## Special Feature: Metal Forming and Processing

*Research Report*

# Stamping Simulation for Surface Deflection of Automotive Outer Panels

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**ABSTRACT** We established a new system to evaluate surface deflection objectively. Regarding the measurement and evaluation of the degree or extension of surface deflection in outer panels, the cross-sectional curvature and optical Moiré interference stripes have been used until now. However, there is concern regarding the differences between each examiner's evaluation. Furthermore, it is necessary to be able to use the finite element method (FEM) to evaluate the restriking process, which is a common countermeasure technology for surface deflection. However, conventional FEM for sheet metal forming cannot be applied to restriking, because the shell elements used in stamping FEM are based on the Mindlin-Reissner assumption. Therefore, in this paper, we formulate the stress distribution in the panel thickness direction and propose a calculation method that can consider restriking. We demonstrate that the proposed method for the restriking process is practical. Comparing the results from FEM with the actual fender panel, our proposed method produces results that are equivalent to the measurement results in both range and magnitude. In contrast, surface deflection occurred over a wider range according to conventional FEM than in the actual panel, and the index of the deflection level was larger than the actual index.

**KEYWORDS** Surface Deflection, Sheet Metal Forming, Restriking, Finite Element Method, Constitutive Model, Steel, Elastoplasticity

## 1. Introduction

Automotive customers increasingly diversify their demands, and the designs of minivan outer panels are changing from small curvatures to complicated shapes containing concave-convex surfaces. It is difficult to deform such shapes with high surface quality. Especially, surface deflections that occur on outer panels are undesirable based on automotive appearance and commercial value. Therefore, it is important to prevent such deflection.

The following difficulties are associated with these surface deflections. The shapes are dents with a depth of about 0.01 mm and a width of 300 mm. Therefore, it is difficult to measure or evaluate these surface deflections, but many studies have been performed to evaluate them. Evaluation methods using the cross-sectional curvature (i.e., second-order differential coefficient)[1,2] and optical Moiré interference[3] have been proposed. The inspection of surface deflections by the latter evaluation method is shown in **Fig. 1**. An examiner highlights the panel and judges the surface condition by the bending of the highlights. Because this conventional evaluation depends on the examiner, there is concern regarding the differences between each examiner's evaluation.

Therefore, we have developed the following system based on previous research for the objective evaluation of surface deflections[4] that quantifies the bending of the highlights as evaluated by the examiner. In the developed system, the panel shape is first measured using a 3D non-contact measuring instrument, and

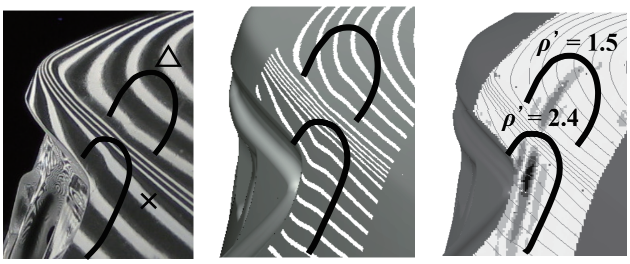
**Fig. 1** Surface quality inspection of a panel.

the measurement data are changed into point group data. Next, the positions of the light source, panel, and observed point are calculated, and the reflected lights at the observed point are displayed in white. These calculations are performed for all point groups, and highlight lines are shown on the outer panel surface. Then, the rate of change of the highlight line curvature ($\rho$') is calculated in order to quantify the bending of the highlight lines. **Figure 2** shows the results calculated by the surface quality examiner's evaluation and the developed system (called the highlight evaluation system). Figure 2(a) shows the examiner's evaluation result, Fig. 2(b) is the highlight shown by the system, and Fig. 2(c) shows the distribution of $\rho$'. The validity of the developed system has been proved, as shown in these figures.

