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Development of Forming Methods for Functional Improvement of Car Body Structural Parts

Ryuichi NISHIMURA* Yasuharu TANAKA
Takashi MIYAGI Misao OGAWA
Kenichiro OTSUKA Yoshiaki NAKAZAWA

Abstract

To further reduce car body weight and improve crash safety, in addition to increasing the strength of individual parts, increasing the strength and stiffness of joints between body structural parts is also effective. Two new sheet forming methods and related technologies have been developed. One of the new methods enables forming of ultra-high-strength steel (UHSS) sheets into parts having a notchless flange joint without corner notches, which, together with optimum part design, significantly improves the body stiffness and crash performance. The other developed method, Free Bend Sheet Forming, can form UHSS sheets into parts in an L or T shape having inscribing curved joints; it significantly enhances part functions through strength increase and suppression of thickness decrease. The forming methods of UHSS sheets greatly contribute to car weight reduction and crash safety enhancement.

1. Introduction

Lighter weight and higher strength are required for automotive bodies in response to the increasing need to suppress global warming and enhance crash safety. For this reason, use of high-strength steel sheets for body parts is rapidly increasing, and the application ratio of ultra-high-strength steel (UHSS) sheets having tensile strength greater than 780 MPa is increasing year by year.[1)] As a general rule, however, steel ductility decreases with increasing strength, and as a result, there is a certain limit to the strength of steel usable for body structural parts of complicated shapes, unless the shape is simplified. If higher-strength steel is to be used for car body parts, therefore, their shape has to be simplified. We, however, considered that, to further reduce body weight and enhance crash safety, it was effective to increase the strength and rigidity of the joints between body structural parts, in addition to increasing their strength, rather than simplifying their shape. As seen in **Fig. 1**, there are roughly two types of joints between body structural parts: (1) a flange joint at the longitudinal end of one part connecting to another, and (2) an inscribing curved joint of a part in an L or T shape; either of them are prone to fracturing or wrinkling during forming.

In consideration of the above, and to develop two types of high-strength, high-functionality body structural parts, namely (1) those having a continuous flange at an end, and (2) L- or T-shape parts having an inscribing curved joint, we developed a new package of

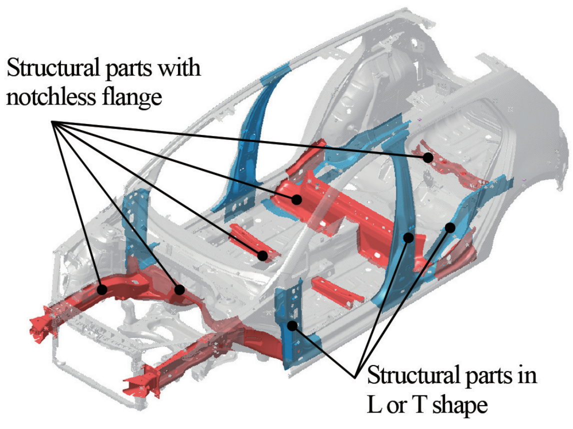

Fig. 1 Body structural parts to which developed forming methods are applicable

* Senior Researcher, Dr. Energy Sc., Integrated Steel-Solution Research Lab., Steel Research Laboratories
1-8 Fuso-cho, Amagasaki City, Hyogo Pref. 660-0891

technology focusing on steel sheet forming. First, a new press forming method was pursued from the viewpoints of dispersion and suppression of strain and control of deformation paths. Then, functional shape design of high-strength parts manufactured by the developed forming method was studied, and excellent functions of those parts were confirmed through function evaluation. Based on these results, practical applicability of the developed forming technology was verified through test manufacture of real body structural members using UHSS sheets. This paper relates to the development of such high-functionality automotive body structural members.

2. Development of High-functionality Automotive Body Structural Members with Continuous Flange Joint

To join one cross member or a similar structural part of an automotive body to another, a flange joint is provided at its longitudinal end as shown in **Fig. 2**.[2, 3] Very high stretch flanging performance is required for forming the corner portions,[4, 5] and on the other hand, since the flange is meant for joining with another body part, it exerts important functions in terms of body stiffness and the performance under a crash impact. Conventionally, however, to avoid highly demanding forming work of stretch flanging, especially with high-strength steel sheets of tensile strength exceeding 440 MPa, the flange was divided by notches at the section corners, and the advantages of high-strength steel were not fully exploited for the structural function of the body.

To solve the problem, aiming at developing high-performance structural parts with a continuous flange joint without corner notches and made of high-strength steel sheets, we tackled the development of new sheet forming methods and functional shape design of body structural members.

