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FLEXIBLE ROLL FORMING PROCESS DESIGN FOR VARIABLE CROSS-SECTION PROFILE

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ABSTRACT−Roll forming is a continuous bending operation in which a long strip of sheet metal is passed through sets of rolls mounted on consecutive stands, each set performing only an incremental part of the bend, until the desired cross-section profile is obtained. Roll forming technology has been widely used in the automotive industry due to its various advantages, such as high production speed, reduced tooling cost and improved quality. Recently, flexible roll forming process which allows variable cross sections of profiles by adaptive roll stands was developed. In this study, profile design for the hat-channel has been analytically performed on the basis of established longitudinal strain during the flexible roll forming. The effect of geometrical parameters such as base section width, side wall height and flange width on the longitudinal strain was analyzed. The analytical analysis was experimentally verified by lab-scale flexible roll forming machine. The results show that the profile design method preformed in this study is feasible and the parts with variable cross sections can be successfully fabricated with flexible roll forming process.

KEY WORDS : Flexible roll forming, Longitudinal strain, Process design, Variable cross section

NOMENCLATURE

L_0 : initial length at edge
D_n : inter-distance between forming passes
w_1 : base section width at roll pass number n-1
w_2 : side wall height at roll pass number n-1
w_3 : flange width at roll pass number n-1
w_4 : base section width at roll pass number n
w_5 : side wall height at roll pass number n
w_6 : flange width at roll pass number n
A_1 : target bent angle of side wall at roll pass number n-1
A_2 : target bent angle of side wall at roll pass number n
B_1 : target bent angle of flange at roll pass number n-1
B_2 : target bent angle of flange at roll pass number n

1. INTRODUCTION

Recently, high strength steel has been widely used to improve safety and fuel efficiency in automotive industry (Zhang *et al*., 2010; Bae and Huh, 2012). Roll forming is a well established forming technology to produce constant cross-sectional parts with high strength steel (Tehrani *et al*., 2006; Heo *et al*., 2012; Lindgren, 2007; Lee and Kim, 2013; Kim *et al*., 2012; Hong *et al*., 2001, Seo *et al*., 2012). Roll forming has drown the attention of automotive industry due to its various advantages, such as high production speed, reduced tooling cost and improved quality (Joo *et al*., 2012; Sheikh and Palavilayil, 2006; Zeng *et al*., 2009; Zeng *et al*., 2009; Lee and Kim, 2009; Sweeney and Grunewald, 2003). Various automotive parts such as bumpers, door beams, frame rails, and roof bows are made by roll forming process. In recent years, flexible roll forming process which allows variable cross sections of profiles by flexible rolling stands was developed. Flexible roll forming characteristics using ultra high strength steel was studied (Mäntyjärvi *et al*., 2009; Chun *et al*., 2012) and case study on variable width U-channel was performed using COPRA®RF coupled with MSC.Marc® (Gülçeken *et al*., 2007). Hat-channel profiles which has variable depth and width were fabricated using experimental equipment (Lindgren and Ingmarsson, 2009). An one-step-model to fabricate wrinkle free 3D U-profiles was developed and verified using analytical and experimental method (Groche *et al*., 2011). In this study, studies on optimum profile design for flexible roll forming of variable profile were performed by analytical and experimental methods. An analytical equation that can evaluate longitudinal strain was developed considering inter-distance between forming passes, base section width, side wall height and flange width. The relationship between geometrical parameters and longitudinal strain was analyzed and investigations on the optimal profile design were performed. With the results, a roll flower pattern and roll profile that can avoid process defects such as wave and twist were designed and experimentally verified.

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2. ANALYTICAL ANALYSIS FOR HAT-CHANNEL PROFILE

To analyze flexible roll forming process of hat-channel profile, an analytical equation that can evaluate the longitudinal strain during flexible roll forming process has been developed considering the dimensions of initial blank and bent angles at each station. As shown in Figure 1, initial profile is changed during flexible roll forming process. In this process, the initial length at edge (L_0) can be expressed by Equation (1).

$$L_0 = \sqrt{(w_1+w_2+w_3-w_4-w_5-w_6)^2+D_n^2} \tag{1}$$

where D_n is inter-distance between forming passes, w_1, w_2 and w_3 are base section width, side wall height and flange width at roll pass number n-1, respectively. w_4, w_5 and w_6 are those at roll pass number n.

