Simulation Research on Roll Forming in Container Roof

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Abstract. The finite element simulation of the roll forming process of the container roof is carried out, and the stress, strain, and history curves of key nodes are analyzed. It is proved that the rolling process will produce edge wave and wrinkle defects in the flat section, and the influence of parameters on the edge wave wrinkle is studied. Studies have shown that: the length of the transition section increases, the number of wrinkle decreases; the distance between the arches increases, which suppresses the generation of side wave defects, but after more than 350mm, the effect on the side wave remains unchanged; the width of the sheet edge increases, and the side wave defects follow the increase.

1. Introduction

Cold-formed steel is a kind of economical cross-section profile. Because of its high production efficiency, good dimensional accuracy, and diversified varieties, it is widely used in automobiles, construction, transportation, and other fields [1-2]. With the continuous development of society, roll forming technology is increasingly used in traditional processing fields, but the design and production of roll forming still mainly rely on some empirical formulas or the experience of designers. And because of the complexity of the variable cross-section forming process, the flange part of the profile is prone to forming edge waves and wrinkles after forming, which affects the forming accuracy of the parts. Therefore, many scholars at home and abroad have discussed the edge wave wrinkles in the roll forming process. The law of influence has been studied in depth. Tehrani [3-4] believe that the edge wave phenomenon is caused by the first bending angle exceeding a certain value. And Sebastian Berner [5] studied from the stress point of view and believed that the edge wave was caused by the critical stress of the leg in the roll forming process being lower than the actual stress in the leg. Luo Xiaoliang [6] found that the larger the yield strength, the strengthening coefficient, and the thickness anisotropy coefficient, the smaller the trend of edge waves; the increase of the strengthening index, the slower the trend of edge waves. Wang Zhenxiao [7] found that the deformation path has a great influence on the formation of side waves; increasing the number of passes and the distance between passes can reduce the occurrence of side wave effects. Based on many kinds of research on cold-formed technology by predecessors, this article takes container roof as the research object and proposes a new roll forming technology in the container roof.
2. Modeling

2.1. Introduction to cold-rolled products

![Figure 1. Structure Chart of Roof.](image)

2.2. The research object of this article is the container roof.

There are five corrugations. The basic dimensions are 2356mm in length, 1045mm in width, and 2mm in thickness. The structure of the roof is shown in Figure 1. The container roof is different from the ordinary corrugated plate in that there is a variable cross-section in the longitudinal direction, which is a wide cross-section corrugated plate. Combined with the roof structure, a simultaneous pass system is adopted; the roll pass design adopts the vertical movement method of the center of curvature; the number of forming passes of the container roof in this article is based on the actual situation and combined with the RT angle method to determine the six forming passes; the roll bending process passes through 10°, 21°, 33°, 44°, 54°, 53.1° six-pass molding; considering the length of the top plate itself is too large, and the later cutting the roll is driven. The roll diameter is 200mm. The position of the roll and the transition section of the variable cross-section needs to be matched with each other, so there needs to be an angle difference between the front and rear roll parts [8].

2.3. The finite element simulation model

This paper uses the three-dimensional software CATIA to design the roll model and then imports the model into MARC software for simulation. Set the roll as a rigid body and only rotate in the axial direction, and the plate is defined as a deformed body. The container roof is composed of five identical corrugations, and the five corrugations are symmetrical. In order to reduce the calculation time, the half-wave of the top plate is simulated. When analyzing the side wave defect of the top plate, half of the top plate divided by the neutral line is simulated. Analysis. In the simulation of the forming process, the sheet size is set to 111.9×800×2mm, and the sheet size is set to 570×800×2mm for the edge wave problem.

The forming process of the top plate is to move forward in a straight line under the driving of the rollers, and its transverse plate width direction gradually shrinks, and the plate can only move forward along the rolling direction, that is, the X-axis direction. In order to avoid side slip during the movement of the plate, the Y direction displacement of the node on the centerline is 0, that is, FIXEDDISPLACEMENTY=0 is set in the boundary conditions. During the rolling process, the friction coefficient between the roll and the sheet is set to 0.1. Adopt the method of pressing down the first pass upper roller to realize the biting way of the plate.