2.1 Development of new forming method, NSafe™-FORM-RU

Our first aim was to develop a forming method by which it was possible to form a UHSS sheet into a body structural part having a continuous flange without corner notches at an end. The flange forming method consists of trimming the edges of a material sheet to the contour of the part before bending and forming, and then, after forming it into a square section, flange-up forming of a continuous flange along an end circumference. Since the edge trimming stage has significant effects on the stretch flanging limit in the flange-up forming, we studied methods for improving formability in both stages.

Through studies of the edge trimming process, it became clear that the effects of this stage on stretch flanging performance were different from those in the case of piercing along a closed contour such as a circle, cases about which there have been many study reports. The following findings were obtained through studies (no illustrations given):[6] (1) with UHSS sheets, the sheet material bends excessively and very large burrs appear at the trimmed edge even when the clearance between the die and the punch is as small as 20% of the sheet thickness, and the flange forming performance may deteriorate significantly; (2) if it is possible to prevent the sheet material from bending between the dies, the incidence of large burrs and consequent deterioration of stretch flanging will be suppressed.

Next, the results of the studies on the flange-up forming are explained in detail.[4, 5, 7] When a conventional bending method is applied to the flange-up forming, deformation concentrates at the position of a flange corner, a fracture develops or wrinkles form there, and for this reason, it is impossible with high-strength steel sheets to obtain a continuous flange without notches.[4, 5] To solve the problem, we studied new forming methods from the viewpoint of strain dispersion.[7]

Figure 3 shows the early stages of the developed and conventional flange-up forming methods. By both the methods, a flat sheet is formed into a brimmed channel section (hat section) in the first process, and at the same time, a longitudinal end portion is bent by 60 degrees to form a notchless end flange, and then in the second process, the end flange is further bent from 60 degrees to the designed angle.[4, 5, 7] The difference between the two methods lies in the first process.

The developed method, named NSafe™-FORM-RU, uses a pad (hereinafter called the lower pad) supported by the pressing mechanism on the lower punch side (the lower shaded portion in Fig. 3(b)). At the beginning of the forming process, the lower pad is held at a position higher by its vertical stroke (S_{lp}) than the upper surface of the punch, and during the forming process, the width center of the blank is maintained at that height. As a result, as shown in a cross section in Fig. 3(b), the blank is bent at two points along the flange root. After the upper pad bottoms to the surface of the die, the upper pad and the die move as one unit, and the lower pad moves down. At the lower dead center of the press stroke, the level at which the blank was held becomes equal to the punch surface, and the forming of the first process ends here. As explained, by the developed method, the bending for flange forming is made to occur at two positions of the flange root to disperse the strain of the stretching flange edge.

Test forming into a basic model shape simulating a typical body structural part was conducted according to the developed method to verify its effects. Material sheets of two strength grades were used, a 590 MPa grade high-strength sheet (referred to as 590Y in figures) and a 980 MPa grade UHSS sheet (980Y), the flange height H was fixed at 15 mm, the vertical stroke of the lower pad (S_{lp}) was changed from 0 to 25 mm, and forming performance was evaluated in terms of the thickness strain at the thinnest part of the flange