The contact point of roll and edge at roll pass number n-1, P_1, and that at roll pass number n, P_2, can be expressed with bent angles at the roll passes;

$$\begin{aligned} P_1 &= (x_1, y_1, z_1)\\ x_1 &= w_1+w_2\cos(A_1)+w_3\cos(B_1)\\ y_1 &= w_2\sin(A_1)-w_e\sin(B_1)\\ z_1 &= 0 \end{aligned} \tag{2}$$

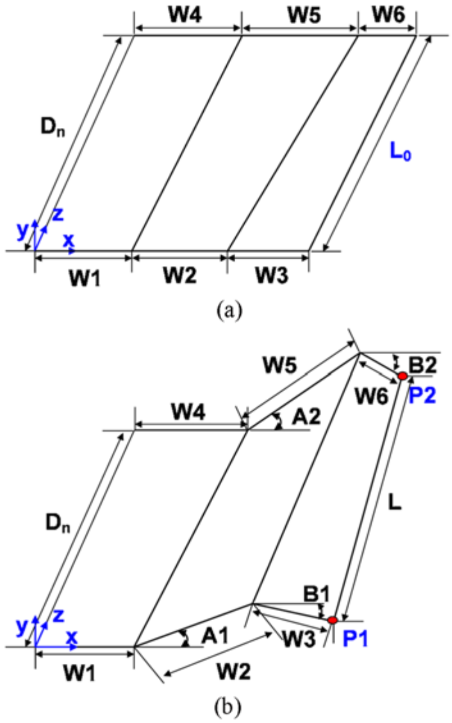

Figure 1. Schematic of half profile change during flexible roll forming process: (a) initial blank; (b) formed blank.

$$\begin{aligned} P_2 &= (x_2, y_2, z_2)\\ x_2 &= w_4+w_5\cos(A_2)+w_6\cos(B_2)\\ y_2 &= w_5\sin(A_2)-w_6\sin(B_2)\\ z_2 &= D_n \end{aligned} \tag{3}$$

where A_1 and B_1 are target bent angles of side wall and flange at roll pass number n-1, respectively. A_2 and B_2 are those at roll pass number n.

The longitudinal strain (ε_1) can be expressed as a function of x_1,y_1,z_1 and x_2,y_2,z_2

$$\begin{aligned} \varepsilon_1 &= \ln\frac{L}{L_0}\\ &= ln\frac{\sqrt{(x_2-x_1)^2+(y_2-y_1)^2+(z_2-z_1)^2}}{L_0} \end{aligned} \tag{4}$$

The effect of geometrical parameters on the establishment of longitudinal strain during forming was analyzed by equation (4). The forming angle of each station was 15º and the number of forming steps were classified into 6 stations (0º–15º–30º–45º–60º–75º–90º). Inter-distance between forming passes was 350 mm and base section width (w_1), side wall height (w_2) and flange width (w_3) at roll pass number n-1 were set to 200 mm, 50 mm and 30 mm, respectively. Base section width (w_4), side wall height (w_5) and flange width (w_6) at roll pass number n were set to variable, respectively and the other values were the same as those at roll pass number n-1.

Figure 2 shows calculated longitudinal strain at edge for various base section width. Longitudinal strain at w_4 of 150, 200 and 250 mm ranged from 0.13 to 0.99, from 0.01 to 0.17 and from –0.09 to –0.66%, respectively. When w_4 was higher than w_1, longitudinal strain shows lower value than that of conventional roll forming ($w_4 = w_1$). When w_4 was lower than w_1, longitudinal strain shows higher value than that of conventional roll forming. The maximum absolute value of longitudinal strain at w_4 of 150, 200 and 250 mm were 0.99, 0.17 and 0.66%, respectively. When w_4 was higher than w_1, the maximum absolute value of longitudinal strain was smaller than that of the case when

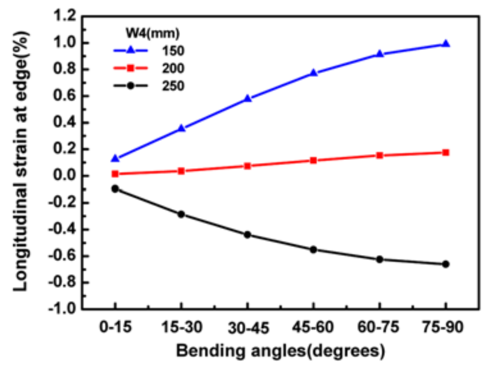

Figure 2. Longitudinal strain at edge with respect to base section width (w_4), w_5 = 50 mm, w_6 = 30 mm.

