cycles increases. Therefore, the shortening of the calculation time is limited. As such, a new approach that is different from the adaptive method is required.

The influence on the forming analysis accuracy of the drawing process is great in drawbead and die shoulder areas of the dies. In other words, the areas that have a significant influence on the analysis accuracy are obvious prior to the analysis. Therefore, we propose a method by which to bring the analytical model of the drawbead and the die shoulder close to the actual shape. Specifically, we create a database of the drawbead and the die shoulder and replace the analysis results for the normal forming process with the information registered in the database. In the proposed method, the calculation time in the forming analysis does not increase because the analysis model is the same as in the normal forming analysis. The procedure is described below. First, the high-speed forming process with a coarse mesh size, the shape of which does not match the actual shape, is performed. Then, the shape, stress, equivalent plastic strain, and sheet thickness concerning the drawbead and the die shoulder obtained from the normal forming analysis are replaced with the values registered in the database. By the above database mapping process, the analysis model used for the springback analysis can express the actual state well. As a result, highly accurate springback analysis is expected. In the present paper, the accuracy of the analysis based on the proposed method is verified by conducting a forming experiment.

2 A novel approach to springback analysis using a drawbead and a die shoulder database

The procedure of the proposed method is described in the following. First, the analysis in the forming process using the equivalent drawbead model is performed using the same procedure as normal analysis in the forming process. Detailed partial analysis

of the drawbead and the die shoulder are then performed, and the results are stored as a database. The shape, stress, equivalent plastic strain, and sheet thickness of the workpiece in the drawbead, the die shoulder, and the portion passing through the drawbead or over the die shoulder (mainly the vertical wall) are then replaced by the values of the database obtained by detailed partial analysis. The above procedure is shown in Fig. 1. The “forming analysis” mentioned in the present paper is denoted as process (1) in Fig. 1(b), and the “springback analysis” is denoted as process (5) in Fig. 1(b). In this section, we describe the creation method of each database, the method of morphology mapping, and the method of data mapping of stress, equivalent plastic strain, and sheet thickness.

2.1 Detailed partial analysis of the drawbead part and creation of the database

2.1.1 Analysis model of the drawbead

Analytical models are created to pass a strip-shaped workpiece between upper and lower dies simulating the cross-sectional shape of the drawbead, as shown in Fig. 2. The

Fig. 2 Drawbead model

workpiece is then pressed between the upper and lower dies until the clearance between the upper and lower dies reached the set value with the end of one side of the workpiece fixed. The set value of the clearance is determined by referring to the clearance between the upper and lower dies at bottom dead center in the analysis of the forming process performed before the analysis of the drawbead. Thereafter, the position of the die is fixed to the set clearance with the workpiece clamped between the upper and lower dies. The fixing condition of the end portion on one side of the workpiece is canceled. Then, the drawing process of the workpiece is performed by applying a constant speed to the end portion of the workpiece. When performing the drawbead analysis, the plane strain constraint is imposed in the width direction of the workpiece. Furthermore, the mesh size of the workpiece must be divided into three or more corner radii in the drawbead in order to express the actual deformation. Regarding the other analysis conditions, there is no problem under the same conditions as in the analysis of the normal forming process. However, the stress distribution can be set with higher precision by considering the contact surface pressure dependence of the Coulomb friction coefficient [11], the strain rate dependence of the flow stress [12], and the Bauschinger effect.

2.1.2 Database for the drawbead

The coordinates on the neutral plane in each element center on the workpiece (x and z coordinates in Fig. 3), the sheet thickness, the stress in each direction, and the equivalent plastic strain are described in the database of the drawbead. In addition, the data are obtained by a detailed partial analysis of the drawbead and are listed in order in the drawing direction of the workpiece. Here, each direction stress and equivalent plastic strain includes all values of each integral point in the cross-

Fig. 1 Conventional and proposed methods of springback prediction

- (1) Distance from the drawbead center in the X-direction
- (2) Coordinate of the neutral plane in the Z-direction
- (3) Thickness
- (4) Equivalent plastic strain (layers 1 through N)
- (5) Local Stress X,Y, and XY (layers 1 through N)
- (6) Drawing direction

Fig. 3 Drawbead database in the case of having N layers in the thickness direction

sectional direction (see Fig. 3). Detailed partial analysis using the FEM is performed on all drawbeads necessary for the analysis of the forming process, and a database is created based for each drawbead analysis.