During the simulation of the forming process, the sheet metal is divided into 5600 units with a total of 11658 nodes. The edge wave problem simulation divides the sheet into 28,400 elements with a total
of 57,486 nodes, and the element type uses solid elements. The material is weathering steel 09CuPCrNi-A, and the mechanical properties are shown in Table 1. The cold bending process is carried out at room temperature, so when setting the material properties, the coefficient of thermal expansion and thermal conductivity can be ignored.

| Material      | Elasticity module (Mpa) | Yield strength (Mpa) | Tensile strength (MPa) | δ₅ | Poisson’s ratio/ν |
|---------------|-------------------------|----------------------|------------------------|----|------------------|
| 09CuPCrNi-A   | 207000                  | 370                  | >600                   | >22% | 0.3              |

3. Course curve of an equivalent strain of forming process and stress-stain

Select node 782 on the upper wave surface, node 4107 on the lower wave surface in the corrugated section, node 2007 on the upper corner, node 663 on the transition section, and node 4349 on the flat section, as shown in Figure 2.

![Figure 2. Position of Nodes](image)

![Figure 3. Strain-stress Curve of Upper Wave Surface Node](image)
Figure 4. Strain-stress Curve of Upper-Bend Node

Figure 5. Strain-stress Curve of Transition Section Node
Figure 6. Strain-stress Curve of Panel Section Node

The four pictures show the equivalent strain curve of each node during the cold bending process. Figure 3 shows the strain curve of the upper wave surface node. It can be seen from the curve that there is no plastic deformation on the upper wave surface during the cold forming process. This is the same as the deformation characteristics of the upper wave surface during the cold forming of the top plate, which is in line with the actual situation.

Figure 4 shows the curve of node strain change at the upper corner. It can be seen from the curve that in the process of cold bending, the strain at the corner of the sheet becomes a step-like increasing curve, and the curve changes more regularly. When the sheet metal enters the first pass roll, plastic deformation occurs at the corner, and its moving distance is small, so its strain value increases rapidly. When the sheet metal leaves the roll, the strain value does not decrease immediately, but in the plate, the material reaches the extreme value after leaving the roll for a short distance. Although there is a certain amount of elastic recovery afterward, due to plastic deformation at the corners, the recovery amount is relatively small and the strain value is relatively stable. This process is repeated every pass. The maximum stress is also concentrated in this area, so in the process of cold bending of the roof, attention should be paid to the forming of the corner area. It can be seen from Figure 5 that the strain change trend at the transition section is the same as the strain change trend at the corners, and both increase stepwise. The difference is that when the transition section enters the first pass roll because the transition section has a small bending amount and is within the elastic deformation range, its strain does not change. The subsequent changes are the same as the corners. It can be seen from Figure 6 that the flat section has not undergone plastic deformation during the cold bending process, and has been in the elastic range.
Figure 7. Displacement Change Curve of Node at Corrugation Section

Figure 8. Displacement Change Curve of Node at Panel Section

7 and Fig.8 shows the displacement curve of each node along the Y-axis during the cold forming process. Figure 7 shows the change curve of the node displacement of the corrugated section. It can be seen from the curve in the figure that with the increase of the bending amount of the sheet, the corrugated surface will continue to move to the basic centerline, and the Y-direction displacement of the nodes on the corrugated section will continue to increase. When the sheet moves to the sixth pass, Since the sixth pass is a shaping roller, the displacement is no longer increased.

Figure 8 shows the change curve of the node displacement of the slab section. It can be seen from the curve in the figure. The displacement change of the slab node is completely different from that of the corrugated section, and the fluctuation is more obvious, but the maximum displacement is significantly smaller than the corrugated section. When the corrugated plate enters the roll, the Y-direction displacement of the flat section gradually increases and reaches the extreme value, and when
the flat section enters the roll, its displacement decreases rapidly. Then, as the plate moves, repeat this process. This is because after the corrugated section at the front end of the flat section enters the roll, the corrugated section has to shrink to the basic centerline. The flat section is restrained by the displacement of the corrugated section, which will also cause a relatively small displacement in the Y direction, but when the flat section moves to the roll when there is a gap, under the constraints of the rolls, the displacement of the flat section will decrease rapidly. When the flat section leaves the roll gap, its displacement will recover to a certain extent. Repeat this process every time. And as the shrinkage of the corrugated section increases in each pass, the shrinkage of the flat section caused by it will also increase. However, when the sheet material passes through the sixth pass, the Y-axis displacement of the node of the sheet metal flat section will decrease, and there will still be a certain amount of displacement, indicating that forming defects will occur at the flat section.

