Research Report

Numerical Prediction of the Spring-Back Behavior of Stamped Metal Sheets

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Abstract

This paper describes our study of the spring-back behavior of a sheet that has been bent into a hat shape, with the goal of establishing a system for predicting all the shape defects that may occur in formed sheet products. We also examine the stamping of a three-dimensional rail panel that would normally be expected to twist. For the sake of computational efficiency, we used the dynamic explicit method in our simulation of the forming process, after which we applied the static implicit method for the unloading process. The most notable finding arising from this study is that, in order to precisely predict the spring-back behavior, the non-linear properties of the sheet material during unloading must be taken into consideration. We propose methods for measuring the nonlinearity, as well as a material model for expressing the characteristic behaviors (i.e., the strain-dependent pseudo-elastic modulus and the Bauschinger effect). The results obtained with the proposed methods (together with the proposed material model) are compared with those obtained experimentally. Furthermore, we also applied the proposed method to the elastic deformation of dies, and the shape obtained theoretically was compared with actual measurements. We confirmed that the proposed method can precisely predict the spring-back shape.

Keywords: Spring-back behavior, Sheet metal forming, Bauschinger effect, Strain-dependent elastic modulus, Elastic deformation of die, Finite element method, Hat-shape forming

1. Introduction

The numerical simulation of sheet metal forming is used widely nowadays, mainly for examining the formability of a vehicle's outer panels. Although numerical simulation can be used to calculate the spring-back shape after forming, to date the accuracy of such simulations has failed to reach a level that can be put to practical use. Further studies of numerical mechanical property modeling and computation techniques are needed to improve the accuracy. Several research projects have already examined the mechanical properties associated with the spring-back behavior of a material,[1, 2] and models based on the results of these studies have been introduced into spring-back calculations to improve the accuracy of two-dimensional problems.[3, 4]

Based on the results of our experiments, in this paper we introduce a means of measuring the mechanical properties during a continuous tensile-unloading-compression process, which is one of the main influences on the spring-back phenomenon, and present the results of our measurements. Our results lead us to adopt a mechanical property model for expressing characteristic behaviors (i.e., the strain-dependent elastic modulus and the Bauschinger effect), which we then introduce into FEM. Furthermore, we also consider the influence of the elastic deformation of the dies used in the stamping process. The spring-back behavior of a sheet bent into a hat-shape and that of a stamped rail panel are calculated using proposed method as a three-dimensional problem, and the prediction accuracy is verified by comparing the calculated results with those obtained experimentally.

2. Measurement method and obtained stress-strain curve

2. 1 Test materials and specimen dimensions

We tested nine kinds of steel sheets, having different thicknesses and tensile strengths. Their mechanical properties are listed in **Table 1**. We selected this range to correspond to the materials used for the stamped parts of a standard automobile body. The dimensions of the specimen, which we determined by FEM analysis, are shown in **Fig. 1**. The length of the parallel part and the width were both less than those of the specimens that are normally used in tensile tests.

2. 2 Measurement method

Two wire strain gauges were attached to the center of the parallel part of the specimen, which was then chucked into a fatigue testing machine, subjected to the required strain, and then compressed. The dimensions of the specimen shown in Fig. 1 were selected to prevent the specimen from buckling in compression. In addition, we used a jig which sandwiched the specimen. **Figure 2** shows the testing apparatus. Next, we measured the relationship between the extension and load, from which we obtained the true stress vs. true strain curve for both the loading and unloading processes.

2. 3 Results of measurement

Figure 3 shows an example of the measurement results. During the test, the specimen was subjected to a strain of 0.03, 0.04, 0.06, 0.08 or 0.11 (pre-strain) and then subsequently unloaded and compressed. The curve for the proposed method coincides well with that for a regular tensile test, which is also shown in the figure. This confirms

Table 1 Mechanical properties of tested materials.