A method for referring to the database is described in the following. Here, it is necessary to ensure that the coordinate system in the forming process analysis does not coincide with the coordinate system of the database. First, the distance between the node coordinates of the workpiece to be referred to the database and the center coordinate of the equivalent drawbead is obtained using the analysis results of the forming process. The distance in the drawing direction (the distance in the x axis direction in Fig. 3) between each node coordinate in the database and the drawbead center coordinate is then calculated using the coordinate system in the database. The node coordinate in the database in which the above two distances coincide is the node coordinate on the workpiece to which the database is referred in the analysis result of the forming process. However, since two such nodes exist, one on the workpiece before passing through the drawbead and one on the workpiece after passing through the drawbead, it is necessary to define a vector in the flow direction of the blank in the database in order to specify the state (before or after passing through the drawbead).

2.2 Detailed partial analysis of the die shoulder and creation of the database

2.2.1 Analysis model of the die shoulder

The workpiece passes over the die shoulder while receiving a rearward tension generated by the drawbead. Therefore, it is necessary to perform a detailed partial analysis of both the drawbead and the die shoulder in order to obtain the database of the die shoulder. A detailed partial analysis model is created, in which a rectangular workpiece passes through the drawbead and over the die shoulder, as shown in Fig. 4. First, the workpiece is sandwiched until the clearance between

Fig. 4 Die shoulder model

the upper and lower dies simulating the drawbead reaches the set value while fixing the end of one side of the workpiece as in the analysis of the drawbead. Then, the position of the upper die is fixed, and the fixed end on one side of the workpiece is released. Thereafter, the end of the workpiece on the tool side simulating the die shoulder is given a constant speed downward. The plane strain constraint is set in the width direction of the workpiece. The other analysis conditions are the same as the detailed partial analysis of the drawbead.

2.2.2 Die shoulder database

In the database of the die shoulder, the coordinates of each element center on the workpiece (x and z coordinates in Fig. 5), the sheet thickness, the stress in each direction, and the equivalent plastic strain are described. In addition, the data are obtained by detailed partial analysis of the drawbead, and the data are listed in order of the drawing direction of the workpiece. Here, each direction stress and equivalent plastic strain includes all values of each integral point in the cross-sectional direction (see Fig. 5). As mentioned in the previous section, the backward tension on the die shoulder depends on the shape of the drawbead before passing over the die shoulder. Therefore, a database of each die shoulder is created for each drawbead.

Furthermore, analysis by the model using only the die shoulder without the drawbead is necessary in order to create the database of parts passing over the die shoulder without passing through the drawbead. Moreover, the coordinates of the center of the die shoulder radius of the die simulating the die shoulder are stored in each database as the center

Fig. 5 Die shoulder database in the case of having N layers in the thickness direction

- (1) Distance from the radius center in the X-direction
- (2) Distance from the radius center in the Z-direction
- (3) Thickness
- (4) Equivalent plastic strain (layers 1 through N)
- (5) Local Stress X, Y, and XY (layers 1 through N)
- (6) Drawing direction

coordinates of the die shoulder radius. The method used to refer to the database is described below. First, the distance between the node coordinates of the workpiece to be referred to the database and the center coordinate of the die shoulder radius is obtained using the analysis results of the forming process. Then, the distance in the drawing direction (the distance on the xz plane in Fig. 5) between each node coordinate and the center coordinate of the die shoulder is calculated using the coordinate system in the database. The node position in the database where the above two distances coincide is the coordinate of the node on the workpiece to which the database is referred in the analysis results of the forming process. However, since two such nodes exist, one on the workpiece before passing over the die shoulder and one on the workpiece after passing over the die shoulder, it is necessary to define a vector in the flow direction of the blank in the database in order to specify the state (before or after passing over the die shoulder).

2.3 Database mapping and morphing method

In this section, we describe the method of modifying the shape, sheet thickness, stress, and equivalent plastic strain in the workpiece at bottom dead center obtained by the forming process analysis. The database created to this point is used in this section.

2.3.1 Classification of each element of the workpiece and data mapping process

All elements of the workpiece are classified into the following seven types focusing on whether or not the workpiece has passed through the drawbead and over the die shoulder during the forming process. The classification is shown in Fig. 6. The classification of each element and the data mapping procedure for each classification are described below. The method of actually classifying each element and the method of choosing the database corresponding to the position of each element are described in the following.

