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Method for Controlling Edge Wave Defects of Parts during Roll Forming of High-Strength Steel

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Abstract: Cold roll forming is suitable for sheet metal processing and can provide a new method for the production and processing of anti-collision beams for commercial vehicles. In order to accurately control the edge wave defects of the parts in the roll forming process, we used the professional roll design software COPRA to design the roll pattern and used the professional finite element analysis software ABAQUS to establish a three-dimensional finite element analysis model of the “b”-shaped cross-section. We analyzed the factors affecting the edge wave by controlling different process parameters (the thickness of the sheet, the height of the flange, and the forming speed), and the best process parameter combination was determined. The results showed that the thickness of the sheet, the height of the flange, and the forming speed all had an effect on the edge wave defects of the “b”-shaped cross-section. The influence of sheet thickness was the greatest, followed by flange height and then forming speed. The final selected parameter combination was a sheet thickness of 3 mm, a flange height of 100 mm, and a forming speed of 150 mm/s. This work provides a theoretical basis for actual production.

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Keywords: edge wave; cold roll forming; process parameters; finite element analysis

1. Introduction

Roll forming is a processing method in which metal sheets sequentially pass through multiple forming rolls to form the required product geometric cross-section profiles. The roll forming process has many advantages, such as high production efficiency, good forming effect, and conservation of forming materials. The roll forming process can produce high-quality cold-formed steel, shorten the production cycle, and improve the production efficiency. Therefore, this processing method is widely used in many fields, such as auto parts, ships, oil and gas pipelines, the power electronics industry, and machinery manufacturing.

High-strength steel has the advantages of reducing weight and improving safety, and it is widely used in key automobile parts, such as anti-collision beams, door sills, and B-pillars. The roll forming process has an excellent forming effect, especially for the processing of complex sections, which is unmatched by the traditional process. Therefore, the use of roll forming technology in the manufacturing process and the use of high-strength steel as material have become the two main ways to achieve lightweight cars and increase crash safety performance [1]. However, due to factors such as material nonlinearity, geometric nonlinearity, and boundary nonlinearity, the deformation of sheet metal during roll forming is quite complex. One of the main problems is that the product produces edge wave defects, which often leads to undesirable product shapes and affects welding performance. Many researchers have studied computer-aided design or numerical simulation of the roll forming process in order to increase productivity and maintain product accuracy during production [2,3]. Cao et al. used COPRA software to analyze the roll forming process of

the asymmetric “8” tube, and the results showed that the defects were mainly caused by uneven force on the top of the section [4]. Paralikas et al. used ANSYS/LSDYNA to study the influence of forming parameters on longitudinal and transverse strain and concluded that the roll spacing plays a leading role in the roll forming process [5–7]. Abeyrathna et al. studied the influence of geometric parameters on longitudinal edge strain through experiments and numerical methods, and found that these strains may affect edge wave defects [8,9].

This paper proposes a new roll forming process—a one-time forming of anti-collision beams for commercial vehicles with a “日”-shaped cross-section—to improve the quality defects in the conventional process, especially the edge wave problem. The main factors that affect the edge wave defects of sheet roll forming are the finite element calculation method, friction coefficient, sheet thickness, flange height, and forming speed. This article conducted research on the latter three aspects.

2. Material Properties and Edge Waves

2.1. Material Properties

This study used B700L automobile beam steel, and some of its material parameters are shown in Table 1. The mechanical properties of the material were measured by a uniaxial tensile test. The data in Table 1 is the average of the three tests. Figure 1a shows a picture of the tensile testing machine, while Figure 1b shows the stress–strain curve of the samples obtained from the test results. The hardening behavior was determined to be isotropic. Since ABAQUS needs the true stress and strain values when entering data, the following calculation formula was used to calculate the required values:

$$\varepsilon = \ln(1 + \varepsilon_0) \quad (1)$$

$$\sigma = \sigma_0(1 + \varepsilon_0) \quad (2)$$

where ε_0 and σ_0 are nominal strain and stress, respectively.

