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Research on Influencing Factors of Rolling Forming Quality of Automobile Variable Section Longitudinal Beam Based on Orthogonal Test

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***Abstract* – The rolling forming process of automobile variable cross-section longitudinal beam is more complex than the traditional constant cross-section roll forming. In the forming process, there will be not only common defects of traditional rolling forming such as thinning, edge wave, wrinkling, springback and distortion, but also unique instability and wrinkling defects caused by cross-section change. In view of the above forming defects, this paper puts forward three quality evaluation indexes: the change rate of wall thickness to evaluate the change of wall thickness, the instability degree of side wave phenomenon, and the maximum bending angle and spring back angle to evaluate the bending or spring back degree of longitudinal beam. In this paper, the quality evaluation and influencing factors of rolling forming of variable section longitudinal beam are studied by means of ABAQUS finite element software. In order to reduce the workload of finite element modeling, this paper establishes the correct finite element model and three-dimensional model by means of orthogonal test. By analyzing the main factors affecting the forming quality of automobile variable section longitudinal beam, it provides a certain reference for the rolling production development of variable section longitudinal beam.**

***Keywords* – Variable Section Longitudinal Beam, Flexible Roll Forming, Orthogonal Test, Finite Element Analysis.**

I. Introduction

Flexible roll forming is a new roll forming technology based on traditional roll forming. The cross-section of the plate can change according to a certain law [1]. The cross section of high-strength steel is formed according to a certain law. The produced parts have excellent mechanical properties, light weight, high stiffness and good stability, which can effectively save metal sheets [2]. Variable cross-section roll forming process has been more and more used in many industrial fields, such as automobile parts, steel structure buildings, highway guardrail plates, transportation containers and bridges.

Compared with the roll forming of constant section longitudinal beam, the stress-strain state of variable section longitudinal beam flange during roll forming is more complex [3]. In the whole process of variable cross-section roll forming, variable cross-section roll bending profile will not only encounter all the forming problems of fixed cross-section roll bending profile, but also suffer additional uneven longitudinal deformation due to the continuous change of cross-section shape [4]. In the process of rolling forming of variable cross-section longitudinal beam, the springback and side wave of longitudinal beam flange are two key factors affecting product quality. The research on springback and side wave has gradually become a hot spot worthy of attention. In dealing with the problem of highly distorted large deformation sheet metal forming, panthi et al. Studied through simulation combined with the elastic-plastic increment law, and considered that the springback after sheet metal forming is closely related to the sheet material properties and forming geometric parameters, while the friction has little effect on the springback [5]. After trying a variety of anisotropic material criteria, Cui Gaojian and others thought that the criteria were more suitable for roll forming of steel plate and achieved good experimental results [6]. Abvabi pointed out that bending is the main deformation mode of roll bending, and residual stress will be introduced into the sheet during the forming process. The thinning of the plate thickness will aggravate the accumulation of tensile residual stress on the plate surface and increase the compressive residual stress of the neutral layer; The thinning of plate thickness will make the equivalent plastic strain of neutral layer higher than its surface[7]; Yan Yu and Li Qiang of North University of technology analyzed the lateral and longitudinal springback of variable section profile by establishing a nine pass variable section roll bending simulation model, and pointed out that the springback in the longitudinal direction is large [8]. Luo Xiaoliang et al. Studied the edge wrinkling of high strength steel by establishing a set of finite element model of roll forming. It points out that the yield strength, strengthening coefficient and other factors of the material will affect the final profile side wave [9].

At present, there are few studies on the factors affecting the roll forming quality of variable section longitudinal beam. Through the way of orthogonal test, starting with the production process parameters, this paper analyzes the relationship between various factors and the stress, side wave, thickness and springback of variable section longitudinal beam, which has important reference value for subsequent scientific research and practical production [10].

II. Roll Bending Process of Variable Section Longitudinal Beam

A. *Material Model*

In this paper, the half section longitudinal beam is used as the research object. The shape after forming is shown in Figure 1. The total length of the longitudinal beam is 5000mm and has an asymmetric section shape. One side of the longitudinal beam is variable section and the other side is fixed section. The material of the longitudinal beam is TRIP590 steel, and the material properties are shown in Table 1. Figure 2 shows the initial sheet shape of the automobile variable section longitudinal beam, in which the dotted line part is the motion track of the roll [11]. The bending passes of the variable section forming roll are set as 6 passes, and the forming angles are 10 °, 25 °, 40 °, 60 °, 75 ° and 90 ° respectively. The forming knurling diagram is shown in Figure 3.

