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New Sequential Forming Process Involving Single-forming Machine for Hat Cross-sectional Panels with Various In-plane Curvatures

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Abstract. Automobile demand is expected to be increasingly diverse in the future. To satisfy this demand, a suitable technology is required to manufacture various car body parts using a single-forming machine. We focus on a technology for the general-purpose production of hat cross-sectional press-formed panels. In general press forming, a single die-set is used for each panel. Manufacturing various panels involves the manufacturing cost of the die-set and the storage space. Herein, we present a new sequential forming process that can form panels with several shapes in the longitudinal direction. This process sequentially performs narrow-width press forming along the longitudinal direction using small dies instead of a die-set. A machine is prototyped to demonstrate this process. Multiple hat cross-sectional panels with different curvatures along the longitudinal direction are formed using this machine. Subsequently, the strengths and shapes of the formed panels are examined. The buckling strength during the bending of the panels is 13% higher than that of panels formed using a general bending machine. However, shape distortion occurred in these panels, which shall be addressed in the future.

Keywords: Press forming; Sequential forming process; Hat cross section; Mild steel.

1 Introduction

In recent years, rising customer demand and increasing preference for customized products have profoundly shaped market dynamics. As a result, the need for greater product diversity and more frequent model changes has become more pronounced [1]. Consequently, companies must exhibit a high degree of flexibility to adapt to these evolving demands [2].

Sheet-metal forming is one of the most prevalent manufacturing processes, and press forming offers distinct advantages for mass production. However, producing small quantities of parts poses challenges owing to the cost and spatial requirements of preparing dies for each part. Consequently, the demand for technology capable of manufacturing small quantities of diverse parts using a single forming machine is growing. For example, in automobile design, car body frames consist of spot-welded panels with hat-shaped cross sections. Thus, a sequential forming technology that enables the production of hat cross-sectional panels without requiring dedicated dies for each panel would be highly advantageous.

Various technologies that can fabricate hat cross-sectional panels and produce multiple shapes have been proposed. However, these technologies face several significant challenges. Incremental sheet forming [3] is a technique in which a small tool continuously contacts sheets of metal; however, forming deep shapes decreases the sheet thickness [4]. Flexible-roll forming [5] and chain-die forming [6] can produce hat-shaped panels, but they necessitate multiple rolls or dies to accommodate hat shapes with varying curvatures. Incremental swivel bending [7] is capable of forming hat shapes with a constant cross section, but it requires pre-formed straight hat panels as input.

In this study, we address these challenges by proposing a novel sheet metal-forming technology that eliminates the need for dies for each panel.

2 Proposed Sequential Forming Process

In this study, we developed a technology capable of general-purpose production of hat cross-sectional press-formed panels without requiring a dedicated die-set for each panel. Hat cross-sectional panels are characterized by continuously connected hat-shaped cross sections. We propose a sequential forming process that produces hat cross-sectional panels along the longitudinal direction. This method fabricates panels with varying in-plane curvatures along the longitudinal axis by strategically rotating the sheet metal within its plane at each forming position.

Fig. 1 shows a schematic of the sequential forming process. In this method, six small narrow-width die-sets

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are employed instead of a full-size stamping die-set. Each die-set consists of upper and lower dies positioned in the out-of-plane direction of the sheet metal. The die-sets are arranged in three rows, with two sets per row. The die-sets in the central row have one side that forms the top plate of the hat cross-sectional panel, while the other side holds the previously formed top plate. The die-sets in the outer rows grip the flange and generate tension through the bead.

