NIPPON STEEL TECHNICAL REPORT No. 103 MAY 2013

Technical Report

UDC 621 . 983 : 669 . 14 . 018 . 262

Advanced Technologies Related to Simulation and Evaluation for Performance of Automotive Exterior Panels

Shigeru YONEMURA* Tohru YOSHIDA
Akihiro UENISHI Shunji HIWATASHI
Satoshi KOSUGI Junichi NAKAGAWA

Abstract

The bake-hardenable steel sheets are often used in exterior automotive body panels, such as doors, hoods, and fenders, because these applications require high strength for dent resistance as well as low yield strength for surface deflection. The dent resistance depends on the yield strength of materials after work hardening by forming and strain ageing by paint baking. In this study, the anisotropy of yield strength has been investigated in a uniaxially prestrained and baked bakehardenable steel. On the other hand, surface deflection is investigated by press forming experiments and their numerical simulations of the exterior door panel model. Emphasis is placed on the effects of mechanical properties and press forming condition on surface deflection are discussed. Furthermore, a new system for evaluation and visualization of surface deflection using Gaussian curvature is presented.

1. Introduction

Steel sheets used for automotive outer panels such as doors, hoods, and fenders are required to possess properties such as superior deep drawability, panel stiffness, dent-resistance, and surface quality (surface deflection). However, these requirements are not always mutually compatible. For example, it is advantageous to use steel sheets with high yield strength to enhance dent resistance, while it is desirable to use steel sheets with low yield strength to prevent surface deflection after stamping. To meet such contradictory requirements simultaneously, bake-hardenable steel sheets have been developed and put into practical use. These sheets are restrained as much as possible from aging at room temperature and bake hardening (BH) in paint-baking processes.

Dent resistance refers to hollow marks on the surface of panels caused by local impacts. To prevent dents, it is necessary to minimize the required steel sheet thickness while maintaining the prescribed dent-resistance properties; thus, it is important to select suitable steel sheets taking into consideration not only the formability and yield strength of the sheets but also work hardening in sheet forming processes and BH in paint-baking processes. Bake hardenability is evaluated by a test that simulates the manufacturing procedure of stamping followed by paint baking. First, a tensile specimen is uniaxially loaded to 2% strain. This is a typical amount of strain given to most of the areas of exterior panels by stamping. The yield strength of this prestrained specimen is already increased by work hardening. The specimen is then baked at 170°C for 20 min. This heat cycle corresponds to a paint-baking process that enhances strain aging. Finally, the yield strength of the prestrained and baked specimen is uniaxially tested in the direction same as that of prestraining. The difference between the final flow stress in prestraining and the yield strength after baking gives bake hardenability. Howev-

* Senior Researcher, Dr.Eng., Kimitsu R&D Lab.
1 Kimitsu, Kimitsu, Chiba 299-1141

er, it is also reported that the increases in yield strength of tensile specimens cut from stamped panels are often lower than those of uniaxially prestrained tensile specimens.[1-3] Although this discrepancy is considered to be due to the strain-path effect on BH, its characteristics have not yet been clarified. In the present investigation, uniaxial tensile prestraining can also be used to achieve various two-stage strain paths by changing the direction of subsequent tensile tests for a single-phase bake-hardenable sheet steel. The anisotropy of bake hardenability as well as work hardenability was examined to obtain a hypothesis for a general explanation about the effect of stamping and baking on the anisotropy of yield strength.

Surface deflection is caused by small and local out-of-plane displacement after stamping. Since this defect is ascribed to elastic recovery in unloading, lower yield strength is favorable to decrease the driving force for the springback phenomenon.[4)] High-strength steels normally suffer from these compromising requirements with respect to yield strength. Therefore, new steel materials and forming techniques are required to help reduce surface deflection. However, the effects of material properties and forming conditions on surface deflection have not yet been fully clarified because surface deflection is an out-of-plane displacement of the panel that is only tens of microns in extent; thus, it is difficult to quantify and interpret dynamically.[4-7)] Therefore, with the aim of obtaining guidelines for forming technology, which will ease surface deflection, we studied the effects of material properties and forming conditions on surface deflection using forming experiments and their numerical simulations of the exterior panel model. In this report, we also present Nippon Steel Corporation's original quantitative evaluation technique for surface deflection on the basis of three-dimensional curvature evaluation, and discuss the validity of this technique according to press forming experiments with the model tools.