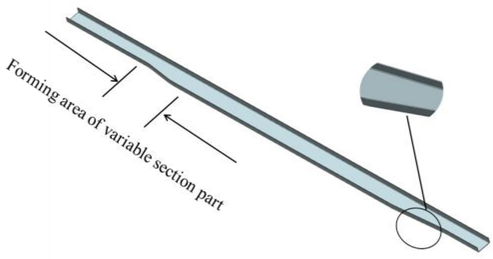


Fig. 1. Three dimensional model of longitudinal beam.

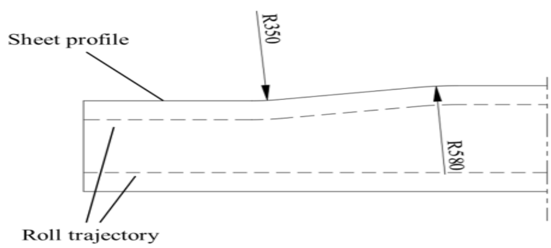


Fig. 2. Schematic diagram of variable section of sheet metal.

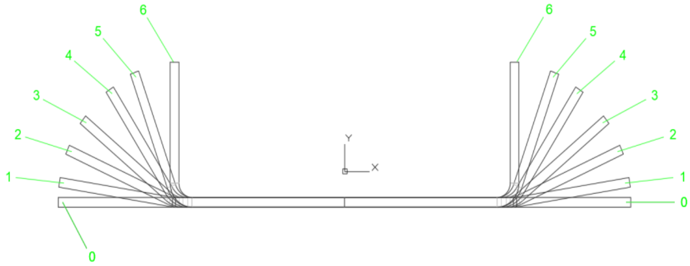


Fig. 3. Sheet knurling drawing.

Table 1. Material performance parameters of TRIP590 steel.

Material	Young's Modulus /GPa	Poisson's Ratio	Density /Kg/m³	Yield Strength / MPa	Tensile Strength / MPa
TRIP590	203	0.38	7850	413	802

B. *Finite Element Model*

The numerical simulation modeling adopts ABAQUS software, as shown in Figure 4. In the roll bending finite element model, the roll is generated by analytical rigid body, the sheet metal is generated by three-dimensional deformable shell element S4R, 9 integration points are set in the thickness direction, and the mesh in the contact area with the roll is locally densified [12]. In the analysis step, the dynamic explicit algorithm is used to simulate the model, the pass spacing between rolls is set to 500mm, the whole roll bending process is defined in 3.8s, and appropriate mass scaling is set to accelerate the simulation speed [13].

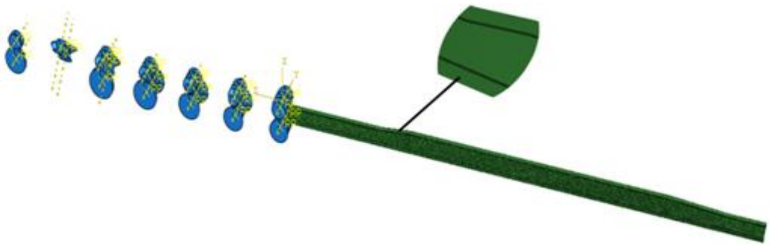


Fig. 4. Assembly diagram.

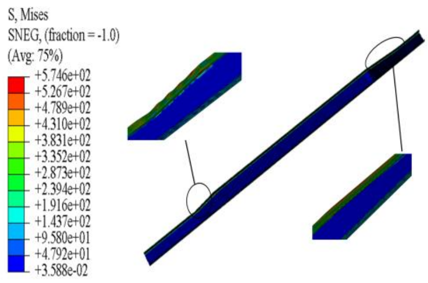
The movement of the roll includes lateral movement and swing along the width direction[14]. The time curve of roll lateral displacement is determined according to the edge line of variable section of sheet metal[15]. During simulation, in order to improve the calculation speed and save time, set the speed of sheet metal along the feed direction as 2000m/s, and the time relationship of roll lateral displacement is shown in formulas (1) and (2):

$$
y = \begin{cases} 190, & (0 \le x < 970) \\ \sqrt{400^2 - (x-970)^2} + 590, & (970 \le x < 1022) \\ 0.1198x + 73.732, & (1022 \le x < 1262) \\ \sqrt{530^2 - (x-1331)^2} - 300, & (1262 \le x < 1332) \\ 230, & (1332 \le x < 3984) \\ \sqrt{530^2 - (x-3984)^2} - 300, & (3984 \le x < 4019) \\ -0.0637x + 484.966, & (4019 \le x < 4588) \\ \sqrt{400^2 - (x-4615)^2} + 590, & (4588 \le x < 4614) \\ 190, & (4614 \le x \le 5000) \end{cases} \tag{1}
$$

