Springback Problems in Forming of High-Strength Steel Sheets and Countermeasures

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Abstract

Springback is one of the most difficult problems in applying high strength steel sheets to automotive body parts. The mechanism of springback behavior classified by the phenomenon and countermeasures based on each mechanism were reported. It was made clear that section opening of member parts was reduced by crash forming and wall tension control. And torsion and camber of complicated shape parts were possible to decrease by planer stress control using the developed analytical methods of CAE. In addition, about the buckling torsion of panels, the mechanism of the occurrence was studied and effects of countermeasures were reported. Basic concept of countermeasure for springback is expected to design the part high rigidity at first, utilize the stress control methods and minimize the compensation of die tools.

1. Introduction

The automotive industry is facing challenges of reducing body weight in consideration of environmental problems and higher collision safety; as a solution for both these factors, use of higher-strength steels for car bodies is expanding.[1] High-strength steels have been developed with different strength levels to give a wide selection of materials for different applications according to the required function. Compared with other light-weight materials, high-strength steels are advantageous in terms of costs, availability of production facilities, etc., and as such, they are used as the principal material for improvement of body weight reduction and collision safety. Higher-steel strength, however, leads to forming problems: low elongation consequent to higher strength increases the risk of sheet breakage during sheet forming, and a higher yield stress causes dimensional defects (springback), wrinkles, and other troubles.

To cope with these problems, forming dies have to be adjusted many times during trial process, which leads to increased die manu-facturing costs and other technical problems. While advanced high-strength steels that are excellent in formability, such as DP (dual-phase) and TRIP (transformation induced plasticity) steels, have been developed and applied to car body manufacturing to solve such problems,[2] approaches from the forming technology side are also very important for further enhancing strength of automotive parts and expanding application of high-strength steels.

As compared with that of steel sheets of conventional strength, in sheet forming of high-strength steel sheets in cold, dimensional accuracy of formed pieces is important. While it is necessary to take adequate measures to cope with increased elastic recovery of high-strength sheets, springback behavior largely depends on the modulus of elasticity, a property specific to the material in question, and there is a certain limit to improvement measures from the material side. A common countermeasure against springback is to design forming dies that anticipate springback compensation, but the compensation amount is a difficult question even for experienced die designers, and field practice is largely based on trial and error. Given the situation, in the first place, this paper classifies typical dimen-
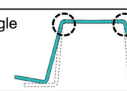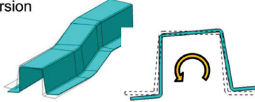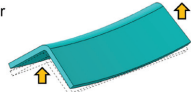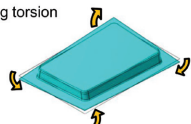
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sional defects due to springback that constitute problems in forming process of high-strength sheets and elaborates the mechanisms that cause them. Then, it reports the effects of different countermeasures in view of the causal mechanisms based on the results of verification tests using models. In addition, based on the understanding that CAE analysis is indispensable in the study of countermeasures in industrial production, its application technique is outlined.

2. Basic Concept of Measures against Dimensional Defects in Sheet Metal Forming

When a formed parts is released from the dies or trimmed flange area, restriction is removed from the work, and residual stress in it causes elastic deformation to bring about a new equilibrium. Since the elastic recovery of high-strength steel sheets is large, it is often difficult to satisfy the dimensional accuracy required for final products. Dimensional defects of forming are typically classified into opening angle, wall warp, torsion, camber, and the buckling torsion of panels (see **Table 1**). In any one of these, distribution of residual stress in the formed sheet exerts a bending or twisting moment, which causes deformation by overcoming the rigidity of the formed parts, which is determined by the elastic modulus, thickness, and shape. The most common dimensional defects seen at a section are opening angle and wall warp. The driving force of such defects is the difference in stress in the thickness direction, and the resistance

to the deformation, namely rigidity, mainly depends on sheet thickness. This understanding of the deformation mechanism leads to the following types of countermeasures.[3]

(1) Reduction of driving force: to make uniformly and lower distribution of residual stress to decrease driving force (moment) of different springback modes.
(2) Increase in rigidity: to change the sheet thickness or the part shape so as to increase the rigidity against different springback modes.
(3) Prediction and compensation of deformation: to differently design the shape of forming dies from the product shape intentionally by anticipating deformation so that after springback, the shape of formed pieces conforms to the intended one.