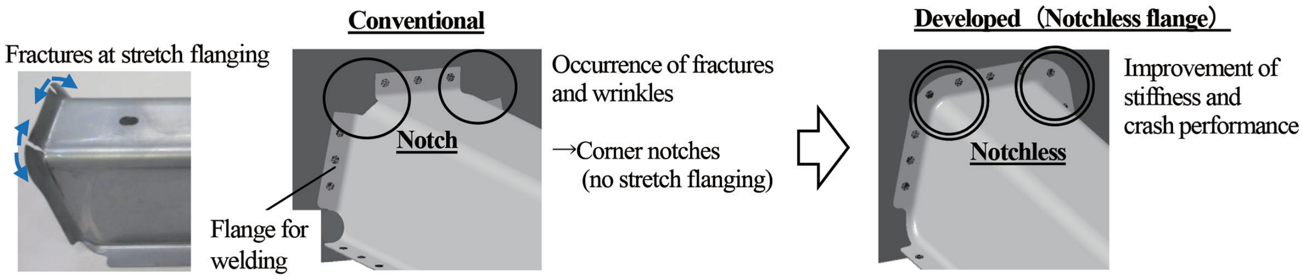

Fig. 2 Conventional problems solved by developed forming method

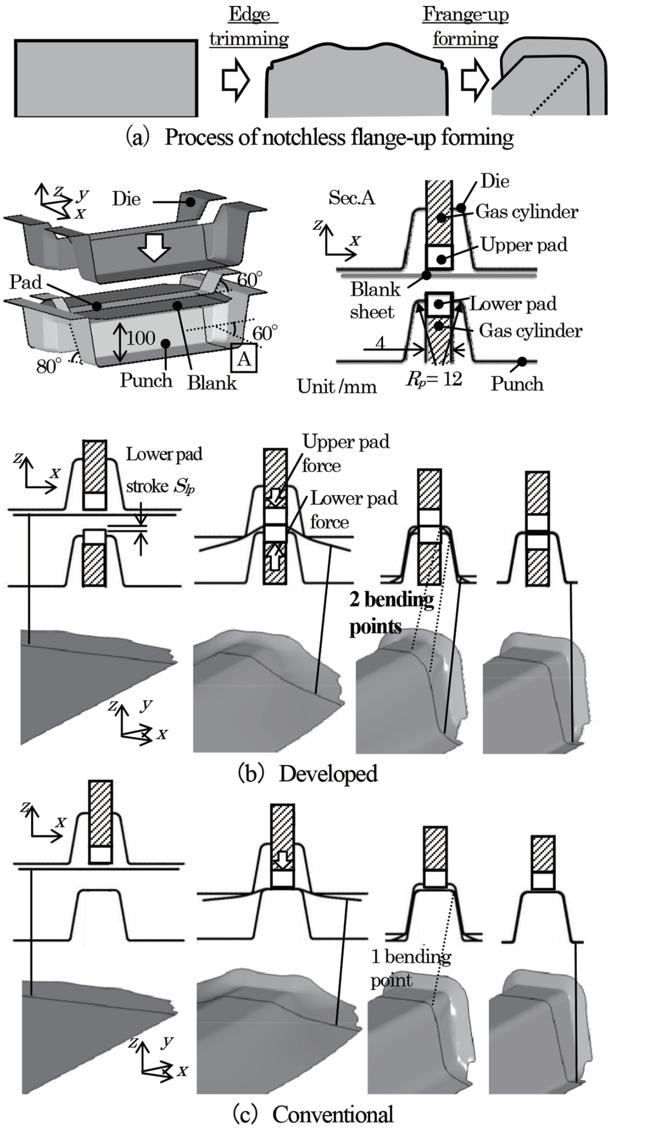

Fig. 3 Mechanism of developed notchless flange-up forming

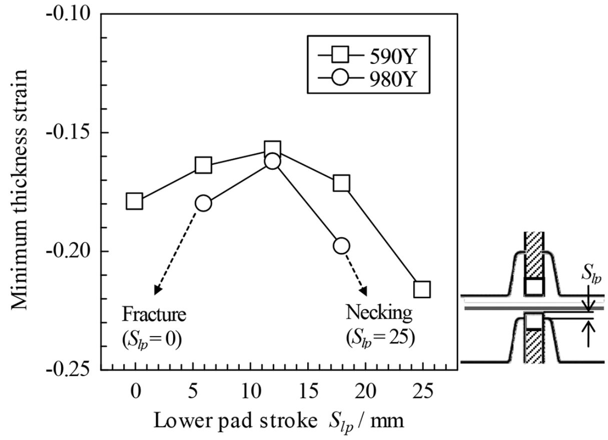

Fig. 4 Improvement of flange-up formability by developed method

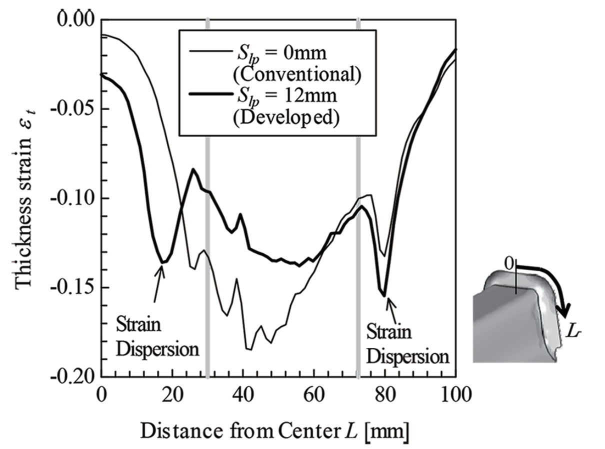

Fig. 5 Improvement of strain dispersion by developed method

edge.

Figure 4 shows the effect of the change of S_{lp} on the flange-up formability. Whereas by the conventional method, by which S_{lp} is 0 mm, stretch flanging failure occurred with the 980Y sheets, by the developed method it did not. It is also clear from the graph that there is an optimum value of S_{lp} to minimize the thickness decrease of the flange. In addition, due to the strain dispersion effect shown in **Fig. 5**, under the optimum condition according to the developed method, the thickness decrease of the 980 MPa grade sheet was substantially equal to that of the 590 MPa grade.[7] As a result, it is now possible to obtain a continuous end flange without corner notches using a blank of a 980 MPa grade sheet trimmed with a die clearance *CL*/*t* of 11%.