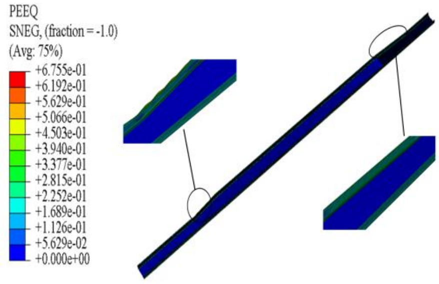
$$x = 2000t \quad (2)$$

C. *Model Post-Processing*

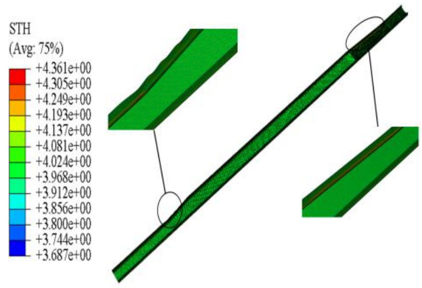
According to the solution results, check the stress nephogram, strain nephogram, thickness nephogram and forming height nephogram of the formed longitudinal beam. As shown in Figure 5.



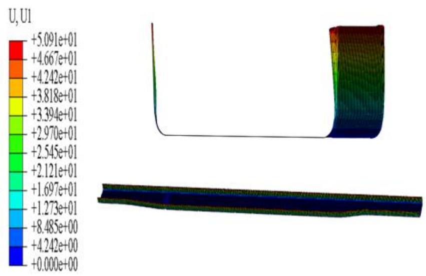
(a) Stress nephogram of longitudinal beam.



(b) Strain nephogram of longitudinal beam.



(a) Thickness nephogram of longitudinal beam.



(d) Height nephogram of longitudinal beam.

Fig. 5. Result cloud diagram.

According to the result cloud diagram, the maximum distribution position of stress and strain is located at the position where the sheet section is narrowed and widened. The stress situation at this position is relatively complex, and there is an obvious side wave phenomenon. However, at the position where the sheet is narrowed and widened and in the middle, the stress and strain are evenly distributed and the forming condition is good. On the whole, the position with large thickness change still appears at the wing plate of variable section. There is obvious material accumulation at the front of the section from narrow to wide, with the maximum accumulation of 0.361mm. There is material thinning at the middle of variable section, with the maximum thinning of 0.313mm. Consistent with the actual forming situation, the height of the longitudinal beam is relatively uniform in the forming direction, and the height difference of the flanges on both sides is no more than 1mm. However, when the plate enters the variable section forming, the height of the flanges on both sides is still unequal. After entering the wide section from the narrow section, the flange height of the longitudinal beam begins to decrease, but after the variable section forming, the flange height increases.

III. FORMING QUALITY EVALUATION

A. *Forming Defect Evaluation Index*

The edge wave phenomenon on the wing plate is a common defect. Due to the geometry of the cross section, the edge tension is inevitable, and the stress at the variable section is complex, which is easy to produce the phenomenon of edge wave [16]. After analyzing the stress and strain at the variable section flange, it is necessary to find out the corresponding parameters to characterize the severity of instability at the flange. The displacement value of the outer edge of the flange can intuitively display the shape of the edge wave of the plate leg. Therefore, the standard deviation of displacement after forming is defined as an index to measure the edge wave of the flange. The larger the standard deviation, the greater the severity of side wave instability. The calculation formula is shown in formulas (3).

$$\Delta U = \frac{1}{n}\sum_{i=1}^{n}(U_i - \overline{U}_i)^2 \tag{3}$$

Springback is an inevitable phenomenon in longitudinal beam rolling processing. The occurrence of springback will directly affect the quality and accuracy of products. However, due to the particularity of variable section roll forming, the final formed longitudinal beam will not only rebound, but also over bend. The forming angle of the outer edge of the variable cross-section side flange is selected, and the angle difference in different areas is used as the evaluation standard of the forming quality. As shown in the following formula (4).

$$\gamma_i = \alpha - \beta_i \tag{4}$$

In the formula α Is the design angle of 90 degrees, β Is the forming angle of each node, γ Is the angle difference of each node, if $\gamma>0$ indicates that the plate is bent, which is called bending angle. if $\gamma<0$ indicates the springback of the plate, which is called the springback angle[17].