Table 2 lists examples of these countermeasures and their characteristics. For example, driving force of wall warp that occurs at draw bending into a hat-shaped section is the bending moment in the thickness direction due to bending and unbending when the sheet goes around a die shoulder, and the problem can be decreased by adequately defining the die shoulder radius to apply reverse bending and increasing unbending tension.[4] A countermeasure that combines an increase in rigidity and a decrease in driving force is being studied, wherein a step is formed in each of the vertical walls of a hat-shaped section.[5] Such countermeasures are important because they can be applied in the early stages of die design, if possible in the part design stage, so as not to adversely affect die costs or productivity.

3. Measures against Forming Defects of Member Parts

3.1 Springback suppression effects by crash forming

Crash forming, a press forming method without blank holders, is becoming popular in forming process of high-strength sheets. **Fig. 1** schematically compares crash forming with draw bending using blank holders; bending of the material sheet around a die shoulder is milder by crash forming, which is expected to reduce bending deformation that causes wall warp. In consideration of this, the authors
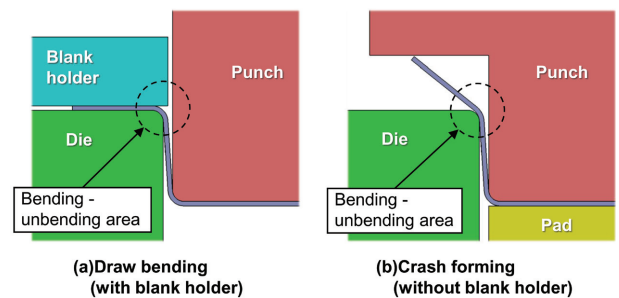
Table 1 Classification of typical springback problems and its mechanisms of occurrence

Parts	Defects of dimensional accuracy	Mechanisms of occurrence
Member	Opening angle	Elastic recovery of bending moment by uneven stress in thickness direction after bending
	Wall warp	Elastic recovery of bending moment by uneven stress in thickness direction after bending and unbending
	Torsion	Elastic recovery of torsion moment by uneven stress in plane with stretch and shrink flange deformation
	Camber	Elastic recovery of bending moment along punch ridgeline by uneven stress in thickness direction
Panel	Buckling torsion	Buckling deformation in unloading by uneven stress in plane in drawing of panel

(a)Draw bending
(with blank holder)

(b)Crash forming
(without blank holder)

Fig. 1 Schematic figures of draw bending and crash forming

Table 2 Basic concept of countermeasures against springback

Mechanism	Countermeasure	Example	Costs	Stability	Effect on parts performance
Reduction of driving force (low moment)	Forming methods	Crash forming tension control	High	Mid.	Mid.
Increase rigidity	Parts design	Emboss, bead	Low	High	Mid. - large
Prediction	Modified die tool	Compensation	Mid. - high	Low	Small

conducted test forming of high-strength steel sheets by crash forming and draw bending using simple-shape dies and examined effects of material strength over dimensional accuracy.

A set of hat-shaped forming dies applicable to both crash forming and draw bending were prepared; to evaluate effects of the angle of the vertical walls, one of the walls was slanted by 5°. Sheets from ordinary steel to high-strength steel (780-MPa class) were formed up to a punch stroke of 80 mm; by draw bending, the blank holding force P was set at 150 kN, and by crash forming, the back pressure F for the punch was set to 20 kN. After forming, the width opening ΔW, the warping radii ρ of the walls, and the change in the angle θ between a wall and a web were measured at a section using a contact-type 3D measuring device.