2. Yield Stress Anisotropy by Straining and Baking of Bake-hardenable Steel

The steel sheet used in this study was a BH steel sheet with a tensile strength of 340 MPa and a thickness of 0.7 mm. First, specimens that were given tensions of 2% and 6% in the rolling direction as a primary deformation were subjected to tensile tests in which a secondary deformation was applied to each specimen at angles of 0° to 90°, in increments of 15°, from the direction of the primary tension (**Fig. 1**). Then, in order to study the anisotropy of BH, specimens that were heat-treated at 170°C for 20 min after application of the primary deformation were also subjected to the above secondary tensile test in increments of 15°. Although the proof stress of the as-received material is independent of the test direction, strong anisotropy appears by prestraining. Both in 2% and 6% prestrained samples, the maximums of proof stress are observed at θ = 45°, whereas the minimums are observed at 90°. On the other hand, the increases in proof stress by baking are significant at 0° and 90°, whereas at 45°, the change gives no aging. As a result, baking weakens the anisotropy caused by prestraining (**Fig. 2**).

In general, the initial yield stress anisotropy of a single-phase polycrystalline material that has been annealed is mainly due to the distribution of crystal orientation. However, it has been shown that the yield stress anisotropy of a material into which a comparatively large prestrain has been introduced is mainly due to the microstructural evolution under two-stage strain paths, rather than the influence of texture evolution by prestraining.[8)] Therefore, we estimated the influence on yield stress of a change in texture caused by a prestrain by comparing the texture of a prestrained material with that of an as-received material; we also calculated the anisotropy of yield stress using Taylor's theory on the basis of the assumption that the critical resolved shear stresses of the individual slip systems are the same. **Fig. 3** shows the orientation distribution functions of an as-received material and a prestrained material. The texture of the as-received material shows a strong γ fiber (<111> component parallel to ND), a strengthening of the (111) $[0\bar{1}1]$ component caused by a uniaxial tensile prestrain in the rolling direction.

Next, on the basis of the above crystal orientation distribution functions, we calculated the anisotropy of yield stress using a full-constraints Taylor model.[9, 10)] **Fig. 4** shows the anisotropy of yield stress for an as-received material and a 6% prestrained material, calculated using the above orientation distribution functions. It is clear that the anisotropy of yield stress cannot be reproduced even when the texture of a material to which a uniaxial tensile prestrain has been applied is used, and that the plastic anisotropy that was observed cannot be explained by lattice rotations. These findings and the fact that the present baking cannot give rise to the evolution of texture suggest that the anisotropy of work hardening and BH can

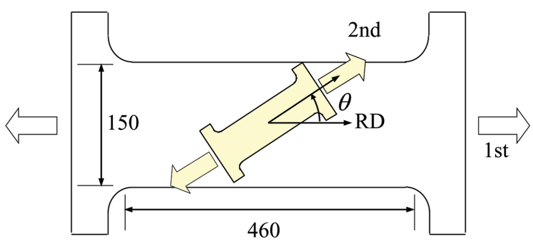

Fig. 1 Experimental procedure

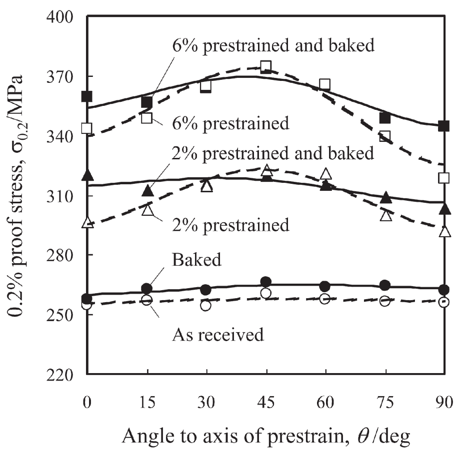

Fig. 2 Anisotropy of 0.2% proof stress

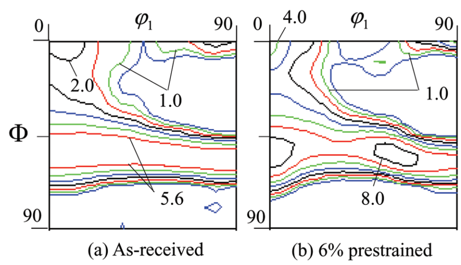

Fig. 3 Orientation distribution function (φ_2= 45° section)

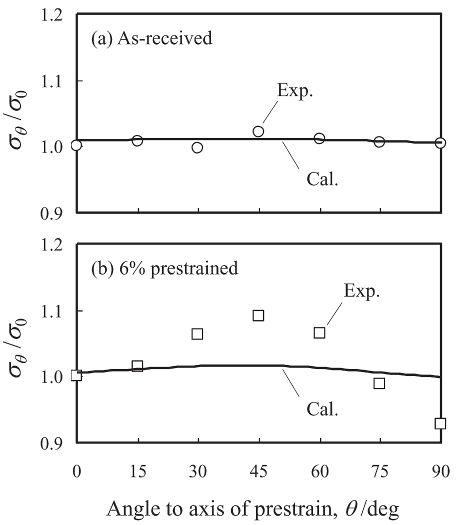

Fig. 4 Comparison of anisotropy between measurement and those calculated from the experimental texture

