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Development of Press Forming Technologies for Closed Polygonal Cross-section Parts for Automobiles with Light Weight and High Performance†

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Abstract:

A new press forming technology has been developed for closed polygonal cross-section automotive parts to achieve both the weight reduction and the crashworthiness improvement. The developed press forming method can be performed by conventional mechanical press machines. A front side member model of a flange minimizing closed hexagonal cross-section manufactured by the developed press forming method shows high crashworthiness and stiffness in comparison with conventional hat-shape parts, and weight reduction can be achieved by combination of optimizing a cross-section shape and using high strength steel sheet.

1. Introduction

Reduction of body weight is an important challenge in automobile development from the viewpoint of preservation of the global environment by reducing CO_2 emissions. At the same time, improvement of properties such as crash safety and body rigidity is also a key issue, and it is essential to satisfy both of these requirements. In members and other frame parts and reinforcements used with doors, hoods, etc., body weight reduction measures are already being implemented by reducing the thickness of steel sheets while continuing to satisfy crash safety by adopting high strength materials in the steel sheets used in these applications. However, in order to achieve further reductions in body weight, an approach from the structural and material aspects is necessary.

Closed section structures are effective for securing crashworthiness and rigidity, and are widely used in existing automobile parts. In general, closed section structures are formed by joining the upper and low flange parts of two press-formed parts by spot welding.

This paper discusses the development of new press forming technologies for closed polygonal cross-section parts which enables weight reduction simultaneously with maintaining part performance, such as crashworthiness and rigidity, by minimizing the size of the flange parts, which are essential when assembling automobile parts by spot welding, and by optimizing the cross-sectional shape.

2. Investigation of Part Performance Improvement by Adoption of Closed Polygonal Cross-section Parts

2.1 FEA Conditions

Fenite element analysis (FEA) was conducted in order to investigate the effect of the cross-sectional shape on the axial crush performance and rigidity of model shapes assuming actual automotive parts. The

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solver used in this study was LS-DYNA (developed by Livermore Software Technology Corp.). In the analysis of axial crush performance, the models used had various closed cross-sectional shapes, such as a hat shape, flangeless rectangular closed cross-section shape, flangeless hexagonal cross-section shape, etc., and a part length of 400 mm, bending radius of 5 mm, and mesh size of 2.5 mm. The material models had a tensile strength level of 590 MPa or 980 MPa, Young's modulus = 210 GPa, sheet thicknesses of 1.4 mm to 1.6 mm, density of 7.85×103 kg/m^3, and Poisson's ratio of 0.3. Absorbed energy was evaluated from the start of crushing in high speed crushing, e.g., impact speed = 10 m/s (36 km/h), to a crush distance of 100 mm. Analysis of torsion rigidity and 3-point bending rigidity was evaluated using OptiStruct (developed by Altair Engineering, Inc.) as the solver. The part length was 900 mm. The material models were the same conditions as those used in the analysis of axial crush performance. 3-point bending rigidity was evaluated as the average of the maximum displacement of the top surface of the part and the maximum displacement of the bottom surface for the case when a load of 2 kN was applied to the center of the long axis of the part. In the torsion rigidity, the torsion angle was evaluated for the case when a moment of 1 kN·m was applied to the part center axis.

2.2 Conditions of High Speed Crush Test

Axial crush performance was evaluated using parts in which the performance evaluation and cross-sectional shape of the part were optimized in the simulation. The conditions of the high speed crush test[1] were the same as those of the simulation. Namely, constant velocity crushing was performed at an impact speed of 10 m/s (36 km/h), and absorbed energy was evaluated from the start of crushing to 100 mm. High tensile strength materials with strength of 590 MPa or 980 MPa were used as test pieces, and sheet thicknesses were from 1.4 mm to 1.6 mm. After specimens were prepared by bend-forming, closed cross sections were formed by either laser butt welding or spot welding at the flange part. The spot pitch was 35 mm. The part length was 400 mm, and the radius of the bending part was 5 mm.

2.3 Effect of Cross-sectional Shape on Part Performance

The cross-sectional shape of automobile structural parts such as front side members, etc. is generally the hat shape shown in **Fig. 1**(a). Flanges are necessary in hat shaped parts, as these parts are assembled by joining an inner part and an outer part by spot welding. A flange width of 20–30 mm is frequently used, and in the case of the front side member, the weight of the flange parts accounts for approximately 20% of the total part weight.