Fig. 2 shows the relationship between the width opening ΔW and the tensile strength σ_B of the specimen sheets by draw bending (DB) and crash forming (CF). The graph shows that the width opening by crash forming is smaller than that by draw bending and that the difference between the two methods increases with steel strength. To clarify the reason for this, the authors looked into the relationship between the causes of the width opening, namely the wall warp, opening angle, and the tensile strength σ_B of the specimens. As seen in in **Fig. 3**, the wall curvature $1/\rho$ is smaller by crash forming than by draw bending, although the decreasing effect of crash forming is different with the vertical and slanted walls, and the effect increases with higher steel strength. On the other hand, although not shown herein, the angle θ between a wall and a web did not significantly change depending on the forming method. From the above, the decrease in the width opening by crash forming is considered to be mainly caused by the smaller wall warping. In addition, as is clear
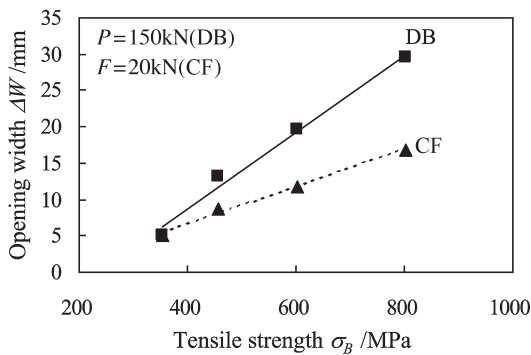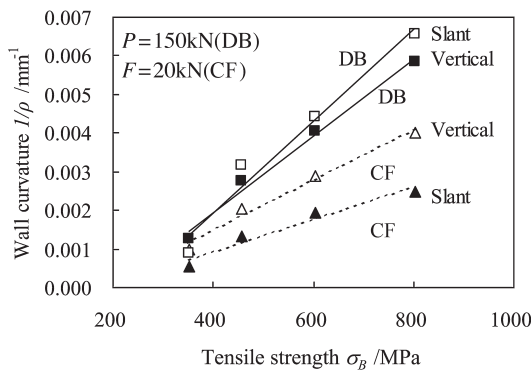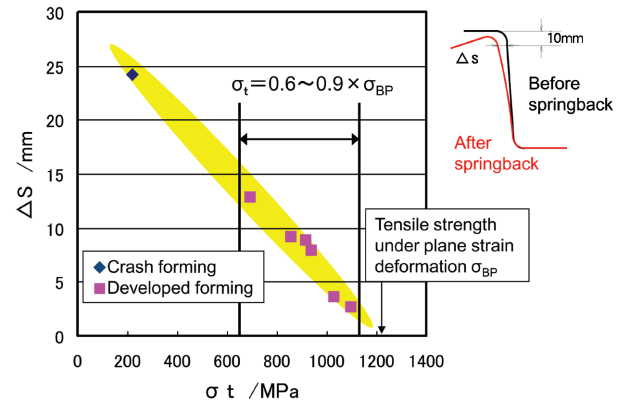

Fig. 4 Relationship between wall tension and opening width ΔS

from **Fig. 3**, the decrease in wall warping by crash forming is more conspicuous in the slanted wall than the vertical one.

This is presumably because by crash forming, whereby the material sheet undergoes less tension during forming work, wrapping of the sheet around the die shoulder is significantly milder on the slanted wall side, where the die clearance is larger, and thus, bending deformation that causes wall warping is smaller. Based on these basic findings, to obtain good springback suppressing effects by crash forming, it is presumed effective to combine measures such as bottoming at the lower dead center with the punch ridge and a measure against angle change taking advantage of the spring-go utilizing the sag at the punch head face.