Material	σ_Y /MPa	TS /MPa	n-value	r-value	Thickness /mm
A	224	347	0.226	0.931	1.938
B	234	334	0.198	0.964	2.871
C	287	364	0.136	0.898	4.410
D	364	472	0.169	0.883	2.002
E	313	452	0.174	0.930	2.928
F	360	465	0.144	0.936	4.478
G	522	602	0.121	0.906	2.030
H	493	571	0.124	0.962	2.895
I	514	582	0.120	0.846	4.498

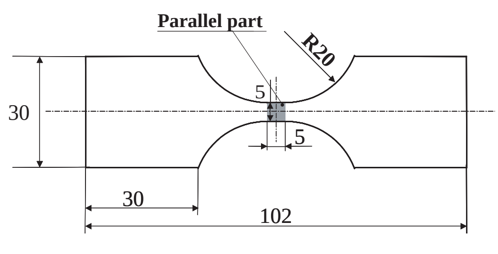

Fig. 1 Dimension of specimen.

that the specimen deformation was entirely uniaxial in the test. The actual unloading curve and that obtained with the isotropic hardening model are plotted in Fig. 3. The actual curve lies above that obtained with the model, and descends more gradually. This implies that the material has a non-linear property that results from the so-called Bauschinger effect during unloading. **Figure 4** shows the relationship between the instantaneous slope (i.e., the pseudo-elastic modulus) of the tensed sheet at the beginning of unloading and pre-strain. The pseudo-elastic modulus falls within a range of 10 to 20% when a pre-strain is applied, and is almost constant for pre-strains in excess of 0.02.

3. Mechanical property modeling during unloading

Given the above results, we can say that, during unloading, (1) the tangential pseudo-elastic modulus during unloading depends on the pre-strain, and (2) the non-linearity of the stress-strain curve (S-S curve) is significant. A simple and direct expression model (SD model) for the S-S curve is shown in **Fig. 5**. We then applied a linear combined hardening model composed of parallelograms. This was made to fit the measured curve only within the region in which the material will actually experience strain during unloading, as shown in Fig. 5. Since the shape of the S-S curve varies with the pre-strain, we prepared a different approximation for every pre-strain value. If we look at the S-S curve for reloading after complete unloading, we find that it is very different from that during unloading. The proposed model, however, expresses the actual property during unloading directly and thus precisely. This method thus offers the advantage of allowing the unloading

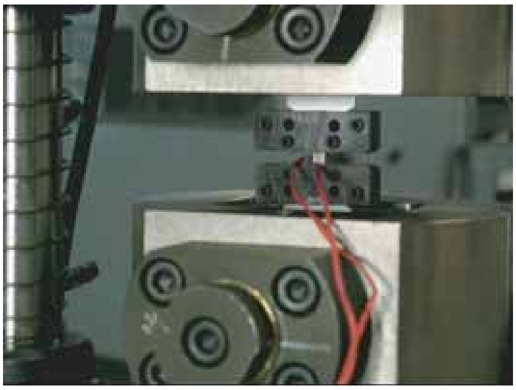

Fig. 2 Photographical view of proposed test.

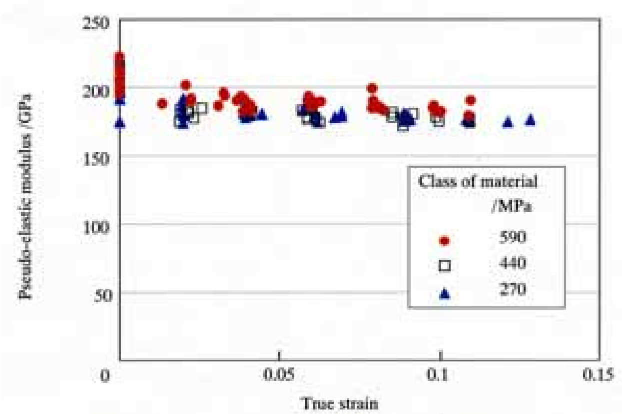

Fig. 4 Variation of pseudo-elastic modulus with pre-strain.

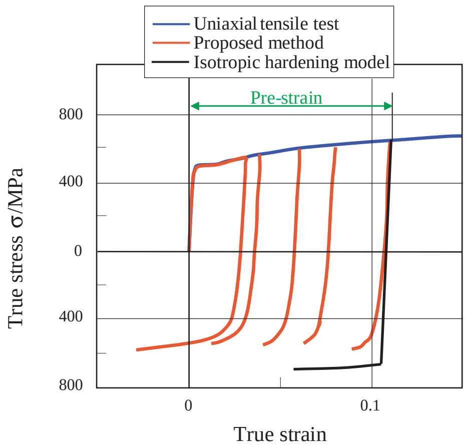

Fig. 3 Stress-strain curve during tension-compression test.