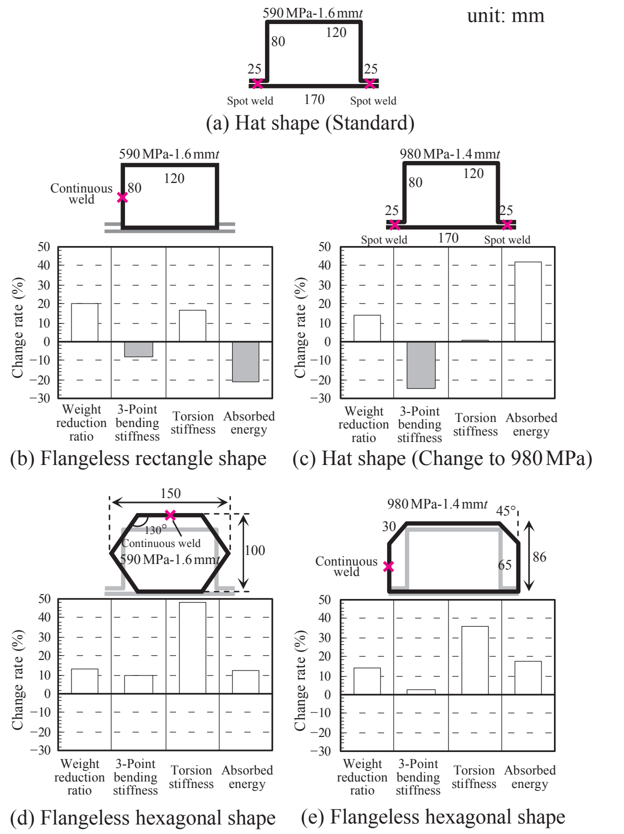


Fig. 1 Effect of cross-sectional shape on various properties of closed section shape

Accordingly, a structure which omits the flanges is one conceivable measure for reducing the weight of parts. However, as shown in Fig. 1(b), weight reduction is possible if the flange parts of the hat shape are simply omitted, but the axial crush performance and rigidity necessary in the front side member are remarkably reduced. On the other hand, as shown in Fig. 1(c), if the material thickness of the hat shape is reduced by simply adopting high tensile strength steel, impact performance are improved, but the decrease in rigidity is large. To date, improvement of impact performance by adoption of a polygonal cross-sectional shape, such as a hexagonal or octagonal shape, has been reported[2]. Figures 1(d) and 1(e) show examples of the part cross section and property changes in case of a hexagonal closed cross section. Not only is it possible to achieve a maximum weight reduction of 12% in comparison with the hat shaped cross section, but at the same time, rigidity and impact properties are also higher than with the hat shape. Thus, omission of flanges by adoption of a closed polygonal cross section is an effective method for simultaneously realizing weight reduction and improved performances in parts.

Figure 2 shows the weight reduction ratio of various flangeless closed cross-section samples in comparison with the standard hat shape when the cross-sectional shape is changed so that the absorbed energy calculated

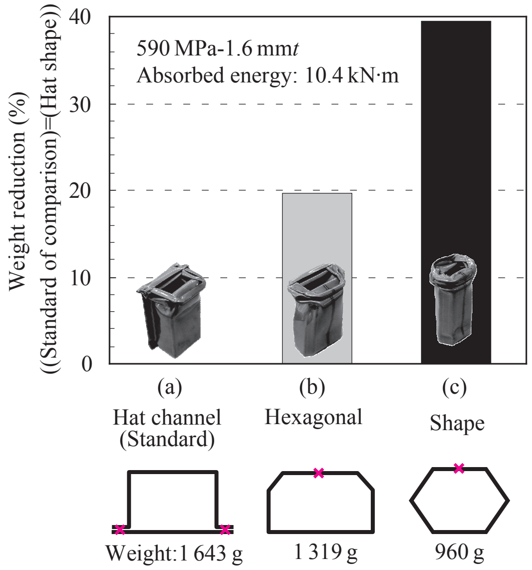


Fig. 2 Effect of cross-sectional shape on weight reduction ratio

from the results of crush tests is 10.4 kN·m. In the case of the flangeless closed hexagonal cross section evaluated in this study, the results confirmed that a weight reduction of approximately 40% is possible in comparison with the hat shape.

