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Cross-sectional distortion of LSAW pipes in over-bend straightening process

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ABSTRACT

In the over-bend straightening process of longitudinally submerged arc welding (LSAW) pipes, the cross section tends to be distorted due to the axial curvature variation in the reverse elastic-plastic bending. Based on the minimum work principle, a analytical model of the cross-sectional distortion of the curved pipe with initial curvature in the reverse axial elastoplastic bending is established, and the prediction error is not more than 10% compared with the experimental value of the maximum distortion coefficient. Especially for smaller deformations and thinner pipes, the prediction accuracy is higher. Compared to ovality, the maximum distortion coefficient with a smaller error can be used as an effective prediction parameter. In addition, the application of this prediction model is analyzed by an example of a straightness-offgrade LSAW pipe. The results show that the maximum value and position of cross section with most serious distortion can be determined once the initial curvature of a curved pipe is measured, which can be compared with the standard to adjust the shape of the straightening tools and process parameters.

1. Introduction

Longitudinally submerged arc welding (LSAW) pipes are widely used in the construction of oil and gas transportation pipelines, and most of such pipes are made from steel plates by the JCOE process (progressive forming process of J-shape, C-shape and O-shape, welding and mechanical expanding) and UOE process (progressive forming process of U-shape and O-shape, welding and mechanical expanding). Generally, a pipe with a diameter-to-thickness ratio of more than 20 is considered as a thin-walled pipe, otherwise, a thick-walled pipe. Therefore, the LSAW pipe, with the diameter of 406.4–1422.2 mm and wall thickness of 6.4–44.5 mm, is typical large-scale thin-walled pipe. The current piping standard API Spec 5 L [1] stipulates that the straightness deviation of the finished pipe shall not exceed 0.2% of the length. At the same time, the ovality is specified as follows: the end should not exceed 1.5% (for the diameter less than 610 mm) or 1.0% (for the diameter greater than 610 mm), and the body should not exceed 2% (for the diameter less than 610 mm) or 1.5% (for the diameter greater than 610 mm). However, the straightness is not easy to meet the standard owing to the welding thermal stress or equipment error, so the straightening process is necessary for the production of the LSAW pipes.

The bending feature of LSAW pipes is that the deflection curve is a single-peak plane curve, making it more suitable for multi-step three-point bending straightening [2] and multi-point bending one-off straightening [3], and the former is more popular with manufacturers. The common principle of these straightening processes is over-bend straightening, that is, the pipe with the initial curvature of K_0 is bent to the curvature K; after unloading, the curvature after springback K_p is close to zero, so that the straightness meets the standard requirements.

In the bending process of the pipe, the cross section tends to be ovalize or flatten due to the axial curvature variation in the reverse elastic-plastic bending, which is defined as cross-sectional distortion in this paper, also known as Brazier effect after Brazier's work [4]. The reduced bending resistance caused by cross-sectional distortion will affect the straightening accuracy, and the setting round process will be added, once the cross-sectional ovality exceeds the specified value. Therefore, it is important to predict the cross-sectional distortion for the shape control of LSAW pipes.

In 1927, Bazier [4] first discovered the cross-section flattening phenomenon during the bending test and established a simplified mechanical model to describe this highly nonlinear mechanical problem. Based on this, many researchers have studied the cross-section deformation during the axial bending process. One of the most commonly used methods is energy method. Ades [5] employed the energy principle and iterative numerical method to determine the relationship between the bending moment, curvature and flattening of the cross

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section, which is well suited for computer applications. According to the energy theory, Prinja and Chitkara [6] obtained the theoretical solution of the bending moment and the flattening under the plastic bending condition by using the plane bar mechanism with four hinges to describe the distortion section. Knaster et al. [7] applied the energy theory to analyze the influence of sectional ovality on the design of thin-walled component, where the analytical model of deformation energy was not general. In the research of Kale and Thorat [8], the total energy was utilized for the mechanical work done in bending, and some energy is stored as potential energy. In addition, Shima et al. [9] stated that the energy cost for a multilayered cylinder under bending was a sum of strain energy associated with the circum-ferential displacement, axial strain and cylindrical surfaces in the radial direction. It can be seen that the energy theory has unique advantages in the analysis of plastic deformation problems, which mainly involves the solution of a hypothetical displacement field based on energy analysis and boundary conditions. Therefore, the theoretical model is not unique, but rather based on specific situations. Luongo et al. [10] believed the pipe with a deformable cross section, possibly filled with structural foam, is bent in the elastic regime, and deduced the softening moment-curvature relationship applying the virtual work theorem to analyze the contribution of the foam core in preventing instability phenomena. Zhang et al. [11,12] proposed a simplified model of maximum cross-section flattening based on the energy approach, aiming at the continuous rotary straightening process, but the initial curvature was ignored in analytical analysis.

