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Influence Law of Different Factors on the Roll Forming Precision of Aluminum Alloy Cylinder with Variable Curvature Section

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ABSTRACT: High precision roll forming of cylinders with variable curvature section is a technical challenge for high-performance manufacturing of oil and gas transportation tanks. In this work, the large cylinder with variable curvature section was taken as the object of study, a four-roll roll bending FE (Finite Element) model of large cylinder with variable curvature section was established to investigate the influence of driving roll speed on the precision of cylinder forming quality, and the influence of adjacent arc segment size on the precision of cylinder roll forming was obtained by the segmental forming simulation of the cylinder. The results show that the forming radius increased sharply after the speed exceeded the threshold value and the main factors of roll forming radius error is the radius and length of the front arc, the radius and length of the middle arc, and the radius and length of the rear arc.

Keyworks: Cylinder with variable curvature section; Four-roll roll bending; Precision control

1. Introduction

Large cylinder is an important component of tanks in petrochemical, special vehicle, ship domain and other fields. It usually serves under harsh working conditions such as high pressure, vibration impact and corrosion, and thus its working performance and service life are crucial. The section of the cylinder can be designed as a "narrow top and wide bottom" special-shaped section composed of multiple circular arcs. This complex cylinder cannot be precisely shaped by traditional rough method, and the three-roll bending machine with less adjustment function can also not form precisely. The use of four-roll bending machine can manufacture complex shaped section cylinder, but the roll forming process requires multiple manual trials and adjustments currently, so the forming

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cycle is long, and there is a large docking gap or stack material after forming.

Scholars have done a lot of research on roll forming. Shim et al. [1] made a hypothesis of equal curvature at every point in the deformation zone during four-roll roll rounding, which provides theoretical support for four-roll roll rounding. Wu et al. [1] established mathematical and FE model of four-roll roll bending, and the test results proved the reliability of the proposed mathematical model. Ktari et al. [3] established a three-roll roll bending FE model based on the ABAQUS platform, the simulation results were consistent with the data obtained by using empirical formulas. Feng et al. [4] carried out the simulation of three-roll roll forming based on LS-DYNA software to investigate the relationship between the forming radius of the plate and the displacement of the side rolls. Gandhi et al. [5] used ANSYS/LS-DYNA to perform the simulation of roll bending and studied the effect of the number of forming passes and the hardening phenomenon of the plate on the forming quality. Hua et al. [6] used ABAQUS platform to simulate four-roll roll forming and investigated the effect of plate thickness on forming precision. Fu et al. [7] obtained the influence law of process parameters on the springback of roll forming based on the ABAQUS platform, and the prediction and control method of springback was proposed. Naofal et al. [8] investigated the regularity of the effect of variation of hardening model and elastic modulus on the springback prediction of roll forming, and the results show these two factors have significant effect on the springback precision. The literature mentioned above have conducted a lot of research on roll forming, but the investigation of the factors influencing continuous roll forming of cylinders with variable curvature section and the influence law is lacking. In this work, the influence of driving roll speed and adjacent arc segment size on the forming precision of cylinder with variable curvature section was investigated.

2. FE simulation of roll forming of cylinder with variable curvature section

2.1. FE model of cylinder with four-segment circular arc variable curvature section

The FE simulation modeling was carried out based on the ABAQUS platform (Fig 1). In this model, the plate material selected 5083-O state aluminum alloy, the thickness of the plate is 6mm, the material density $\rho = 2.7\text{g/cm}^3$, the material elastic parameters need to input the elastic modulus E = 70GPa, and the Poisson's ratio $\nu = 0.33$. Since the length and width of the plate are much larger than the thickness of the plate, the plate was given three-dimensional shell cell properties to reduce the computation time; the contact method was selected as surface to surface algorithm; the S4R shell cell is applicable to the plane bending problem, and the S4R reduced integral shell cell type was given to the plate and the work roll in consideration of the computation precision and time cost, and the overall mesh number of the model is 25000.