- (1) Elements of the workpiece passed through the drawbead and over the die shoulder during the forming process

For each element of the workpiece, the corresponding die shoulder database is selected in reference to the drawbead through which the workpiece passes. The values of stress, sheet thickness, and equivalent plastic strain described in the selected database after passing over the die shoulder are then replaced with the values of each of the elements of the workpiece.

- (2) Elements of the workpiece passed over only the die shoulder during the forming process

The stress, sheet thickness, and equivalent plastic strain after passing over the die shoulder, which are described in the die shoulder database analyzed with a die and without a drawbead, are replaced with the values of each of the elements of the workpiece.

- (3) Elements of the workpiece passing through the drawbead after the forming process and remaining on the die shoulder at bottom dead center

Fig. 6 Classification of elements of the workpiece

For each element of the workpiece, the corresponding die shoulder database is selected with reference to the drawbead through which the workpiece passes. The shape, stress, sheet thickness, and equivalent plastic strain corresponding to the position of each element of the workpiece are then extracted from the database and replaced with the values of each of the elements of the workpiece.

- (4) Elements of the workpiece do not pass through the drawbead during the forming process and remain on the die shoulder at bottom dead center

For each element of the workpiece, the corresponding die shoulder database is selected with reference to the die shoulder model without the drawbead. The shape, stress, sheet thickness, and equivalent plastic strain corresponding to the position of each element of the workpiece are then extracted from the database and replaced with the values of each of the elements of the workpiece.

- (5) Elements of the workpiece only passed through the drawbead during the forming process

The drawbead through which the workpiece passes is referred to in order to select the corresponding drawbead database for each element of the workpiece. The stress, sheet thickness, and equivalent plastic strain after passing through the drawbead, as described in the selected database, are then replaced with the values of each of the elements of the workpiece.

- (6) Elements of the workpiece remaining on the drawbead at bottom dead center

The drawbead through which the workpiece passes is referred to in order to select the corresponding drawbead database for each element of the workpiece. The shape, stress, sheet thickness, and equivalent plastic strain corresponding to the position of each element of the workpiece in the selected database are then replaced with the values of each of the elements of the workpiece.

- (7) Elements that do not pass through the drawbead or over the die shoulder

No processing is performed for the elements that do not pass through both the drawbead or over the die shoulder.

2.3.2 Distinguishing the elements passing the drawbead and the method of data mapping and morphology mapping

In this section, the accompanying drawbeads are identified for all nodes of the workpiece with the line elements of

the equivalent drawbeads used in the analysis of the forming process. Here, the accompanying drawbeads indicate drawbeads estimated assuming the forming process continued without breaking. Details of the specified method are shown below. First, the distance from each node on the workpiece before forming to each node constituting the equivalent drawbead is calculated. The node constituting the equivalent drawbead at the closest distance from each node on the workpiece is identified. Then, two angles formed by a line element including the node on the equivalent drawbead identified above and a line element connecting the node on the workpiece and the node on the equivalent drawbead identified above are obtained. The smaller of the angles is set as the line element of the equivalent drawbead to which the node on the workpiece is related. In such a procedure, it is possible to define the accompanying drawbead for all nodes of the workpiece. The above procedure is shown in Fig. 7. Furthermore, when creating the analysis model, the node numbers that make up the equivalent drawbead must be defined as

1: Sort nodes on the workpiece by the closest drawbead node

2: Sort nodes on the workpiece before deformation by the associated drawbead segment

Fig. 7 Procedure for the classification of nodes on the workpiece by the associated drawbead segment

follows. First, the drawbead vector is defined as the vector connecting the nodes on the equivalent drawbead in order of the node number. The right-hand side of the drawbead vector is the inside of the drawbead (vertical wall side), and the left-hand side of the drawbead vector is the outside of the drawbead (flange side). Then, the nodes that may pass through the drawbead during forming are the nodes on the left-hand side of the drawbead vector. After forming, all nodes of the workpiece that may pass through the drawbead are projected in a direction perpendicular to the press stroke direction. The nodes on the workpiece passing through the drawbead are the nodes on the right-hand side of the relevant drawbead vector. The nodes that do not pass through the drawbead center are the nodes on the left-hand side of the drawbead vector (see Fig. 8). Here, note that the direction of the drawbead vector is reversed on the left- and right-hand sides of the flange shown in Fig. 8. The method of finding the nodes deformed by the drawbead is as follows. The distance between the node of the workpiece and the line element formed by the accompanying equivalent drawbead is calculated. The node for which the distance is smaller than the drawbead length in the database is a node deformed by the drawbead. The elements deformed by the drawbead are the elements constituting the nodes on the workpiece detected by the above method. Then, each element is divided into five equal elements with respect to the elements deformed by the drawbead. The distance between each node deformed by the drawbead and the drawbead center is collated with the database, as shown in Section 2.1. The nodes are moved in a direction perpendicular to the flange surface. The drawbead described in the database is morphology mapped to the workpiece by the above procedure, as shown in Fig. 9. At the same time, the stress, sheet