In recent years, with the development of finite element analysis and detection technology, numerical simulation and physical experiments have become important research methods. Ting [13,14] and Chen et al. [15] investigated the stress distribution in anisotropic cylindrical pipes under pressure, shear, torsion and tensile loads. Strano [16] obtained the empirical expression of the maximum flattening by using the experimental method. To solve the stress analysis of curved pipes subjected to in-plane bending forces, Fonseca and Melo [17] presented an alternative formulation to current meshes dealing with finite shell elements. Jiang et al. [18] applied the CNC bending machine to study the bending deformation of medium-strength TA 18 tube, and obtained the curve in terms of the flattening and bending angle. Meshii and Ito [19] used the finite element method to analyze the deformation behavior of thin-walled pipe under bending load, and obtained the relationship between the bending moment and the deformation displacement. Michael et al. [20] used the empirical formula to deal with the relationship between the bending moment and the sectional ellipticity of the thin-walled pipe under the plane bending condition. Kolesnikov [21] investigated the inflation of curved pipe with large elastic strain by nonlinear membrane theory. Sarvestani and Akbarzadeh [22] used a displacement approach of toroidal elasticity to analyze the thick isotropic curved pipes subjected to axial load, torque, and bending moment. Barsotti and Ligarò [23] investigated the mechanical response of inflatable cylindrical beams under bending and shear, and carefully considered the geometrical nonlinearities due to both the cross-sectional ovalization and wrinkling. Christo Michael et al. [24] carried out the limit analysis considering geometric nonlinearity to determine the collapse load equations for semi-oval cross section under in-plane bending and internal pressure, and compared them with the existing elliptic cross sections to determine the suitability of the two assumed cross sections. However, the data charts and empirical formulas obtained from experiments and simulations are often targeted for specific vessels under specific conditions, with poor adaptability and portable generalization.

As already reported, the study of sectional deformation in reverse elastic-plastic bending for curved pipe is still limited to the experiments and simulations, and there is no analytical method available for the cross-sectional distortion of LSAW pipes in straightening process. According to the pure bending equivalent principle for over-bend straightening, the quantitative calculation of theoretical straightening moment based on the initial deflection distribution was developed by the authors [3], which also provided a method for the strain analysis of curved beam in the bending process. For the straightness-offgrade LSAW pipes caused by welding thermal stress, the initial cross-section ovality can be approximately neglected. In this paper, a simplified prediction model of cross-sectional distortion in the axially elastoplastic bending for the over-bend straightening of LSAW pipe is proposed based on the minimum work principle, and its validation is investigated.

2. Mechanical model

2.1. Basic assumptions

(1) Neutral layer coinciding assumption: the strain neutral layer, stress neutral layer and geometric neutral layer always coincide during the deforming process;
(2) Initial equivalent strain assumption: the curved beam with the initial curvature K_0 is obtained by bending the straight beam in some way, so the curved beam with the thin-walled ring section has a initial equivalent strain ε_0.
(3) Plane section assumption: any cross section of the curved beam remains a plane before and after deformation, and the strain on the cross section is linear. Then the initial equivalent strain ε_0 satisfies the relationship

$$\varepsilon = vK, \tag{1}$$

where v is the distance from the particle to the neutral layer.

Taking into account the initial curvature, the equivalent strain ε_{eq} is introduced as the relative change in the length of the micro-beam, and is defined as the algebraic sum of the true strain ε_{tr} and initial equivalent strain ε_0:

$$\varepsilon_{eq} = \varepsilon_{tr} + \varepsilon_0 \tag{2}$$

Therefore, the study object is further defined as the micro-beam section with an axial bending angle of $d\theta$ intercepted from the curved pipe, with the initial curvature and bending curvature of K_0 and K, respectively.

2.2. Strain analysis

The micro-beam before and after reverse bending accompanied by cross section distortion is shown in Fig. 1. According to the coordinate system, the curvature of the curved beam toward the forward direction of the y-axis is defined as positive, otherwise negative. Then the initial curvature and bending curvature are opposite in sign in the straightening process.

It is assumed that the geometric center layer of the section before straightening is the standard circle with the radius of r, as shown in Fig. 1b. In the reverse bending process, the particle Q_0 on the cross section S_0 moves along the radius to the point Q forming a non-standard elliptical section S, which satisfies the equation

$$\begin{cases} x = (r + r\xi)\sin\varphi \\ y = (r + r\eta)\cos\varphi \end{cases}, \tag{3}$$

where ϕ is the angle between the particle and the y-axis; ξ and η are two undetermined constants, and $\xi > 0$ and $\eta < 0$. The two constants can characterize the change rate of the long and short half-axis relative to the radius r.

The introduction of two parameters ξ and η defines a permissible displacement field forming a flattened section shown by Eq. (3), so their solution is the key to predict the sectional deformation.

Assuming that there is no elongation or shortening on the middle surface of the pipe circumferentially, so there is