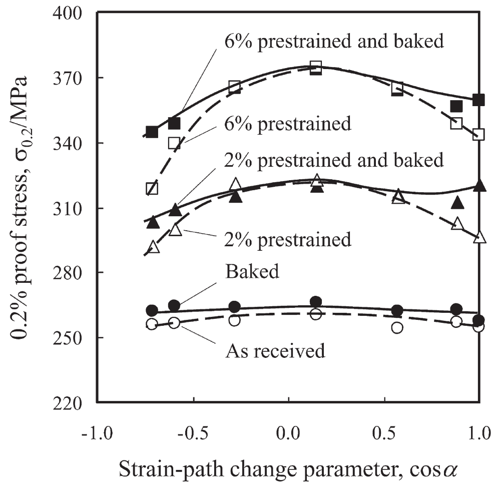

Fig. 5 Effect of strain-path change parameter on 0.2% proof stress in a prestrained and baked bake-hardenable steel

be ascribed to the interaction of the newly activated slips and the previously introduced dislocation substructure (and the pinning of dislocations by aging).

In addition to such microscopic explanations, a scalar parameter useful to characterize two-stage strain-path changes has also been proposed.[11)] It is defined as the double-contracted tensor product

$$\cos\alpha = \mathbf{A}^1 : \mathbf{A}^2 = A^1_{ij} A^2_{ij}$$

where $\mathbf{A}^1$ denotes the plastic strain-rate mode tensor in prestraining, and $\mathbf{A}^2$ is the mode tensor of the subsequent plastic strain rate. For a proportional path, which gives $\cos\alpha = 1$, the subsequent yield stress coincides with the flow stress at the end of prestraining. For a strain reversal, which gives $\cos\alpha = -1$, the Bauschinger effect is observed. The cross effect is observed in paths that satisfy $\cos\alpha = 0$. The angle of the subsequent tensile test to the prestrain axis on the sample is, indeed, different from that between the first and second strain-rate modes in the strain-rate space. Assuming the r-value independent of the in-plane direction and of prestrain for simplicity, one can approximately obtain the transformation from θ to $\cos\alpha$ for the present tests (**Fig. 5**). A tensile-axis change of about 50° is an orthogonal path ($\cos\alpha = 0$) in the strain-rate space, whereas $\theta = 90°$ gives $\cos\alpha = -0.71$, which is relatively close to the strain reversal ($\cos\alpha = -1$). By using the relationship between θ and $\cos\alpha$, the proof stresses in Fig. 2 are replotted against the parameter $\cos\alpha$, as shown in Fig. 5. In Fig. 5, the tendency schematically shown in the literature[11)] is confirmed for the present prestrained specimens before baking. In addition, it has been shown that the anisotropy of BH can also be expressed uniquely by $\cos\alpha$—a scalar product of previous and current strain-rate mode tensors: BH is small for a strain path change where $\cos\alpha$ is close to 0, but large when the value of $|\cos\alpha|$ is close to 1. As a result, baking weakens the anisotropy caused by prestraining.

The microstructural understandings may allow $\cos\alpha$ to be regarded as the degree of reactivation of slip systems.[12)] Namely, $\mathbf{A}^1$ corresponds to the residual stresses internally developed during the previous plastic deformation. This is caused by the heterogeneous deformation behavior of microstructural components, such as grains, particles, and dislocation cell walls. For the present material with a prestrain of 2%, intergranular stress by compatible deformation of grains can be predominant. On the scale of nanostructure, back stresses by dislocation pile-ups may be relevant. $\mathbf{A}^2$ corresponds to the interaction between the newly activated slips and the previously introduced microstructural evolution. For a given two-stage strain path, therefore, one can qualitatively estimate the subsequent yield stress and the microstuctual evolution through this parameter. By regarding this parameter as the degree of reactivation of slip systems, the anisotropy of BH observed after prestraining and baking was microscopically explained from the viewpoints of residual stress, crystal plasticity, and dislocation pinning.[13)]