Table 1. Properties of the elastic stage of the material.

Material	Modulus of Elasticity (GPa)	Mass Density ($\text{g}\cdot\text{cm}^{-3}$)	Poisson Ratio	Yield Strength (MPa)	Tensile Strength (MPa)
B700L automotive beam steel	216	7.85	0.22	728	918

Figure 1. (a) Picture of the tensile testing machine. (b) The stress–strain curve of B700L automotive beam steel.

2.2. Causes of Edge Waves and Evaluation Methods

During the roll forming process, the sheet moves along its forming direction, as shown in Figure 2. Different roll angles will cause different deformations of the sheet in different parts in the forming direction. The edges of the sheet will be elongated due to the increase in height. The space curve CD is longer than the straight line AB in the plane area. Because different parts of the profile have different paths between the two passes, the path length of the side is often greater than the straight-line distance between the two passes. Therefore, the actual formation boundary is inconsistent with the theoretical formation boundary. The outer edge of the sheet is wavy; that is, an edge wave defect is formed. A schematic diagram of an edge wave is shown in Figure 3a. In this paper, the edge wave defects created in the roll forming process were evaluated by the sum of wave heights generated at 100–800 mm in the sheet forming direction. The schematic diagram is shown in Figure 3b, and the calculation formula is:

$$H_{wave} = \sum_{i=1}^n h_i \quad (3)$$

where H_{wave} represents the total wave height, and h_i represents the height of the i -th wave. The standard deviation of longitudinal strain ($\Delta\varepsilon$) was used to measure the influence of each process parameter on the edge wave of the “b” tube, and the calculation formula is:

$$\Delta\varepsilon = \sqrt{\frac{\sum_{i=1}^n (\varepsilon_i - \bar{\varepsilon})^2}{n}} \quad (4)$$

where n is the total number of nodes measured, ε_i is the longitudinal strain of the i -th node, and $\bar{\varepsilon}$ is the average value of the longitudinal strain of the node.

Figure 2. Part of the pass in the roll forming process.

Figure 3. (a) Diagram of an edge wave; (b) The evaluation method of edge waves.

3. Establishing a “b”-Shaped Cross-Section Finite Element Analysis Model

3.1. “日”-Shaped Cross-Section Forming Method

The section of the anti-collision beam used in commercial vehicles is a “日”-shaped structure. There are two traditional processing methods for “日”-shaped cross-sections.

The first method is divided into three steps: (1) using roll forming equipment (Shulan General Machinery Co., Ltd., Jilin, China) to process two U-shaped tubes; (2) cutting out a rectangular tube; and (3) welding the two U-shaped steel channels with to rectangular tube, as shown in Figure 4a. The second method is carried out in two steps: (1) using roll forming equipment to process a rectangular tube and a U-shaped tube; and (2) welding the rectangular tube to the U-shaped tube, as shown in Figure 4b. The welding process in the above two methods is very complicated and requires repeated welding to achieve the forming effect, which not only increases workload, but also results in low production efficiency and poor product quality, and the mechanical properties of the products are difficult to guarantee. In this paper, we adopted a challenging forming method for roll forming the anti-collision beam of commercial vehicles with a “日”-shaped section at one time, as shown in Figure 4c. This method firstly involves roll forming a “b”-shaped section with roll forming equipment, and performing automatic welding on the inner welding seam; then, rolling the “b”-shaped section again to make the vertical side roll into a U-shaped tube to obtain a “日”-shaped section; and finally, welding the outer weld seam to the edge position after forming. This method not only reduces solder joints, improves material utilization, and production efficiency, but also greatly improves the mechanical properties of the product. In order to reduce the influence of edge wave defects in the forming process and save calculation time, this paper only simulated and analyzed the “b”-shaped section. The product was tested on a self-developed roll forming process production line, as shown in Figure 4d. The specific product is shown in Figure 4e.