Fig. 8 Positional relationship between the node on the workpiece and the node on the drawbead

- 1: Search the nodes for which the distance from the drawbead center is within the drawbead database

- 2: Search the elements that include all nodes identified by the previous step

- 3: Subdivide the elements identified in the previous step

- 4: Configure the Z-coordinate with reference to the distance from the drawbead center

Fig. 9 Procedure of morphology mapping of the drawbead

thickness, and equivalent plastic strain are corrected with reference to the database.

2.3.3 Distinguishing the elements of the workpiece passing over the die shoulder and the method of database mapping and morphology mapping

It is necessary to prepare a file describing the group of nodes at the entrance and the exit of the die shoulder node on the die (hereinafter referred to as the node group file) in order to distinguish the elements passing over the die shoulder. This is because the position of the die shoulder on the die cannot be determined based on the analysis results of the ordinary forming process. It is possible to identify the die shoulder to which each node on the workpiece is related using the entrance node group on the die shoulder described in the node group file. This procedure is similar to the identification of the drawbead (see Fig. 7). As shown in Fig. 10, the nodes deformed by the die shoulder can be identified as follows. First, the distance L_{in} is defined as the distance between each

Fig. 10 Die shoulder identification procedure

node on the workpiece and the entrance node group on the die shoulder. Then, the distance L_{out} is defined as the distance between each node on the workpiece and the exit node group. Furthermore, the distance between the entrance node group and the exit node group is $\sqrt{2}a$ (a : die shoulder radius). When $L_{in} < \sqrt{2}a$ and $L_{out} < \sqrt{2}a$, the nodes are bent by the die shoulder. Furthermore, when creating the node group file, the order of the description must be as follows. The die shoulder entrance and exit nodes are defined in order from the right-hand side in the forward direction toward the inside of the die shoulder (vertical wall side), as in the case of the drawbead, and the die shoulder entrance and exit nodes are defined in order from the left-hand side in the forward direction toward the outside of the die shoulder (flange side). Then, the die shoulder entry vector can be defined as the vector connecting the entry node group of the die shoulder in order as defined in the node group file. The nodes on the left-hand side of the die shoulder entry vector are the nodes on the workpiece that may pass over the die

shoulder by the forming. As in the case of the drawbead, after the forming, all nodes of the workpiece that may pass over the die shoulder are projected in a direction perpendicular to the press stroke direction. At this time, the nodes on the workpiece that do not pass over the die shoulder are nodes on the left-hand side of the die shoulder entry vector. Based on the above considerations, the nodes that passed over the die shoulder are the nodes on the left-hand side of the die shoulder entry vector before the forming analysis and the nodes on the right-hand side of the die shoulder after the forming analysis. Then, each element is divided into five equal elements with respect to the elements bent by the die shoulder, as in the case of the drawbead. After that, the distance between each node bent by the die shoulder and the center of the die shoulder is collated with the database, and the nodes are moved in the direction of the center of the die shoulder. The die shoulder described in the database is morphology mapped to the workpiece using the above procedure shown in Fig. 11. At the same time as the morphology mapping, the stress, sheet thickness, and equivalent plastic strain are modified with reference to the

Fig. 11 Procedure of morphology mapping of the die shoulder

database, as in the case of the drawbead. In addition, the stress in each direction is converted from the coordinate system in the detailed partial analysis to the coordinate system in the forming analysis.

2.3.4 Element subdivision method

The method used to subdivide the elements on the workpiece identified to be the drawbead and the die shoulder is described in the following. As shown in Fig. 12, one side of the mesh used in the analysis of the forming process is divided into five elements. When both subdivided areas and non-subdivided areas exist for each side constituting one element, the areas are classified as follows and are divided as shown in Fig. 12, where (a) shows the case in which three sides are subdivided, (b) shows the case in which two adjacent sides are subdivided, (c) shows the case in which two opposing sides are subdivided, and (d) shows the case in which one side is subdivided.