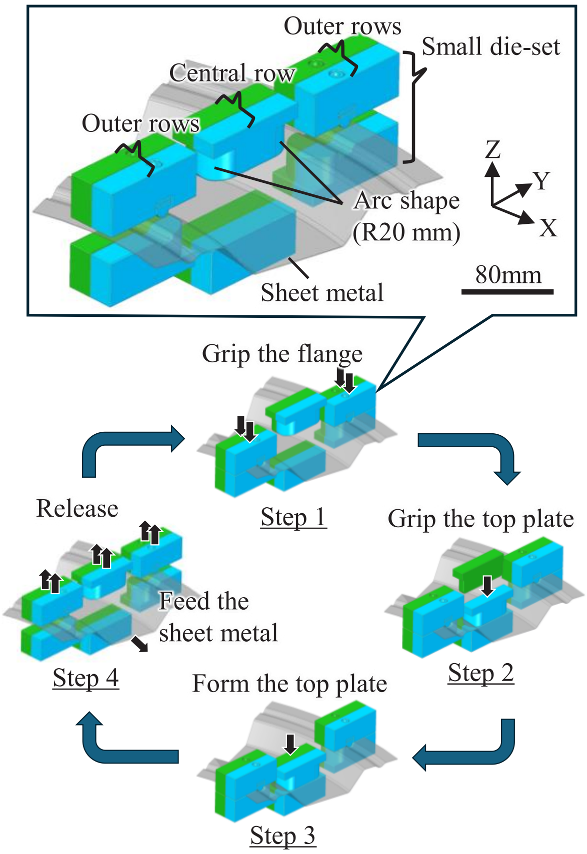


Fig. 1. Proposed sequential forming process.

The machine operations at each forming position involve the following four steps:

1. The four die-sets in the outer rows grip the flanges.
2. One side of the die-set in the central row holds the previously formed top plate.
3. The opposite side of the die-set in the central row shapes the new top plate.
4. All upper dies are released to feed the sheet metal to the subsequent forming position.

By iterating these four steps, hat cross sections can be continuously formed. Additionally, as depicted in Fig. 1, the small dies were designed with an arc shape and a radius of R20 mm. This design was specifically intended to enable the formation of cross-sectional panels with varying curvatures. The lower dies of each row shown in Fig. 1 can be changed to a single piece. A more flexible configuration was adopted to consider forming processes with different operations from those in this study.

3 Methods

We validated the ability of the proposed sequential forming process to produce cross-sectional panels with varying curvatures along the longitudinal direction. Additionally, the shape accuracy and buckling strength of the formed panels were assessed via bending tests. Evaluating the buckling strength was necessary because of periodic marks left by the small dies on the ridgelines between the top plate and walls of the formed panels, which could potentially influence the structural integrity of the panels.

3.1 Prototype Machine

We developed a preliminary prototype to verify the proposed methods. Fig. 2 shows the prototype machine image. To implement the proposed sequential forming process, mechanisms for vertically moving the small dies and feeding the sheet metal were essential. Electric servomotors and cylinders were employed to control the vertical movement of the dies, and two XY stages were utilized to feed the sheet metal.

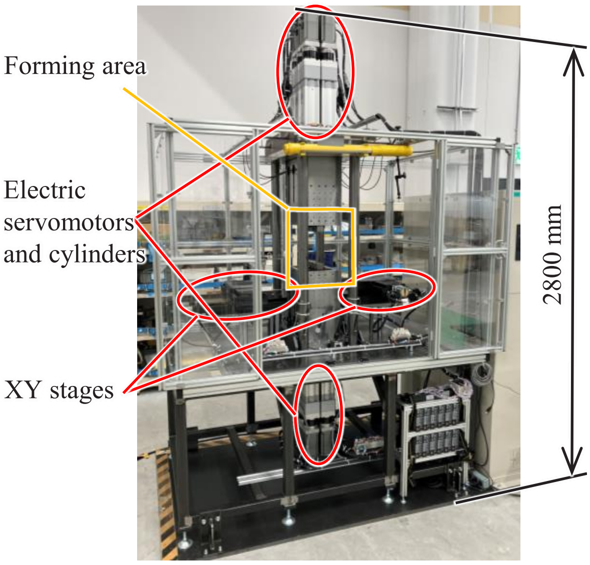
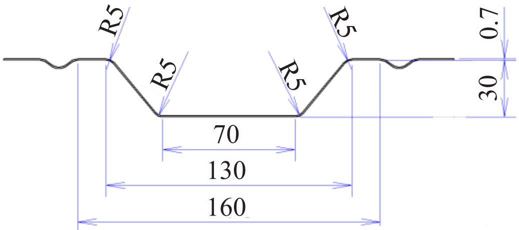


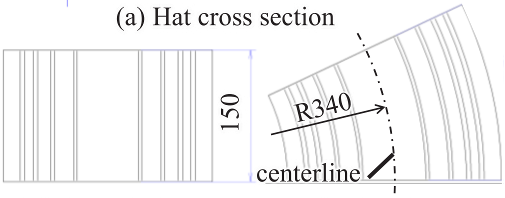
Fig. 2. Prototype machine for the proposed sequential forming process.