2.2 Part shape design

In parallel to the development of the forming technology, the optimum shape of a part having a continuous flange was examined from the functional viewpoint. Cross members were one of the study subjects; they are arranged in the body width direction, and undergo torsional deformation during running, and axially collapsing deformation at side crash to minimize the deformation of the cabin. In consideration of this, the study for shape optimization was focused on the torsional stiffness and the axial collapsing behavior in an early stage of a side crash.

2.2.1 Study of part shape optimization based on basic model

We studied how the functions of a part are improved by optimizing its sectional shape, besides the improvement of joint strength and stiffness by elimination of the corner notches of the flange.

First, to study an optimum sectional shape from the viewpoint of structural stiffness, the influence of sectional shape on the torsional stiffness *C* of a part was numerically analyzed based on a simplified model.[8] **Figure 6** shows the effects of the section corner radius R_p on the torsional stiffness *C*. In the analysis, the subject part was assumed to be 500 mm in length and have a square section 100 mm in height *h*, the section corner radius R_p was set at 0, 5, 12, 30 and 50 mm, the part was restricted at one end, and torsional deformation was applied at the other. The ratio of the part stiffness (*C*) when the corner radius R_p was 5, 12, 30 and 50 mm to the stiffness when it was 0 mm (C_{Rp}=0 mm) was plotted along the ordinate of the graph, and the ratio of the corner radius R_p to the section height *h* along the abscissa. The graph also shows a theoretical curve calculated from an equation (omitted) given in Timoshenko's literature.[9] The torsional stiffness *C* was largest, either by the theory or by the analysis, when the corner radius R_p was 12.5% of the sectional height *h*. The

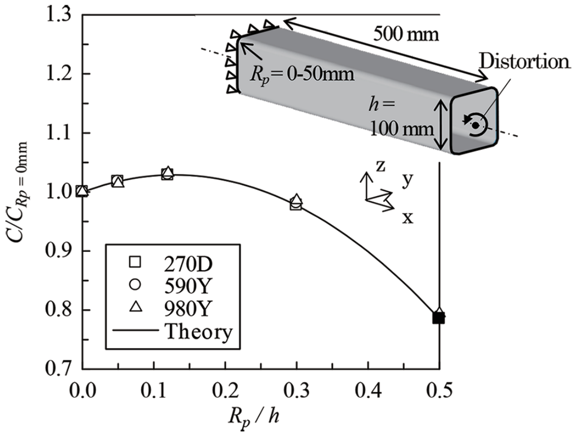

Fig. 6 Effect of sectional shape on torsional stiffness

value of R_p/h at which the torsional stiffness was largest also remained unchanged even when h changed.[8)]

Next, axial crashing behavior of a body structural member was studied using a different model shape. Although no illustrations are given of the study results, increasing the corner radius R_p was effective at improving the deformation characteristics in an early stage of an axial collapse, the characteristics of which are essential for deformation suppression members.

Thus, it was confirmed that the torsional stiffness and crash performance of a square-section member 100 mm in section height are improved by increasing the section corner radius R_p from conventional 5 mm or less to approximately 12 mm. Note here that the above finding is advantageous both to functionality and formability because the increase in the corner radius R_p also decreases the stretch flanging ratio of the flange forming.

2.2.2 Verification of function improvement based on shape of real body part

We verified the function improvement effects of a model part simulating a real body member having an optimum shape (R_p=12 mm, with continuous end flange without corner notches) as compared with another of a conventional shape (R_p=3 mm, with end flanges notched at corners) by numerical analysis.

Figure 7 shows the configuration of the model parts for the analysis, and **Fig. 8** the effects of the corner radius R_p and the flange shape on the performance of the parts. It is clear from the graph that with the optimum sectional shape, torsional stiffness is enhanced by 17% and the axial collapsing characteristics are in an early stage of crashing by 30%, approximately.

2.3 Trial forming of simulated body part and commercial application of developed forming method

Body parts simulating a cross member or the like were manufactured by the developed forming method, applying the section shape most adequate for torsional stiffness and impact resistance explained in sub-section 2.2. **Figure 9** shows a formed part made of a 980 MPa grade steel sheet. The flange joint, which was conventionally divided at the corners, is continuous in the same height as in the portions along the top plane and the side walls, and there are weld spots in the corners of the flange.