4. The influence of parameters on edge wave wrinkling

During the cold forming process of the roof, the roll applies a longitudinal bending moment on the blank at the variable cross-section of the formed roof. As the depth of the wave at the corrugation section of the roof increases, the width of it continuously decreases, but the width of the panel section is unchanged, which results in the transverse metal flow of the panel is different at the longitudinal direction, and the panel section under the restraint of the displacement of the corrugation section will also cause relatively small transverse shrinkage. The transverse metal flow of the panel is different in the corrugation section and the panel section of the roof and thus causes wrinkle at the panel section.

This paper uses the standard deviation of strain $\Delta \varepsilon$ as an indicator to measure the amount of wrinkle and the size of the edge wave.

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

(1)

Where, N is the number of nodes; (i=1, 2,…, N) is the node stress; $\bar{\varepsilon}$ is the mean value of each node strain.

Figure 9. Position of Wrinkling Node
4.1. Influence of parameters on wrinkling

Figure 10. Position of Side-wave Node

Figure 11. Transverse Strain Distribution of Different Lengths of Transition Sections

Figure 12. Comparison of standard deviations of different transition lengths
4.1. The influence of transition section length on the forming of flat section. Figure 11 shows the transverse strain distribution of the middle nodes of the top slab section under different transition section lengths. It can be seen from the figure that as the length of the transition section increases, the transverse strain value of the corresponding slab section node decreases, and the transverse strain distribution at each node becomes more uniform. It can be seen from Table 2 that when the length of the transition section is 20mm, the standard deviation of the transverse strain reaches 24.06×10^-4, and the wrinkle is the largest. As the length of the transition section increases, the standard deviation of transverse strain gradually decreases, and the amount of wrinkles also gradually decreases.

Figure 12 is a comparison chart of the standard deviation of the transverse strain of the slab node under different passes. As the length of the transition section increases, the standard deviation of transverse strain gradually decreases. For different transition section lengths, the changing trend of the wrinkle amount of the flat section in different passes is the same. From the first pass to the fourth pass, the wrinkle amount gradually increases, and the fifth and sixth passes gradually decrease. This is the same as the previous analysis of the cause of wrinkling of the flat section.

4.2. The Influence of parameter on side wave

Figure 13 and Figure 14 respectively show the maximum stress changes in the corner area and the upper wave surface node under different roll diameter differences. It can be seen from the curve in the figure that as the roll diameter difference increases, the highest stresses in the corner area and the upper wave surface node gradually increase. When the roller diameter difference is 0mm, the maximum stress at the corner is 435.5MPa, and the maximum stress on the upper wave surface is 232.4MPa. When the roller diameter difference increases to 1.5mm, the maximum stress at the corner reaches 521.5MPa, and the maximum stress on the upper wave surface is 353.6MPa. The difference in roll diameter increases, and the moving speed of the plate driven by the back roll increases, which increases the tension of the plate during the forming process, so the stress at the corner and the upper wave surface node increases.

**Table 2. Standard Deviation of Transverse Strain of Node**

| Length of transition section | 20mm | 24mm | 28mm | 32mm |
|-----------------------------|------|------|------|------|
| $\Delta \epsilon /10^{-4}$   | 24.06| 16.09| 11.37| 10.20|

**Figure 13. Chart of Maximum Stress Change in the Bend Area**
Figure 14. Chart of Maximum Stress Change in Upper Wave Surface

Figure 15 shows the longitudinal strain distribution curve of each node on the edge of the top plate under four different roll diameter cases. It can be seen that when the roller diameter difference is 0mm, $\Delta \varepsilon = 11.41 \times 10^{-4}$, the longitudinal strain distribution curve fluctuates greatly, indicating that the side wave is large. As the roll diameter difference increases, the longitudinal compression at the corners of the sheet is reduced, and the longitudinal strain distribution of the nodes is more gentle, so the edge wave defects are reduced. When the roller diameter difference is 1.5mm, the standard deviation $\Delta \varepsilon = 5.5 \times 10^{-4}$, the curve oscillation amplitude is small, and no side waves are generated.

