Development of Press-Forming Technique for Bent Automotive Body Parts Using In-Plane Shear Deformation^{*1}

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A new press-forming technique using in-plane shear deformation was developed for suppressing fractures and wrinkles of curved shapes in the height direction, for automobile body parts such as the front-side member rear. The developed technique is a two-step processes, draw-forming to induce in-plane shear strain and bending into a curved shape. From experiments on a simplified curve part, in-plane shear deformation which is effective for suppressing fractures and wrinkles occurred in the first process when the press stroke changed along the longitudinal direction of the part. When the induced in-plane shear deformation was increased, a part with a higher curved angle in the height direction could be formed in the second process. Then, we conducted press trials of a front-side member rear model using a 1180 MPa-grade ultrahigh-strength steel sheet to evaluate the effectiveness of the developed technique. The results suggested that a complex curved part could be formed without fractures or wrinkles when in-plane shear deformation was induced in the first process. [doi:10.2320/matertrans.P-M2021854]

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1. Introduction

In order to achieve both weight reduction and improvement of collision safety of automobiles, the strength of car body parts is increasing,¹⁾ and the use of ultra-high strength steel sheets with tensile strength of 1180 MPa grade or higher is expanding. Some of the main problems in press forming of ultra-high strength steel sheets are fractures due to low ductility or wrinkles due to high yield strength.²⁾ The auto body parts bent in the height direction are generally formed by draw-forming. At this time, tensile deformation occurs on the outside (Portions A and C) of bend and compressive deformation occurs on the inside (Portions B and D) of the bend, as shown in Fig. 1. Fractures due to the tensile deformation and wrinkles due to the compressive deformation inhibit further strengthening of such shaped parts. As countermeasures against the fracture, a method for reducing the tension in the material around the punch shoulder by reducing the frictional resistance or deformation resistance of the material,^{3,4)} and a method for increasing the material strength around the punch shoulder⁵⁾ have been proposed. As a countermeasure against wrinkles, a method has been proposed in which emboss shapes are added to the bottom of the punch to absorb excess material,⁶⁾ but this method cannot be applied in many cases because the shape of the product changes. Therefore, the maximum strength of steel sheets applied to such shaped parts is still limited to the 590 MPa grade.

It has been reported that when forming of parts are bent in the height direction, in-plane shear deformation occurs in the wall (ABCD in Fig. 1) of the straight section, and the larger the in-plane shear deformation, the smaller the tensile deformation and compressive deformation at the bend sections.⁷⁾ Therefore, in this study, we developed a press

Fig. 1 Schematic of curved part and deformation caused in conventional press forming.

forming technique of parts bent in the height direction with a preform process for generating large in-plane shear deformation to the wall ABCD in Fig. 1. The first, the effectiveness of the developed forming technique was confirmed by forming experiments of parts with simplified shapes, and factors affecting the formability were investigated. The effect of this method was then verified by applying it to a model simulating an actual part including flange portions.

2. Forming Technique Utilizing In-Plane Shear Deformation

2.1 Aim of developed method and verification of effect with simplified shape

As described above, when a part bent in the height direction is formed by the conventional forming method, fractures could occur in the region of tensile stress and wrinkles could occur in the region of compressive stress in the bent portion. If the straight side wall is deformed by in-plane shear deformation like a parallelogram ABCD during forming, the tensile and the compressive stresses become small. In the conventional forming, in-plane shear deformation does not sufficiently occur. If sufficient in-plane shear deformation is given in advance, there is a possibility that fractures and wrinkles can be suppressed by conventional forming. This situation can be achieved by using the cylindrical deep drawing of the strip blank having a width narrower than the punch diameter as shown in Fig. 2. In this

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Fig. 2 Schematics of processes in new forming technique.

case in-plane shear deformation occurs in the wall portion in Fig. 2(a). The in-plane shear deformation occur because the material at the center in the width direction enters the die cavity by a distance G_{CD} earlier than the material at both ends in the width direction at the same position in the longitudinal direction. The shear deformation occurs sequentially between the center and both ends in the width direction as the material flows in. The regions to which the successive in-plane shear deformation were applied are made to coincide with the ABCD position in Fig. 2(b), and the ridge lines are bent, whereby the shape bent in the height direction is obtained without generating the above mentioned tensile and compressive deformation. The developed forming technique consist of the first process of cylindrical deep drawing of the strip blank to provide in-plane shear deformation and the second process of bending ridge lines.

In this chapter, first, it is confirmed that in-plane shear deformation occurred by cylindrical deep drawing of strip blanks by FEM analysis. Second, the effect of amount of the in-plane shear deformation generated in the first process on the bending angle in the height direction of the formed product after the second process is investigated by forming experiments of simple shaped part.

