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Research and application of roll bending method for welded pipe with large length and small diameter to thickness ratio

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Abstract Because of the inefficiency of the existing production process for large diameter longitudinal submerged arc welded (LSAW) pipe, a roll bending process is proposed, but it is difficult to control the pipe straightness with large length and small diameter to thickness (D/T) ratio. A method of deflection compensation with reverse bending top roll is proposed to solve the problem. The mechanical model of the roll bending process is established, and the forces on the plate and the roll, the deflection of the top roll and the torque are analyzed systematically. A set of roll bending machines was designed and developed, and the process parameters of different specifications of products were tested. The results show that the straightness of the pipe is less than 0.1 % of full length, and the error between theoretical analysis and test data is less than 15 %. The theoretical analysis method can be used to direct the production.

1. Introduction

As an efficient and low-cost transportation method, pipeline transportation is especially suitable for long-distance transportation of inflammable and explosive high-risk fluids or gases, such as oil and natural gas, the main material of which is the large diameter longitudinal seam submerged arc welding (LSAW) pipe, whose main characteristics are the large axial length and small ratio of diameter to thickness (D/T). According to the production status of LSAW pipe, there are two main production technologies: UOE [1, 2] process based on integral molding and JCOE [3, 4] process based on sectional molding. UOE, one of the earliest processes, can be completed in two steps: to press the steel plate as a whole into U-shape and to press the U-shape into an open-seam o-shaped pipe. JCOE is a new production process developed to reduce the investment, which adopts the step-by-step feed and segmented pressing method to form o-shaped pipe. In the circular direction, only a small arc length can be pressed at a time, and the number of pressing times is different for different pipe diameters, but the production efficiency is low and the product stress distribution is uneven. With the increasing market competition, manufacturers are more inclined to small investment, high production efficiency, high product quality, and low production costs of production technology.

The continuous roll bending process [5, 6] has high production efficiency, product precision, uniform stress and small investment, but it is only used for the production of structural tubes with length less than 4 m and cannot meet the requirements of the production of welded pipe for oil and gas transportation with large length and small diameter to thickness (D/T) ratio. General specifications [7, 8] of LASW pipe for oil and gas transportation are pipe length: 8-12.5 m, pipe diameter: φ508-φ1422 mm, wall thickness: 6-40 mm, steel grade: A25-X80. The two most important features are long axial length and small diameter-thickness ratio; therefore, the minimum length of the top roller is more than 12.5 and the ratio of length to diameter is 25, which makes the straightness of the pipe difficult to control. In this paper, it was analyzed on the difficulty in controlling the straightness of pipe in the production of oil and gas pipe by roll bending process, and putting forward the method of eliminating the top roll deflection by reverse bending. The mechanical model of roll bending was established, and the force in the process of roll bending was analyzed. a set of roll bending machines was designed and developed and the process parameters of different products were tested. The results show that the theoretical calculation method is accurate and the deflection compensation method can solve the problem of top roll deformation in the roll bending process; the straightness of the produced pipe can meet API 5 L standard requirements for LSAW pipe.

2. Principle of deflection compensation and roll bending process

In the process of roll bending, the thick and medium plate [9, 10] is rolled into a closed circular tube on the principle of three points forming a circle [11], and the top roll is enveloped into the closed circular tube [12, 13] (as shown in Fig. 1), so the top roll cannot be supported. The roll bending force makes the top roll deflect, for the distance between the top roll and the lower roll, the middle is larger than both ends. To solve this problem, the traditional method is to increase the rigidity of the top roller, but for products with large axial length and small ratio of D/T, the traditional method is impossible. The reverse bending method is put forward to bend the top roller in reverse, so that the top roller is parallel with the lower roller, the gap between them is consistent along the axial direction, then the straightness of the pipe can be controlled.

On the premise of ensuring the straightness of pipe, the working steps are as follows: 1) The feeding device aligns the longitudinal center of the incoming plate with the center of the roll bending machine; then the plate is transversely moved into the roll bending machine until the edge of the steel plate and the lower roll are parallel; 2) The top roller of the machine goes down to press the steel plate into a certain curvature; 3) Reverse bending devices push upward to eliminate the top roller deflection; 4) The three rollers start up for rolling, rollers are synchronously controlled during the rolling process to ensure the three rollers output torque together; 5) The stress state of top roller is the combination of bending and twist during rolling process. Considering the maximum stress and life factor that the top roller can bear, it usually takes 3-4 times to achieve the required pipe curvature.