The cross-sectional angles and side length ratio also have a large effect on performance improvement by adoption of a hexagonal shape. **Figure 3** shows the effect of the cross-sectional angle θ_1 on absorbed energy during axial crushing for the closed hexagonal cross section in Fig. 1(d). Absorbed energy shows its largest value when the cross-sectional angle θ_1 is between 130° and 140°. As shown in Fig. 3, the fold density of the crushed part increases when the cross-sectional angle is in the above-mentioned range. It is thought that flow stress increases and absorbed energy displays its maximum value for this reason. The cross-sectional angle θ_1 in Fig. 1(d) is 130°, and from the above-mentioned results, it is considered that performance improvement was remarkable and the weight reduction effect was also large.

Figure 4 shows the effect of amount of reduction (shoulder length) of the upper right and left corners on various types of performance in the case of flangeless hexagonal shapes like that in Fig. 1(e). In comparison with the base model (hat shape), torsion stiffness and 3-point bending stiffness are improved by adoption of the closed hexagonal cross section, but absorbed energy decreases due to the shorter circumferential length. As the amount of reduction at the upper corners increases, the weight reduction effect becomes greater. At the same time, the flow stress in the axial crushing direction of the cross section increases, and as a result, absorbed energy also increases. It may also be noted that there is virtually no change in torsion stiffness as the shoulder length increases, but 3-point bending stiffness shows a decreasing tendency when the corner reduction amount (shoulder length) reaches 40 mm. Based on these results, a closed hexagonal cross section with a shoulder length of 30 mm was selected as the cross-sectional shape for the model parts for trial manufacture, as this shape showed the largest performance improvement, while also achieving a large weight reduction effect.

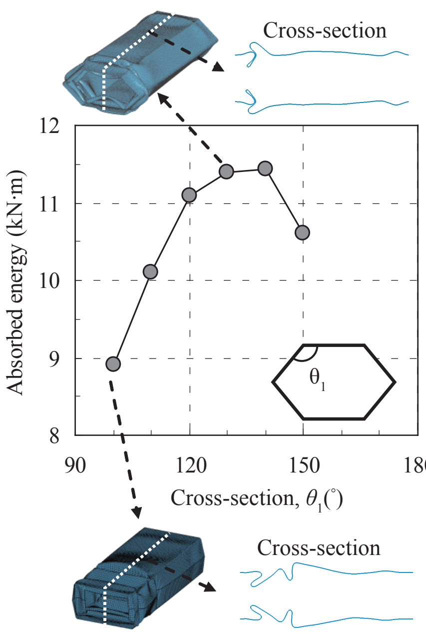


Fig. 3 Relationship between cross-section angle (θ_1) and absorbed energy

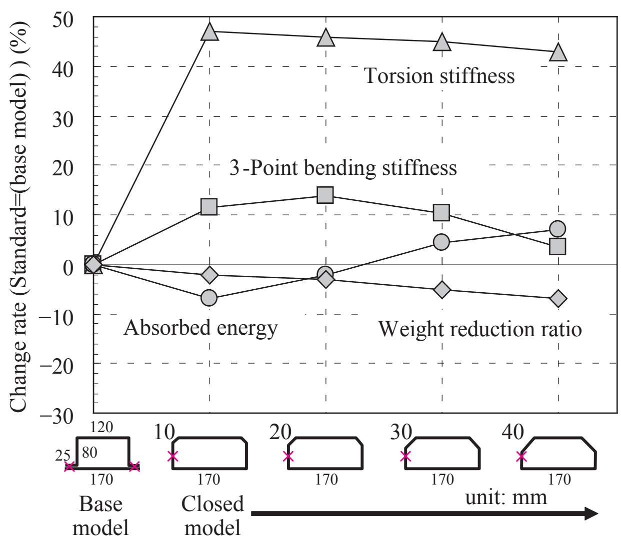


Fig. 4 Relationship between cross-section shape and various properties on flangeless hexagonal shape

3. Development of Forming Technology for Flangeless Closed Cross-section Parts by Press Forming

3.1 Cam Bending Method and Temporary-Fixing-in-Die Technique

3.1.1 Shape of trial part

Figure 5 shows the shapes of the front side member models used in trial manufacture. The cross-sectional shapes at the edges shown in Fig. 5 are similar shape of the hexagonal cross section shown in Fig. 1(d). The trial parts have a shape in which the part height from the part front edge to the back edge was increased from 80 mm to 150 mm, while the total length of the part was 450 mm. Crush beads, which function as initiation points for axial crushing in a collision, were also provided on the front edge of the part.