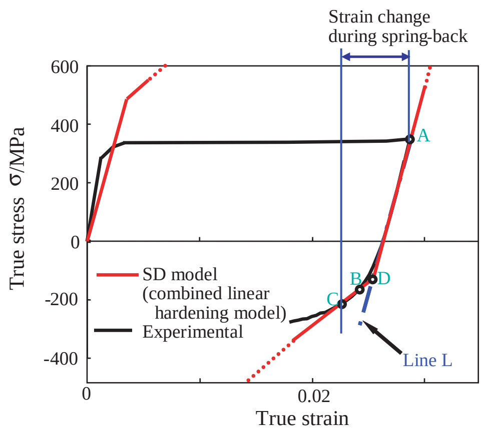

Fig. 5 SD model of S-S curve during unloading.

process to be calculated easily by using a commercially available software material model. Next, the input data is modified to express the unloading property. Some new material constants and back stress are added and the equivalent plastic strains are modified.

4. Consideration of elastic deformation of dies

In sheet metal forming simulations, the dies are generally assumed to be rigid bodies that do not deform. When, however, the deformed shape is three-dimensional and can be expected to twist after the dies are opened, it is usually assumed that the stress distribution of the panel at the bottom dead center will be influenced by the elastic deformation of the dies. In this case, the dies are modeled as an elastic body. The dies are divided into solid elements, and a load of 1.43 KN which is actual load applied by each hydraulic cylinder (**Fig. 6**).

5. Results and discussion

The forming process was modeled using the commercially available LS-DYNA code as a 3D problem, which features a dynamic explicit algorithm. The blank is subdivided into assumed strain elements. To suppress the dynamic effect as much as possible, the forming speed was set to 2 m/s and 1 m/s after several trials. The unloading process was calculated using the commercially available JOH-NIKE code, which features a static implicit algorithm. Additionally, the authors improved the code to allow the inclusion of back stress in the input data.

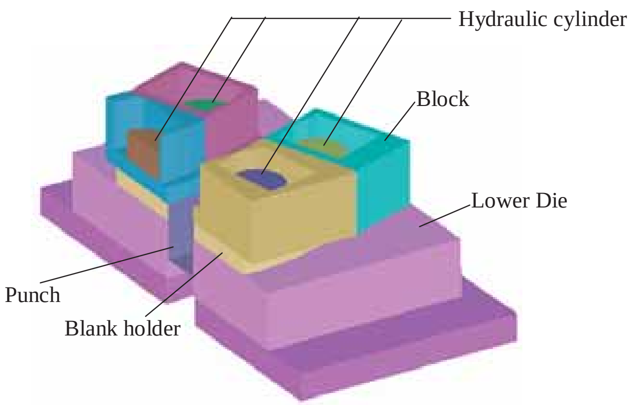

Fig. 6 Modeling of elastic die.

The proposed numerical method was verified by applying it to the hat-shape bending process and a stamped rail model panel.

5. 1 Hat-shape bending process

Figure 7 shows the set-up of the dies. To evaluate the features of the spring-back, the rim expansion and irregular warping in the cross-section of the sheet were measured, as shown in **Fig. 8**, and compared with the results of the experiments.

Figure 9 shows the relationship between the normalized punch load (= load divided by cross-section ×ultimate tensile strength of the material) and the opening distance *d* after spring-back. Several cases were tested with a range of blank-holding forces in order to check the effect of the tension applied to the blank. The normalized punch load was used for comparing the results for all of the test conditions. This figure confirms that the numerical results obtained with both of the proposed methods agree well with the experimental results. Namely, it is very effective in taking particular

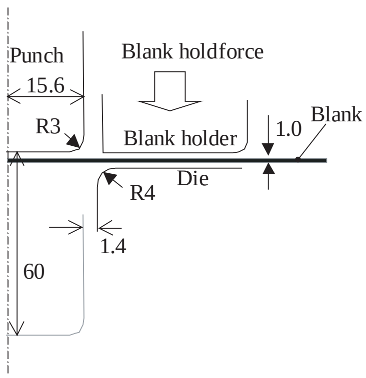

Fig. 7 Tool set-up and the blank.

