A FEA Method for Mathematical Calculation and Prediction Analysis Cross-sectional Ovalization of Tubes under Rotary Straightening

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Abstract. The section flattening phenomenon (namely Bazier effect) will occur in the large bending deformation stage of thin-walled pipe in the continuous straightening process. The maximum section flattening amount and the residual section flattening amount are important process parameters, which are the basis for calculating the subsequent process parameters of the flattening circle, and directly determine the roundness of the final pipe and the product quality. However, it is hard to be obtained by the theoretical or experimental methods. Therefore, based on the structure and process parameters of the leveler, a finite element model was built to simulate the section flattening process. Then, ANSYS/LS-DYNA software was used to dynamically simulate the bending flattening phenomenon of thin-walled pipe in the continuous straightening process, and the stress and strain nephographic of the flattening deformation zone was obtained. By recording the position curve of the key nodes in the preventing process, the section flattening amount of the thin-walled pipe in the large bending deformation stage in the continuous straightening process was determined. The simulation results show that the dynamic simulation method can effectively predict the section flattening of thin-walled pipe in the process of continuous straightening.

Keywords: thin-walled circular pipe, straightening, cross-sectional flattening, maximal ovalization, FEA method.

1. Introduction
In recent years, the demand of high-precision thin-walled metal pipes in industry, military, medical, aerospace, petrochemical and other fields has increased sharply. In order to make the pipes have higher straightness and roundness, they must be straightened before delivery or use [1]. Thin-wall pipe is usually straightened by continuous bending deformation through multiple sets of equal-curvature straightening rollers arranged in axial direction by multi-inclined roll straightening equipment. Each pair of straightening rollers is designed with a single radius of curvature. The radius of the straightening roller is different in different positions. Since the size and direction of the initial curvature of the pipe are different along the axis, the bending radius of the straightening roller is set close to the ultimate bending radius in the initial straightening stage at the entrance, and the bending
degree of the pipe is unified by large plastic deformation, so that each section of the pipe has the same initial curvature in the subsequent straightening. In the process of large bending, the section of pipes, especially thin-walled pipes, will flatten continuously with the increase of bending degree (namely, the Bazier effect). Therefore, the section of the pipe will be distorted after the initial bending, and the section must be straightened by radial extrusion in the subsequent straightening process. In order to set the flattening amount of the straightening roll accurately, the maximum flattening amount in the initial large bending process and the residual flattening amount after springback must be determined first. At the same time, when the bending increases to a certain extent, the section flattening will not be restored and buckling instability will occur. Therefore, the maximum flattening quantity must be controlled to make it less than the ultimate flattening quantity, and it is particularly important to establish an accurate analytical model of the maximum flattening quantity.

For a long time, many scholars have studied the section flattening of thin-walled pipes in the bending process: Yu et al. [2] presented the general method and principle of dealing with the section flattening deformation during bending, and extended the energy method used by Brazier to deal with the elastic stability of cylindrical shells to the plastic field. However, more targeted work is needed for specific problems, and a simple spring-supported beam model is used to explain the bending flattening mechanism. Intuitive but not suitable for precise calculation. Knaster et al. [3] used the energy theory to analyze the influence of cross-section ellipticity on the design of thin-walled shells, but the analytical model of deformation energy established by them is not general for specific problems. B.F.Tatting et al. [4] established the governing differential equations based on the relevant principles of the nonlinear plate and shell theory to analyze the influence of the material and structural parameters of the isotropic cylindrical shell on the pure bending response. However, the solution of the differential equations is difficult, and there is still a certain gap between the solution and the experimental results. Jiang et al. [5] used CNC pipe bender to study the deformation behavior of TA18 pipe with medium strength during bending, and obtained the flattening relationship curve between the section flattening rate of pipes of different specifications and the bending Angle. Toshiyuki Meshii et al. [6] used the finite element method to analyze the deformation behavior of thin-walled pipe under bending load, and obtained the relationship curve of section bending moment and deformation displacement. T. Christo Michael et al. [7] used empirical formulas to deal with the relationship between bending moment and section ellipticity of thin-walled pipes under plane bending conditions. However, data charts and empirical formulas obtained from test and simulation results are often poor in adaptability and portability for specific pipes under specific test conditions. However, the above studies usually dealt with the tube’s ovalization by theoretical modeling, and the calculations were not compared well with experiments. Meanwhile there is no model for determining the maximum and residual flattening amount of section flattening in the process of thin-walled pipe straightening. Therefore, the finite element simulation becomes the only way to predict the section flattening amount.
2. Finite element model

In order to simplify the numerical calculation process and save the calculation time, only the first pair of straightening rollers are modeled in 3D. The finite element model thus obtained is shown in Figure 2, which is composed of a pair of equal-curvature straightening rollers, a thin-walled pipe, a pair of guide plates and a guide sleeve. Among them, the length of the pipe $L = 400\text{mm}$, the diameter of the pipe $D = 21\text{mm}$, the wall thickness $T = 1\text{mm}$, the original bending radius of the pipe $R_0 = 4.92\text{m}$, and the reverse bending radius of the straightening roller is $4.26\text{m}$. The material property Settings of the finite element model are shown in Table 1. The thin-walled pipe is made of elastoplastic material and the other parts are made of rigid body. All contact surfaces are set to automatic contact and the coefficient of friction is set to 0.15.