3.1.2 Press forming process

Figure 6 shows the developed forming process of closed cross-section parts using a conventional mechanical press machine. First, in the 1st step, pre-forming is performed. In this process, forming is performed so that the various parts of the part have the same cross-sectional circumferential length as in the final shape. The 2nd step is pre-bending forming of the part bottom. In the 3rd step, cam mechanism of the press die moves the cam in the part center-axis direction while the part bottom surface is fixed with a pad, thereby forming the longitudinal (vertical) wall part. After the walls are formed, the punch descends from above and temporarily fixes the open top of the part. Assuming it is possible to secure perfect butt structure of the closed portion at the top of the part, butt welding can be performed in the following welding process. It was presumed to be extremely difficult to secure the necessary welding accuracy. Therefore, a process of temporary fixing in the press die was used in this study.

As shown in **Fig. 7**, two fixing methods were studied:

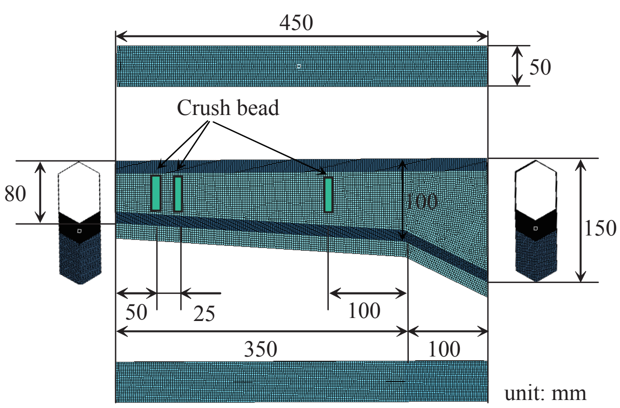


Fig. 5 Schematic diagram of the front side member model

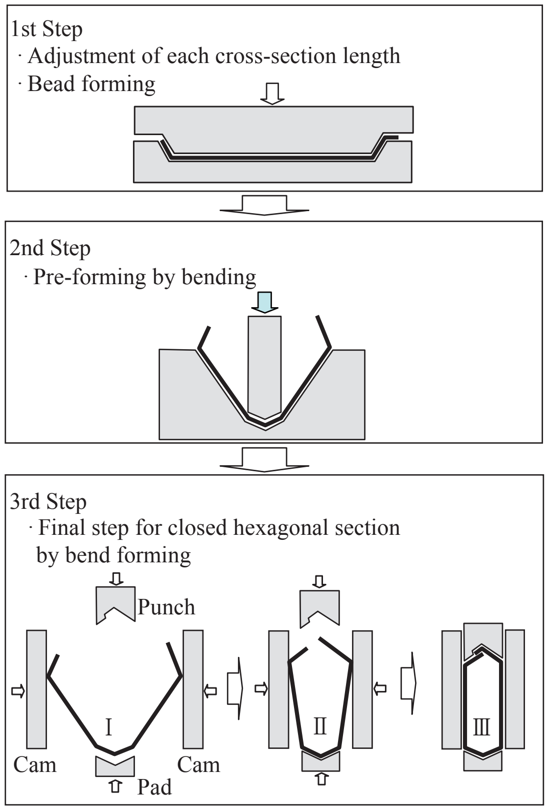


Fig. 6 Schematic diagram of the developed press forming method

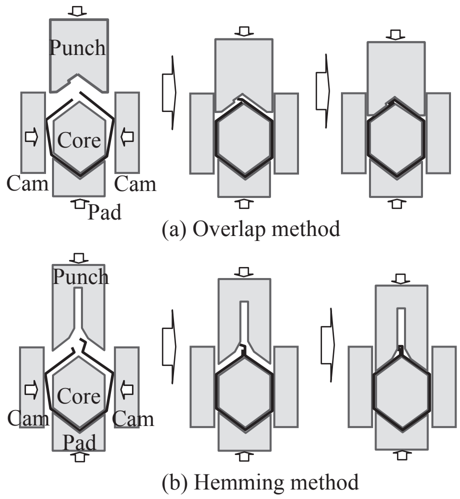


Fig. 7 Schematic diagram of temporary fix methods

(a) an overlap method and (b) a one-side flange hemming method. In (a) overlap method, a lap allowance of approximately 5 mm is provided on one side edge of the part where the blank parts are joined, and this 5 mm part is lapped over the adjoining surface by folding-bending by the punch press load. In (b) one-side flange hemming method, a projecting part for use in hemming is provided in a portion of the butt part of the blanks, and hem-bending under the punch press load is performed by a special punch with a hem-bending mechanism, temporarily fixing the top of the part. **Table 1** shows the