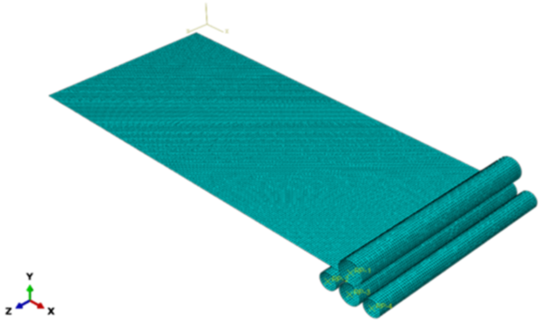


Figure 1. FE model of four-roll bending

2.2. Four-roll roll bending forming technological process

The roll forming process of the variable curvature section cylinder was proposed on basis of the traditional roll forming process (Fig 2) by taking the cylinder with four-segment circular arc variable curvature section as an example. The details are as follows: (a) alignment, (b) pre-bending, (c) partial roll bending, (d) roll bending the first half of the first arc, (e) roll bending the second arc, (f) roll bending the third arc, (g) roll bending the fourth arc, (h) roll bending the second half of the first arc. Then, the roll bending forming of the cylinder with four-segment circular arc variable curvature section ends, the roll forming method for other cylinder with multi-arc (such as six-arc, eight-arc) variable curvature section is similar. In order to make the forming radius of the front and rear ends of the roll forming consistent, the plate is divided into the initial section and the end from the middle point of the first arc in the four arcs. In this way, the forming radius of the initial section after forming is R_1, and the forming length is $1/2L_1$, which is recorded as "the first half of the first arc". The forming radius of the end is R_1, and the forming length is $1/2L_1$, and this section is recorded as the "the second half of the first arc", so that the initial section and the end forming radius can be kept consistent after forming, so as to reduce the difficulty of subsequent welding in actual production.

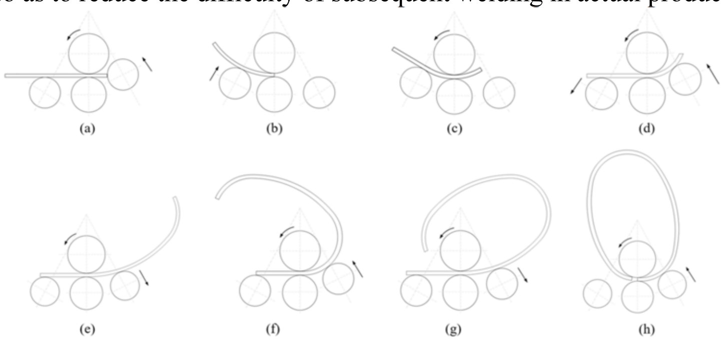


Figure 2. Roll bending forming process of cylinder with four-segment circular arc variable curvature section

2.3. FE simulation result of the cylinder with variable curvature section

The relationship between the bending radius of the plate before springback r' and the bending radius after springback r is expressed as formula (1).

$$r' = \frac{1 - \frac{K_0 \sigma_s}{E}}{\left(1 + \frac{2rK_1\sigma_s}{Et}\right)} r \quad (1)$$

Formula (1) was used to calculate the process parameters for each process step of roll forming, and the FE simulation of roll forming of cylinder with four-segment circular arc variable curvature section was carried out, the results are shown in Fig 3.

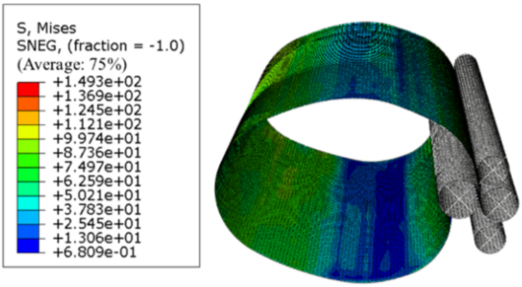


Figure 3. Roll forming simulation result of four-segment circular arc variable curvature section cylinder

In order to verify the forming precision, nine coordinate points of each segment of the arc were extracted along the edge of the plate, and the coordinate node data were divided into three groups and imported into MATLAB to calculate the forming radius, the results obtained are shown in Table 1. It can be seen that the error of forming radius of each segment is between 3.3~12.9%, the overall forming quality is poor.

