Numerical simulation and analysis of JCOE pre-bending of submarine pipeline

Daobiao Liao¹, a, Jixiang Gao¹,b*, Liejun Li²,c, Gongyi Liao¹,d
¹Guangdong Polytechnic Normal University, Guangzhou 510635, China
²National engineering research center for near-net-shape for metallic materials, south china university of technology, 510640, Guangzhou, P. R. China
ª1158070630@qq.com,
*Corresponding author: bemail: gaojx@gpnu.edu.cn
cliliejun@scut.edu.cn, d1352939621@qq.com

Abstract. In this paper, the chemical composition and mechanical properties of L360M pipeline steel are analyzed, and the formulation method of JCOE prebending process for submarine pipeline steel pipe is introduced. Based on the Augmented Lagrange, Ansys software was used to simulate the prebending process numerically with the whole process from model establishment to boundary condition and parameter setting is introduced in detail. The process of bending, yielding and springback of steel plate was analyzed to obtain the general rule of elastic-plastic change of steel plate during JCOE prebending forming. Comparing the theoretical and simulated values of the springback, the ultimate stress and the residual stress after springback in the JCOE pre-bending process, the relative errors are 7.8%, 6.6% and 15.2% , which are within the allowable error range. The results show that the JCOE finite element analysis model is effective and feasible.

1. Introduction
With the continuous development of industrialization, terrestrial oil and gas resources have been unable to meet the needs of industrial production, and oil and gas exploitation has gradually shifted from land to the ocean with more abundant resources. The pipe industry characterized by high pressure, large pipe diameter and harsh application environment and the metallurgical industry characterized by microalloying, ultra-pure smelting and using advanced TMCP technology promote each other and develop together, pushing the pipeline industry, pipeline steel and line pipe production into a new development period. Line pipe shows a trend towards refinement and personalization. For the convenience of construction and safety in service, the pipeline engineering puts forward higher requirements on the external form and internal performance quality of the line pipe. Therefore, JCOE forming method has the characteristics of low production cost, large output and good service safety. So, it was adopted in large numbers[1,2].

The molding process can be adjusted according to the actual situation in order to realize the molding technology innovation to meet higher product quality requirements. Therefore, the research method of finite element simulation is of great significance to the research of line pipe forming. In recent years, many scholars at home and abroad have studied JCOE forming technology by using finite element simulation method. They successfully developed a simulation computing platform based...
on the whole process, and detailed research on part of the molding process. However, the research on molding process and the influence of mold on product quality is less, which can't meet the high requirements of modern industry on product quality[3,4].

In this paper, Ansys software was used to simulate the prebending and bending process of JCOE pipe, in order to providing a process parameter which can be used in actual production and reduce the cost and improve the production efficiency by analyzing the forming mechanism of the JCOE pipe.

2. Experimental materials and JCOE forming process

L360M pipeline steel was used in the test, and its chemical composition and physical properties are shown in Table 1 and Table 2.

| Chemical composition | C     | Mn    | P      | S      | Si     | Nb  |
|----------------------|-------|-------|--------|--------|--------|-----|
| Chemical composition | 0.04~0.15 | 1.30~1.65 | ≤0.022 | ≤0.005 | 0.10~0.30 | ≤0.05 |

| Chemical composition | V  | Ti  | Cu  | Cr  | Mo  | Ni  |
|----------------------|----|-----|-----|-----|-----|-----|
| Chemical composition | ≤0.05 | ≤0.040 | ≤0.35 | ≤0.30 | ≤0.20 | ≤0.50 |

The specification of the plate raw material used in this simulation is 12.7mm×1546mm×12150mm, and the size of the elbow pipe is φ 508mm×12.7mm×12000mm. The adopted yield strength is 472MPa at room temperature, and the tensile strength is 573MPa.

Table 2 Mechanical properties of L360M pipeline steel

| Material | Modulus of elasticity /GPa | Poisson ratio | Yield strength /Mpa | Strength of extension /Mpa | Yield ratio | Elongation /% |
|----------|---------------------------|---------------|---------------------|---------------------------|------------|--------------|
| L360M    | 207                        | 0.3           | 360~510             | 460~760                   | 0.90       | 27           |

The machine used in this pre-bending process is BWQ-2000/3000×5100 steel plate pre-bending machine. The pre-bending process diagram and the pre-bending process parameters are shown in Fig. 1 and Fig. 2 respectively. The profile of the upper die bending part is involute, the base circle radius is 586.6mm, and the arc Angle is 45° to 90°.

Table 3 Pre-bending process parameters

| Mould          | Rack distance | Bending length | The degree of lower mold regression | Theory pressure |
|----------------|---------------|----------------|-------------------------------------|-----------------|
| 1# upper mold  | 1100±50mm     | 434mm          | 11mm                                | 320T            |

Fig.1. Schematic diagram of pre-bending process

Fig.2. BWQ steel plate prebending machine
3. JCOE simulation analysis model and conditions

3.1 Model selection

The Augmented Lagrange which is based on the penalty function was used in the simulation. The contact pressure is defined by increasing the radial spring. Contact pressure \( F = Kx + \lambda \), where \( K \) is the normal stiffness and \( \lambda \) is the adjustment factor. Based on the Prandtl-Reuss flow theory and the Miss-von stress yield criterion of the fourth strength theory, the rate-type constitutive equation can be written as follows.

\[
\dot{\sigma}_{ij} = D_{ijkl} \dot{\varepsilon}_{kl}
\]

where, \( \dot{\sigma}_{ij} \) is Jaumann stress rate, \( D_{ijkl} \) is Elastoplastic constitutive matrix, \( \dot{\varepsilon}_{kl} \) is strain rate.