3. Force analysis of roll bending

Based on the principle of roll bending, a mechanical model of cold bending was established and its stress was analyzed. To simplify the calculation process, the following assumptions were made: 1) In the process of roll bending, the plate bending is caused by the normal stress produced by the bending moment, the effect of shear stress is very small and negligible. So it can be considered as pure bending; the assumption of plane section about elastic bending in material mechanics is still applicable to plastic deformation. The geometric center layer and neutral layer of the plate are always the same during the bending process, so the tangential force of the roller is neglected, and the working load in the process of roll bending is mainly normal positive pressure; 2) The width/thickness of the plate is larger, ignoring the influence of the deformation of the material along the width of the plate on the bending deformation. Based on the above two assumptions, theoretical analysis was conducted on the force situation of the working roller during the rolling process. When determining the pressing force and rolling torque, the plastic deformation of the sheet along the entire length was considered based on the fact that all the stresses on the material have reached the yield limit.

3.1 Analysis of pressing force and rolling torque

Construct a bending deformation mechanics model based on the principle of roll bending to analyze its force and energy parameters. The distribution of bending stress on the section of the bent steel plate is shown in Fig. 2.

The maximum bending moment of this section is:

$$M = 2\int_{2}^{\delta/2} \sigma_s L y \, dy = \sigma_s L \delta^2 / 4 . \quad (1)$$

In the formula:

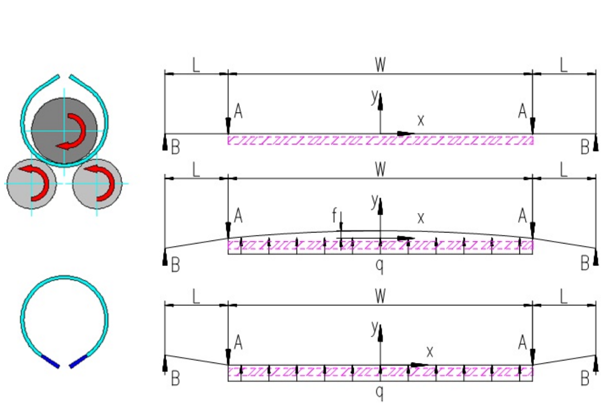

Fig. 1. The principle of roll bending and top roller reverse bending.

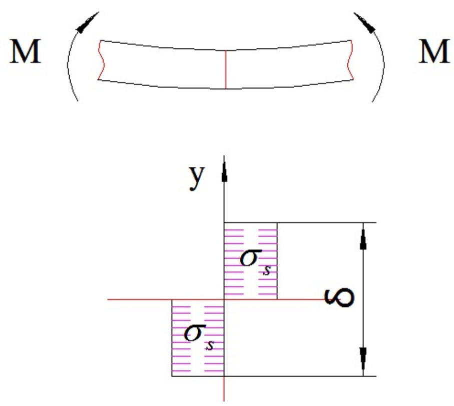

Fig. 2. Bending stress diagram.

L δ —— Maximum width and thickness (m)

σ_s —— Yield limit of the material (N.m^2)

Considering the presence of strengthening during multipass deformation, a strengthening coefficient K is introduced to modify the above equation, then:

$$M = K\sigma_s Lt^2 / 4 . \quad (2)$$

K = 1.10 ~ 1.25; when δ/R is large, the hardening coefficient is selected as a larger value.

According to the principle of balancing work on per unit arc length during the roll bending process (shown in Fig. 3), the force acting on the top roller by the plate can be obtained F_2:

$$F_2 = \frac{M}{R\sin\theta} \quad (3)$$

θ —— The angle between concentric line OO_1 and OO_2

a —— The center distance of lower rollers (m)

d_{min} —— Minimum diameter of pipe to produce (m)

D_2 —— Lower roller diameter (m)

According to the force balance, the force top roller act on the steel plate F_1:

$$F_1 = 2F_2\cos\theta . \quad (4)$$

The required deformation torque during rolling is:

$$T = \frac{MD_2}{d_{min}} . \quad (5)$$

During the rolling process, various frictions need to be overcome, including the rolling friction between the top and lower rollers and the steel plate, the sliding friction between the roller neck and the shaft sleeve, the rolling friction between the top and lower roller support rollers, and the sliding friction between the support roller neck. The required torque for these frictions can be calculated with the following formula. The force model of the top roller is as follows, and the torque required to overcome friction is:

$$T_U = fF_1 + f(F_1 + 2F_3)(1 + D_1 / D_3) + \mu F_3 d_3 . \quad (6)$$

The force on the lower roller is the model with a conventional support roller, and the torque required to overcome friction is:

$$T_L = 2fF_2 + 2fF_2(1 + D_2 / D_4) . \quad (7)$$

The total torque is:

$$T_T = T + T_U + T_L . \quad (8)$$

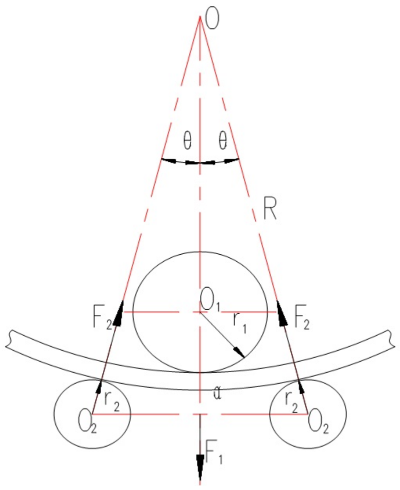

Fig. 3. Force diagram of steel plate.

3.2 Deflection compensation and reverse bending force analysis

During the roll bending process, the steel plate needs to overcome the comprehensive load caused by the deformation force, elastic load limit force, and plastic limit force of material. The pressing force is applied through the top roller. As the top roller is not an absolute rigid body, it will inevitably undergo bending deformation under the action of its own gravity and the reaction force of plate. The deflection of the top roller will affect the straightness of the pipe, so it is necessary to control its deflection to meet the requirements. The basic idea of deflection control is: Within the allowable range of the top roller material, a deformation opposite to the direction of the pressing force is preset to the top roller, and the deformation value is precisely controlled to be equal to the deformation generated during actual operation, so that the top roller does not undergo bending deformation, thus achieving compensation for bending deformation As shown in Fig. 4.

The top roller deflection value is:

$$f_x = \frac{ql^3x}{24EI}(1 - 2\xi^2 + \xi^3) \quad (9)$$

l —— The distance between two pressing points

E —— The elastic modulus of steel

I —— Inertia moment of top roller

$$\xi = x / l .$$

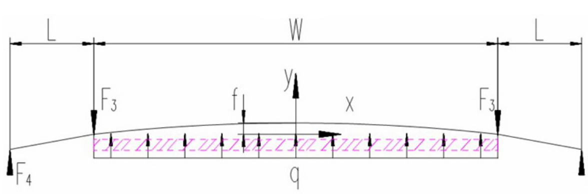

Fig. 4. Force diagram of top roller.

The reverse bending force is:

$$F_4 = qLl / 8l_1 . \quad (10)$$

Total pressing force is:

$$F_3 = F_4 + qL / 2 . \quad (11)$$

4. The process test of roll bending process

A roll bending machine [14, 15] was designed and developed, its structure is shown in Fig. 5; it is mainly composed of frame 1, lower roller assembly 2, top roller assembly 3, pressing device 4, reverse bending device 5, transmission device 6, electrical system and Hydraulic system.

The frame adopts the combined welding structure, the distance between the two columns is 15 m and the factor of safety is larger than 5. Two lower rollers are installed on the lower beam of the frame; the top roller is arranged between the two lower rollers; the pressing devices are installed on the top part of the two columns of frame, and the bending devices are installed on the two sides of the lower beam. To meet the requirements of deflection compensation, the top roller is lengthened to 21 m, The two pressing points are located 15 m away from the center on both sides, and the reverse bending points are located three meters outside the pressing points, When compensating for deflection, the deflection of the top roller is eliminated by the reverse bending device acting on the reverse bending point O_4 with the pressing point O_3 as the fulcrum. According to the two factors of pipe diameter and wall thickness, considering the factors of pipe diameter and wall thickness, a scheme was adopted with replaceable top rollers, shared lower rollers, and synchronized control of three separate rollers. Corresponding top rollers were replaced for products of different specifications.

During roll bending, the pressing device 4 goes down and contacts with the top roll at point the O_3; the plate is pressed into a certain curvature, the top roll deforms under force, while the reverse bending device 5 rises in contact with the top roll at point the O_4. Under the reverse bending force, the top roller is bent back to eliminate its deflection. The top roller and two lower rollers start and rotate synchronously to perform roll bending on the plate. This structure can not only effectively compensate for the deflection of the rollers on the large span of the roller forming machine, but also has the advantages of simple structure and flexible operation.