Table 1. Forming precision of each arc

Forming section	Average forming radius /mm	Pre-forming radius /mm	Error of forming radius
The first half of the first arc	714.2	680.1	5.0%
The second arc	2091.9	1894.4	10.4%
The third arc	657.9	680.1	3.3%
The fourth arc	1650.3	1894.4	12.9%
The second half of the first arc	649.3	680.1	4.5%

3. Influence of driving roll speed on forming precision of cylinder

3.1. Influence law of driving roll speed on roll forming radius of the plate

The driving roll speed is a crucial process parameter that determines the forming quality of the cylinder to a certain extent in the roll forming process. The coordinates of 15 nodes at the edge of the plate at each forming speed after simulation were extracted separately to investigate the effect of the driving roll speed on the forming radius, and the radius of five groups at each driving roll speed were calculated (Table 2).

Table 2. Influence law of driving roll speed on roll forming radius of the plate

speed	Calculated value of radius of each component	Average forming radius
0.1rad/s	673.3, 678.4, 682.7, 672.9, 674.3	676.32
0.2rad/s	673.1, 677.6, 682.35, 674.1, 677.6	676.95
0.3rad/s	679.9, 677.3, 682.3, 674.5, 677.1	678.22
0.6rad/s	680.5, 679.7, 681.6, 683.3, 685.6	682.14
1rad/s	713.6, 711.3, 714.6, 717.4, 719.9	715.36

When the forming speed increases from 0.1rad/s to 0.6rad/s, the forming radius increases by 0.86%, the fluctuation is small. Therefore, the forming radius of the plate will be increased after increasing the forming speed within a certain range, but the change is relatively small. The average forming radius increases from 682.14 mm to 715.36 mm when the roll bending loading speed increases from 0.6 rad/s to 1 rad/s, the corresponding forming radius growth rate is 4.9 %. The reason is when the loading speed of roll bending exceeds a certain threshold, there will be significant relative sliding between the plate and the working roll, and part of the plate will not be fully formed, resulting in a large forming radius, which affects the overall forming radius of the cylinder.

3.2. Influence law of driving roll speed on the strain of plate roll forming

The equivalent plastic strain fluctuation values of each group under the rotation speed of 0.1rad/s, 0.2rad/s, 0.3rad/s and 0.6rad/s are extracted along the length direction of the plate (Fig 4) to investigate the forming uniformity of the plate. It can be seen that when the driving roll speed is 0.1rad/s, the equivalent plastic strain of plate fluctuates very gently and stays in a stable and small interval, indicating excellent forming uniformity and high precision, but the processing efficiency is low in actual production because of the small loading speed. The equivalent plastic strain of the plate fluctuates widely and the degree of fluctuation becomes more and more violent when the roll bending loading speed increases from 0.1rad/s to 0.6rad/s, which indicates that when the roll bending loading speed is increased, the forming uniformity and quality of the plate become worse and worse, however, the processing efficiency can be significantly improved by increasing the driving roll speed, which is suitable for the case of mass production.