3.2 Target Shape

To assess the formability of different shapes along the longitudinal direction, two target shapes were selected for validation, as shown in Fig. 3. Both shapes were



(a) Hat cross section



(b) Straight shape (c) Fan shape

Fig. 3. Two types of target shapes and cross sections.

fabricated from 0.7 mm thick mild steel sheets and featured a hat cross-sectional shape with a depth of 30 mm (Fig. 3(a)). Additionally, the feed pitch between each forming position was set to 12 mm. The first shape exhibited a straight configuration along the longitudinal direction (Fig. 3(b)), while the second shape followed a fan-shaped curve, with the centerline of the top plate having a radius of 340 mm (Fig. 3(c)). A depth of 30 mm was reached through six successive layers, each with a thickness of 5 mm.

3.3 Evaluation of Shape Accuracy

The shape accuracy of the panels was evaluated according to the two target shapes described in the preceding section. First, the geometries of the formed panels were measured using a 3D scanner (MetraSCAN 3D, CREAFORM), with an interval of 0.2 mm between measurement points. Subsequently, these measured shapes were superimposed onto 3D models of the target shapes (generated via CAD software) by using the least-squares method. The errors relative to the target shapes were quantified and visualized using color contour maps.

3.4 Evaluation of Buckling Strength

Although no fractures occurred during the forming process, periodic undulations were observed along the ridgeline. We performed buckling strength tests to examine the effect of the undulations on the buckling strength. A specialized test method was developed to load compressive stress on the ridgeline, enabling a comparison between different ridgeline shapes. A schematic of the test setup is presented in Fig. 4. The apparatus consisted of two L-shaped bending tools connected by a hinge along a rotational axis. The test piece was secured by clamping the hat cross section on both sides using the bending tools, with the flanges fixed to the upper surface of the tools. By applying pressure along the rotational axis of the hinge, stress was concentrated at the ridgeline of the test piece, causing buckling. The load was measured using a load cell attached to the indenter, and the buckling strength was assessed by comparing the maximum loads observed during the tests.

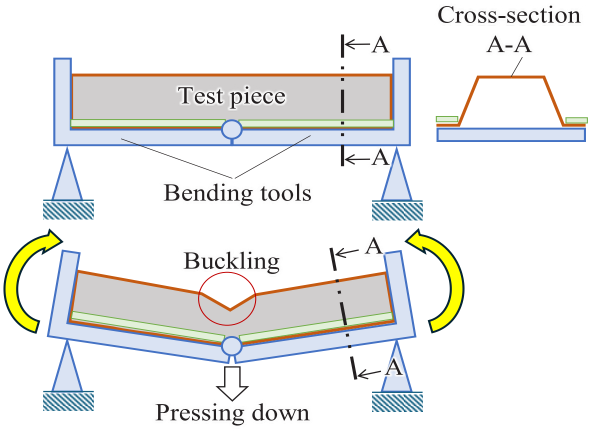
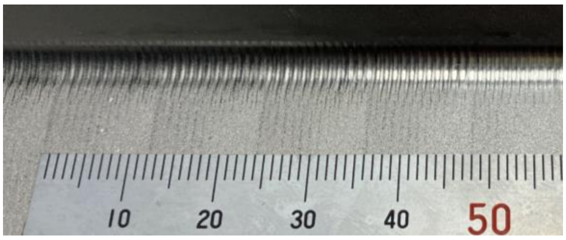
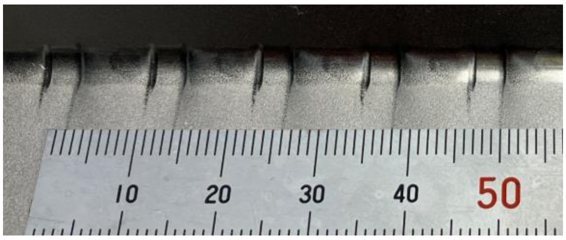


Fig. 4. Schematic diagram of the buckling test method used to concentrate stress on the ridgeline.