In the case of a strain path change when the absolute value of $\cos\alpha$ ($|\cos\alpha|$) is close to 1 (i.e., the currently active slip system and the formerly active slip system have much in common), the internal stress plays a noticeable role. This internal stress resists the current mobile dislocation when the direction of slip remains the same before and after a change of strain path; conversely, the internal stress assists the movement of the current mobile dislocation when the direction of slip is reversed. The Bauschinger effect manifests itself in a change of strain path where the latter component is predominant ($\cos\alpha$ is close to -1). In such a change of strain path, when a baking finish is applied after the primary deformation, the former mobile dislocation is seized onto the current active slip system, posing a strong impediment to the activity of the slip system. This is considered to increase BH. Conversely, the angle between the first and second strain-rate modes is nearly orthogonal. Therefore, most of the subsequent active slip systems are latent during prestrain. The dislocations developed during prestrain are strong obstacles against the activation of different slip systems even before aging and the start of subsequent slips is insensitive to the pinning of dislocations. As a result, the proof stress in this strain path is already high and is not affected by baking. On the basis of the knowledge obtained in the present experiment, the BH effect can be summed up as follows. The dent resistance of an automotive outer panel obtained by biaxial stretch forming follows a strain path close to proportional loading ($\cos\alpha = 1$) and good dent resistance can be secured by a strong BH effect (**Fig. 6**).

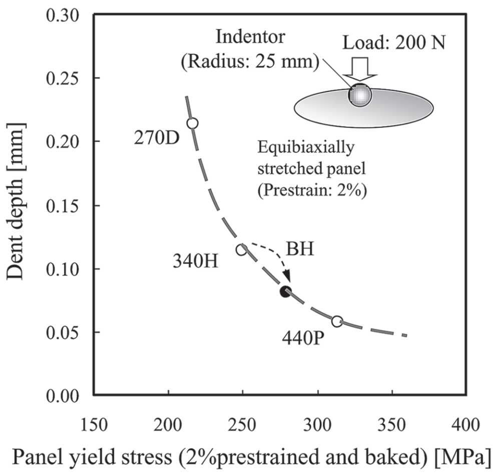

Fig. 6 Relationship between yield stress in a prestrained and baked various steels vs. dent resistance

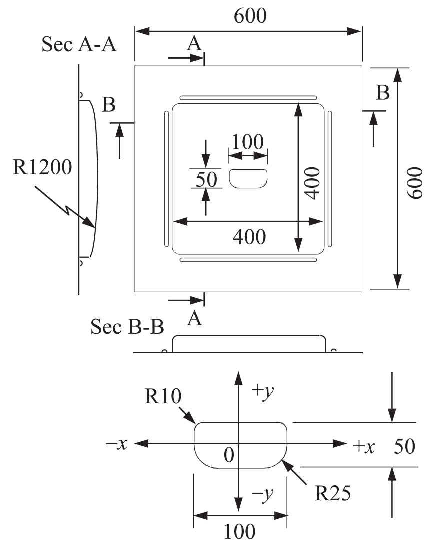

Fig. 7 Tools for the handle portion of the exterior door panel

3. Influences of Material Properties and Forming Conditions on Surface Deflection and Development of a Method for Quantitative Evaluation of Surface Deflection

3.1 Influences of material properties and forming conditions on surface deflection in the vicinity of handle portion in a door panel model

The steel sheet used in this study was a BH steel sheet with a tensile strength of 340 MPa and thickness of 0.7 mm. In the press forming test, a door panel model tool with a punch bottom of cylindrical surface with a radius of curvature of 1,200 mm was used; a 600 mm × 600 mm square blank was set in position such that the direction of curvature 0 of the punch bottom coincided with the rolling direction and the blank was stamped to a height of 25 mm (**Fig. 7**). The blank was stamped under a holding force of 800 kN and unloading process; then, the panel out-of-plane displacement was measured using a three-dimensional contact-type profile-measuring instrument. In addition, the distribution of the quadratic differential coefficient at an evaluation span of 30 mm was calculated from the cross-sectional profile of the surface and used as an index for evaluation of surface deflection (**Fig. 8**).

Finite element codes are generally used for stamping simulations in the automotive industry. The dynamic explicit code was used for stamping simulation, while the static implicit code was used for springback phenomenon. In the simulations, the blank steel sheet that was subjected to the experiment was divided into 1.0 mm elements, and a combined hardening model[14] based on Hill's anisotropic yield function and the following Lemaitre-Chaboche equations was used as the material model.

$$f = \sigma_e(\boldsymbol{\sigma}, \mathbf{X}) - R(\varepsilon^p)$$

$$R(\varepsilon^p) = R_0 + R_{sat}(1 - e^{-C_r\varepsilon^p})$$

$$d\mathbf{X} = C_x(X_{sat}\mathbf{N} - \mathbf{X})\,d\varepsilon^p$$

where $\sigma_e(\boldsymbol{\sigma}, \mathbf{X})$, ε^p, $\mathbf{X}$, $R(\varepsilon^p)$, and $\mathbf{N}$ denote equivalent stress, equivalent plastic strain, back stress, isotropic hardening stress, and plastic strain-rate mode tensor, respectively, and R_0, R_{sat}, C_r, X_{sat}, and C_x are material parameters (**Table 1**). The parameters of the mixed hardening model were identified by ① a monotonic simple shear test and ② reversed simple shear tests after 10%, 20%, and 30% forward shear (Bauschinger tests)[15] (**Fig. 9**). To obtain the nonlinear stress-strain behavior in unloading, the approximation model proposed by Uemori et al.[16] was used.