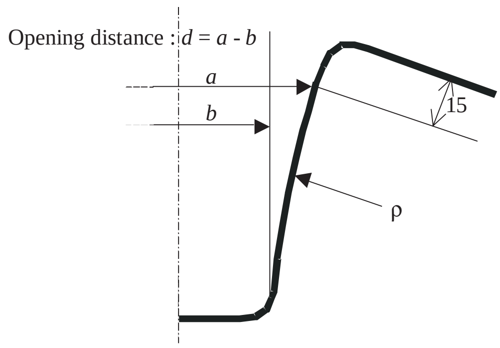

Fig. 8 Measure of sheet geometry after spring-back.

properties into account during unloading, such as the apparent decrease in the pseudo-elastic modulus and the Bauschinger effect. The mechanical property model used in the process simulation barely influences the shape after unloading. On the other hand, the conventional isotropic hardening model produces smaller values for the opening distance *d* than those derived from the experiments.

Figure 10 shows an example of the spring-back shape of a sheet for a normalized punch load of about 0.5. On the right-hand side of this figure, two numerical results are depicted together with that obtained by experiment. The shape predicted by the proposed method almost coincides with that obtained by experiment. When the isotropic hardening model is applied, the entire sheet is unloaded elastically. When the proposed model is applied, however, the plastic deformation occurs over a broad area during the unloading process. This is due to the low pseudo-elastic modulus and the Bauschinger effect causing a large spring-back similar to that observed in the experiments.

5. 2 Stamped rail model panel

The deformed shape obtained with the adopted model process is shown in **Fig. 11**. The cross-section is a hat-shape similar to that shown in Fig. 7, and the top-view of the central part is circular, as shown in **Fig. 12**. The work was held with a blank holder, and was deformed into the hat-shape with a punch. It was deformed so as to have a cross-section like that produced by the hat-shape bending process. The wall curvature changes with the position, since the tension differs between the shrink-flanging and the stretch-flanging. We expected that the non-uniform tension distribution would cause the panel to twist. Moreover, it has been reported that the length of the flange and the in-plane stress within the flange influence the spring-back behavior of the panel.[5)]

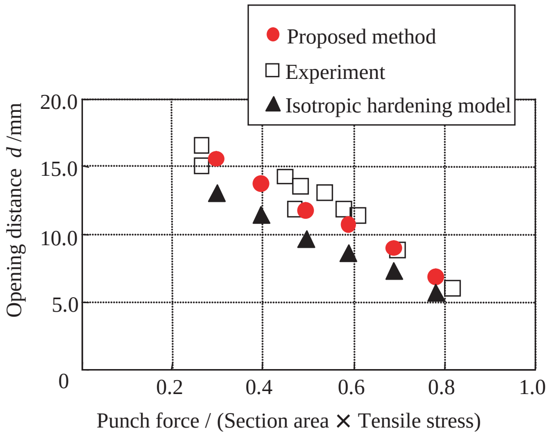

Fig. 9 Rim opening distance *d* vs. normalized punch load.

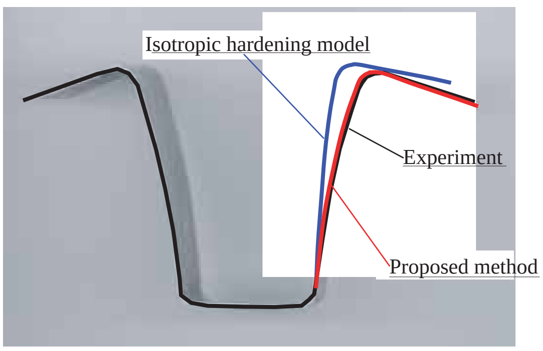

Fig. 10 Comparison of spring-backed shapes.

Fig. 11 Photographical view of stamping rail model panel.

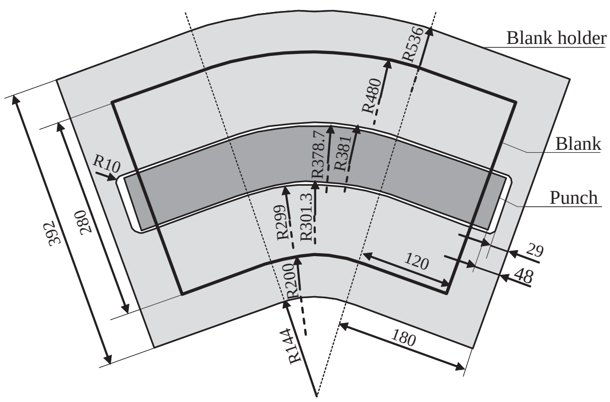

Fig. 12 Shape of die face from top view.