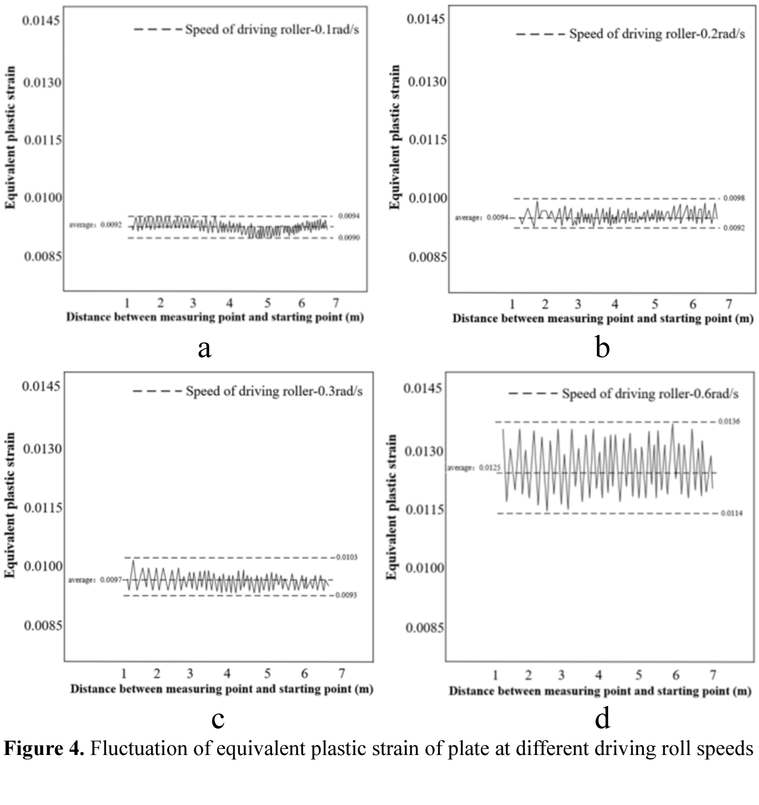


Figure 4. Fluctuation of equivalent plastic strain of plate at different driving roll speeds

4. Influence of adjacent arc section size on the cylinder roll forming precision

4.1. Segmented roll forming simulation of cylinder with variable curvature section

The driving roll speed was selected as 0.3rad/s in consideration of forming quality and processing efficiency. In order to reveal the influence of the size of adjacent arcs on forming precision, the FE simulation of segmented roll forming of the variable curvature cylinder was carried out by taking cylinder with four-segment circular arc variable curvature section as an example, and the simulation result obtained is shown in Fig 5.

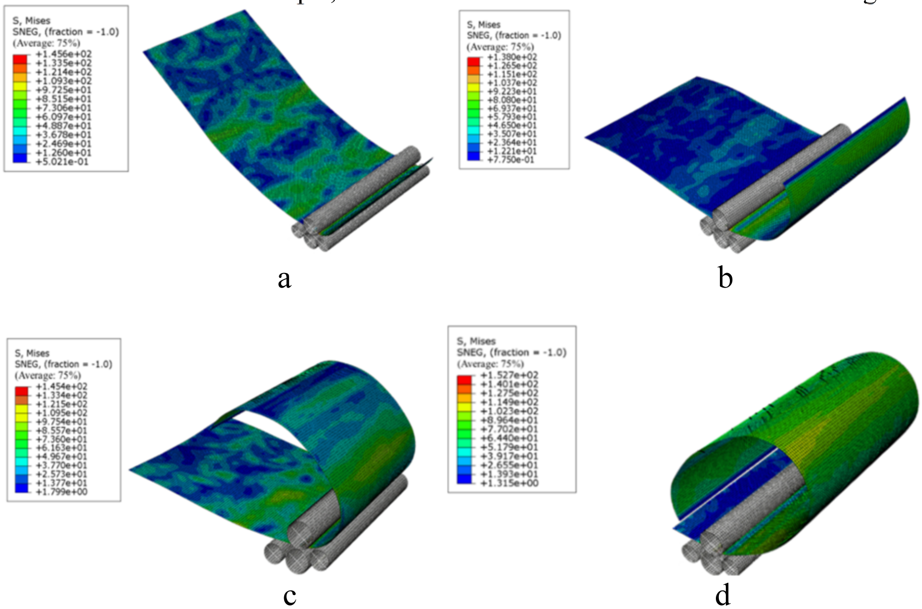


Figure 5. Simulation of segmented roll forming of cylinder with four-segment circular arc variable curvature section: (a) FE simulation of roll bending the first half of the first arc, (b) FE simulation of roll bending the first arc and the second arc, (c) FE simulation of roll bending the first arc, the second arc and the third arc, (d) FE simulation of roll bending the first arc, the second arc, the third arc and the fourth arc