The above development of the new forming method and the optimum section shape have been commercially applied to the manufacture of auto body parts of high-strength steel sheets with continuous flanges, contributing to car body weight reduction and crash safety enhancement.

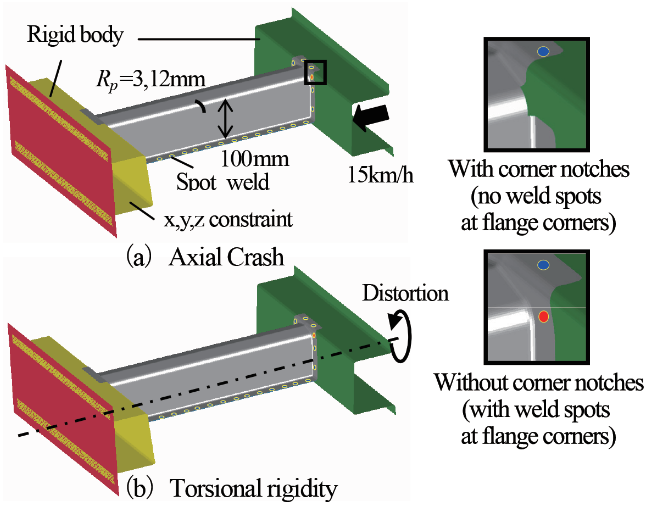

Fig. 7 Performance evaluation model simulating actual auto-body parts

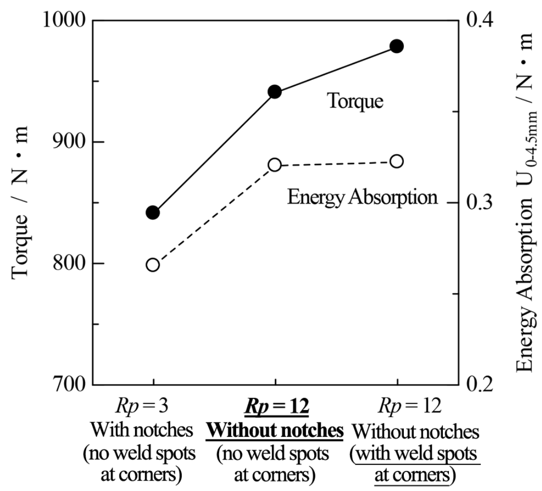

Fig. 8 Performance improvement by notchless flange and shape optimization

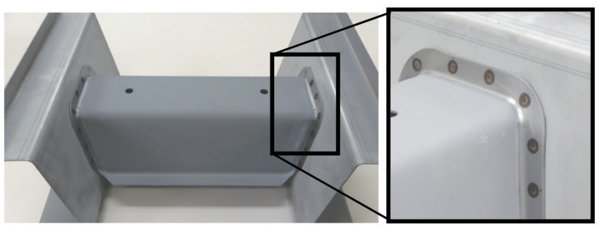

Fig. 9 Simulated cross member of UHSS sheet having flange joints without notches

3. Improvement of Strength and Functionality of Curved Structural Parts by Free Bend Sheet Forming Method

Body structural parts in an L or T shape having inscribing curved joints have sectional length that changes greatly from portion to portion, and are difficult to form.[10)] Forming of high-strength steel sheets into such parts by conventional drawing was considered commercially impracticable. In consideration of this situation, we addressed improvement of the functionality of body structural parts by developing a new sheet forming method that enables forming of UHSS sheets into such difficult-to-form parts based on a new principle,[11, 12] and verified improved functions of the parts manufactured by the method eventually developed.

3.1 Development of free bend sheet forming method, NSafe™-FORM-LT

Figure 10 shows a T-shape model part for the fundamental study for a new forming method, and **Fig. 11** compares the sheet forming process to the model part by the developed method, which was named Free Bend Sheet Forming, or NSafe™-FORM-LT, and the conventional method by draw forming. When a high-strength steel sheet is formed into a curved shape by the conventional method, wrinkles appear at the top flat portion, and when a high tension is applied to the blank to suppress the wrinkles, fractures occur. To solve the problem, the developed method includes the following measures as shown in Fig. 11: a pad to restrict the blank at the top flat portion to prevent the wrinkles; bending method applied to prevent fracture; and material flow control to accelerate the flow of the blank material into the portions where fracture is feared to occur.

Figure 12 compares the deformation behavior of the portions prone to fracture and wrinkles during forming by the developed method with that by the conventional method. Looking at the top flat portion, where wrinkles are likely to appear, strain is widely distributed in areas where the strain ratio is less than −1 by the conventional forming method, but by the developed method, in contrast, the minimum major strain is kept under control and the strain ratio remains near the uniaxial deformation side. Next, looking at the stretch flanging portions, where fracture is feared to occur, by the conventional method large strain was imposed on the portion of uniaxial deformation along the edge and the portion of drawing/plane strain deformation away from the edge, and fracture occurred, but by the developed method strain was kept under control in either of those portions.