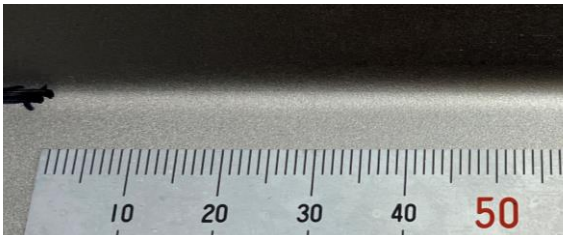
The test pieces were formed into a straight shape with the cross section as shown in Fig. 3(a), and then cut to a width of 160 mm and a length of 200 mm. The sheet metal used was 0.7 mm thick mild steel. Three distinct types of test pieces, each with different ridgeline shapes, were processed. The ridgeline shapes of each type of test piece are shown in Fig. 5. Two types of test pieces, featuring undulations on the ridgeline, were fabricated using the sequential forming process. To investigate the impact of the undulation spacing, the sheet metal feed was set to 1 mm and 12 mm during the forming process. The spacing of the undulations on the ridgeline varied according to the amount of feed used. The third type of test piece, which did not feature undulations, was fabricated using a conventional bending machine. We then conducted tests to compare the average maximum loads of all three types of test pieces.



(a) Sequential forming process
(sheet metal feed of 1 mm)



(b) Sequential forming process
(sheet metal feed of 12 mm)



(c) General bending machine

Fig. 5. Differences in the ridgeline shapes of each type of test piece.

4 Results and Discussion

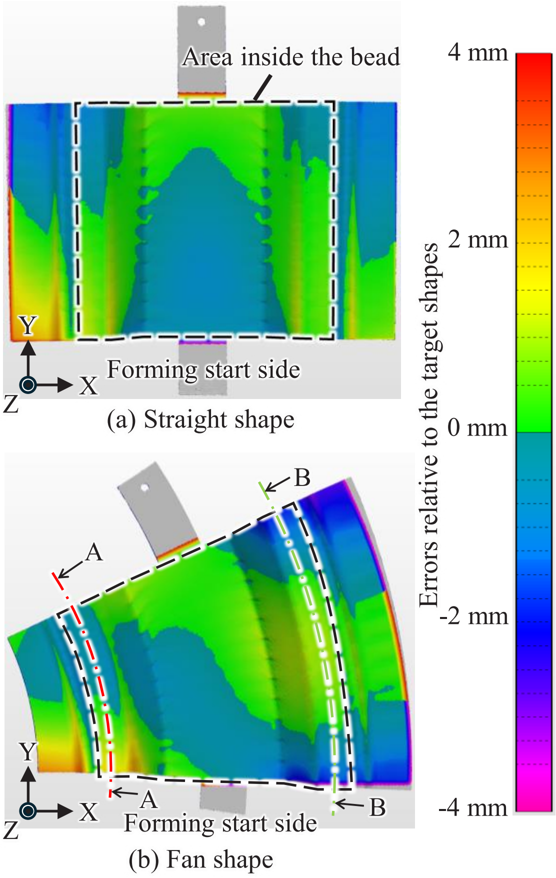
4.1 Shape Differentiation

Fig. 6 shows the centerline of a panel with its top plate curved to a radius of 340 mm (a straight shape was also successfully formed). As discussed in Section 3.4, periodic undulations are visible along the ridgeline. These undulations were created by the corners of the small dies during the forming process.

Fig. 6. Fan-shaped panel formed using the proposed sequential forming process.

4.2 Evaluation of Shape Accuracy

Fig. 7 presents the color contours indicating the errors between the formed panels and target shapes. Typically, the area within the bead considered the panel. In this area, more than 90% of the measurements exhibited errors within a 1 mm range.



(a) Straight shape

(b) Fan shape

Fig. 7. Errors between the formed panels and target shapes.

For the straight shape, the hat depth significantly decreased from the start to the end of the forming process. In addition, the error distribution was generally symmetrical. This tendency can be addressed by adjusting the forming depth. However, for the fan shape, different variations were observed between the inner and outer flanges. Fig. 8 displays the profiles of the A-A and B-B sections indicated in Fig. 7. In the A–A section, a downward convex distortion occurred, while in the B–B section, an upward convex distortion occurred. This disparity was attributed to the inadequate stretching and shrinking of the sheet metal at the walls and flanges of the hat panel.