Longitudinal beam flange, especially the part with changed section, will be affected by complex stress interaction in the process of rolling forming, and then the thickness will change. If the wall thickness is excessively thinned, tearing will occur. Therefore, the change of longitudinal beam flange wall thickness is an important factor affecting the forming quality. In order to evaluate the change of flange thickness, the thickness change rate is selected ε As an evaluation index, As shown in the following formula (5).

$$\varepsilon = \frac{\delta-\delta_0}{\delta_0} \tag{5}$$

In the above formula δ_0 is the original thickness of the flange, δ Is the thickness after forming.

B. *Analysis of Orthogonal Factors*

In order to study the influence of process parameters on the forming quality of variable section edge flange, this paper selects three process parameters with great influence, such as pass spacing, gap between roll and forming number, and sets each factor at three levels, as shown in the table 2:

Table 2. Test factor level table.

Level	**Factors**		
	A **Forming Number**	**B** **Roll Clearance/°**	**C** **Pass Spacing/mm**
1	5	0	400
2	6	1	500
3	7	2	600

L^9 (3^4) orthogonal test table is used for the three factor and three level test scheme. The test programme is in

the table 3.

Table 3. Test programme.

No.	A Forming Number	B Roll Clearance/°	C Pass Spacing/mm
1	5	0	400
2	5	1	500
3	5	2	600
4	6	0	600
5	6	1	400
6	6	2	500
7	7	0	500
8	7	1	600
9	7	2	400

According to the test scheme arranged in Table 3, nine analysis models are established according to the data in the table. The test results are in the table 4:

Table 4. Simulation results of orthogonal test.

No	Maximum Stress /MPa	Instability Degree of Side Wave	Maximum Thinning Rate/%	Maximum Thickening Rate/%	Maximum Bending Angle/°	Maximum Rebound Angle/°
1	894.0	0.692	4.33	10.15	8.7	2.3
2	799.8	1.007	4.62	10.20	10.8	2.6
3	714.9	1.759	4.32	9.98	9.7	2.8
4	682.3	0.870	8.02	15.00	7.7	1.9
5	561.8	1.358	9.52	11.30	7.1	2.3
6	574.6	1.684	7.82	9.02	6.0	2.4
7	699.4	0.699	3.15	9.15	7.5	2.6
8	716.3	1.500	3.35	11.20	3.4	2.5
9	618.7	1.43	3.10	8.70	3.1	2.2

According to the results in Table 4 above, the range analysis of the influence of various factors is as follows: Influence of each factor level on stress is in the table 5:

Table 5. Influence of each factor level on stress.

	Results	A Forming Number	B Roll Clearance/°	C Pass Spacing/mm
Maximum Stress (MPa)	K_1	2408.7	2275.7	2074.5
	K_2	1818.7	2077.9	2073.8
	K_3	2034.4	1908.2	2113.5

	Results	A Forming Number	B Roll Clearance/°	C Pass Spacing/mm
	$\bar{K}_1$	802.9	758.6	691.5
	$\bar{K}_2$	606.2	692.6	691.3
	$\bar{K}_3$	678.1	636.1	704.5
	R	196.7	122.5	13.2

From the range analysis results of various factors in the table 5, it can be seen that the number of passes has the greatest impact on the stress; The effect of roll gap on stress is the second; The effect of pass spacing on stress is the least; The number of passes has the least effect on the stress. The maximum stress decreases with the increase of pass times and roll gap; With the increase of pass spacing, the maximum stress decreases first and then increases.

Influence of each factor level on instability degree of side wave is in the table 6:

Table 6. Influence of each factor level on instability degree of side wave.

	Results	A Forming Number	B Roll Clearance/°	C Pass Spacing/mm
Instability degree of side wave	K_1	3.46	2.26	3.48
	K_2	3.91	3.87	3.39
	K_3	3.63	4.87	4.13
	$\bar{K}_1$	1.15	0.75	1.16
	$\bar{K}_2$	1.30	1.29	1.13
	$\bar{K}_3$	1.21	1.62	1.38
	R	0.15	0.87	0.25

The instability degree of side wave represents the stability of variable section wing plate in side wave and wrinkling; The larger the value, the more unstable the contour and the more serious the side wave phenomenon. From the range of factors in the above table, it can be seen that the roll gap has the greatest influence on the instability degree of side wave, followed by the pass spacing; The influence of pass times is small, and the instability degree of wing plate becomes more and more intense with the increase of roll gap; The degree of instability decreases with the increase of the number of passes and the distance between passes.

Influence of each factor level on thickness variation is in the table 7:

Table 7. Influence of each factor level on thickness variation.