2.3.5 Example of the mapping process

In this section, an example of the mapping process described above is presented. An example of classification of the elements shown in Fig. 6 is shown in Fig. 13. Element A in Fig. 13 is present outside the drawbead before forming and moves into the drawbead after forming. Therefore, element A is classified as (6) in Section 2.3.1. Moreover, a schematic diagram of the morphology mapping is shown in Fig. 14. After the drawbead and the die shoulder on the workpiece are identified, these elements are subdivided. At the same time, the boundaries between the subdivided region and the non-subdivided region are combined as shown in Fig. 12.

Fig. 12 Patterns of mesh subdivision

3 Springback analysis for the forming experiment using the proposed method

3.1 Experiment setup

Drawing experiments were performed using a die, a blank holder, and a punch having the dimensions shown in Fig. 15. The material of the workpiece is extremely-low-carbon cold-rolled galvanized steel sheet of 270-MPa grade and 0.7-mm sheet thickness. The mechanical properties are shown in Table 1. The dies were made of spheroidal graphite cast iron, and the surface was chrome plated. The blank holder pressure was set at 60 kN, and the stroke of the punch was set at 50 mm.

3.2 Calculation conditions of the FE analysis

For the calculation of the forming process, LS-DYNA (commercially available FEM software) was used as a dynamic explicit method, and JOH-NIKE was used as a static implicit method in the springback analysis. The mesh on the workpiece was divided such that the average element side length was 3 mm. The number of elements was 16,874. Other analysis conditions are shown in Table 2. In addition, the Bauschinger effect was taken into consideration using a method of changing the material properties with reference to the prestrain in the springback analysis [13, 14]. The equivalent drawbead model was used for the drawbead. The dies in the analysis model in the forming process was changed such that die shoulder radius was 3 mm because the bending deformation cannot be expressed by the analysis using the workpiece mesh of 3 mm for a die shoulder radius of 1 mm. In the proposed method, after analyzing the forming process, the bending shape of the workpiece achieved by the die shoulder radius of 1 mm is reproduced using the database. The number of calculation cycles for the dynamic explicit method was 101,614.

3.3 Creation of a database of the drawbead and the die shoulder

As shown in Fig. 16, the dies in the experiment considers three drawbeads and a die shoulder radius of 1 mm. Three drawbead databases and two die shoulder databases are created. Although only one die shoulder is considered, two databases are required: a database for the case in which the workpiece passes through drawbead C and a database for the case in which the workpiece does not pass through drawbead C. The clearance between the upper and lower dies in the analysis was set to 0.95 mm, which was obtained analytically in the forming process. The detailed partial analysis of the drawbead was performed using a shell element with a mesh size of 0.35 mm. The detailed partial analysis of the die shoulder was performed using a solid element with a mesh size of 0.05 mm. The other analysis conditions were as listed in

Fig. 13 Schematic diagram of the example of element classification

Table 2. The calculation time of the detailed partial analysis was approximately 100 min in the case of using the shell element and approximately 250 min in the case of using the solid element. The calculations were conducted using a Xeon X5680 processor, and parallel computation was not performed.

3.4 Results and discussion

The three drawbead databases and two die shoulder databases described above were applied to the analysis of the forming

process using the equivalent drawbead model. Figure 17(a) shows the shape and the equivalent stress distribution of the workpiece at bottom dead center in the normal forming analysis. Figure 17(b) shows the shape and the equivalent stress distribution on the workpiece to which the shape in the database is morphology mapped and to which the values in the database are mapped by the proposed method. These figures indicate that the shapes and stress distributions of the drawbeads and die shoulders changed greatly as a result of the use of the database.

Figure 18 shows a photograph of the product obtained in the forming experiment and the position at which the cross-sectional shape was evaluated. Figure 19 shows the cross-sectional shapes obtained using the proposed method, the conventional method, and experimentally. The root-mean-square-error of the cross-sectional shape obtained by the experiment and that obtained by the proposed method was 0.35 mm, whereas that obtained by the conventional method was 0.88 mm. Therefore, improvement of the prediction accuracy of the springback was able to be confirmed. The difference between the experiment and the analysis was large for the flange end and the vertical wall indicated by (A) through (C) in Fig. 19. Therefore, the prediction errors of the shapes in (A) through (C) in Fig. 19 are shown in Fig. 20. The distance between the flange ends of the experiment and the analysis is shown at sites (A) and (B), and the maximum value of the experimentally and analytically obtained distances in the