Figure 4. (a) The first method of forming “日”-shaped cross-sections. (b) The second method of forming “日”-shaped cross-sections. (c) One-time roll forming method. (d) Photo of the products. (e) The production line for the roll forming process.

3.2. Design of the Roll Pattern for the “b”-Shaped Cross-Section

The roll pattern is a schematic cross-sectional view of the roll forming unit when the sheet is formed. The forming sequence of the “b”-shaped cross-section was designed through the roll pattern design module of COPRA, as shown in Figure 5. The rounding radius was 5.0 mm, the thickness of the sheet was 2.0 mm, and the outside angle was first formed to 75°, with a total of five passes. Then, the two inner corners were formed to 90°, with a total of six passes. Finally, remaining outside corners that were not yet formed were shaped, and each pass was formed at 5° for a total of 3 passes. With the addition of the guide roll of the first pass, the total number of forming passes was 15 passes. The sheet metal passed through each roll from the first pass, and finally passed through the fifteenth pass to form the required cross-sectional shape.

Figure 5. Roll pattern of “b”-shaped cross-section.

3.3. Optimization of “b”-Shaped Cross-Section Rolls Based on DTM Analysis

According to the process described above, through the deformation technology module (DTM) of COPRA, the DTM analysis of the pre-designed roll pattern was performed to obtain the strain magnitude of the strip under a given roll pattern design. Figure 6a,b show the front view of the designed “b”-shaped cross-section roll pattern DTM analysis and the resulting strain curve with longitudinal distance, respectively. It can be seen from the figure that the strain received by the sheet metal during the forming process is very uneven. As the longitudinal distance increases, the strain increases continuously. This is also in line with the roll forming production process; that is, the sheet metal forming angle is gradually increased to obtain the desired cross-sectional shape of the profile. The strain is controlled below 2.5%, and the maximum and minimum strain difference is controlled at 2%. This indicates that if roll bending molding is carried out in accordance with the designed forming order, the sheet will not be unstable and other behaviors that damage the material structure during the molding process will be absent, indicating that the designed roll pattern can meet the molding requirements.

Figure 6. (a) DTM analysis. (b) The changing curve of strain with longitudinal distance.

3.4. Establish a Finite Element Analysis Model for the “b”-Shaped Cross-Section

In this paper, the COPRA2021 software from the German company data M company (Valley, Germany) was used to design the roll pattern, and the generated roll pattern diagram was imported into the ABAQUS2017 software from the American company DS

SIMULIA company (Providence, USA) for roller design. In order to simulate the actual roll forming process, the length of the sheet was set to 900 mm, and the sheet was set as a deformable body. The mesh used C3D8R solid elements [10,11], and the thickness direction was divided into two layers, with a total of 11,340 elements. The roller was set as an analytical rigid body and the roller was angle-relieved [12], the diameter of the upper roller was set to 150 mm, the diameter of the lower roller was set to 100 mm, and the diameter of the vertical roller was set to 100 mm. The pass spacing between the rollers was set to 350 mm. General contact was selected between the roller and the plate, and the friction coefficient was set to 0.2 [13]. The assembly drawing of the “b”-shaped cross-section model is shown in Figure 7. The above simulation conditions and workpiece geometry are shown in Table 2.

Figure 7. Assembly drawing of “b”-shaped pipe.

Table 2. Simulation and workpiece conditions.

Roller Conditions		Workpiece Conditions	
Total number of models	15	Grid vertical size	3.0 mm
Center distance of roller	350 mm	Number of elements	11,430
Coulomb friction coefficient	0.2	Number of meshes in the thickness direction	2
Type of steel body	Analytical rigid body	Mesh type	C3D8R