2.2 Prediction of in-plane shear deformation by FEM analysis

2.2.1 FEM analysis conditions

The amount of in-plane shear deformation caused in the first process was predicted by FEM analysis. Figure 3 shows an analysis model of the die and blank. Four different punch radii R_p were examined: 12.5, 16.5, 20.0 and 25.0 mm as

Fig. 3 Details of FEM model used in the first process to obtain in-plane shear deformation.

Table 1 Mechanical properties of test material.

Grade	Thickness/mm	YP/MPa	TS/MPa	EL/%
270	0.5	163	297	50
1180	1.2	818	1234	11

shown in Fig. 3(b), which is schematic top view of Fig. 3(a). The blank was a rectangle with a width of 30 mm and length of 180 mm, and was shaped symmetrically at M-M'. The shoulder radii of both the punch and the die were 5 mm. The forming height was 50 mm. The solver was LS-DYNA® Ver 9.7.1 R5 (Livermore Software Technology Corp.) using the dynamic explicit method. Table 1 shows the mechanical properties of the test material used in the FEM analysis. The blank was a shell element with an element size of 2 mm. The blank holder force was 9.8 kN, and the friction coefficient was 0.15. In this paper, in-plane shear strain was defined as engineering shear strain.

2.2.2 FEM analysis results

An example of the predicted in-plane shear strain distribution after the first process is shown in Fig. 4. In-plane shear strain was predicted in the region ABCD of the side wall. Fracture was predicted at the punch shoulder only under the condition of 1180 MPa grade steel sheet and $R_p = 12.5$ mm. Figure 5 shows the distribution of shear strain at the cross section O-O' of the middle of the sidewall in the width direction.

Fig. 4 Calculated distribution of in-plane shear strain at sidewall of punch in case of $R_p = 12.5$ mm and Grade 270 MPa.

Fig. 5 Calculated distribution of in-plane shear strain along O-O' cross section in the 1st process for each material and punch radius R_p .

Fig. 6 Relationship between average in-plane shear strain γ_{Ave} and punch radius R_p in the 1st process.

In-plane shear strain was negligible at point O of the center of the blank width and at point O' of the edge, and displayed its maximum value at the center between those two points. In-plane shear strain of the two test materials were almost equal. Figure 6 shows the effect of R_p on the average value of in-plane shear strain γ_{Ave} generated in the range of positions from 2 to 12 mm from the blank width center in Fig. 5. As R_p decreased, in-plane shear strain increased. The reasons for this change are considered in the following section.

2.2.3 Discussion

Since the shapes of the die and blank are symmetrical on the M and M' sides with respect to N-N', as shown in Fig. 3, in-plane shear deformation is canceled at point O in the center of the blank width. Whereas, because the material inflow in the circumferential direction is not restricted at point O' near the edge, a material inflow to the sidewall occurs with shrinking in the circumferential direction. For this reason, we consider that the difference in the inflow velocity between the edge side and the center in the width direction is reduced, and in-plane shear deformation is less likely to occur at those points. As a result, it is estimated that the in-plane shear strain distribution shown in Fig. 5 is generated between point O and point O' and reaches its maximum near the center. Since G_{CD} increases as the R_p decreases, it is considered that in-plane shear strain becomes larger as the difference of the inflow velocity to the side wall increases.

2.3 Experimental method and results

2.3.1 Purpose and method of experiment

Specimens were bent in the second process after in-plane shear deformation was induced in the first process. The curved angles in the height direction would depend on the in-plane shear deformation. The effect of in-plane shear deformation on the curved angle were examined.

The die used in the first process was the same shape as that in the FEM analysis (Fig. 3). R_p were 16.5, 20.0 and 25.0 mm, and various in-plane shear deformation were given to the blanks. The blank material was the 270 MPa grade steel sheet in Table 1. A square grid pattern with a size of 5 mm was printed on the blank surface. The blank was then draw-formed using a 500 kN deep-drawing instrument and cut along P-P', as shown in Fig. 7(a) which is a formed panel in the 1st process. In the second process, the pre-formed blank was formed into a part with a U-shaped cross section by sheet

Fig. 7 Forming method in the second process; (a) formed panel in the first process.

metal processing using a hammer and jig, as shown in Fig. 7(b). When the second bending process is conducted by press forming using an ordinary die, the pre-formed part is formed to the predetermined die shape and the investigation of the curved angle cannot be performed. This is the reason why forming by a hammer and jig was applied in the second process. In this second process, the sequence of material deformation was performed to be as close as possible to that in the press forming with an ordinary die. First, the pre-formed blank was bent along the ridge lines at the positions where the widths of the top portion and vertical walls were each 10 mm. Next, the curved surface was flattened in the order of the vertical walls followed by the web, and was then processed so that the angle between the top and the walls was 90°. The influence of in-plane shear deformation on the curved angle was determined by measuring angles θ_R and θ_L of the formed parts obtained by sheet metal processing as described above (Fig. 7(c)).