From the formability evaluation results given in **Fig. 13**, even though by the conventional method the thickness decrease in the portions prone to fracture becomes significant with increasing steel strength, and the curvature fluctuation range, an indicator of wrinkling, also worsens, by the developed method, in contrast, the danger of wrinkling and fracture due to the use of high-strength sheets is kept under control.

The above results corroborate the high possibility of the developed free bend sheet forming method to form even UHSS sheets into curved, difficult-to-form shapes through the control of deformation paths and strain in the portions where wrinkles and fractures are likely to occur.

3.2 Verification of function improvement of parts made by developed forming method

The preceding sub-section described in detail the formability improvement mechanisms of Free Bend Sheet Forming that is expected to be effective at further strengthening difficult-to-form structural parts. Now, verification by numerical analysis of the crash resistance improving effects of the developed method and its results are explained below.

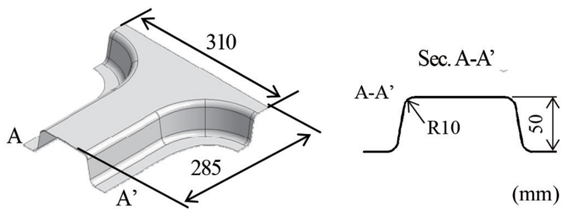

Fig. 10 "T"-shape model

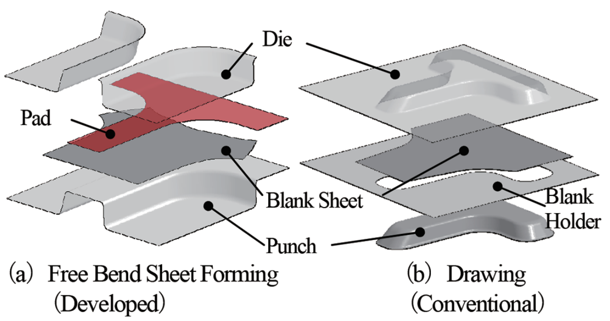

Fig. 11 Comparison between developed and conventional forming method

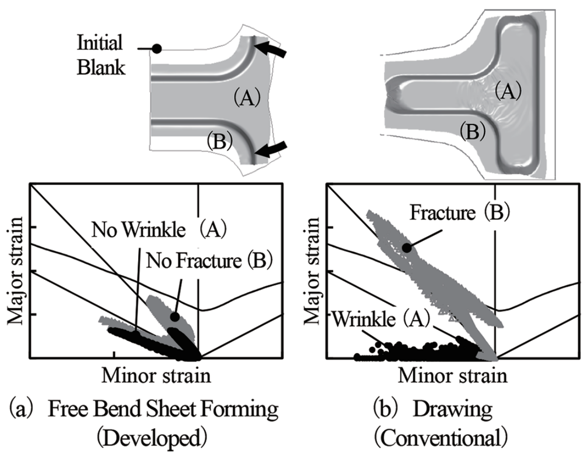

Fig. 12 Mechanism of formability improvement by Free Bend Sheet Forming

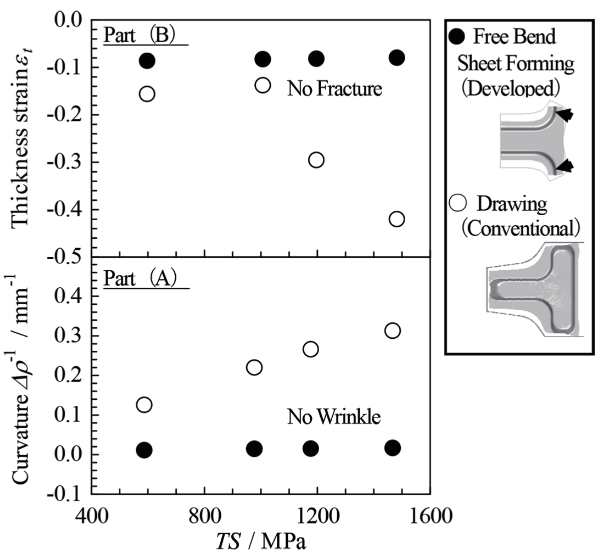

Fig. 13 Improvement of formability by Free Bend Sheet Forming

Figure 14 shows a crash analysis model of a simulated B pillar reinforcement made of high-strength steel sheets of 440 to 980 MPa grades. Forming analysis was conducted first, and after strain mapping, crash analysis was conducted. To verify the effects of the forming method, the developed free bend sheet forming method and the conventional method were compared by forming analysis. In common body structures, the impact energy of a side crash is absorbed by collapsing of the B pillar in the lower portion. To evaluate the energy absorbed (*E.A.*) by the lower portion of the B pillar, an impactor was assumed to strike there, and the change in the *E.A.* value during the impactor stroke from 0 to 150 mm was calculated.