\[
D_{ijkl} = 2G[\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk} - \frac{\nu}{1-2\nu}\delta_{ij}\delta_{kl}] - \frac{3\sigma_{ij}^\prime\sigma_{kl}^\prime}{2\sigma^\prime(1+Y/3G)}
\]

where, \( G = E/2(1+\nu) \), \( E \) is modulus of elasticity, \( \nu \) is Poisson's ratio. \( \sigma^\prime \) is equivalent stress, \( Y \) is the derivative of yield stress with respect to strain. \( \dot{\sigma}_{ij}^\prime, \sigma_{ij}^\prime \) is deviatoric stress, \( \delta_{ik}, \delta_{il}, \delta_{ij}, \delta_{kl} \) are Kroneckerf symbols. The hardening function of the workpiece material used in the calculation is determined by the following formula.

\[
\sigma = C(a + e^p)^n
\]

where, \( \sigma \) is effective stress, \( e^p \) is effective strain, \( C \) is coefficient, \( a, n \) is constant which can be determined by regression method according to material and deformation speed.

So equivalent modulus of elasticity at yield \( E' = Cup(a + e^p)^{p+1}e^{p-1} \), the stress-strain curve of L360M pipeline steel is as follows.

In order to improve the efficiency of finite element simulation, the stress-strain curve is simplified to Multilinear Isotropic hardening which can be used for large deformation analysis.

In order to avoid the negative slope of the line segment in ansys software analysis caused by the impact, the negative slope of the line segment needs to be removed.

In this paper, the yield stage in the stress-strain curve is simplified as a linear segment.

The curve at the stage of necking is simplified to a curve with a small slope which will not not affect the results of finite element analysis\(^{[5,6]} \).

\[\text{Fig. 3. Stress-strain curve of L360M}\]

3.2 JCOE simulation conditions

Solid186 unit is used in the pre-bending process simulation. The upper and lower molds are set as rigid bodies. Contact is frictional contact. The friction coefficient is 0.2. The normal stiffness coefficient is 0.01. The normal penetration tolerance is 10-6mm. The tangential penetration tolerance
is 10-7mm, which is one tenth of the normal penetration tolerance by default, namely. Due to the modeling error, there is a geometric gap between the upper mould and the plate, resulting in a rigid collision between the plate and the upper mould after displacement. To eliminate the gap, insert a command flow (keyopt, cid, 9) in the contact command to modify the keyword 9. Turn on the normal steady state damping coefficient and set it to 0.005. Contact detection method is Gauss Point Detection. Set the gridding size to 5mm in the bending section and 10mm elsewhere. The lower mould and the plate are curved contact. Opening the high-order plane element can prevent the point contact from being affected by the additional stress generated by line contact, which will affect the accuracy of the results. The boundary condition is set to fix the clamping position of the upper die and the plate, and give the lower die a round-tripping displacement of 283mm up and down. Set the initial step size to 50, minimum step size to 4, and maximum step size to 500. The solution type is iterative solution. Convergence criteria is Forces Convergence. Turn on the large deformation.

4. Simulation results and field experiment analysis

As shown in Fig.5, when t=0.34595s, the maximum bending deformation reaches 97.905mm and the steel plate reaches its elastic limit. The maximum ultimate stress is 414.99mpa.

As shown in Fig.4 b), the maximum stress point is at the bending point of the plate, and close to the plate edge.

![Stress distribution nephogram of simulation results of steel plate prebending process](image)
As shown in Fig. 4 a), then the steel plate begins to enter the yield stage. When \( T = 1 \text{s} \), the lower mould begins to fall, the steel plate begins to rebound, and the stress begins to drop. The final stress stays at 156.77 Mpa, as shown in Fig. 4c), which is the residual stress after the steel plate is pre-bending\(^7\). According to the bending calculation formula, Rebound radius

\[
R' = \frac{R_P}{1 - \frac{4.46(1 - \nu^2)\sigma_y R_P}{Et}}
\]

Where, \( \nu \) is Poisson's ratio, \( t \) is plate thickness, \( E \) is elastic modulus, and \( \sigma_y \) is the yield limit. Set the plastic strengthening modulus of the material to 0 and the radius of curvature after springback can be obtained through calculation. Finally, the springback, maximum stress and residual stress are calculated according to the constant arc length theory of neutral layer\(^8-10\).

| Simulation and theoretical parameters of JCOE prebending process |
|-------------------|------------------|----------------|
| springback /mm    | limiting stresses /Mpa | residual stresses /Mpa |
| Simulation value   | 63.91            | 414.9          | 156.77          |
| Calculated value   | 58.88            | 389.1          | 184.9           |
| error              | 7.80%            | 6.60%          | 15.20%          |

The theoretical and simulation errors of springback, limit stress and residual stress are all within the allowable range. Therefore, the numerical simulation model can be considered to be effective and feasible.

5. Conclusions

(1) Based on the Augmented Lagrange, the paper introduce the creation of 3d finite element model for the pre-bending process of JCOE welded pipe and ensure the accuracy of the model by combining with the actual process. Then the creation of 3d FINITE element simulation model of JCOE forming, the setting of boundary conditions and the adjustment of parameters are explained in detail. These work provides a specific finite element numerical simulation method for the actual production of JCOE welded pipe.

(2) This paper analyzes the process of JCOE welded pipe prebending from bending to yielding and then to springback. The validity and feasibility of JCOE numerical simulation model are verified by comparing the theoretical and simulated values of springback, maximum stress and residual stress.

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