2.3.2 Experimental results

Figure 8 shows the formed parts obtained in the first and second processes. The blanks could be formed without fracture or wrinkle under all conditions. The ruled lines were distorted in a parallelogram shape between the width center and the edge portions at the sidewall formed by the first process, confirming that in-plane shear deformation occurred (Fig. 8(a)). In the second process, formed parts bent in the height direction were obtained, and the effect of applying in-plane shear deformation was demonstrated (Fig. 8(b)).

The four areas indicated by the broken lines in Fig. 9 were selected from the center of the sidewall formed by the first process, and γ_{Ave} was obtained from the lattice deformation. The relationship between γ_{Ave} and R_p is shown in Fig. 10. As R_p became smaller, γ_{Ave} increased. Moreover, these values were in good agreement with the FEM analysis results. The curved angles θ_L and θ_R after the second process became larger as R_p in the first process became smaller. Figure 11 shows the effect of γ_{Ave} in the first process on the curved angle after the second process. The curved angle was proportional to γ_{Ave} , and the sizes of curved angles θ_L and θ_R were almost the same.

Fig. 8 Formed parts in processes.

Fig. 9 Draw-formed panel and magnified wall portion.

Fig. 10 Relationship between average in-plane shear strain γ_{Ave} and punch radius R_p in the 1st process.

The degree of contribution of in-plane shear deformation to the curved angle of the formed part measured in the above experiment was verified. Figure 12 shows a schematic diagram explaining the effect of in-plane shear deformation at the straight wall and elongation at the bent portion on the curved angle. When the wall portion deforms to a parallelogram due to in-plane shear deformation, an angle change occurs in the height direction. Therefore, using γ_{Ave} , the curved angle θ_γ in the height direction caused by in-plane shear deformation was geometrically calculated by the following equation, where π indicates the circumference ratio.

Fig. 11 Effect of average in-plane shear strain γ_{Ave} on curved angle in the height direction.

Fig. 12 Schematic of effect of curved angle on in-plane shear strain and stretched deformation.

Fig. 13 Experimental angle and estimated one for $R_p = 16.5$ mm.

$$\theta_\gamma = 180/\pi \tan^{-1} \gamma_{Ave} [^\circ] \quad (1)$$

Figure 13(a) shows the result of a comparison of the calculated curved angle θ_γ and the measured angle θ_L when R_p was 16.5 mm. The angle θ_γ calculated from the measured in-plane shear deformation was smaller than the measured angle θ_L , which was approximately 47%. This means that another factor also contributes to the angle θ_L of the formed part in the second process. Next, the contribution of elongation at the bent portion was verified. Assuming the elongation in the longitudinal direction caused by tensile deformation at the punch or the die shoulder portions in the first process is L , the angle change θ_ϵ of the formed part in the second process was geometrically calculated by the following equation, where H represents the wall height of the second formed part.

$$\theta_\epsilon = 180L/(\pi H) [^\circ] \quad (2)$$

The elongation L predicted by the FEM analysis at the punch shoulder in the first process was substituted into eq. (2) to obtain the predicted value θ_ϵ . Figure 13(b) shows the sum of the predicted values θ_ϵ and θ_γ . The sum of θ_ϵ and θ_γ was approximately equal to the measured value θ_L . These results show that the developed technique, in which a strip blank was draw-formed to a cylindrical shape in the first

Fig. 14 Target model of curved part.

Fig. 15 FEM model in 1st process of developed method (a) and schematic of T-T' cross section of die (b).

process, caused the curved angle in the side view of the formed part in the second process due to a combination of in-plane shear deformation of the sidewall and tensile deformation at the punch or die shoulders in the first process.

3. Evaluation of Press Formability Using Model Simulating Actual Part

The developed technique was applied to a model simulating a front side member rear (Fig. 14), which is one of the auto body parts bent in the height direction, and the degree of formability improvement compared with the conventional technique was evaluated. First, the die shape in the first process was determined by a FEM analysis to maximize the in-plane shear deformation and then press forming trials of the first and second processes were conducted.

3.1 Determination of die shape in the first process by FEM analysis

3.1.1 Analysis conditions

Figure 15 shows the die model of the first process for the FEM analysis. The final shape is different from that in section 2.3 and has a hat-shaped cross section with flange portions. Therefore, a flat portion corresponding to the flange in the first process was provided (Fig. 15(b)). The blank was a rectangle with a width of 340 mm and length of 1500 mm.

Table 2 Distance G_{CD} between portions C and D.