Table 1 Characteristics of various temporary fix methods

	Hat shape (standard)	One-side flange	Overlap	Flange less
Cross-section shape				
Weight reduction ratio (%)	0 (Standard)	10	14	16
Increasing rate of absorbed energy (%)	0 (Standard)	27	24	22
Difficulty level of forming	○	○	○	△
Difficulty level of welding	○	○	○	△

○ : Easy
△ : Difficult

features of the temporary fixing methods investigated in this study. The perfect butt welding method has the highest weight reduction effect, but at the same time, high welding accuracy is required. As features of the overlap method and one-side flange hemming method, these methods have the advantage of securing the necessary accuracy for welding while realizing impact properties equal or superior to those of the conventional hat shape, and also maintaining a weight reduction effect in comparison with the hat shape.

3.1.3 Die structure and results of trial manufacture

Photo 1 shows a general view of the lower die used in trial manufacture in this study. The die is a press forming die with a cam mechanism. A pad is provided on the bottom side of the part on the opposite side from the punch, and cams are arranged on the right and left sides of the die to form the vertical walls by bending-forming. The pad and cams are driven by cam drives

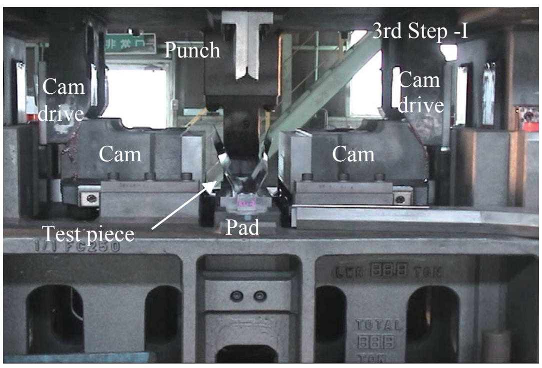
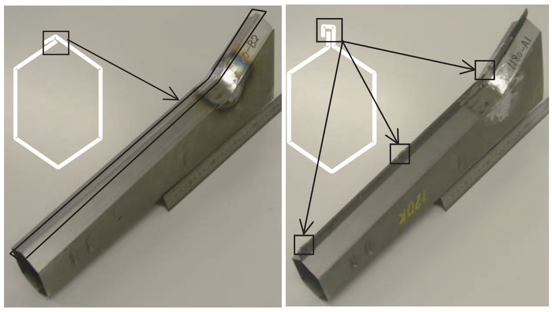


Photo 1 Photo of trial die assembly (Third step-I)



(a) Overlap (b) One-side flange

Photo 2 Appearance of front side member models after press trial

arranged in the top die, and the slide is driven when the die descends. The die material is FC350 (JIS G 5501 (JIS: Japanese Industrial Standard)) without surface treatment, etc. In trial manufacturing, 590 MPa grade material (thickness: 1.6 mm) and 980 MPa grade material (thickness: 1.2 mm) were used. However, no die damage was observed, as the process mainly consists of bending. **Photo 2** shows the results of forming by (a) overlap method and (b) one-side flange hemming method. No cracks, wrinkles, or similar problems occurred in the temporarily fixed part with either method.

3.1.4 Evaluation of high speed crush performance of trial parts

Figure 8 shows the absorbed energy in the high speed axial crush test and the weight reduction ratio for trial parts manufactured by the overlap method relative to a hat shape part as a standard. The overlap part of the trial part was fabricated by continuous welding using laser welding, and the axial crush test conditions were the same as in the previous section. The cross-sectional shape of the hat shape part used for comparison was the same as that in Fig. 1(a). The hat shape specimen was