To further improve dimensional accuracy for forming of ultra-high-strength steel sheets, the authors developed a new efficient bending method based on crash forming, whereby a blank holding force is applied to the flanges just before the punch hits the lower dead center. **Fig. 4** shows the results of bending steel sheets having a tensile strength of 980-MPa into a hat shape by the developed method. The graph, wherein the wall tension σ_t, in terms of the average in the sheet thickness direction, is plotted along the abscissa, and the width opening ΔS along the ordinate, shows that there is a linear correlation between them and that the width opening could be significantly suppressed by applying tension of 60 - 90% of the fracture stress in plane-strain deformation to the vertical walls.

3.2 Measures against torsion and camber of rear member model

No general measures have been established against three-dimensional forming problems that occur in industrial production, such as torsion and camber. In consideration of this, using a set of dies for a rear member model having curvatures in the in-plain and punch-stroke directions (see **Fig. 5**), the authors investigated the mechanisms that cause torsion and camber and studied countermeasures.

High-strength steel sheet specimens of tensile strengths from 270 to 980 MPa were formed at a reference blank holding force (BHF) of 400 kN and using rust-preventive oil as a lubricant. To evaluate effects of lubricating conditions, some specimens of 980 MPa steel (1.2 mm thickness) were coated with Teflon sheets. To evaluate dimensional accuracy, the torsion angle θ_{AB} and the camber δ_B between sections A and B were obtained by calculating coordinates defined through non-contact shape measurement. **Fig. 6** compares the torsion angle and camber of the formed specimens. While both of them tended to increase with material strength, sheet thickness and lubrication were found to have significant effects. One of the reasons why it is difficult to work out measures against forming
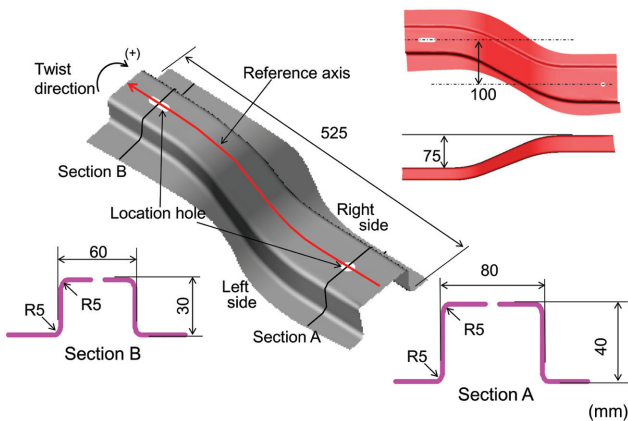

Fig. 2 Effect of reducing opening width ΔW by crash forming

Fig. 3 Effect of reducing wall curvature $1/\rho$ by crash forming

Fig. 5 Dimensions of rear member model

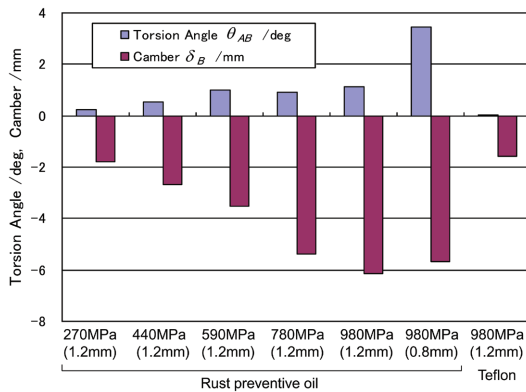Fig. 6 Torsion angle θ_{AB} and camber δ_B of formed specimens

problems of parts involving a three-dimensional shape change is that the positions at which the dimensional defects are detected and the locations of the causes are different.