No.	1	2	3	4	5	6	7
G_{CD} (mm)	11	20	30	37	46	54	63

Fig. 16 Relationship between average in-plane shear strain γ_{Ave} and distance G_{CD} in the 1st process. Fig. 17 Numerical result in the 1st process ($G_{CD} = 54$ mm, height = 274 mm).

The material used was 1180 MPa grade steel sheet. The die height was 600 mm. The blank holder force was 500 kN. The seven conditions of G_{CD} shown in Table 2 were simulated to evaluate the degree of in-plane shear deformation and the occurrence of fractures and wrinkles.

3.1.2 Results of analysis

Figure 16 shows that the relationship between γ_{Ave} and G_{CD} at the middle of the sidewall (T-T' section in Fig. 15(a)). Although γ_{Ave} increased as G_{CD} increased, wrinkle occurred when G_{CD} was 54 mm or more, as shown Fig. 17. This result shows that the maximum value of G_{CD} where the part can be formed without wrinkle and the maximum in-plane shear strain can be obtained was 46 mm in this experiment. According to this result, the forming trial was carried out at $G_{CD} = 46$ mm.

3.2 Forming trials and discussion

3.2.1 Trial conditions

Figure 18 shows the process of the developed technique. The test material was 1180 MPa grade steel. As in the FEM analysis, the first process was draw forming with $G_{CD} = 46$ mm. The forming height was 600 mm, and the blank holding force was 500 kN. The second process was also draw forming. The blank holding force was 1200 kN, and the pad load was 200 kN. The standby position of the blank holder

Fig. 18 Experimental model in developed method.

Fig. 19 Experimental model in conventional method, which is same as 2nd process of developed method.

(a) Appearance of experiment

(b) Formed panel (Forming height is 600 mm)

Fig. 20 Experimental model in developed method.

was 53 mm upward from bottom dead center. For comparison with the developed technology, the conventional technology, in which a strip blank is directly formed by draw forming by using the second process die (Fig. 19), was conducted. The blank holding force and the pad load were the same as in the second process of the developed technique.

3.2.2 Trial results

Figure 20(a) shows the appearance of the trial in the first process using the developed technique and (b) a photograph of the formed panel. The upper end of the blank was constrained by a jig on the punch. No fractures or wrinkles appeared in the formed panel. Figure 21 shows a photograph of the panel formed in the second process. The developed technique could form the target shape without fractures or

Fig. 21 Panel formed by 2nd process of the developed method (forming height: 80 mm).

Fig. 22 Panel formed by conventional method (forming height: 60 mm).

Fig. 23 Results of press trials using conventional and developed techniques.

wrinkles. Whereas, in the conventional technique, fracture and wrinkle occurred around the bent portions, as shown in Fig. 22. Then, blanks were formed with forming heights at intervals of 10 mm, and the forming height at which fractures or wrinkles occurred was examined. Figure 23 shows the results for the occurrence of fractures or wrinkles at each forming height with the conventional technique and the second process of the developed technique. With the conventional method, wrinkle occurred at the forming height of 30 mm on the concave web, and fracture occurred at the forming height of 60 mm on the punch shoulder. With the developed technique, no fractures or wrinkles occurred up to the bottom dead center (forming height: 80 mm).

3.2.3 Discussion

γ_{Ave} of the side wall and the elongation L at the punch or die shoulder were calculated from a FEM analysis of the first process, and its effect on the curved angle of the part formed in the second process was evaluated by using eqs. (1) and (2). Figure 24(a) and (b) shows the result at the θ_L side and the θ_R side, respectively. The predicted angle change due to in-plane shear deformation induced in the first process was 12° . The sums of the angle change due to elongation at the bent portion and in-plane shear deformation were predicted as 16° on the θ_L side and 11° on the θ_R side. These values were equivalent to 41% on the θ_L side and 28% on the θ_R side for the curved angle of 39° of the target part. These ratios of in-plane shear deformation and elongation at the bend portion, which were induced in the first process of this technique, are considered to correspond to the degrees of contribution to suppression of fractures or wrinkles.

Fig. 24 Experimental and estimated angle using γ_{Ave} and stretched length in 1st process.

4. Conclusion

- (1) Press forming technique which can form parts bent in the height direction without fracture or wrinkle was developed by adding a pre-forming process to induce in-plane shear deformation at the wall of the straight portion of the part.
- (2) In-plane shear deformation at the wall of the straight portion and tensile deformation at the bent portion contribute to the formability of the bent part. In-plane

shear deformation at the wall is caused by draw forming in the part longitudinal direction using a strip blank, and the amount of in-plane shear strain is determined by the shape of the die.

- (3) As a result of press trials of a model simulating an actual part with 1180 MPa grade ultra-high strength steel sheets, the target part could be formed successfully without fractures or wrinkles by the developed technique. Whereas, fracture occurred with the conventional technique. These results prove the effectiveness of the developed technique.

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