Figure 15 compares the crash performance of the B pillar reinforcements of different steel strengths formed by the developed and the conventional methods. By the conventional method, the forming condition was such that wrinkles and fractures were unlikely to occur with 440 and 590 MPa grade sheets, but with 980-MPa grade sheets, forming work was inviable owing to fractures or wrinkles. By the developed forming method, on the other hand, forming work progressed with all specimen sheets up to 980 MPa grade without fractures or wrinkles. It is clear from the graph that the *E.A.* increased with increasing steel strength; this was remarkable especially with the 980 MPa class sheets, which could be properly formed only by the developed method. In addition, with sheets of either 440 or 590 MPa grades, the *E.A.* of the part formed by the developed method was higher than that of the one made by the conventional method in spite of the same material and the same shape. To clarify the reason for this difference, the forming strain distribution near the collapsed portion was calculated regarding the B pillar specimens formed by the developed and the conventional methods; **Fig. 16** shows the result: the thickness decrease of the vertical wall near the collapsing portion proved to be smaller by the developed method than by the conventional method, which indicates that the difference in the forming performance of the two methods also affects the value of *E.A.*

The above results corroborate that the developed free bend sheet forming method allows use of steel sheets of higher strength and suppresses the thickness decrease during forming, and thus contributes to significantly improving the functions of body structural parts.

3.3 Trial forming of simulated body parts and commercial application of developed forming method

The enhanced ability of the developed free bend sheet forming method to form steel sheets into curved difficult-to-form shapes has been explained in detail in sub-section 3.1, and the crash resistance improving effects of the method in sub-section 3.2. The present sub-section verifies the commercial applicability of the method based on trial manufacture of simulated reinforcements for A and B pillars, typical examples of curved structural parts. **Figure 17** shows examples of parts of 1 470 MPa class UHSS sheets trial formed by the developed method (R/F meaning reinforcement). [13, 14]

The L-shape portion, which is difficult to form, of the A pillar reinforcement was formed by the developed method. Although not illustrated with figures, in the first stage, the upper portion of the piece was formed by drawing, then in the second stage, the lower L-shape portion by Free Bend Sheet Forming, and in the third stage, the embossments of the top flat portion, etc. by stamping. [13] The T-shape portion of the B pillar reinforcement, likewise, was formed by the developed method. Since the center portion of the latter is

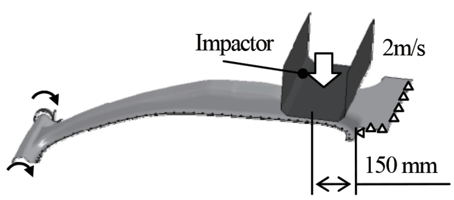

Fig. 14 Crash analysis model

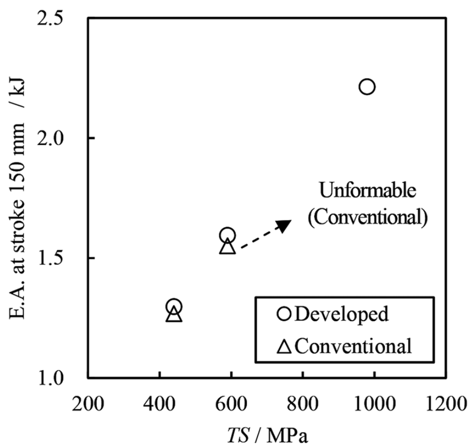

Fig. 15 Improvement of crash performance of structural parts formed by Free Bend Sheet Forming