$$E = E_0 - (E_0 - E_a)(1 - e^{-s\varepsilon^p})$$

Fig. 8 compares the profiles of $y = +35$ cross section with the

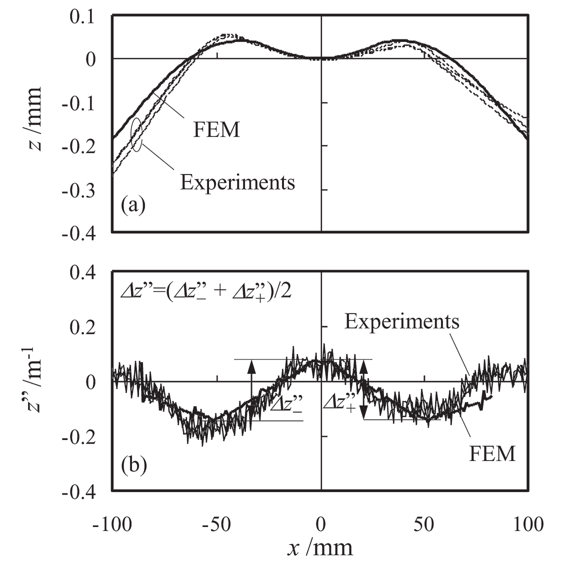

Fig. 8 Surface deflection of the exterior door panel model obtained by experiments and FEM calculations

Table 1 Material parameters used for FEM

R_0 (MPa)	R_{sat} (MPa)	X_{sat} (MPa)	C_r	C_x	E_0 (GPa)	E_a (GPa)	s
143	189	83	18	148	205	169	52

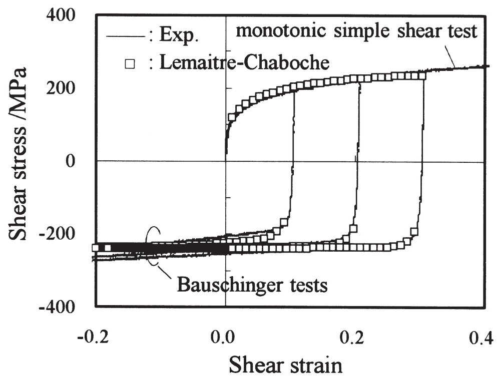

Fig. 9 Measured and calculated shear stress-strain curves Monotonic and reversed simple shear tests after 10, 20 and 30% forward shear (Bauschinger tests)

measured and calculated distributions of quadratic differential coefficients. It can be seen that the analysis reproduced the experiment well. Thus, it was confirmed that surface deflections could be predicted with sufficient accuracy by selecting an appropriate material model and analytical technique, including element subdivision. As such, we used forming experiments and forming analysis to study the influence of material properties and forming conditions on surface deflection.

In order to study the influence of yield stress on surface deflection, we carried out a forming simulation using virtual material parameters; the yield stress was varied by ±20 MPa, and we evaluated the maximum/minimum difference ($\Delta z''$) of the quadratic differential coefficient of $y = \pm 35$ cross section. In addition, we used pieces of the blank cut out at 0°, 45°, and 90° from the rolling direction to study the influence of in-plane anisotropy of *r*-value on surface deflection in a press forming experiment. We found that yield stress is the material property that influences the surface deflection of the handle portion the most; however, the effects of plastic anisotropy are also important (**Figs. 10** and **11**).

Fig. 11 (a) shows the relationship between angle θ—the angle formed by the direction of maximum curvature at the punch bottom (i.e., the direction perpendicular to the longitudinal direction of the handle portion) and the rolling direction—and evaluated surface deflection ($\Delta z''$) at $y = \pm 35$ cross section. When the cutting direction of the blank was changed, the observable surface deflection also changed noticeably: the minimum deflection appeared at 45° and the maximum at 90°. Therefore, considering that the uneven distribution of the stress component perpendicular to the longitudinal direction of the handle portion would determine the amount of surface deflection, the above relationship was re-expressed using the r-value in the direction perpendicular to the longitudinal direction of the handle portion; a good correlation was observed between them (Fig. 11 (b)), which may be explained as follows. Even for steel sheets with the same yield stress, increasing the r-value increases the major principal stress in the stress space. This increases the springback of the steel sheet during the recovery of its elasticity, which in turn causes out-of-plane deformation to increase.[17]