The finite element method (FEM) is available for predicting the surface deflection of an outer panel.[5-7] However, conventional FEM cannot be applied to the restriking process, which is a standard method of reducing surface deflection by applying a high pressure load on the deflection area by narrowing the clearance between the upper and lower dies. The reason is that the shell elements used in stamping FEM are based on the Mindlin–Reissner assumption.[8] While there are some proposals for shell elements in which the stress in the thickness direction $\sigma_z$ can be considered with a pseudo node,[9] there is no verification given for the prediction accuracy of the surface deflection.

Therefore, we formulated a stress distribution in the panel thickness direction that is unable to be measured by conventional shell elements[10] and proposed a calculation method that can consider restriking. Then, we implemented this method into an FEM program. The numerical results were compared with the experimental results of the developed evaluation method, and it was confirmed that restriking effectively reduces surface deflection.[11] In this paper, we present a numerical method that expresses the surface deflection reducing effect of restriking, and we present analyses of actual automotive outer panels using the abovementioned method.




(a) The picture of a panel (b) Digital highlight (c) $\rho$' distribution

**Fig. 2** Comparison of a panel with the digital highlight inspection system.

## 2. Simulation Method of Restriking Process

It is required to incorporate the stress in the thickness direction $\sigma_z$ in order to calculate the restriking process in FEM analysis. However, the stress $\sigma_z$ is disregarded in conventional sheet metal forming simulations using shell elements. Therefore, we have proposed a numerical method where $\sigma_z$ can be treated in elastic-plastic FEM analysis and implemented in a main dynamic explicit solver.

### 2. 1 Formulation of Stress in Thickness Direction

We propose the following formulation of the stress in the thickness direction ($\sigma_z$):

1) $\sigma_z$ is calculated using the contact pressure ($q$) between the blank and the dies based on Reissner's theory.

2) The equation for calculating the distribution of $\sigma_z$ is as follows ($h$: thickness):

$$\sigma_z = -\Delta q\ \frac{3}{4}\left\{\frac{2}{3} - \frac{2z}{h} + \frac{1}{3}\left(\frac{2z}{h}\right)^3\right\} - q_{min}\,,$$

$$\Delta q = |\, q_{upper} - q_{lower}\,|, \quad q_{min} = \min\,(q_{upper}\,,\, q_{lower}), \quad (1)$$

where the variable $z$ indicates the coordinate in the thickness direction. The range of $z$ is from $-h/2$ to $+h/2$, where $h$ is the current thickness of the sheet metal. The variable $q$ is solved by interpolating the integration point with the value of the reaction force divided by the effective area. The subscript on $q$ indicates the upper or lower surface of the sheet metal.

### 2. 2 Implementation of Proposed Formulation into FEM

The proposed numerical method is introduced into the FEM to calculate the stress from the strain increment of the main FEM program based on the calculation flowchart shown in **Fig. 3**. This is different from the calculation flow of a conventional sheet metal forming simulation using shell elements in the following points:

1) The contact pressure is calculated at the contact location, and the through-thickness stress is computed from the contact ($\sigma_z$) using Eq. (1).
2) The stresses are computed to satisfy the yield criterion when $\sigma_z$ is given.

The implemented sheet metal forming FEM changes the loop for updating the stress from the strain increment, and the other computational procedures remain unchanged. Therefore, it is easy to introduce the proposed numerical method into all FEM codes.

## 3. Results and Discussion

### 3. 1 Validation of Restriking Simulation Method

The proposed method was verified by investigating the stress history in the restriking model test shown in **Fig. 4**. The process of the model test is as follows. First, a square steel sheet (100 mm × 100 mm × 0.7 mm) was stretched in the diagonal direction at 25 kN and 15 kN. Next, the restriking area of Fig. 4 in the sheet was compressed in the z-direction at 500 MPa (i.e., the restriking process) and was then unloaded. The stress history of the test was compared with the FEM using the proposed method, solid elements, and conventional shell elements, as shown in **Fig. 5**. The Mises yield function was adopted in all of the methods. It was expected that the stress in the y-direction did not change in the analysis using conventional shell elements under compression in the z-direction. On the other hand, in the analysis using the proposed method, the in-plane stress was increased due to the compression in the z-direction. The y-stress history for the proposed method corresponds with that using solid elements during both the compression and unloading processes. The abovementioned observations confirm the validity of the proposed method.