Figure 16 shows the longitudinal strain distribution curve of each node on the edge of the roof under the four cases of archway spacing. It can be seen from the figure that as the archway spacing increases, the oscillation amplitude of the longitudinal strain curve of each node on the roof edge tends to be uniform, and the archway spacing increases the shrinkage of the edge area of the sheet material per unit length is reduced, the sheet material is formed sufficiently, and the edge wave defect is not easily generated. When the distance between the arches is 250mm, the longitudinal strain curve oscillates the most with a standard deviation of 0.001832, and the edge of the top plate will be longitudinally stretched and deformed, resulting in larger side waves. When the archway spacing is 350mm and 400mm, the longitudinal strain distribution curve of the edge node changes relatively little, the standard deviation changes very little, the strain level is relatively low, and the longitudinal stretch of the edge is small, so continue to increase the archway spacing, and the opposite side The wave has little effect.

Figure 15. Longitudinal Strain Distribution Curve
Figures 17 and 18 are graphs of the maximum stress changes at the nodes in the corner area and the upper wave surface under different archway spacing. It can be seen from the curve in the figure that as the distance between the arches increases, the maximum stress of the nodes in the corner area decreases significantly, while the maximum stress of the nodes on the upper wave surface decreases less. When the distance between the arches is 250mm, the maximum stress at the corner is 568.8MPa, and the maximum stress on the upper wave surface is 344MPa. When the roller diameter difference increases to 1.5mm, the maximum stress at the corner is 495.3MPa and the maximum stress on the upper wave surface is 333.2MPa. As the distance between the arches increases, the deformed length of the plate between the two rolls increases, which reduces the amount of strain per unit length and the plate forms more smoothly, so the equivalent stress at the corners gradually decreases. Since the upper wave surface does not undergo plastic deformation during the forming process, the stress changes are not obvious.
Figure 18. maximum stress change in nodes at the upper wave surface

Figure 19. Longitudinal Strain Distribution Curve

Table 3. The standard deviation of the longitudinal strain

| Width of margin | 41mm | 51mm | 61mm |
|-----------------|------|------|------|
| $\Delta \varepsilon / 10^{-4}$ | 5.83 | 6.92 | 14.40 |

Fig.19 shows the longitudinal strain curve and it also shows that the longitudinal strain of the node on the edge is the minimum when the width of margin is 41mm, $\Delta \varepsilon = 5.83 \times 10^{-4}$, without side wave. When the width of the margin becomes 61mm, the longitudinal strain of the node on the edge is the maximum, $\Delta \varepsilon = 14.4 \times 10^{-4}$, with the most obvious side wave phenomenon. This shows the longitudinal strain value of the node on the edge increases, the strain standard deviation also increases, and the side wave phenomenon is more obvious, as the width of the panel margin increases.

5. Conclusions
1 The upper wave surface and the flat plate section have not undergone plastic deformation during the roll forming process, and are always in an elastic state. The strain at the corner is the place where the strain is greatest in the whole forming process. The changing trend of the strain in the transition section is the same as the strain change trend at the corners, both of which increase stepwise. The difference is
that when the transition section enters the first pass roll, the strain of the transition section does not change due to the small bending amount. The subsequent changes are the same as the corners.

2 As the length of the transition section increases, the standard deviation of transverse strain gradually decreases, and the number of wrinkles also gradually decreases. The roll diameter difference has little effect on the wrinkle amount of the plate section.

3 The distance between the arches is increased, the shrinkage of the edge area of the sheet per unit length is reduced, and the generation of side wave defects is suppressed. But continuing to increase the distance between the archways has little effect on the side waves. The increase in the diameter difference of the rolls reduces the longitudinal compression at the corners of the sheet, thus reducing the edge wave defects. As the width of the sheet edge increases, the tendency to generate side waves increases.

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