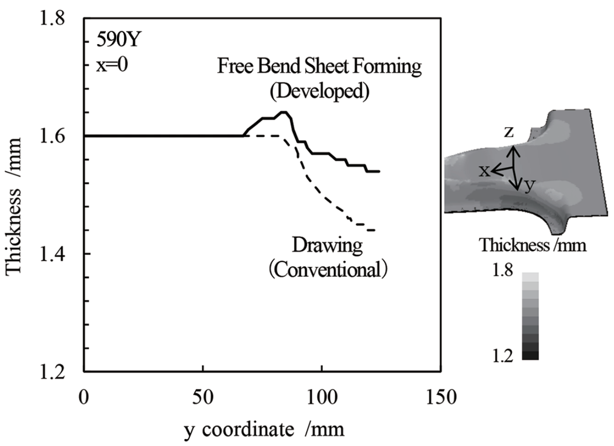

Fig. 16 Suppression of thickness decrease by Free Bend Sheet Forming

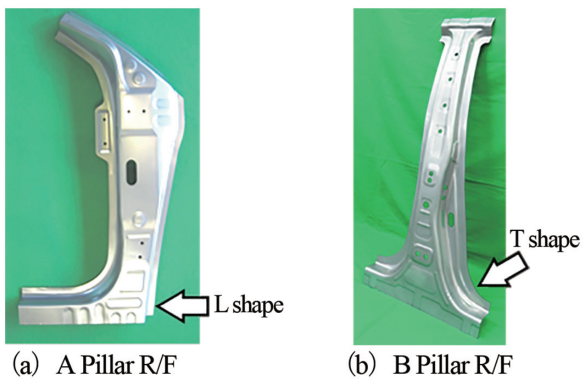

Fig. 17 Structural parts formed by Free Bend Sheet Forming [13, 14]

curved in a side view, flange wrinkles are feared to occur during bending, and to avoid this, the center portion was formed by light drawing before the free bend forming by the developed method. When UHSS sheets are used, neither of these parts can be formed by the conventional methods because of excessive wrinkles, but the developed free bend sheet forming method proved capable of forming them into these shapes without fractures or wrinkles.[13, 14] In addition, it has been proven that, by the developed method, the excess area of blanks for parts of any shape can be made much smaller than by the conventional drawing, significantly improving product yield.

Free Bend Sheet Forming can be applied to the forming of real automotive body structural parts having difficult-to-form curved joints without causing defects, and as such, contributes to further strengthening car bodies and reducing their weight.

4. Conclusion

To further reduce the weight of automotive bodies and enhance their crash safety, strengthening and stiffening the joints between component parts is effective, in addition to strengthening individual parts. Typical of such joints are (1) a flange joint at a longitudinal end of a part and (2) an inscribing curved joint of a part in an L or T shape; either of them are difficult to form because fractures or deep wrinkles are likely to occur during their forming. To develop body structural parts of high strength and functionality having such joints, we developed a group of steel sheet forming technologies from the viewpoints of dispersion and control of strain and control of deformation paths.

4.1 Development of high-functionality body structural parts having notchless flange joint

(1) The method for forming a continuous flange joint without notches at sectional corners, which has been developed with the aim of adequately dispersing strain, minimizes the thickness decrease at flange portions where fracture is likely to occur, and enables the formation of continuous end flanges using trimmed blanks of UHSS sheets.

(2) When a square-section structural part is optimally designed (i.e. the corner radius is changed to 12 mm from the conventional 3 mm, and the joint flange at its longitudinal end is made continuous without corner notches), its torsional stiffness increases by 17%, and the axial collapsing characteristics in an early stage of a crash by 30%, approximately.

4.2 Enhancement of strength and functions of curved structural parts by free bend sheet forming method

(1) Due to adequate control of deformation paths and strain in the portions where fracture and wrinkles are likely to occur, it is possible by the developed free bend sheet forming method to form UHSS sheets into difficult-to-form parts having portions tightly curved in the plane direction.

(2) The developed forming method enables use of high-strength steel for body structural parts, and significantly enhances their functionality. In addition, by the method, the thickness decrease during forming is minimized, which also enhances the functionality of the parts even when the shape and the steel strength are the same.

The developed technologies have been applied to the commercial manufacture of automotive body structural parts having notchless end flange joints or those in an L or T shape having inscribing curved joints using high-strength or UHSS sheets, and thus contribute to the weight reduction and enhancement of automotive crash safety.

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Ryuichi NISHIMURA
Senior Researcher, Dr. Energy Sc.
Integrated Steel-Solution Research Lab.
Steel Research Laboratories
1-8 Fuso-cho, Amagasaki City, Hyogo Pref. 660-0891

Misao OGAWA
Senior Manager
Design & Advanced CAE Technology Dept.
Quality Management Div.
Nagoya Works

Yasuharu TANAKA
Senior Manager, Head of Dept.
Design & Advanced CAE Technology Dept.
Quality Management Div.
Nagoya Works

Kenichiro OTSUKA
Senior Researcher
Nagoya R & D Lab.

Takashi MIYAGI
Senior Manager
Design & Advanced CAE Technology Dept.
Quality Management Div.
Nagoya Works

Yoshiaki NAKAZAWA
General Manager, Head of Dept., Dr. Eng.
Research Administration Dept.
R & D Planning Div.