As an analysis example of an actual automobile, the drawing process for a fender panel (see **Fig. 6**) was analyzed. In the restriking area, the clearance between the upper and lower dies is narrower than the thickness of the sheet by 0.1 mm. The sheet metal

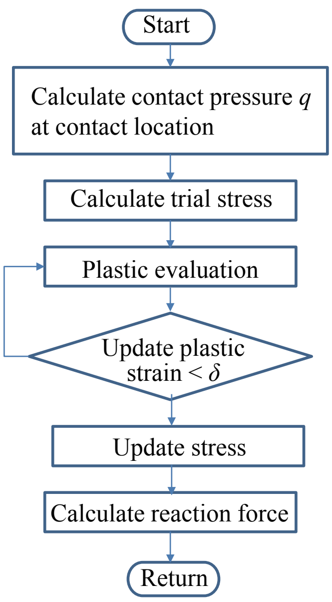



**Fig. 3** Flowchart of the numerical algorithm for stress time integration using the proposed method.

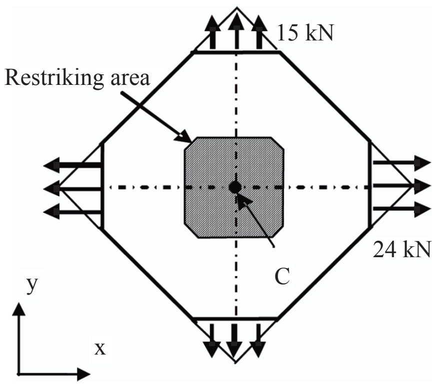



**Fig. 4** Diagonal biaxial tensile test.

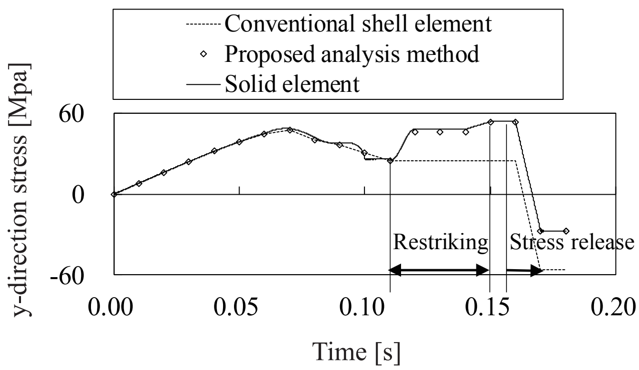



**Fig. 5** Change in y-direction stress.

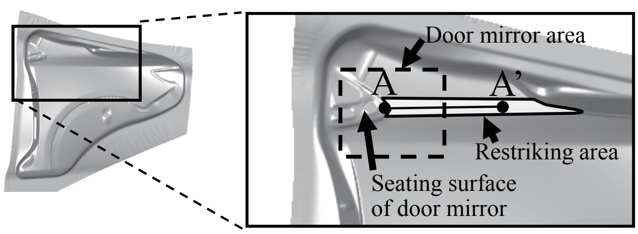



**Fig. 6** Analysis model of a fender panel.

forming process was analyzed by dynamic explicit FEM, and the spring-back behavior was simulated by the proposed method. Hill's out-of-plane anisotropic yield function and stress-strain curve measured with a uniaxial tensile test were adopted. The tools were modeled as a rigid body, and the motion of the upper die was controlled by the load like in an actual sheet metal forming process. The restriking process was analyzed using conventional shell elements and using the proposed method incorporating z-stress, and these results were compared. **Figure 7** shows the result for the $\rho$' distributions of the door mirror calculated by the digital highlight evaluation system from the front of the vehicle. The value of $\rho$' and the deflection area of the FEM analysis by the proposed method corresponded with those of the actual panel. It is possible to simulate the reduction in surface deflection deviation by the restriking process, whereas $\rho$' and its deflection area calculated by the conventional numerical simulation were not in good agreement with those of the actual panel.