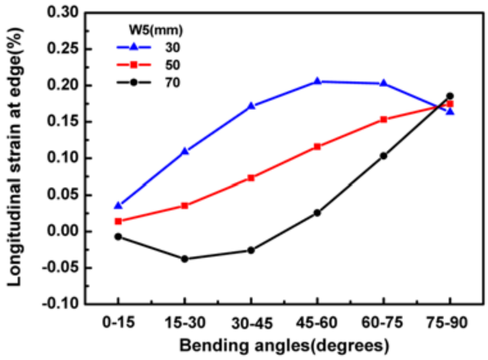

Figure 3. Longitudinal strain at edge with respect to side wall height (w_5), w_4 = 200 mm, w_6 = 30 mm.

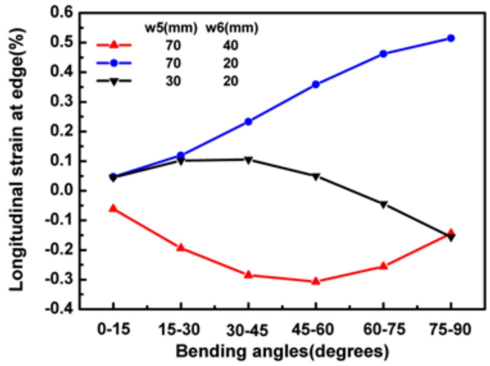

Figure 5. Longitudinal strain at edge of hat profiles, w_4 = 200 mm.

w_4 was lower than w_1. Process defects has been known to be easily generated at higher longitudinal strain (Tehrani *et al*., 2006; Lindgren, 2007). Therefore, forming the profile from wide section to narrow section is recommendable in flexible roll forming process on the viewpoint of preventing defects.

Figure 3 shows longitudinal strain at edge for various side wall height (w_5). When w_5 was larger than w_2, longitudinal strain decreased smoothly at initial stage and increases rapidly at later stage. In this case, forming angle at initial stage can be increased to reduce the number of forming stations, while forming angle at later stage should be reduced to avoid defects. When w_5 was smaller than w_2, longitudinal strain increased rapidly at initial stage and decreases at later stage. Forming angle at later stage can be increased and forming angle at initial stage should be reduced.

Figure 4 shows longitudinal strain at edge for various flange width (w_6). As shown in the figure, longitudinal strain at edge shows similar tendency to longitudinal strain at edge for side wall height. When w_6 was larger than w_3, forming angle at initial stage can be increased and forming angle at later stage should be reduced. In the case when flange width increases during the process, forming angle at later stage can be increased and forming angle at initial stage should be reduced.

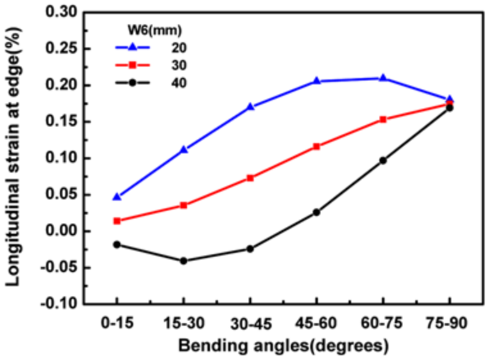

Figure 4. Longitudinal strain at edge with respect to flange width (w_6), w_4 = 200 mm, w_5 = 50 mm.

Figure 5 shows longitudinal strain of complex profiles. Side wall height and flange length were changed during the process, simultaneously. When w_5 was larger than w_2 and w_6 was larger than w_3, longitudinal strain decrease rapidly at initial stage and increased rapidly at later stage. When w_5 was smaller than w_2 and w_6 was smaller than w_3, longitudinal strain increased smoothly at initial stage and decreases rapidly at later stage. In the case when w_5 was larger than w_2 and w_6 was smaller than w_3, longitudinal strain increases steadily. Also, the maximum absolute value of longitudinal strain was larger than other cases. In this case, process defects can be easily generated.