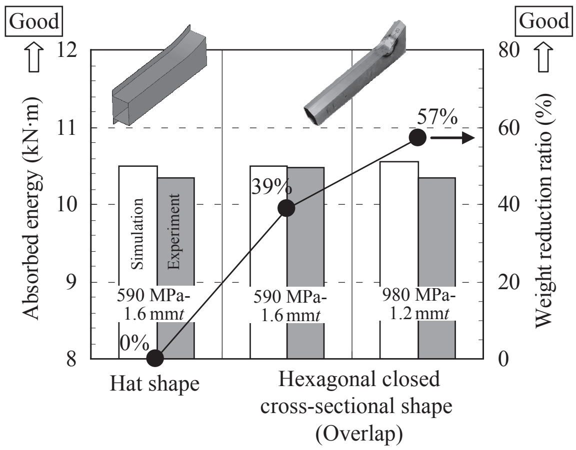


Fig. 8 Absorption energy and weight reduction ratio of front side member model

prepared using 590 MPa (thickness: 1.6 mm) material and had a total part length of 450 mm. The hat shape part was welded to the bottom plate by spot welding. With the trial part prepared using 980 MPa grade material with a thickness of 1.2 mm, the weight reduction ratio relative to the hat shape part was 57%. On the other hand, with all the sample parts, absorbed energy during crushing was 10.4 kN·m. Thus, the trial parts possessed the same energy absorption capacity as the conventional hat shape part.

3.2 Die Extrusion Method and Butt Welding Technology

3.2.1 Shape of trial part

Figure 9 shows the shape of the trial part. The object is a front side member model. The cross-sectional shape of the front edge is an analog of the hexagonal cross section (shoulder length: 30 mm) shown in Fig. 1(e). The height, total length, and crush bead configuration of the trial product are the same as those of the trial product in the previous section. The vertical wall of the part was a shape with a curved surface in the longitudinal direction. An edge-abutting shape without flanges was adopted as the closed cross section part.

3.2.2 Press forming process

Figure 10 shows the developed forming process using a conventional mechanical press machine. Pre-forming is performed in the 1st step. In this process, the various cross sections of the part are formed to the same cross-sectional circumference lengths as in the finished shape, and crush bead is also formed at the same time. In this operation, the part between the punch and the pad in the 2nd step is formed to a shape having a curvature of R = 24 mm. Although the part with this curvature becomes flat in the final step, if this part is formed to a flat shape from the initial step, the part is formed by a bending and unbending method. That is, with ultra-high tensile strength steel materials such as 980 MPa grade and the like, this is a part which is prone to bend cracking. If the part is formed to a shape with curvature, forming is possible while minimizing the bending and unbending modes.

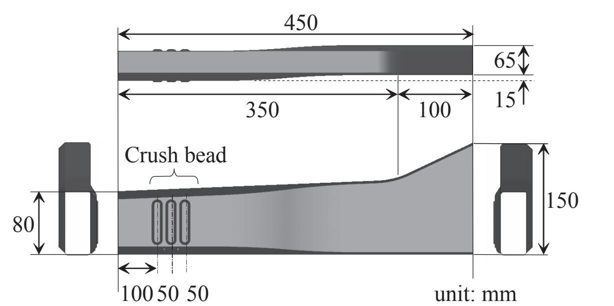


Fig. 9 Schematic diagram of the front side member model

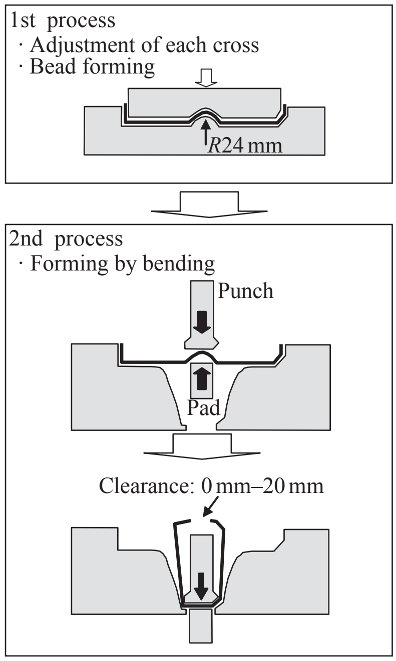


Fig. 10 Schematic diagrams of a developed press forming process (Die extrusion method)

The 2nd step is the process in which the curved lines of the bottom surface and vertical walls are bent. First, the part with the curvature of R = 24 mm, which was formed in the previous step, is clamped between the punch and the pad, thereby flattening the R part. After flattening, the R part is left in this clamped condition between the punch and the pad, the punch is moved downward in the die, and the vertical wall of the part is formed by pushing up on the die face. After the punch descends to the bottom dead point, the bottom surface of the part is flattened to the final shape by increasing the pad pressure, and at the same time, the inclined surfaces adjoining the bottom surface of the part are formed to the target shape by clamping and pressing between the bottom part of the die set and the projecting part of the punch. After forming is completed, the parts which were initially the two edges of the blank material become the opening in the part. Although a high level of technology is necessary in welding this butt welding position in the following welding process, high accuracy butt welding is possible using the newly-developed welding equipment described in the next section. In order to set the formed part in the welding device in that process, it is necessary to secure an opening distance on the order of 0–20 mm in the opening after forming.