Next, to study the influences of forming conditions on surface deflection, two levels of forming conditions were simulated: one in which only the handle portion depth was varied, with the blank holding force (BHF) maintained at a constant value, and the other in which only the BHF was varied (**Fig. 12**). The results indicated that

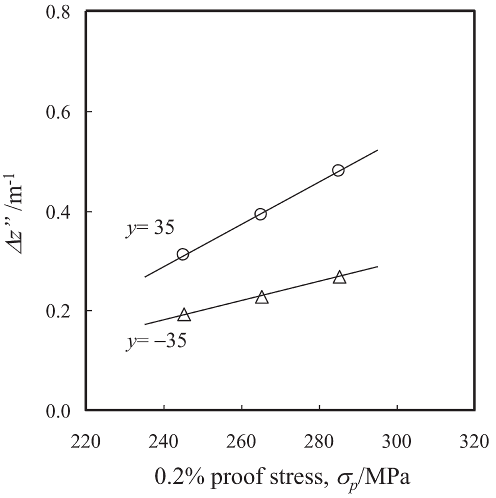

Fig. 10 Relationship between yield stress vs. surface deflection

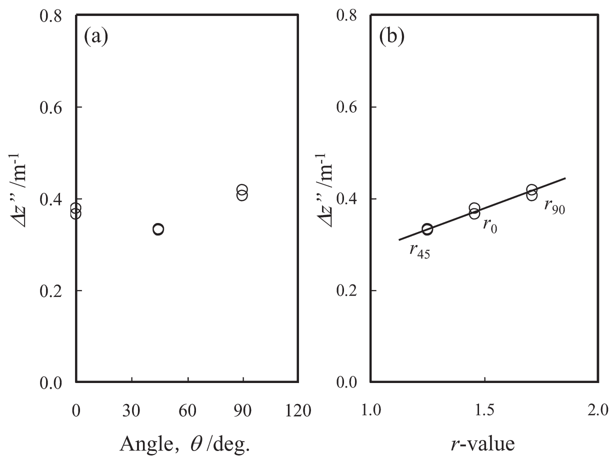

Fig. 11 (a) Angle between punch maximum curvature direction and sheet rolling direction vs. surface deflection. (b) Relation between r-value in the punch maximum curvature direction vs. surface deflection

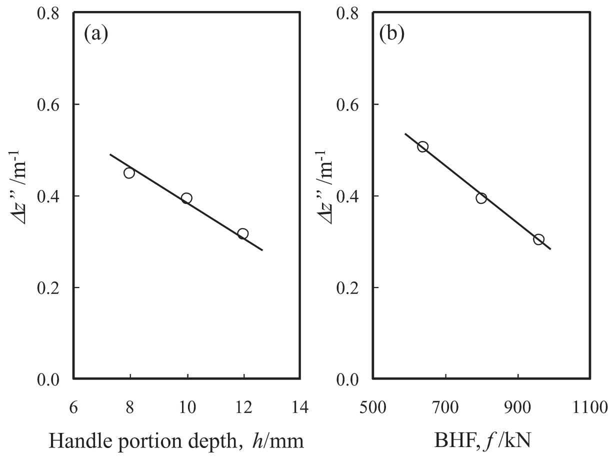

Fig. 12 (a) Relation between handle portion depth and surface deflection. (b) Relation between blank holding force (BHF) and surface deflection

handle portion depth and BHF are closely correlated with the evaluated surface deflection, Δz", and that surface deflection tends to decrease as the handle portion depth and BHF are increased. This can be explained as follows. As the handle portion depth is increased, the panel stiffness increases, the springback is restrained, and the running-in at the punch surface improves. In addition, the in-plane stress distribution at the bottom dead center of the press becomes more uniform for larger applied stretching-tension, thereby reducing the difference in the elastic recovery after stamping.

Door panels with handle portions are formed only by the punch surface for some time after the start of the forming process. Subsequently, the panel is die-formed by an embossing punch that is fixed to the die side. In this process, a large plastic strain is introduced to the straight side section around the handle portion by plane strain tensile deformations, whereas the change in the plastic strain in the vicinity of the embossed corners is small. A difference in elastic recovery strain occurs when the load is removed from this stress state, causing an out-of-plane deformation. Therefore, in order to reduce surface deflection, it is effective to level the uneven in-plane distribution of stress in the vicinity of the handle portion while the press is at the end of the loading process. To that end, it is considered effective to increase parameters such as the radius of handle portion corners, the depth of the handle portion, and BHF. However, application of excessive tension to the steel sheet increases the risk of fractures. Therefore, it is important to conduct a comprehensive study of undesirable phenomena such as shape defects and fractures; this can be achieved by effectively utilizing the method for quantitative evaluation of surface deflection described in the following section and CAE and by incorporating the results into the technical guidelines for forming and the selection of optimum materials.