3. EXPERIMENTAL VERIFICATION

The analytical analysis was experimentally verified by lab-scale flexible roll forming machine. Figure 6 shows schematic of lab-scale flexible roll forming machine. The machine consists of three forming stands and each stand has two units. The unit can move both axially and rotationally. The speed of the respective motions can be controlled independently. The unit of lab-scale flexible roll forming machine is shown in Figure 7.

Test material was carbon steel which has yield strength of 145 MPa, tensile strength of 425 MPa, total elongation of 42% and thickness of 0.8 mm.

Figure 8 shows dimension of four types of initial blanks. As shown in the figure, the blanks have variable width with its longitudinal direction. The width of trapezoid shape and straight-trapezoid shape changes with constant angle and the width of convex shape and concave shape changes with constant radius. The blanks were roll formed with the blank moving direction of from wide section to narrow section and opposite direction. The target shape was U-profile which has side wall height of 15 mm. As shown in Figure 9, tool pass for flexible roll forming of U-channel profile was set to parallel to the out line of blank and the off-set

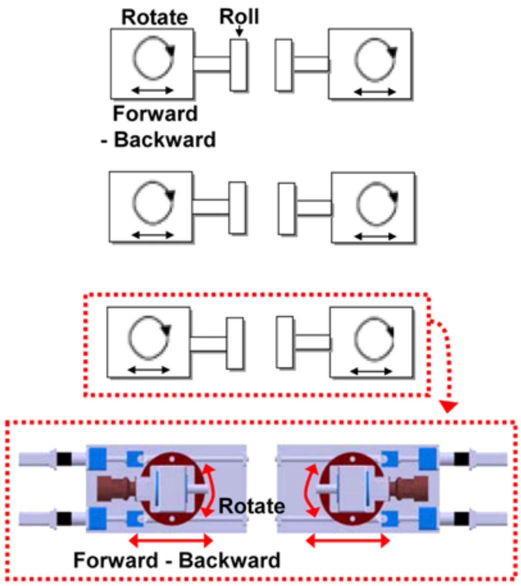

Figure 6. Schematic of lab-scale flexible roll forming machine.

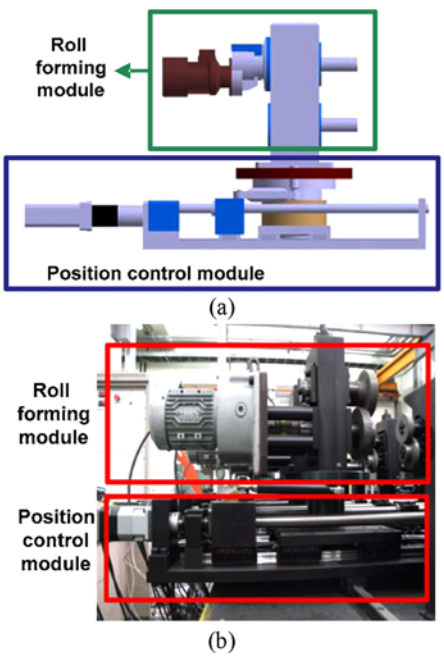

Figure 7. Unit of lab-scale flexible roll forming machine: (a) schematic of the unit; (b) unit of lab-scale flexible roll forming machine.

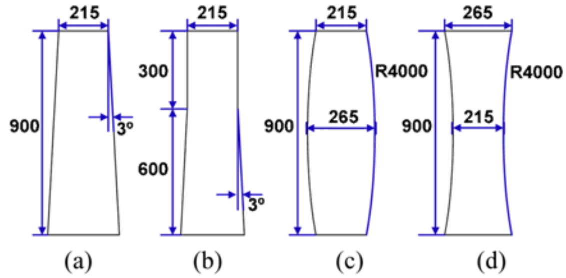

Figure 8. Dimension of initial blanks: (a) trapezoid shape; (b) straight-trapezoid shape; (c) convex shape; (d) concave shape.

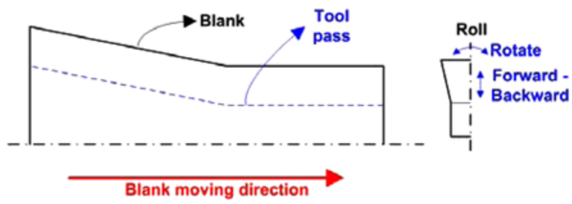

Figure 9. Tool pass for flexible roll forming of U-channel profile.