4. Results and Discussion

4.1. Analysis of the Simulation Results for the “b”-Shaped Tube

It can be seen from the simulation results that the front flange of the pipe tends to shift to the inside. This is due to the complex deformation force of the sheet metal when the rolls are engaged during the roll forming process. Therefore, in order to ensure the accuracy of the simulation results, the stress change at the flange at 100–800 mm in the length direction of the sheet was selected to be measured. As shown in Figure 8, the stresses at the top, middle, and bottom nodes of the flange are distributed within the longitudinal distance. It can be seen that the stress relationship is greatest at the top of the flange, followed by the middle of the flange, and is lowest at the bottom of the flange. It can also be seen from the figure that the stress and strain curves at the top node of the flange have greater volatility and peak values than the stress and strain curves at the middle and bottom nodes, indicating that the longitudinal stress and strain distribution at the top of the flange is the most uneven, and the longitudinal stress and strain at the bottom of the flange are the same. The strain distribution is the most uniform. Therefore, the top of the flange is most prone to edge wave defects.

Figure 8. (a) The curve of stress changing with longitudinal distance. (b) The curve of strain changing with longitudinal distance. (c) L11 (strain tensor component). (d) L22 (strain tensor component). (e) L13 (strain tensor component). (f) Identification of the flange parts.

According to the above analysis, it can be concluded from the post-processing of the model that along the roll forming direction, the sheet edge has longitudinal strain, and along the sheet transverse direction, there is shear strain during sheet metal forming. Taking a sheet flange height of 100 mm, a thickness of 3 mm, and a forming speed of 300 mm/s as an example, the stress at the top node of the flange and the curve of the node coordinates with the longitudinal distance were analyzed. Figure 9a shows the Mises stress cloud diagram of the “b”-shaped tube. It can be seen that the stress distribution of the entire pipe is uneven, but the overall trend is that the closer the corner is to the pipe, the greater the stress. Figure 9b shows the changing curve of the stress and coordinates of the joints at the top of the sheet metal with the longitudinal distance. Figure 9c shows the equivalent strain cloud diagram of the “b”-shaped tube. It can be seen that the strain in the tube mainly occurs at the corners. Figure 9d shows the curve of the strain and the coordinate of the node at the top of the sheet as a function of the longitudinal distance. The generation of edge waves at the flange is closely related to stress and strain, and edge wave defects are most likely to occur at the top of the flange. Next, combining different process parameters, the stress and strain of the top node of the flange was analyzed.

Figure 9. (a) Cloud map of Mises stress for “b”-shaped pipe. (b) The changing curve of the stress and coordinates of the joints at the top of the sheet metal with the longitudinal distance. (c) Cloud map of equivalent strain for “b”-shaped pipe. (d) The changing curve of the strain, the coordinates of the joints at the top of the sheet metal, and the longitudinal distance.

4.2. Flange Height and Edge Wave

In order to explore the influence of different flange heights on the edge waves of roll forming parts, the parameters set in the simulation were as follows: the sheet thickness was 3 mm, the forming speed was 300 mm/s, and the flange heights were selected as 100 mm, 120 mm and 140 mm. Figure 10a,b show the variation curves of equivalent stress and equivalent strain of the top node of the sheet with longitudinal distance under different flange height conditions. Figure 10c shows under the condition of this processing parameter, the variation curve of the sum of wave heights generated. It can be seen from the figure that as the height of the flange increases, the maximum equivalent stress and strain values of the top node increase, and the increase in the height of the flange will have an adverse effect on the forming process, resulting in aggravated edge wave defects at the flange. This is because an increase in the height of the flange will increase the edge tension of the stretching zone, the compression at the edge of the compression zone will also increase, and the increase of the edge compression will directly lead to greater edge wave defects. Therefore, in the actual manufacturing process, we can control the edge wave by reducing the height of the flange on the basis of meeting the size requirements of the part.

Figure 10. (a) The changing curve of the equivalent stress of the top joint of the sheet metal with the height of the flange. (b) The changing curve of equivalent plastic strain of the top joint of the sheet metal with the height of the flange. (c) The changing curve of the sum of wave heights with the height of the flange.