To measure the relevant process data in the process of roll bending, pressure sensors are installed in the hydraulic control system of the press device 4, the reverse bending device 5 and the transmission device 6; the pressing force reverse bending force and torque are measured. The pressing force is the product of the pressing cylinder area and pressure, the bending force is the product of the bending cylinder area and pressure, and the torque is also calculated through the hydraulic motor displacement and pressure. Displacement sensors are installed on both sides of the pressing device 4 and the reverse bending device 5 to directly measure the pressing displacement and the reverse bending displacement. To reduce the influence of torque loss during torque transmission on measurement results, the actual torque value is measured by measuring the torsional strain of the top and lower rollers.

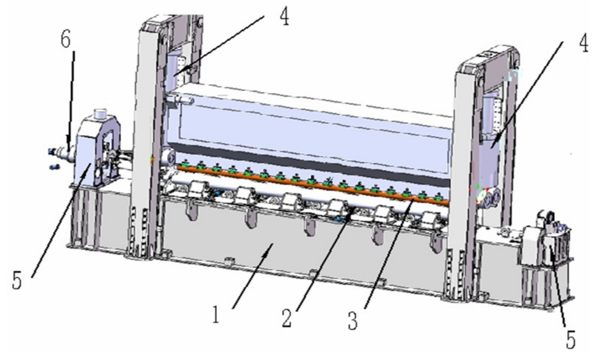

Fig. 5. The structure diagram of roll bending machine.

5. Results and discussion

5.1 Results of theoretical analysis

The basic structural parameters of the model are as follows: the distance of lower rollers: 500 mm-900 mm, diameter of top roller d_1 = 600 mm, diameter of lower roller d_2 = 400 mm, diameter of top backup roller d_3 = 800 mm, diameter of lower backup roller d_4 = 200 mm, diameter of top roller shaft d_5 = 380 mm, the roll bending speed V = 2-6 m/min, the rolling friction between roll and plate is 0.8 mm, the sliding bearing friction coefficient μ is 0.05, the sliding friction coefficient m between roller and plate 0.18 and the elastic modulus is 2.11×10^{11}.

According to the requirements of the product outline, this article selected twelve representative product specifications that can be tested on site for analysis and calculation. Fig. 7 shows the diameter to thickness ratio of the selected specification, material is X80, pipe diameter range is from Φ 508 mm to Φ 1016 mm and wall thickness range is from 8 mm to 30 mm.

Fig. 6. The test site.

Table 1. Test data of force/torque/displacement and process.

DxT mm	Working pressure MPa	Pressing force kN	Reverse bending force kN	Pressing Dis. mm	Reverse bending Dis. mm	Total torque kN.m	Ratio of D/T
Φ508x8	4.15	1736.64	968.76	67.2	28.80	198.10	63.50
Φ508x10	6.43	2688.59	1470.39	64.5	27.64	219.69	50.80
Φ508x12	9.51	3979.80	2175.80	61.3	26.27	453.79	42.33
Φ508x16	17.07	7139.52	3903.87	58.6	25.11	814.57	31.75
Φ711x16	15.24	6377.07	4197.60	43.4	18.60	473.65	44.44
Φ813x16	14.71	6153.00	3365.25	37.9	16.24	616.07	50.80
Φ813x12	5.56	2327.80	1475.99	67.39	28.88	301.61	67.75
Φ813x16	11.58	4844.32	2648.88	64.3	27.56	541.39	50.81
Φ813x20	18.45	7716.06	4219.22	59.4	25.46	612.63	40.65
Φ813x25	29.36	12283.92	7149.60	55.6	23.83	1372.59	32.52
Φ914x24	21.37	8940.89	4889.36	76.9	32.96	735.92	38.08
Φ1016x30	28.12	11765.09	6434.10	93.82	40.21	936.45	33.87

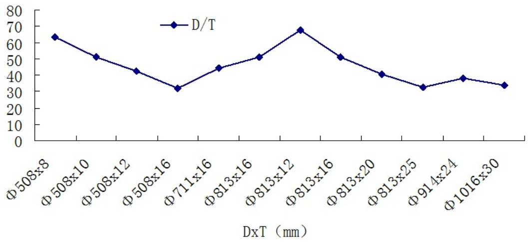

Fig. 7. Diameter-to-thickness ratio of selected pipe.

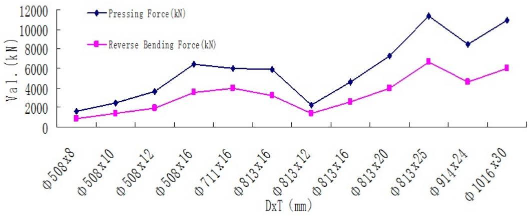

Fig. 8. Pressing force and reverse bending force.