### 3. 2 Mechanism of Reducing Surface Deflection by the Restriking Process

The surface deflection around the seating surface shown in Fig. 7 stems from a surplus of sheet metal, which occurs due to the difference in the forming amount in the seating surface of the door mirror in which the corner shape was sharp relative to the mirror circumference. **Figure 8** depicts the distribution of the minor principal stress along the A-A' section shown in Fig. 6 calculated by the proposed method. The direction of the minor principal stress coincides with line A-A'. The distribution lines are plotted at the press machine bottom dead center and 0.1 mm above bottom dead center. The former represents before restriking, and the latter represents after restriking. The minor principal stresses around 10 mm from point A are compressive before restriking, but they turn to tension after restriking, and the stresses become more uniformly distributed. This behavior is considered to reduce the level of surface deflection. Since the compression area of the FEM due to restriking is approximately equal to that of the actual panel measured by pressure-sensitive paper, as shown in **Fig. 9**, it is verified that the stress in the thickness direction calculated by the proposed method is appropriate, and our method for the restriking process predicts the appropriate pressure in the restriking process to reduce the surface deflection.

## 4. Conclusion

Our recent research was reviewed in this paper, in which a computational analysis method was developed to predict and analyze the surface deflection of actual automotive outer panels. The proposed numerical method using FEM enables us to not only predict the degrees and areas of deflection but also to evaluate the effect of the restriking process. To further shorten the preparation-for-production period, it is necessary to raise the predictive accuracy for the surface deflection in other steel and aluminum alloy parts. With such parts, the surface deflection may be influenced by the in-plane anisotropy(12) and its change accompanying the strain increase.(13) This research is still ongoing, and

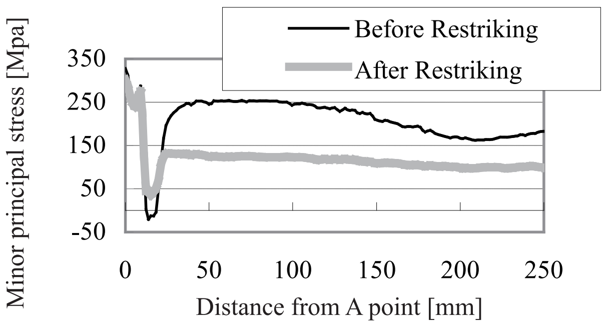



**Fig. 8** Minor principal stress distribution along A-A' section.

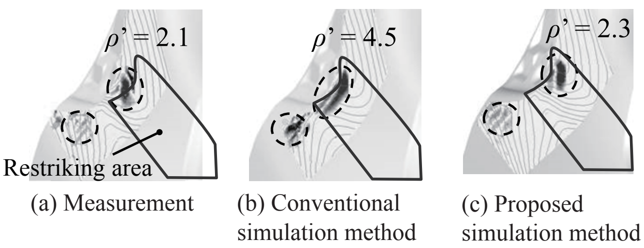



**Fig. 7** Comparison of surface deflection.

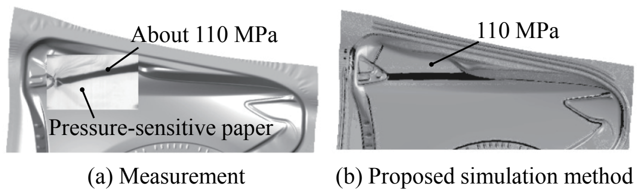



**Fig. 9** Comparison of pressure distribution.

we will introduce the results in a future presentation. The measurement and modeling of the stress-strain relationships in other panels where the maximum strain is more than the uniform elongation of the tensile test[14,15] and where the strain path changes suddenly[16] are topics for future research. Many researchers are addressing these issues, and analysis will be used for production preparation in the future.

## References


(1) Ujihara, A., "*Menhizumi, Hyoukahou*", *J. JSTP* (in Japanese), Vol. 24, No. 275 (1983), pp. 1220-1226.

(2) Satoh, S., Amaike, T. and Ujihara, A., "*Kyokuritu niyoru Menhizumisokutei Hyoukahou*", *J. JSTP* (in Japanese), Vol. 24, No. 275 (1983), pp. 1227-1230.