3.2 Method for quantitative evaluation of surface deflection

Surface deflection is a minute surface inaccuracy that occurs in automotive outer panels. Of the various defects encountered in press forming, it is one of the most difficult to deal with. The degree of surface deflection can be judged by grinding the panel surface with an oilstone and checking how it feels. In many cases, however, the degree of deflection is judged by an experienced inspector on the basis of sight and touch during shipping inspection. Since surface deflections that occur at the manufacturing site have seldom been evaluated quantitatively, the effects of any measure to counteract them are yet to be grasped quantitatively. Besides, since surface deflections are minute phenomena, examination by CAE analysis is difficult. Today, in view of the ever-growing demand for lighter outer panels, studies have been conducted with the aim of increasing the strength and decreasing the thickness of panels. In fact, a steel sheet with higher yield stress and smaller thickness is more susceptible to surface deflection. Thus, surface deflection has become an important problem in production engineering when it comes to applying high-strength steel sheet to outer panels. As a result, technology is required for quantitative evaluation of where and how frequently surface deflections occur.

Some conventional techniques exist for the evaluation of surface deflections in a laboratory setting, e.g., the mapping of contours utilizing moirés and the digitalization of cross-section measurement coordinates by quadratic differentiation. However, the application of moirés is limited because it cannot adequately quantify surface deflections, although it does permit rough approximations of their locations. Evaluation using a quadratic differential coefficient is the same as evaluating change in curvature using a three-point gauge. Since it represents an index obtained from a cross-sectional profile in a certain direction, it does not always correspond to the direction of maximum curvature at the point of measurement. Furthermore, since this technique does not provide positional information to indicate the extent of surface deflection, it can rarely be applied to conduct necessary modifications to tools.

Therefore, we developed a universal 3D curvature evaluation technique for curved surfaces using a field function, rather than the conventional curvature evaluation that depends on the direction of measurement. The following Gaussian curvature, which indicates the degree of deflection of a curved surface, was used as the evaluation value.

$$K = \frac{f_{uu}f_{vv} - f_{uv}^2}{(1 + f_u^2 + f_v^2)^2}$$

where f_u and f_v are partial derivatives of variables u and v when the 3D curved surface function of the field is assumed to be $f(u, v)$, and f_{uu}, f_{vv}, and f_{uv} are the quadratic partial derivatives associated with the appropriate variables. The points where K is positive produce a concave or convex surface, while those where K is negative produce a saddle-shaped curved surface. Therefore, it is possible to express even minute deflections with a high degree of sensitivity. In addition, since K is a scalar quantity, the extent of surface deflection can be expressed by means of a contour map. This technique is applicable to the results of 3D profile measurement such as that conducted using a digitizer. In this case, however, suitable pretreatment is required since there is variation in the interval between the groups of measuring points. Since the curvature depends on the evaluation length, the point groups obtained before the evaluation of K must be interpolated to a grid of equal intervals.

We conducted quantitative evaluation of surface deflections according to the above technique through forming tests using model tools that simulate a handle portion. The materials used were 270 MPa to 590 MPa steel sheets with thickness of 0.7 mm to 0.8 mm. From the panels obtained, 3D point groups were detected by a contact-type digitizer and subjected to numerical processing by the developed system to calculate the distribution of 3D curvature. **Fig. 13** illustrates contour maps of Gaussian curvature for 340 MPa and 590 MPa steel sheets: compared to the 340 MPa steel sheet, the 590 MPa steel sheet displays a region with a large change in curvature in the vertical direction near the embossed corners. When the total sum of Gaussian curvatures (absolute values) within the specified region of the contour was assumed as the evaluated surface deflection of the panel, the evaluation results obtained by the developed technique exhibited good correlation with the results of functional evaluation by an inspector. Thus, it is possible that this technique is also applicable in the final inspection of panels (**Fig. 14**). In addition, since the system developed for the quantitative evaluation of surface deflections is applicable to evaluation results obtained by CAE, it should be possible to use the system to predict surface deflections