4.3. Sheet Thickness and Edge Waves

In order to explore the influence of different sheet thicknesses on the edge wave of roll forming steel, the parameters set in the simulation were as follows: the flange height was 100 mm, the forming speed was 300 mm/s, and the sheet thicknesses were 2 mm, 2.5 mm and 3 mm. Figure 11a,b show the curves of equivalent stress and equivalent strain of the top node of the sheet with the longitudinal distance under different sheet thickness conditions. Figure 11c shows the curve of the change of the sum of wave heights with the thickness of the sheet. It can be seen from the figure that as the thickness of the sheet increases, the required stress during sheet deformation increases, while the sum of wave heights gradually decreases. This is because the increase in sheet thickness increases the forming rigidity of the outer flange, thereby improving its ability to resist edge wrinkles and reducing the occurrence of edge wave defects. Therefore, thicker plates can produce higher-quality wide profiles. Therefore, in actual processing, on the basis of meeting the required thickness of the parts, we can increase the thickness of the plate to reduce the occurrence of edge wave defects.

Figure 11. (a) The changing curve of equivalent stress of the top joint with the thickness of the sheet metal. (b) The changing curve of equivalent strain of the top joint with the thickness of the sheet metal. (c) The changing curve of the sum of wave heights with the thickness of the sheet.

4.4. Forming Speed and Edge Wave

In order to explore the influence of different forming speeds on the edge wave of roll-forming steel, the parameters set in the simulation were as follows: the flange height was 100 mm, the sheet thickness was 3 mm, and the forming speed was 150 mm/s, 200 mm/s and 300 mm/s. Figure 12a,b show the curves of equivalent stress and equivalent strain at the top node of the sheet metal with longitudinal distance under different forming speed conditions. Figure 12c shows, under the condition of this processing parameter, the variation curve of the sum of wave heights generated with the forming speed. It can be seen from the figure that as the forming speed increases, the peak equivalent stress value and the equivalent strain value of the top node of the sheet also increase. This is because for the roll forming process, the sheet metal forming speed set in the macroscopic view can be understood as the strain rate of the sheet metal from the microscopic point of view. According to the plastic forming theory of metal materials, an increase in strain rate will cause the work hardening of the material, and it is the internal strengthening of this material that requires greater deformation force. In addition, the increase in forming speed will also change the friction characteristics between the roll and the sheet metal, and ultimately lead to further aggravation of the edge wave defect of the roll forming steel. Therefore, in the actual manufacturing process, on the basis of meeting the required time of production, we can control the edge wave by reducing the forming speed in order to obtain high-quality roll forming steel.

Figure 12. (a) The changing curve of equivalent stress of the top joint with the forming speed of sheet metal. (b) The changing curve of equivalent strain of the top joint with the forming speed of sheet metal. (c) The changing curve of the sum of wave heights with the forming speed.

4.5. Analysis of Orthogonal Experimental Results of “b”-Shaped Tube Edge Waves

Through the above exploration, we determined the influence of different process parameters, namely flange height, sheet thickness, and forming speed, on the edge wave of the “b”-shaped cross-section. Then, we further explored the effect of each process parameter on the edge wave through orthogonal experiments. The degree of influence and the results of the orthogonal experiment are shown in Table 3. The larger the longitudinal strain standard deviation ($\Delta\epsilon$), the more severe the edge wave, and the larger the range ΔR , which indicates a greater degree of influence on the edge wave defect. From the data in the table, it is shown that every three experiments from the first experiment were used as an experimental group. This intra-group control showed that each process parameter affected the severity of the edge wave, which further verifies the above-mentioned exploration conclusions. Under the conditions of Experiment 21, the longitudinal strain standard deviation ($\Delta\epsilon$) of the “b”-shaped cross-section formed below was the largest, indicating that the edge wave of the “b”-shaped tube section was the most intense under this process condition. For the longitudinal strain standard of the “b”-shaped cross-section formed under the conditions of Experiment 7, the difference ($\Delta\epsilon$) is the smallest, indicating that the edge wave defect of the “b”-shaped cross-section is the smallest under this process condition. When performing inter-group control, considering the complexity of the data, we selected experiments 1, 2, 3, 7, 16, 25, 21, 24, and 27 for calculations. The calculation results are shown in Table 4. It can be seen from the data in the table that the largest difference is the experimental result of changing the thickness of the sheet, the height of the flange is the second largest, and the forming speed is the smallest, indicating that of the process parameters, sheet thickness has the greatest influence on the edge wave of the roll forming product, followed by flange height and then forming speed.