(3) Le Port, A., Thuillier, S., Borot, C. and Charbonneaux, J., "Analysis, Simulation and Prediction of Cosmetic Defects on Automotive External Panel", *AIP Conf. Proc.*, Vol. 1383, No. 1 (2011), pp. 228-236.

(4) Ichijo, N., Iwata, N., Iwata, T., Mita, T., Niihara, M. and Tsutamori, H., "Surface Evaluation Method and Stamping Simulation for Surface Deflection of Automotive Outer Panels", *AIP Conf. Proc.*, Vol. 1567 (2013), pp. 439-442.

(5) Singh, B. and Konieczny, A., "Changing of Stamping Process Design and Practice Due to Integrated Design Approach to Car Body Quality Enhancement", *SAE Tech. Paper Ser.*, No. 970983 (1997).

(6) Chung, W. J., Kim, W. S., Kim, J. H., Seo, J. H. and Jung, T. C., "Evaluation of Surface Deflection in Automobile Exterior Panel by Curvature Based Method", *AIP Conf. Proc.*, Vol. 1383, No. 1 (2011), pp. 1072-1077.

(7) Thuillier, S., Le Port, A. and Manach, P., "Surface Deflects in Sheet Metal Forming: A Simulative Laboratory Device and Comparison with FE Analysis", *AIP Conf. Proc.*, Vol. 1383, No. 1 (2011), pp. 839-846.

(8) Reissner, E., "The Effect of Transverse Shear Deformation on the Bending of Elastic Plates", *J. Appl. Mech.*, Vol. 12 (1945), pp. A68-77.

(9) Kazama, K., Ito, K., Hong, L. and Nagai, Y., "New Shell Element Considering Sheet Normal Stress for FEM Stamping Simulation", *J. JSTP* (in Japanese), Vol. 45, No. 525 (2004), pp. 832-836.

(10) Iwata, N., Tsutamori, H., Niihara, M., Ishikura, H., Umezu, Y., Murata, A. and Yogo, Y., "Numerical Prediction of Springback Shape of Severely Bend Sheet Metal", *AIP Conf. Proc.*, Vol. 908 (2007), pp. 799-804.

(11) Ichijo, N., Iwata, N., Iwata, T., Mita, T. and Tsutamori, H., "Development of Surface Evaluation Method and Stamping Simulation for Surface Deflection of Automotive Outer Panels", *J. JSTP* (in Japanese), Vol. 54, No. 628 (2013), pp. 421-425.

(12) Barlat, F., Brema, J. C., Yoon, J. W., Chung, K., Dick, R. E., Lege, J., Pourboghrat, F., Choi, S.-H. and Chu, E., "Plane Stress Yield Function for Aluminum Alloy Sheets—Part 1: Theory", *Int. J. Plasticity*, Vol. 19, No. 9 (2003), pp. 1297-1319.

(13) Kuwabara, T., Ikeda, S. and Kuroda, K., "Measurement and Analysis of Differential Work Hardening in Cold-rolled Steel Sheet under Biaxial Tension", *J. Mater. Processing Tech.*, Vol. 80-81 (1998), pp. 517-523.

(14) Iwata, T., Kamiyama, M., Yogo, Y., Iwata, N., Ishikawa, T. and Suzuki, K., "Application of Ring Compression Test for Thin Sheet Metals", *J. JSTP* (in Japanese), Vol. 54, No. 632 (2013), pp. 836-840.

(15) Iwata, T., Yogo, Y., Iwata, N., Kato, S., Ishikawa, T. and Suzuki, S., "Flow Stress Measurement Considering Plastic Anisotropy of Steels", *J. JSTP* (in Japanese), Vol. 54, No. 632 (2013), pp. 841-845.

(16) Kuroda, K., Kuwabara, T., Narihara, K. and Takahashi, S., "Stree-based Forming Limit Criterion for Aluminum Alloy Tube", *J. JSTP* (in Japanese), Vol.45, No.517 (2004), pp. 123-128.

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