	Results	A Forming Number	B Roll Clearance/°	C Pass Spacing/mm
Maximum thinning rate (%)	K_1	13.27	15.50	16.95
	K_2	25.36	17.49	15.59
	K_3	9.60	15.24	15.69

	Results	A Forming Number	B Roll Clearance/°	C Pass Spacing/mm
	$\bar{K}_1$	4.42	5.17	5.65
	$\bar{K}_2$	8.45	5.83	5.20
	$\bar{K}_3$	3.20	5.08	5.23
	R	5.25	0.75	0.45
Maximum thickening rate (%)	K_1	30.33	34.30	30.15
	K_2	35.32	32.70	28.37
	K_3	29.05	27.70	36.18
	$\bar{K}_1$	10.11	11.43	10.05
	$\bar{K}_2$	11.77	10.90	9.46
	$\bar{K}_3$	9.68	9.23	12.06
	R	2.09	2.20	2.60

From the range of factors in the table7, it can be seen that the number of passes has the greatest impact on the sheet thinning rate, followed by the roll clearance; The least influence is the pass spacing; The maximum thinning rate increases first and then decreases with the increase of pass times and roll gap. As for the thickening rate of sheet metal, in the process of sheet metal forming, the variable section wing plate is compressed due to bending, and the thickening phenomenon occurs under compression. From the range of factors in the above table, it can be seen that the pass spacing has the greatest influence on the thickening rate of the formed longitudinal beam; The influence of roll clearance is the second; The influence of track number is the least; The plate thickening rate decreases with the increase of roll gap; It decreases first and then increases with the increase of track spacing, and increases first and then decreases with the increase of track times.

Influence of each factor level on forming angle difference is in the table 8:

Table 8. Influence of each factor level on thickness variation.

	Results	A Forming number	B Roll clearance/°	C Pass spacing/mm
Maximum bending angle (%)	K_1	29.20	23.90	18.90
	K_2	20.80	21.30	24.30
	K_3	14.00	18.80	20.80
	$\bar{K}_1$	9.73	7.97	6.30
	$\bar{K}_2$	6.93	7.10	8.10
	$\bar{K}_3$	4.67	6.27	6.93
	R	5.07	1.70	1.80
Maximum rebound angle (%)	K_1	7.70	6.80	6.80
	K_2	6.60	7.40	7.60

Maximum bending angle (%)	**Results**	**A** **Forming number**	**B** **Roll clearance/°**	**C** **Pass spacing/mm**
	K_3	7.30	7.40	7.20
	$\bar{K}_1$	2.57	2.27	2.27
	$\bar{K}_2$	2.20	2.47	2.53
	$\bar{K}_3$	2.43	2.47	2.40
	R	0.37	0.20	0.27

From the range of factors in the table 8, it can be seen that the number of passes has the greatest influence on the forming angle error of sheet metal, while the influence of roll clearance is the smallest; For forming bending angle and springback angle, the influence of pass times is greater than that of roll gap and pass spacing, and the influence of roll gap is the least. With the increase of the number of passes, the bending angle decreases gradually, and the springback angle first decreases and then increases; With the increase of roll gap, the bending angle decreases and the springback angle increases; With the increase of pass spacing, the bending angle and springback angle increase first and then decrease;

IV. Conclusion

In this paper, the rolling forming process of automobile variable cross-section longitudinal beam is designed, including the selection of longitudinal beam material, the determination of variable cross-section forming passes, the distribution of forming angle and the determination of frame spacing. The finite element modeling of automobile variable cross-section longitudinal rolling forming is studied, and the stress-strain distribution of each part on different sections, the side wave in local area and the forming height are analyzed, the defects of the wing plate after the forming of the profile are found.

Three factors and three levels orthogonal experimental table of three process parameters affecting the rolling forming quality of longitudinal beam: pass times, roll gap and pass spacing are designed, and a large number of finite element simulation experiments are carried out. It is concluded that the primary and secondary order of process parameters affecting stress is forming number A > roll gap B > pass spacing C; The primary and secondary order of process parameters affecting the instability degree of side wave is roll gap B > pass spacing C > forming number A; The primary and secondary order of process parameters affecting the maximum thinning rate is: forming number A > roll gap B > pass spacing C; The factors that have great influence on the maximum thickening rate are pass spacing C > roll gap B > forming number A; The factor affecting the maximum bending angle is the number of passes A, and the bending phenomenon decreases with the increase of the number of passes; The most influential factor on the maximum rebound angle is the pass spacing C. With the increase of pass spacing, the maximum rebound angle first increases and then decreases.

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