4.2. Influence of adjacent arc section size on roll forming precision of cylinder

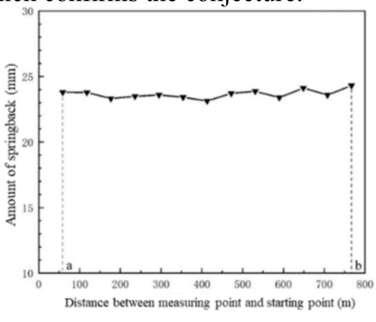
The distribution of the springback amount after each simulation group was extracted along the length direction of the plate to further analyze the causes of the error (Fig 6).

The springback change curve corresponds to Fig 6(a) when only forming the first half of the first section, the springback amount fluctuates within 24±1mm, and the corresponding average error of forming radius is 4.3mm, the error of forming precision is about 0.63%, which means a high forming precision.

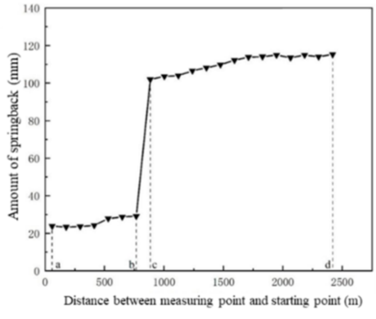
When the first half of the first arc and the second arc was formed, the springback curve corresponds to Fig 6(b), the springback amount of ab segment arc is about 27 ± 1mm, the corresponding average error of forming radius is +35.6mm, the forming precision error is 5.24 %, the springback amount and forming radius are larger than the theoretical value. The springback volume of segment arc bc is 110 ± 9mm, the corresponding forming radius error average is -63.3mm, and the forming precision error is 3.34%, the springback volume and forming radius are less than the theoretical value, the ab segment arc has an obvious change in the amount of springback and forming precision. Analyzing the reason of this phenomenon, the ab segment arc of Fig 6(b) is affected by the cd segment arc after forming compared with the ab segment arc of Fig 6(a), when the ab segment arc is formed and springback to the set curvature, the cd segment arc is formed next, however, since the cd segment arc has different forming radius, its corresponding springback rate is also different, when the cd segment arc is formed and unloaded, its elastic deformation part will be elastic recovery, this process will have a pulling effect on the previous segment of the arc (ab segment), increasing the amount of the arc springback, and the cd segment is pulled by the ab segment because of the mutual force, so that it also cannot spring back to the predetermined curvature, resulting in its forming radius is less than the theoretical value.

Fig 6(c) shows the springback variation curves when forming the first half of the first arc segment, the second segment and the third segment of the arc. The springback rate of ab segment arc is 27±1mm, the corresponding forming radius average error is +36.9mm, and the forming precision error is 5.43%. It is obvious that the difference of forming precision between ab segment arc of Fig 6(b) and ab segment arc of Fig 6(c) is not significant, the difference is only 0.19%. It is conjectured that the ab segment is not directly connected to ef segment, most of the continuous springback impact of ef segment is transferred to cd segment, so the impact of the ab segment by ef segment is very slight and can be neglected. The amount of springback of the cd segment arc is 110±7mm, and the corresponding average value of forming radius error is -55.3mm, the forming precision error is 2.92%. It is obvious that the amount of springback of the cd segment arc in Fig 6(c) is smaller compared with cd segment arc in Fig 6(b), the forming precision is improved instead. The reason is that during the forming process, the effects of ab segment arc and ef segment arc on cd segment arc are opposite, and the effects of continuous springback will offset part of each other. The springback amount of ef segment arc is 21±1mm, and the average forming radius error is -29.7mm, the forming precision error is 4.37%, the springback amount and forming radius is less than the theoretical value, the reason is that when ef segment arc occurs elastic recovery after unloading, it is pulled by cd segment arc, reducing the forming precision.