Given the situation, the authors analyzed the causes of the defects based on CAE analysis of torsion and camber to locate positions of stress unevenness that cause such defects; the details of the analysis methods are given in reference report.[6] With respect to torsion, the analysis made it clear that position of the main cause at which the twisting moment is the largest was the vertical walls, especially the regions where stretch flanging deformation was large. With respect to camber, on the other hand, the problem was found to originate from the web and the flange on the side where stretch and shrink flanging were significant. Based on the findings, the authors conducted tests of two measures against the forming problem to disperse or reduce the stress in specific portions: (1) forming of partial beads; and (2) width expansion/reduction. High-strength steel sheets of 980 MPa class, 1.2 mm in thickness, were used as the specimens for the tests. The tools (dies, punch, and blank holders) were divided into several sections so that the measure was only applied to intended positions by changing the sections.

(1) In the study of partial beads, to disperse or reduce the longitudinal stress imposed on the vertical walls that caused the torsion, beads were formed along the corners in the portions where shrink and stretch flanging occurred, and their effects were examined. Beads, of a round section 3 mm in radius (on the die side) and 2 mm

in height, were formed as shown in **Fig. 7**. The torsion and camber of the formed pieces with the beads at different positions are shown in **Fig. 8**.

With respect to torsion, the torsion direction reversed depending on whether a bead was formed in the stretch or shrink flanging region, and the improvement effect was significant when the bead position was in the stretch flanging region on the wide-end side (type 1). This is supposedly because the partial bead increased the residual stress in specific portions of the walls and flanges, and thus, the overall balance of the twisting moment was improved to decrease the torsion angle. Further, as seen with types 4-6, a bead in the shrink flanging region caused the torsion angle to reverse; the reverse torsion was large, especially with type 4. Type 1 was also found to be effective at controlling camber, and so was type 4 (shrink flanging region on the wide-end side).

(2) In the study of width expansion/reduction, width expansion (WE, i.e., narrow local width in the first step is widened in the second step) and width reduction (WR, i.e., wide local width in the first step is narrowed in the second step) were applied to stretch and shrink flanging regions as shown in **Fig. 9**. As seen in **Fig. 10**, either WE or WR was applied to the wall on one side in three different patterns: to the stretch flanging region; to the shrink flanging region; and to both. **Fig. 11** shows the results. Both WE and WR proved effective at suppressing torsion. The effect of WE was more significant when it was applied to both the stretch and shrink flanging re-
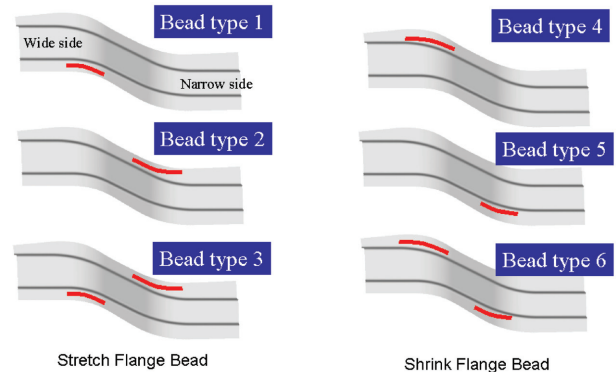

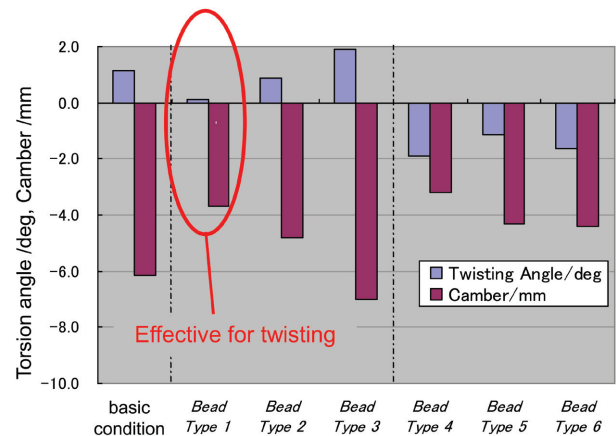Fig. 7 Positioning of partial bead in rear member model