3.2.3 Die structure and results of trial manufacture

Photo 3 shows general views of the die assembly used in trial manufacture. Photo 3(a) shows the upper die (punch) used in the 1st step, (b) shows the lower die

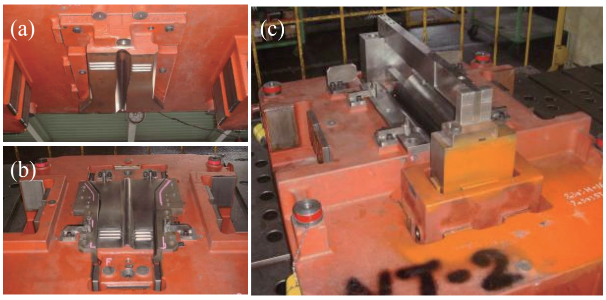


Photo 3 Photos of the die assembly ((a) Upper die for first process, (b) Lower die for first process, (c) Lower die for second process)

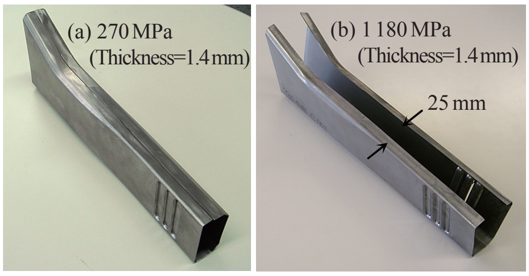


Photo 4 Appearance of front side member models after press trial

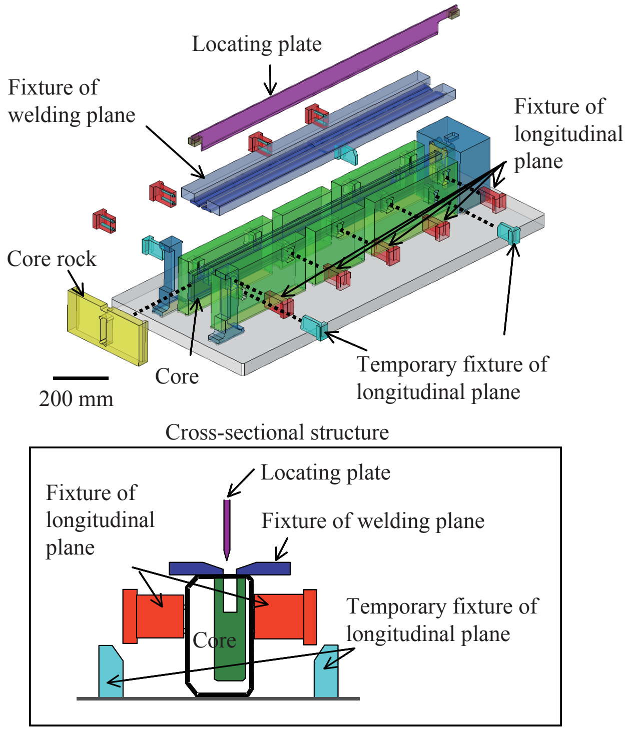


Fig. 11 Schematic diagrams of developed welding equipment

in the 1st step, and (c) shows the lower die set for the 2nd step. As the developed forming process comprises mainly bending forming, die wear and damage are slight. Therefore, FC350 was adopted as the die material in all dies. For the same reason, surface treatment of the die was considered unnecessary. It is thought that this can contribute to reduction of costs related to the die.

Photo 4 shows trial parts formed using 270 MPa material and 1 180 MPa material (thickness: 1.4 mm). Because these two parts were formed at the same pad pressure, a difference in the opening at the top of the part could be seen, depending on the material. The trial part of 270 MPa material remained perfectly closed after mold release, whereas the width of the opening with the trial product using the 1 180 MPa material was approximately 25 mm. This is attributed to the large springback of the 1 180 MPa material, and the fact that the shape with a curvature of R = 24 mm formed at the bottom of the part could not be perfectly flattened. In the case of the 1 180 MPa material, when using a pad pressure of 588 kN, the width of the opening exceeds the 20 mm limit for entry into the dedicated welding jig, as described below. However, the opening width can be reduced to 20 mm or less, which is within the target range, by increasing the pad pressure from 588 kN to 980 kN.