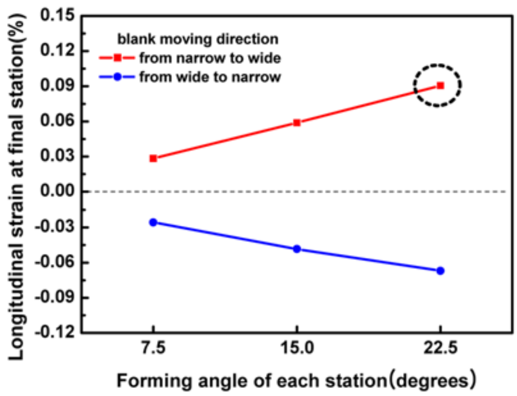

Figure 10. Longitudinal strain of trapezoid shape at final station with respect to blank moving direction and forming angle of each station.

was 15 mm. Inter-distance between forming passes was 380 mm.

Figure 10 shows longitudinal strain of trapezoid shape at final station based on the analytical equation. Absolute value of longitudinal strain increases with increasing forming angle of each stations. When forming angle of each station was the same, absolute value of longitudinal strain with the blank moving direction of from wide section to narrow section was lower than that of opposite direction. Absolute value of longitudinal strain at forming angle of 22.5° with blank moving direction of from narrow to wide was even higher than other cases. In this case, process defects can be easily generated.

Figure 11 shows fabricated sound flexible roll formed parts. When bending angle of each stand was set to 7.5° or 15.0°, all the shapes can be fabricated without defects. However when bending angle of each stand was increased to 22.5°, conical shape and straight-conical shape can only

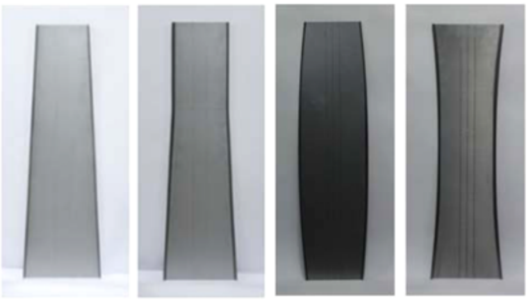

Figure 11. Fabricated flexible roll formed part: (a) Trapezoid shape; (b) Straight-trapezoid shape; (c) Convex shape; (d) Concave shape.

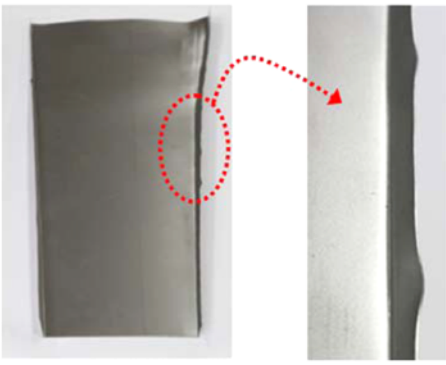

Figure 12. Wrinkling at bending angle of 22.5°.

be fabricated with the blank moving direction of from wide section to narrow section. Also, convex shape and concave shape were not formed without defects with bending angle of 22.5°. Figure 12 shows, wrinkling defects occurred with bending angle of 22.5°.

In the analytical analysis, it was shown that when w_4 was smaller than w_1, the maximum absolute value of longitudinal strain was larger than that of the case when w_4 was larger than w_1. The case when w_4 is larger than w_1 is desirable than opposite case because defects can easily be occurred at larger longitudinal strain. The experimental result shows reasonable agreement with the analytical result. It means that the process design on the basis of established longitudinal strain during flexible roll forming is feasible.

4. CONCLUSION

In this study, process design for the flexible roll forming was performed analytically on the basis of longitudinal strain established during roll forming. To prevent process-induced defects, forming from wide section to narrow section is recommendable in flexible roll forming. When side wall height or flange width decreases during the process, forming angle at later stage should be reduced. When side wall height or flange width increases during the process, forming angle at initial stage should be reduced. Based on the analytical model, initial blank and forming roll were designed and experimentally verified. The experimental results show that the process design on the basis of longitudinal strain during flexible roll forming is feasible methodology.

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