Fig. 8 Influences of partial bead positioning on torsion angle θ_{AB}, and camber δ_B
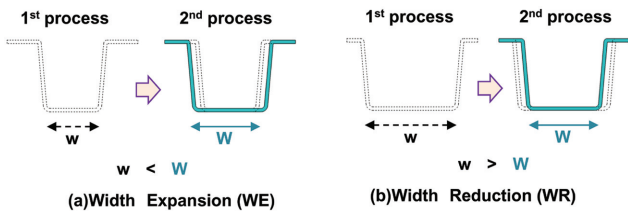
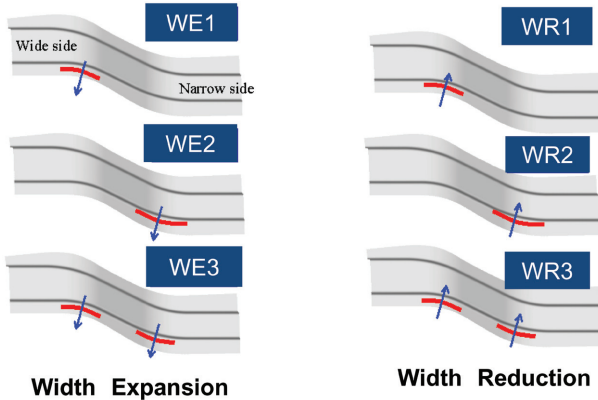Fig. 9   Forming methods of width expansion and width reduction

Fig. 10   Positioning of width expansion and reduction in rear member model

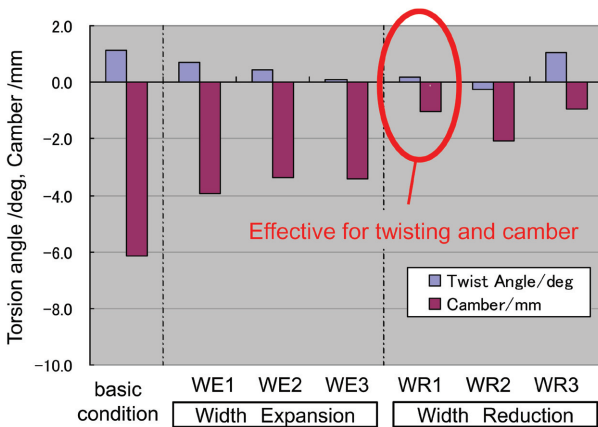
Fig. 11   Influences of width expansion and reduction on torsion angle θ_{AB} and camber δ_B
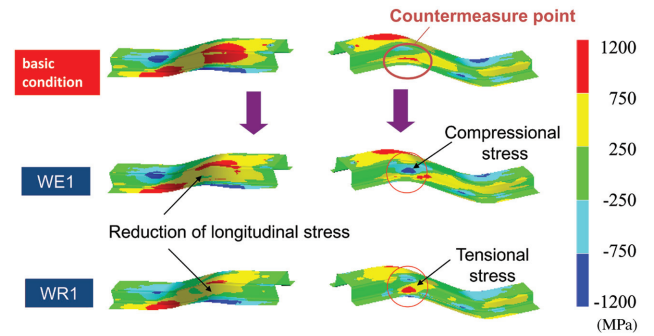

Fig. 12   Planer stress transition by width expansion and reduction

stretch flanging region, and in the case of WR1, in contrast, the width reduction in the second step left tensile residual stress locally, and thus, residual stress was effectively dispersed. In addition, in both WE1 and WR1, residual axial stress was reduced at both the walls of the region where the width was changed. This seems to indicate that width expansion/reduction decreased and lead to dispersal of residual stress, which effectively suppressed torsion and camber.