3.2.4 Development of closed cross-section welding equipment

Figure 11 shows a general view of the closed cross-section welding equipment. The equipment comprises a core, devices for fixture of the welding plane and fixture of the longitudinal plane (vertical walls), and a locating plate. The welding position can be set with good accuracy using a method in which, first, the position of the opening edge surface on one side is determined, and then the other edge surface is pressed against the opening edge located in the first step. Welding is possible using general continuous welding methods such as arc welding, laser welding, etc. As a feature of this method, when the formed part is inserted in the welding device, workability is better with parts that are open to a certain width (20 mm or less) than with parts with a perfectly closed cross section.

Photo 5 shows a trial part produced by arc welding using the welding equipment described above. The material is 980 MPa high tensile strength steel with a sheet thickness of 1.4 mm. Although the opening of this part after forming was 20 mm, this experiment confirmed that high accuracy butting is possible using the developed welding equipment, and as a result, continu-

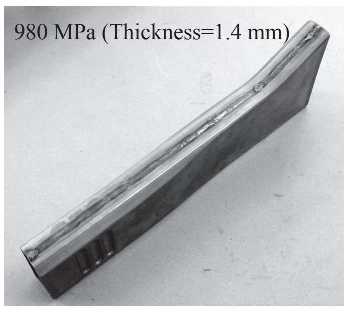


Photo 5 Appearance of the front side member model

ous welding is possible.

4. Application of Closed Cross-section Forming Technology to Parts with Bending Shape

Up to this point, this paper has described a method for forming closed cross sections for parts which do not have a bending shape in the longitudinal direction. However, many automotive parts have curvature shapes. Therefore, the following introduces an example of a technology for forming closed cross sections with products having a bending shape.

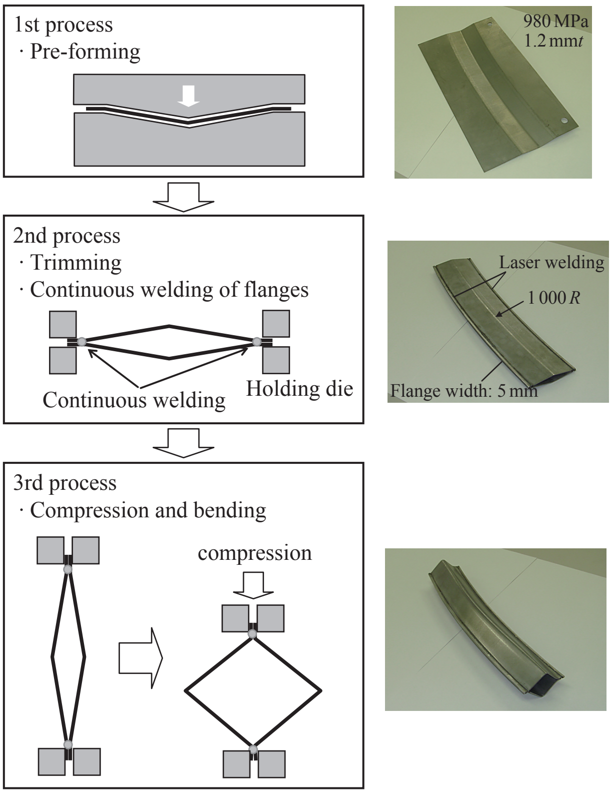


Fig. 12 Schematic diagram and photos of the developed forming process for the part with bending portion

Figure 12 shows a schematic diagram of the forming method and the appearance of a trial part in each process. In the 1st process, a fold is made in the blanks corresponding to the final shape. In the 2nd process, the 2 panels from the 1st process are overlapped, continuous welding of the flange parts is performed, and the flange parts are trimmed. In the 3rd process, the flange parts are grasped and the part is compressed so that the flanges approach each other. The features of this forming method are as follows.

(1) Because forming comprises mainly bending, the forming load is low, even when using ultra-high tensile strength steel materials.

(2) Biaxial bending is also possible by changing the fold line shape in the 1st process.

5. Conclusion

A forming technology which was developed uniquely by JFE Steel for closed cross-section parts was introduced. As features of the new technology, because the forming method comprises mainly bending in all cases, ultra-high tensile strength steel materials can be applied easily, and it is possible to satisfy both weight reduction and improvement of automobile body performance. In the future, the authors hope to contribute to new automobile manufacturing by further improvement of this technology.

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