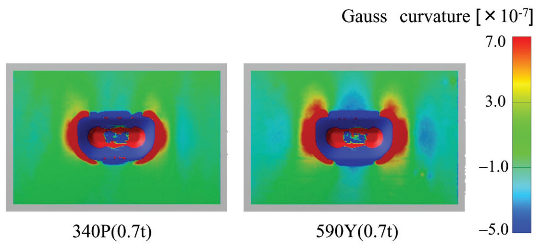

Fig. 13 Contour map of 3D curvature for emboss panels

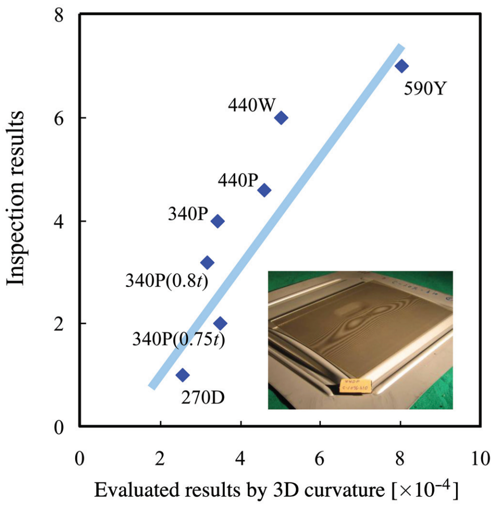

Fig. 14 Relation between evaluated results by 3D curvature and inspection results

and investigate measures to prevent them.

4. Conclusion

Properties such as superior deep drawability, panel stiffness, dent resistance, and surface quality (resistance to surface deflection) are required in steel sheets for use in automotive outer panels. Dent resistance depends on the flow stress and thickness of steel sheets; therefore, by applying a high-strength steel sheet to an outer panel, it is possible to reduce the required steel thickness. However, it should be noted that the dent-resistance properties vary widely according to both the amount and mode of deformation of stamped parts. As a result, to efficiently implement designs for the enhancement of strength and reduction of weight of outer panels, it is important to accurately grasp the hardening behaviors of steel sheets, such as work hardening in sheet forming processes and BH in paint-baking processes. Furthermore, surface deflection is a major impediment to the application of high-strength steel sheets in outer panels. By employing the method presented here for the quantitative evaluation of surface deflections and making the most effective use of CAE in accordance with the guidelines on forming technology, it is possible to optimize the shapes of parts, the design of tools/processes, and the forming conditions to help reduce surface deflections.

To meet the ever-growing demand for automotive outer panels with higher strength and lighter weight, it is important to develop superior new materials and advanced processing technology to allow these materials to be put into practical use.

References

1) Bailey, F. D. et al.: Proc. Symp. High Strength Sheet Steels for the Automotive Industry. 1994, p. 119
2) Okamoto, A. et al.: The Sumitomo Search. September, 1989, p. 183
3) Takechi, H.: Hot- and Cold-Rolled Sheet Steels. TMS-AIME, Warrendale, PA, 1988, p. 117
4) Ishigaki, H.: J. Jpn. Soc. Technol. Plas. 24 (275), 1199 (1983)
5) Yoshida, M. et al.: J. Jpn. Soc. Technol. Plas. 24 (275), 1260 (1983)
6) Usuda, M. et al.: J. Jpn. Soc. Technol. Plas. 24 (275), 1274 (1983)
7) Ujihara, A.: J. Jpn. Soc. Technol. Plas. 24 (275), 1220 (1983)
8) Rauch, E. F. et al.: Mater. Sci. Eng. 113, 441 (1989)
9) Houtte, P. Van: Textures and Microstructures. 7, 29 (1987)
10) Raphanel, J. L. et al.: Int. J. Plas. 2, 371 (1986)
11) Schmitt, J. H. et al.: Mat. Sci. and Eng. 75, 13 (1985)
12) Teodosiu, C. et al.: Proc. NUMIFORM '95. 1995, p. 173
13) Yonemura, S. et al.: Tetsu-to-Hagané. 92 (8), 516 (2006)
14) Chaboche, J. L.: Int. J. Plas. 7, 661 (1991)
15) Suzuki, N. et al.: J. Jpn. Soc. Technol. Plas. 46 (534), 636 (2005)
16) Uemori, T. et al.: J. Jpn. Soc. Technol. Plas. 43 (494), 224 (2002)
17) Yonemura, S. et al.: J. Jpn. Soc. Technol. Plas. 52 (606), 811 (2011)


Shigeru YONEMURA
Senior Researcher, Dr.Eng.
Kimitsu R&D Lab.
1 Kimitsu, Kimitsu, Chiba 299-1141


Shunji HIWATASHI
Chief Researcher, Ph.D.
General Manager, Head of Lab.
Nagoya R&D Lab.


Tohru YOSHIDA
Chief Researcher, Dr. of Information Science
Forming Technologies R&D Center
Steel Research Laboratories


Satoshi KOSUGI
Senior Researcher, Ph.D.
Mathematical Science & Technology Research Lab.
Advanced Technology Research Laboratories


Akihiro UENISHI
Chief Researcher, Dr.
Sheet Products Lab.
Steel Research Laboratories


Junichi NAKAGAWA
Chief Researcher
Mathematical Science & Technology Research Lab.
Advanced Technology Research Laboratories