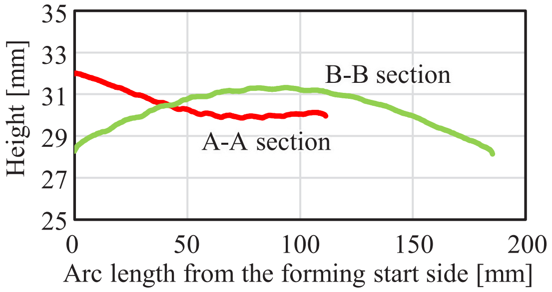


Fig. 8. Errors between the formed panels and target shapes.

4.3 Evaluation of Buckling Strength

Fig. 9 presents the average maximum load for each test condition; the error bars represent the maximum and minimum values of the three tests. The test pieces with undulations on the ridgeline (i.e., those formed using the sequential forming process) exhibited an average maximum load of approximately 5.75 kN under both conditions. This suggested that the feed amount in the forming process had a minimal effect on the strength of the test pieces. In contrast, the test pieces without undulations on the ridgeline (i.e., those fabricated using a conventional bending machine) exhibited an average maximum load of approximately 5.09 kN. The maximum load exhibited by the test pieces with undulations was approximately 0.66 kN or 13% higher than those without undulations.

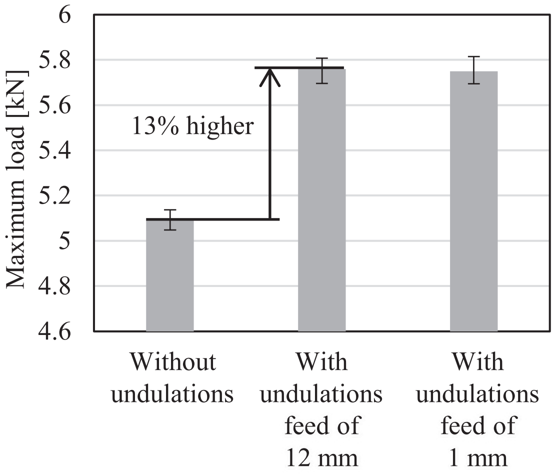


Fig. 9. Comparison between the maximum loads for each test piece.

The difference between the maximum loads can be attributed to the undulations on the ridgeline and work hardening that resulted from the reduction in the sheet thickness during the forming process. Simulations that incorporated these variables were performed using Ansys LS-DYNA. The model employed in the simulations is illustrated in Fig. 10. To reduce the computational load, a quarter model (1/4 model) was utilized.

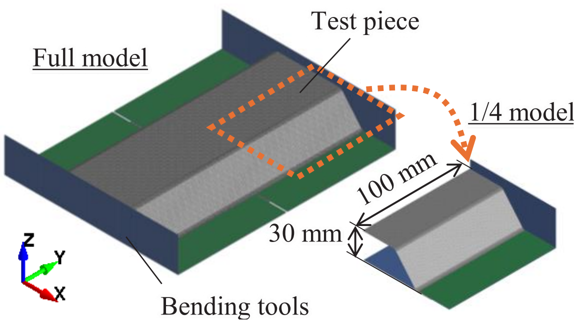


Fig. 10. Model used in the simulation.

The primary computational parameters and material properties of the sheets are listed in Table 1. In addition, only the parameters pertaining to the R-section, including the ridgeline, were varied for the test pieces.

Table 1. Computational Parameters and Physical Properties of Sheet Metal for Computer-Aided Engineering (CAE).