The regularities shown in Fig 6(d) is consistent with the above and are not described here, which confirms the conjecture.



a



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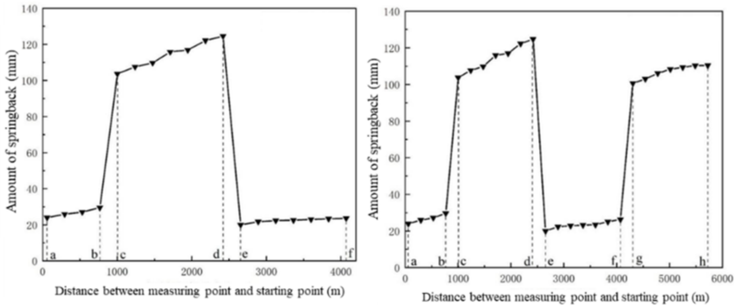

c d

Figure 6. Amount of springback of segmented roll forming of cylinders: (a) Springback of first half of the first arc, (b) Springback of first half of the first arc and second arc, (c) Springback of first half of the first arc, the second arc and third arc, (d) Springback of first half of the first arc, the second arc, the third arc and fourth arc

The following regularities can be derived from the above analysis:

(1) The error of forming radius of each segment of the cylinder with variable curvature section is mainly influenced by the previous segment of the arc and the latter segment of the arc, the non-adjacent arc segments do not affect significantly.

(2) The main influencing factors for the error of roll forming radius of the cylinder with variable curvature section are: The radius and length of the front arc, the radius and length of the middle arc, and the radius and length of the rear arc.

5. Conclusions

(1) A four-roll roll bending FE model of cylinder with variable curvature section was established, the influence of different driving roll speeds on the forming quality of the cylinder was investigated, and it was found that there was a reasonable interval of roll speed, the forming radius increased sharply after the speed exceeded the threshold value.
(2) The influence law of the adjacent arc segment size on roll forming precision of the cylinder was studied, the main factors of roll forming radius error of cylinder with variable curvature section were found as follows: The radius and length of the front arc, the radius and length of the middle arc, and the radius and length of the rear arc.

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References

[1] Dosik S, Dongyol Y, Sungwook C, et al. Optimization of forming steps in the incremental forming of twisted shapes using a line array roll set (LARS)[J]. International Journal of Precision Engineering and Manufacturing, 2010, 11(5), pp: 715-723.

[2] Kai W, Yu S, Chunping C, et al. On Simulation Analysis of Plate Forming and Deformation Compensation Technology of the side roll for Four-roll Plate Bending Machine[J]. Procedia Engineering, 2017, 207, pp: 1617-1622.
[3] Ahmed K, Zied A, Nader H, et al. Modeling and computation of the three-roller bending process of steel sheets[J]. Journal of Mechanical Science and Technology, 2012, 26(1), pp: 123-128.
[4] Zhengkun F, Henri C. Modeling and simulation of asymmetrical three-roll bending process[J]. Simulation Modelling Practice & Theory, 2011, 19(9), pp: 1913－1917.
[5] A.H. G, A.A. S, H.K. R. Formulation of springback and machine setting parameters for multi-pass three-roller cone frustum bending with change of flexural modulus[J]. International Journal of Material Forming, 2009, 2(1), p: 45.
[6] Meng H, Y.H. L. Large deflection analysis of elastoplastic plate in steady continuous four-roll bending process[J]. International Journal of Mechanical Sciences, 1999, 41(12), pp: 1461-1483.
[7] Zemin F, Xiuli T, Wei C, et al. Analytical modeling and numerical simulation for three-roll bending forming of sheet metal, Int. J. Adv. Manuf. Technol. 2013, 69(5-8), pp: 1639-1647.
[8] Jihad N, Hassan Moslemi N, Siamak M. Effects of Hardening Model and Variation of Elastic Modulus on Springback Prediction in Roll Forming, Metals. 2019, 9(9), p: 1005.