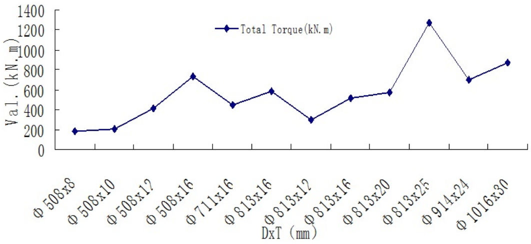

Fig. 9. The total torque.

Pressing down force, reverse bending force as shown in Fig. 8, torque as shown in Fig. 9.

The lower roller distance is 500 mm, diameter is Φ 508 mm, diameter-thickness ratio is from 31.75 to 63.5; the pressing force, reverse bending force and torque increase with the increase of wall thickness. The lower roller distance is 500 mm, the wall thickness is 16 mm, the ratio of diameter to thickness (D/T) is from 31.75 to 50.8. The pressing force, reverse bending force and torque decrease with the increase of diameter. The lower roller distance is 600 mm, diameter is 813 mm, diameter-thickness ratio is from 32.5 to 67.8; the pressing force, reverse bending force and torque increase with the increase of wall thickness. For the product with the highest diameter to thickness ratio Φ 813×25, the pressing force, bending force, and torque are maximum, reaching 11374 k N, 6620 kN, and 1270.9 kN.m, respectively.

The data covers most of the specifications in the product outline. It shows that under the same diameter and lower roller opening, the smaller the diameter to thickness ratio, the greater the pressing force, bending force, and torque. Under the same wall thickness and lower roller opening, the larger the diameter to thickness ratio, the smaller the pressing force, bending force and torque.

5.2 Analysis of tested results

In order to verify the accuracy of the theoretical calculation results, twelve representative product specifications and process parameters were recorded during the production process. The specific data is shown in Table 1.

Fig. 10 shows the relation between theoretical calculation results and test data of pressing force, reverse bending force and torque.

By comparing the calculated results with the test data, it can be seen from Fig. 10 that the trend of reduction force, reverse bending force and torque for roll bending of different specifications is the same; the tested value is 2 %-9 % larger than the theoretical value. The main reason for this result is the change of the coefficient of work hardening in the process of machining; therefore, it is necessary to modify the coefficient of work hardening properly, so that the theoretical calculation result can

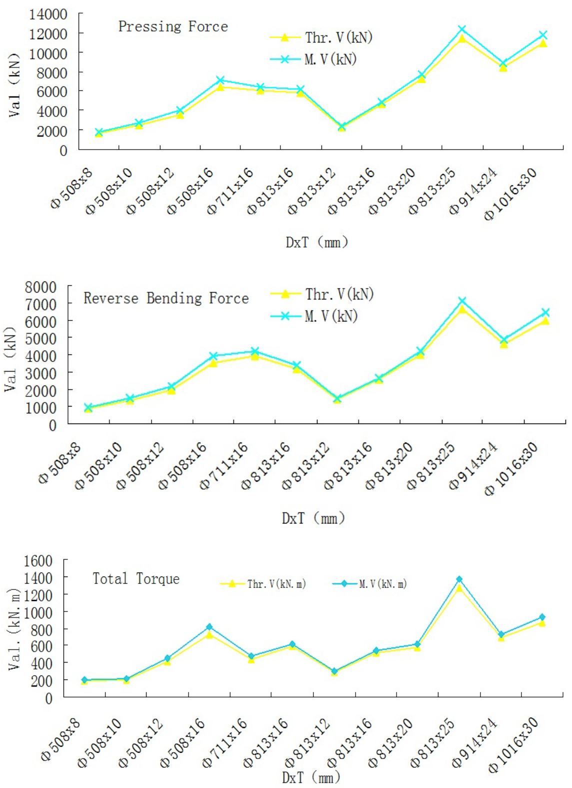

Fig. 10. Parameters comparison of theory data and test data.

accurately reflect the actual data, and the calculation method can be used in engineering applications.

6. Conclusion

To solve the problem of straightness control of small D/T large diameter submerged arc welded pipe produced by roll bending process, a reverse bending method is proposed to control the top roll deflection; the results of theoretical calculation were compared with the collected test data:

1) The deflection compensation method of reverse bending top roller can solve the straightness control problem of pipe with large axial length and small diameter-thickness ratio. The straightness of the pipe is less than 0.1 % of full, which can meet the standard requirements of API 5L.

2) Based on the principle of three-point circle forming, the mechanical model of cold bending was established, and the force and energy parameters, such as press force, reverse bending force and torque, were calculated. The error is less than 15 % compared with the measured results, and the calculated results can be used as the basis for engineering application.

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