4. Measures against Forming Defects of Panel Parts

Sometimes, shallow drawn panels exhibit a large twist after forming. The geometric characteristics of shallow panels are such that the rigidity against in-plane bending is by far larger than that against out-of-plane bending and sectional torsion, and thus, when released from the restriction by dies, such a work piece tends to undergo not only in-plane bending in the most difficult direction but also a combination of out-of-plane bending and sectional torsion, which can occur easily. In such a case, where a forming defect is directly attributable to the geometry of the part, it is very difficult to work out preventive measures without changing the part design. There have been reports that propose measures to minimize internal stress by coining of the punch head face and beading of flanges based on tests using model dies.[7] However, the shapes of industrially used panels are more complicated, and simple measures do not always prove successful in controlling torsion. In consideration of the situation, the authors tried to clarify the mechanism of buckling torsion of shallowly drawn model panels and studied countermeasures using CAE analysis.

Test panels were drawn from 0.7-mm-thick sheets of 590-MPa class high-strength steel using square punches 420 mm × 260 mm in size to a stroke of 25 mm. The following different punches were used: one having a flat head face (corresponding to Base in **Fig. 13**); a second with a longitudinal groove, 3 mm in depth, cut in the head face (E01); a third with three such grooves (E03); a fourth with five grooves (E05).The torsion angle between the two longitudinal end sections was measured after forming the specimen panels. Fig. 13 shows the measurement results together with the torsion predicted by CAE analysis. Here the abscissa represents the twist angle per unit length of the deformation in which elastic strain energy attains a stable equilibrium; the angle was calculated from the stress at the bottom dead center of the forming stroke by CAE analysis.[8] Only the specimen of base case without the longitudinally embossed protrusions was free of torsion, while all the other specimens had twisted protrusions, but the angle varied depending on their number, which agreed with the prediction by CAE analysis.

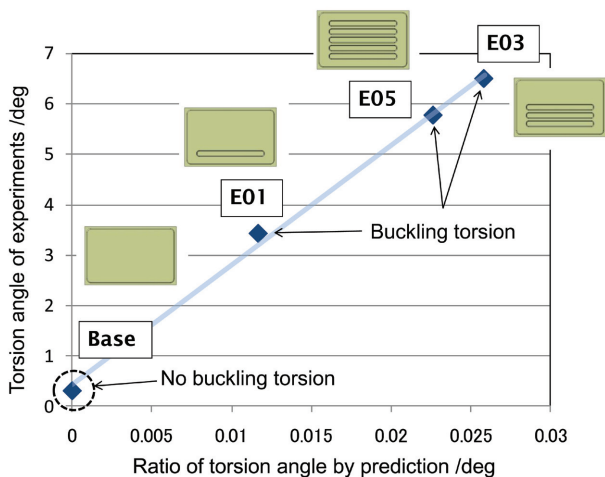CAE analysis was conducted using the specimen with five pro-

gions (WE3) than when applied to either one of them (WE1 or WE2). On the other hand, while the effect of WR was the largest when applied to the stretch flanging region (WR1), the torsion direction was reversed when applied to the shrink flanging region (WR2), and the effect decreased when applied to both the regions (WR3).

With respect to camber, width reduction was found to be more effective than width expansion; the improvement effect of WR1 was found to be the largest. To examine these test results, the authors conducted FEM analyses of the width expansion (WE1) and reduction (WR1). **Fig. 12** shows the result in terms of the stress in the longitudinal direction when the forming punch was at the lower dead center. The analysis showed that, in the case of WE1, the width expansion in the second step left compressive residual stress in the

Fig. 13 Comparison between torsion angle of experiments and ratio of torsion angle by prediction
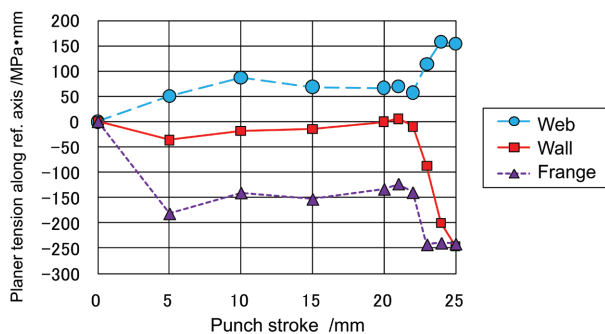
Fig. 14 Transition of planer tension along ref. axis on each area in forming process (E05)