Computational conditions	
Material model for sheet metal (Element type) [mm]	Out-of-plane anisotropic elasto-plastic material (shell element)
Mesh size for sheet metal [mm]	1.0 (R-section divided into 10 parts)
Material model for tool (Element type)	Rigid body (Shell Element)
Movement speed of bending tool corner [mm/s]	100
Coefficient of friction between sheet metal and tool [-]	0.1
Physical properties of sheet metal	
Sheet thickness [mm]	0.7
Density [g/cm^3]	7.85
Young's modulus [GPa]	206
Poisson's ratio [-]	0.3
R-value (Lankford coefficient) [-]	1.4
Work hardening law (Swift's equation)	$\sigma = K (\epsilon_0 + \epsilon_p)^n$
K-value [MPa]	470
n-value [-]	0.2
ε_0-value [-]	0.002

A detailed list of different conditions of the ridgeline is provided in Table 2. The spacing and height of the undulations on the ridgeline were incorporated into a CAD model based on the measured geometries of the formed panels, with a pitch spacing of 10 mm. Work hardening was simulated by calculating the equivalent plastic strain from the difference between the sheet thicknesses before and after the forming process. The simulation results were evaluated based on the moment around the rotational axis rather than the load. This approach was chosen because, in the experiment, the rotational axis was subjected to downward pressure, whereas in the simulation, the bending tool was rotated around the rotational axis for simplicity.

Table 2. Conditions of the ridgeline.

No.	Undulations	Sheet thickness reduction	Work hardening
1	Without	Without	Without
2	With	With	Without
3	With	With	With
4	With	Without	With

Fig. 11 presents a comparison between the maximum moments around the rotational axis in the simulation. For the condition without undulations, the maximum moment was approximately 133.9 N·m. In contrast, for the condition with undulations, and accounting for the reduction in the sheet thickness and work hardening equivalent to the experimental conditions, the maximum moment was approximately 149.4 N·m. This represented an increase of approximately 12%, which closely aligned with the experimental ratio. Among the three conditions with undulations, the maximum moment was the highest when only work hardening was considered, and it was the lowest when only the reduction in the sheet thickness was considered. Furthermore, the moment values for both the condition without undulations and the condition that considered only the reduction in the sheet thickness were approximately 133 N·m, indicating similar results. This suggests that the increased strength of the test pieces that were fabricated using the proposed sequential forming process can be primarily attributed to work hardening that resulted from the reduction in the sheet thickness, rather than the presence of undulations on the ridgeline. Moreover, within the scope of this study, the presence or absence of undulations on the ridgeline did not significantly impact the buckling strength.

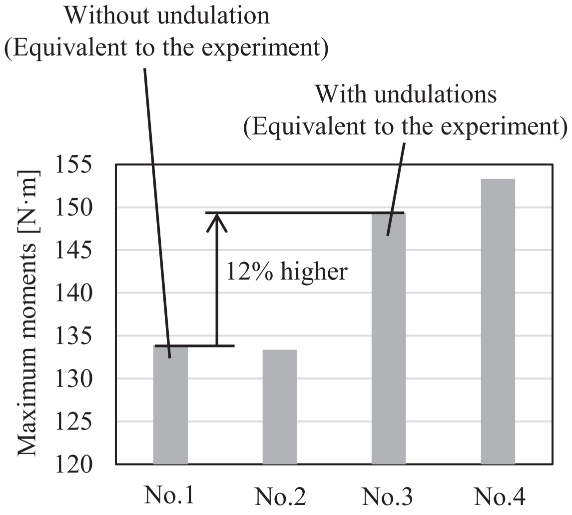


Fig. 11. Maximum moments around the rotational axis in the simulation.

5 Conclusion

To meet the growing demand for diversification in the automotive industry, this study proposed a novel sequential forming process capable of producing cross-sectional panels with varying in-plane curvatures using a single forming machine. Additionally, we demonstrated that this sequential forming process is effective in forming both straight and fan-shaped geometries.

The shape errors of the panels formed via the proposed process were within ±1 mm for more than 90% of the area inside the bead, which is typically used as the panel. In addition, the fan-shaped panels exhibited distinct distortions between the inner and outer flanges. Therefore, further measures are necessary to enhance the shape accuracy. Furthermore, the panels formed using this process exhibited undulations on the ridgeline between the top plate and walls. An investigation into the effect of these undulations on the buckling strength revealed that the formed panels demonstrated greater strength compared to the reference material fabricated via conventional sheet bending. Numerical simulations indicated that work hardening, which resulted from a reduction in the sheet thickness during the forming process, was the primary factor contributing to the increased strength. Additionally, within the scope of this study, the presence or absence of undulations did not have a significant impact on the buckling strength. In future studies, we will consider using practical metals and thicknesses used in manufacturing processes.

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