Table 3. Results of the orthogonal experiments.

Group	Experiment	Flange Height (mm)	Sheet Thickness (mm)	Forming Speed (mm/s)	$\Delta\epsilon$
I	1	100	2.0	150	1.85×10^{-4}
	2	100	2.0	200	1.92×10^{-4}
	3	100	2.0	300	3.79×10^{-4}
	4	100	2.5	150	1.57×10^{-4}
	5	100	2.5	200	1.76×10^{-4}
	6	100	2.5	300	2.68×10^{-4}
	7	100	3.0	150	1.33×10^{-4}
	8	100	3.0	200	1.66×10^{-4}
	9	100	3.0	300	2.16×10^{-4}
	10	120	2.0	150	4.19×10^{-4}
	11	120	2.0	200	4.42×10^{-4}
	12	120	2.0	300	4.75×10^{-4}
	13	120	2.5	150	4.10×10^{-4}
	14	120	2.5	200	4.31×10^{-4}
	15	120	2.5	300	4.45×10^{-4}
II	16	120	3.0	150	3.76×10^{-4}
	17	120	3.0	200	4.01×10^{-4}
	18	120	3.0	300	4.15×10^{-4}
	19	140	2.0	150	6.98×10^{-4}
	20	140	2.0	200	7.42×10^{-4}
	21	140	2.0	300	7.85×10^{-4}
	22	140	2.5	150	5.21×10^{-4}
	23	140	2.5	200	5.56×10^{-4}
	24	140	2.5	300	5.96×10^{-4}
	25	140	3.0	150	3.96×10^{-4}
III	26	140	3.0	200	4.33×10^{-4}
	27	140	3.0	300	4.46×10^{-4}

Table 4. Results of the control experiment between parameters.

$\Delta\epsilon$	Forming Speed	Flange Height	Sheet Thickness
I	1.85×10^{-4}	1.33×10^{-4}	7.85×10^{-4}
II	1.92×10^{-4}	3.76×10^{-4}	5.96×10^{-4}
III	3.79×10^{-4}	3.96×10^{-4}	4.46×10^{-4}
ΔR	1.94×10^{-4}	2.63×10^{-4}	3.39×10^{-4}

5. Conclusions

This paper used COPRA roll design software to design rolls, ABAQUS finite element modeling and analysis software to simulate the roll forming process, design contrast experiments to explore the influence of different process parameters on the “b”-shaped tube edge wave, and design orthogonal experiments to explore the different degree of influence of process parameters on the edge wave, providing a theoretical basis for the production of “日”-shaped tubes. Our conclusions are as follows:

(1) Compared with the traditional roll forming process, the one-time roll forming process used in this paper greatly improved the utilization rate of materials, product performance, and production efficiency.

(2) Different process parameters (flange height, sheet thickness, and forming speed) will have an impact on the edge wave defects of “日”-shaped cross-section roll-forming products. The influence rules are as follows: the intensity of edge wave increases with an increase of flange height, decreases with an increase of sheet thickness, and increases with an increase of forming speed.

(3) Orthogonal experiment results showed that for high-strength steel sheets with certain material properties, the sheet thickness had the greatest influence of the process

parameters on the edge wave during the forming process, followed by flange height and then forming speed. The optimal parameter combination selected to minimize edge wave defects was a sheet thickness of 3 mm, a flange height of 100 mm, and a forming speed of 150 mm/s.

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