Fig. 15 Effects of reducing buckling torsion of experiments by counter-measures (E05)

blanks. **Fig. 15** shows the results. The tests confirmed that any of the measures increased the in-plane tension of the panel, and thus, the torsion angle decreased. However, since all these measures lead to a decrease in sheet thickness of formed parts, care must be taken when there are restrictions to minimum thickness.

5. Closing

Steel materials have been intensively used for automotive bodies in appreciation of excellent recyclability, formability, and weldability. Among them, high-strength steel sheets are expected to be effective at decreasing body weight to reduce CO_2 emission and to enhance collision safety, and their strength will be increased further. In view of the situation, the present report has sorted out the mechanisms that cause dimensional defects, the most conspicuous of the problems related to forming of high-strength sheets, and elaborated the effects of preventive measures against each of the causing mechanisms. Desirable countermeasures basically consist of designing shapes of the parts to form as rigid as possible and minimize springback compensation at the die design stage through residual stress control. Understanding that application of CAE analysis is indispensable in elaborating measures against forming defects in industrial practice, Nippon Steel Corporation has worked out related techniques such as prediction of springback with a higher accuracy and the method of analyzing the causes of forming defects, which were not included herein owing to space restriction; reference report [9] gives more details of the analysis methods.

trusions (E05) to identify the cause of buckling torsion. **Fig. 14** shows the change in the average planar tension in the longitudinal direction in the web, walls, and flanges as the punch stroke *S* advanced. The graph shows that, up to a stroke of 22 mm, the longitudinal stress monotonously changes from tensile in the web (upper portion), around zero in the walls (middle of the panel), to compressive in the flanges (lower portion). Because the stress imposed during forming work is reversed at the upper and lower portions of the panel, stress decreases, and elastic strain energy reaches a stable equilibrium only with bending deformation. In the range of *S* greater than or equal to 23 mm, however, the compressive stress in the vertical walls rapidly increases, the stress does not decrease with bending deformation alone, and therefore, buckling torsion occurs to reduce the outstanding stress. The compressive stress in the vertical walls increases because reduction-of-area deformation occurs in the region where material flow was caused by embossing.

From the above, it became clear that, to decrease the cause of buckling torsion, it is important to change the planar tension in the longitudinal direction due to the embossing toward the tensile deformation side. With these results, using E05 of Fig. 13 as the specimens, the authors studied the following measures to increase tensile deformation during panel forming through tests: increase in flange restriction simulating bead forming; increase in blank holding force during embossing using a variable BHF function; and use of larger
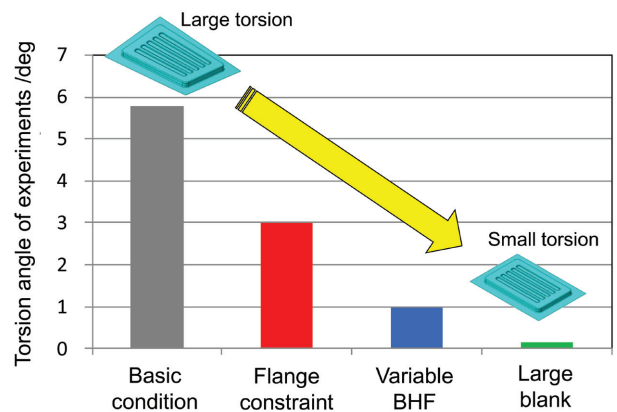
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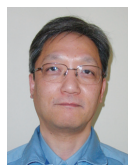
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