Fig. 14 Schematic diagram of the morphology mapping example

Fig. 15 Setup and dimensions used in the drawing test

direction perpendicular to the cross-sectional line at site (C). The product shape obtained in the forming experiment is small compared to parts such as car body panels. Therefore, the maximum shape error between the experiment and the analysis using the conventional method was 2.5 mm. However, in the case of forming of a car body panel, it was inferred that it would be difficult to predict whether a shape obtained by the conventional method would fall within design tolerance,

Table 1 Mechanical properties of the ultralow-carbon steel

YS/MPa	TS/MPa	EL/%	<i>r</i> value	<i>n</i> value
170	305	44	1.50	0.22

Table 2 Analysis conditions of the drawing test

Model of blank sheet	Elastoplastic body (shell element) (average mesh size: 3 mm)
Model of dies	Rigid shell body (shell element)
Formulation of solver	Forming: dynamic explicit Springback: static implicit
Type of elements	Belytschko-Tsay
Contact property model	Surface-to-surface model
Material model	Hill'48
Friction formulation	Coulomb's law (pressure dependence is considered)

because the value of the shape error becomes larger for large products. Consequently, in the past, it was necessary to evaluate springback by repeating the analysis and forming experiments in order to manufacture products within tolerance, which lengthened the springback compensation period. On the other hand, all of the shape errors in the proposed method were within 0.5 mm. Therefore, the possibility of evaluating the springback shape of large products without forming experiments was demonstrated. Table 3 shows the calculation times of the proposed method and the conventional method. The CPU used for the calculation was a Xeon X 5680, and parallel calculation was not performed. The calculation times for the analysis in the forming process using the conventional method and the proposed method were the same at 172 min because both analyses used the same FE model. On the other hand, the calculation time of the springback analysis was 1.3 min for the conventional method. The calculation time of the springback analysis by the proposed method increased to 8.8 min because of the increase in the number of elements and the increase in the number of convergence calculations. However, the increase in calculation time by the proposed method is only approximately 4.3% of the total time because the analysis time of the forming process is much longer. Based

	R_H	r_H	h_H	R_D	r_D	h_D
A	10	9.65	2	11.15	9	2.5
B	5	4.65	3	6.15	4	3.5
C	10	9.65	2	11.15	9	2.5

Fig. 16 Dimensions of the drawbeads

Fig. 17 Workpiece at bottom dead center before and after data and morphology mapping

on the above considerations, using the proposed method, the calculation accuracy can be improved with only a small increase in the calculation time. On the other hand, the proposed method requires a calculation time for detailed partial analysis in order to create a database. However, the number of

Fig. 18 Photograph of the formed workpiece and the evaluated cross section

Fig. 19 Cross sections of workpieces formed by the proposed method and the conventional method

Fig. 20 Prediction errors of the proposed method and the conventional method

Table 3 Comparison of computation time

	Conventional method	Proposed method
Forming	172 min	172 min
Springback	1.3 min	8.8 min
Total	173.3 min	180.8 min

drawbead shapes and die shoulder shapes used in the dies is limited. Therefore, the same database can be used for a variety of products. Once all of the databases are created, highly accurate springback analysis can be performed with a computation time similar to that expected in conventional springback analysis.

4 Conclusions

A springback analysis approach using a database was developed in order to improve the springback prediction accuracy, which can also suppress the increase in calculation time in the analysis of the large automotive parts. The main features of the proposed method and the verification results of calculation accuracy are as follows:

The procedure of the proposed method is as follows. The forming process of the workpiece using the equivalent drawbead model is first analyzed. A detailed partial analysis of the drawbead and the die shoulder is then performed, and the results are saved as a database. Next, the analysis results of the forming process for the shape, sheet thickness, stress, and equivalent plastic strain of the drawbead and the die shoulder are then replaced with the values in the database. By performing springback analysis after the above-described procedure, the springback prediction accuracy can be improved.

The calculation accuracy of the proposed method was verification by a forming experiment. The proposed method was confirmed to greatly improve the prediction accuracy of the shape after springback, despite using the normal FE model in the forming process. The increase in calculation time by the proposed method is only approximately 4.3% of the total time.

In the future, we intend to develop a data mapping method considering the stretch and shrink flange deformation that occurs at the corner. We expect that the springback prediction accuracy of a complicated shape will be further improved by using the improved data mapping method.

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