![Fig. 2 The FEA simulation model](image_url)

| Parts             | Elastic modulus $E$/GPa | Plastic strain-hardening coefficient $E_1$/MPa | Poisson ratio | Yield stress $\sigma_y$/MPa |
|-------------------|------------------------|---------------------------------------------|---------------|---------------------------|
| Tube              | 2                      | 1070                                        | 0.3           | 205                       |
| Working rolls     | 2.06                   | -                                           | 0.3           | 440                       |
| Guide sleeves     | 2.06                   | -                                           | 0.3           | 220                       |
| Guide plates      | 2.06                   | -                                           | 0.3           | 220                       |

3. Simulation procedure

In the simulation process, the thin-walled pipe is fed into two straightening roll slots along the axial direction at an initial speed of $0.28\text{m/s}$. The upper and lower straightening rollers rotate relative to each other at $280\text{RMP}$. Large bending deformation occurs under the extrusion of the roll gap in the pipe. At the same time, the pipe is driven by the straightening roller and rotates along the axis direction. This is shown in Figure 3. The pipe is bent twice for each helical lead it advances. Since the length of the straightening roll is close to 4 leads, 8 cycles of bending occur in the straightening roll gap in the pipe.
4. Numerical results
The Mises stress distributions on the tube surface during the deformation process were illustrated from Fig. 3b to Fig. 3d. From Fig. 3b, when the pipe just entered into the roll’s gap, the stress level was much low. Then it grew much higher as the pipe was entire in the roll’s gap from Fig. 3c. Finally it declined to a lower level when the tube leaves the roll gap completely, as shown in Fig. 3d. Here select the tube section at the middle position of the straightening roller as illustrated in Fig. 3a, the shape of the cross section was described in Fig. 3f. Comparing with its undeformed state shown in Fig. 3e, it was shown that the cross-sectional shape of the pipe has changed from round to oval.

Fig. 3 The numerical simulation for straightening the thin-walled tube causing ovalization to the cross section (a) Large bending deformation of pipe in roll gap (b) The pipe at the entrance of roll gap (c) Pipe in the middle of the roll gap (d) the pipe in the export of roll gap (e) the pipe cross-sectional shape before bending (f) the pipe cross-sectional shape under bending
In order to accurately obtain the flattening amount under large bending deformation of the cross section, select the two nodes C and D at the maximum position of cross section m-m as shown in Figure 3C. The change curve of their Y displacement with time in the simulation process was recorded, as shown in Fig. 4. The maximum flattening can be achieved when t=0.1, 0.2, 0.3... 0.8s, it was the distance of CD diameter, and the test results were listed in Table 2. Through the analysis of the data in the table, it is known that the maximum flattening amount increases with the increase of bending times, but the increase amount is not large, and finally the maximum flattening amount approaches a stable value. This value is the maximum flattening of the section in the continuous leveling process.

![Fig. 4 The change curve of their Y displacement of nodes C and D with time](image)

### Table 2 The maximum flattening of the cross-section m-m at different times

| Time/s | angular displacement/rad | section ovalization/mm | angular displacement/rad | section ovalization/mm |
|--------|--------------------------|------------------------|--------------------------|------------------------|
| 0.1    | π                        | 2.13                   | 0.5                      | 5π                     | 2.42                   |
| 0.2    | 2π                       | 2.32                   | 0.6                      | 6π                     | 2.43                   |
| 0.3    | 3π                       | 2.37                   | 0.7                      | 7π                     | 2.45                   |
| 0.4    | 4π                       | 2.41                   | 0.8                      | 8π                     | 2.45                   |

5. Conclusions

The following conclusions are drawn in this paper:

1) The finite element model can be used to simulate the rotation straightening process of thin-walled pipe.

2) This FEA method can be used to predicting cross-sectional maximum flattening of thin-walled steel tubes in continuous straightening process, in order to prevent plastic instability of the pipe.

3) The cross-sectional flattening increase as the number of bending time increases, but the growth rate is very low. Finally it will become constant in the last seven circles.

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