The calculation method that we used is fundamentally the same as that described in **Section 5. 1.** Furthermore, the elastic deformation of the dies is calculated as part of the same process.

A comparison of the calculated spring-back shape and that obtained by experiment is plotted in **Fig. 13**. The result for a rigid body die is also shown. Although the numerically obtained cross-sectional shape for the rigid die differs from that obtained by experiment, the calculated result when elastic die deformation is taken into consideration is within $\pm 3/2\sigma$ (σ : standard deviation) of the value obtained experimentally. Moreover, we can calculate that the upper surface of the panel used in the experiment is twisted by about 1.5 mm. **Figure 14** shows the numerical contours for the pressure distribution in the flange, which are compared with the results obtained by experiment. The actual pressure at the edge of the flange is higher than that in the other areas. In the case of the rigid die model, the pressure is concentrated at the shrink-flanging part, where the thickness increases. On the other hand, when we take the elastic deformation of the dies into consideration, the calculated results correspond well with that obtained in the experiment. From the results shown in Figs. 13 and 14, we can conclude that, for actual panels that have a three-dimensional shape and for which a non-uniform tension distribution in the walls influences the product shape, the accuracy of the spring-back shape prediction worsens if we do not take elastic die deformation into consideration.

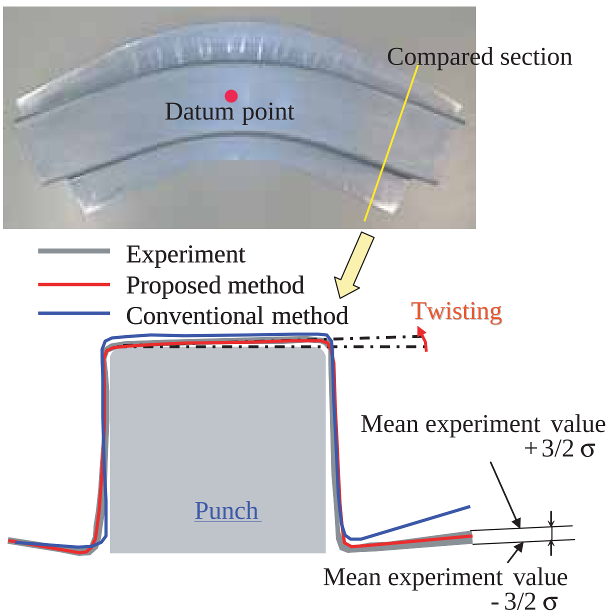

Fig. 13 Comparison of cross sectional shape between actual panel and calculation result (σ : standard deviation).

6. Conclusion

To precisely predict the spring-back of a bent sheet, we have proposed a method of measuring the stress-strain curve during the unloading process. This method considers the non-linear properties of sheet materials during unloading, and the proposed material models are newly introduced into the FEM code. We have confirmed the accuracy of this method's prediction of the spring-back shape of a bent sheet. On the other hand, the results of the same prediction by the existing method, based on the conventional isotropic work-hardening rule, were found to be very poor. Furthermore, when the spring-back shape of a three-dimensional panel was calculated with elastic die deformation taken into consideration, the value for the rim opening, as well as those for the wall curvature and twist, corresponded well with the results obtained by experiment. Accordingly, we can conclude that; (1) If we wish to accurately predict the spring-back shape of any stamped sheet by FEM analysis, it is absolutely essential to measure and precisely formulate material behavior during unloading and introduce this into the program code; (2) Furthermore, in order to predict the shape of three-

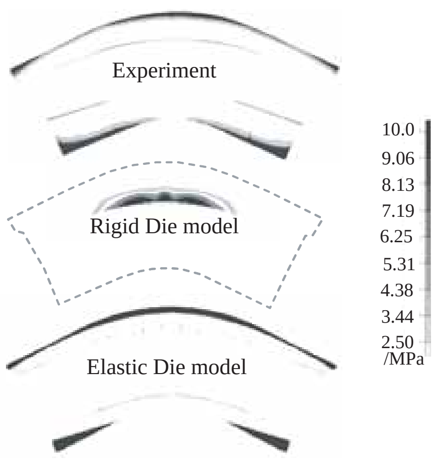

Fig. 14 Comparison of pressure distribution at flange.

dimensional panels that are expected to twist, it is also necessary to take the elastic deformation of the dies into consideration. Doing so, however, increases calculation time considerably. The shortening of this calculation time will be the subject of a future study.

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