JOURNAL OF IRON AND STEEL RESEARCH, INTERNATIONAL. 2016, 23(8): 745-755

Prediction of Maximum Section Flattening of Thin-walled Circular Steel Tube in Continuous Rotary Straightening Process

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Abstract: Cross-sectional ovalization of thin-walled circular steel tube because of large plastic bending, also known as the Brazier effect, usually occurs during the initial stage of tube's continuous rotary straightening process. The amount of ovalization, defined as maximal cross section flattening, is an important technical parameter in tube's straightening process to control tube's bending deformation and prevent buckling. However, for the lack of special analytical model, the maximal section flattening was determined in accordance with the specified charts developed by experienced operators on the basis of experimental data; thus, it was inevitable that the localized buckling might occur during some actual straightening operations. New normal strain component formulas were derived based on the thin shell theory. Then, strain energy of thin-walled tube (per unit length) was obtained using the elastic-plastic theory. A rational model for predicting the maximal section flattening of the thin-walled circular steel tube under its straightening process was presented by the principle of minimum potential energy. The new model was validated by experiments and numerical simulations. The results show that the new model agrees well with the experiments and the numerical simulations with error of less than 10%. This new model was expected to find its potential application in thin-walled steel tube straightening machine design.

Key words: straightening; thin-walled circular steel tube; cross-sectional ovalization; maximal flattening; plastic bending

Symbol List

A_ϕ—Circumferential Lame parameter of middle surface;
E—Modulus of elasticity;
E_1—Plastic strain-hardening coefficient;
E'—Plastic modulus;
R_w—Radius of curvature of deformed tube's neutral axis (bending radius);
R_{wp}—Axial radius of curvature at an arbitrary point on middle surface;
R_ϕ, R_θ—Circumferential and radial radii of principal curvature;
r—Initial radius of tube cross section;
$u^{(z)}$, $w^{(z)}$—Circumferential and radial displacements acting on a surface with a distance z from middle surface;
v, u, w—Axial, circumferential and radial displacements acting on middle surface;
z—Distance from middle surface of shell;
Δ_1, Δ_2—Increases of the arc segment PQ owing to circumferential displacement and radial displacement;
δ—Half of maximum flattening;
δ_a—Maximum flattening throughout tube's cross section;
$\delta_{\lim}$—Allowable flattening;
ε_ϕ, ε_θ—Circumferential and radial strain components acting on middle surface;
$\varepsilon_\phi^{(z)}$, $\varepsilon_\theta^{(z)}$—Circumferential and radial strain components acting on an arbitrary revolution surface at a radial distance z from middle surface;
$\bar{\varepsilon}$—Effective strain;
ζ_j, η_j—Dimensionless unknown coefficients;
θ—Central angle of deformed tube;
ν_i, μ_i—Quantities defined to simplify the expressions;
Π—Internal plastic strain energy per unit length tube;
$\bar{\sigma}$—Effective stress;
σ_s—Yield stress;
$\sigma_\phi^{(z)}$, $\sigma_\theta^{(z)}$—Circumferential and radial stress components acting on an arbitrary revolution surface at a

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Foundation Item: Item Sponsored by National Natural Science Foundation of China (51374063); Fundamental Research Funds for the Central Universities of China (N140303009)

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radial distance z from middle surface;

ϕ—Central angle between point P and the major axis.

The high-precision thin-walled steel cylinders, referred to as thin-walled tubes or pipes, have a wide variety of applications in pipe networks, aerospace structures, military and petrochemical industry. But they are usually curved in rolling and transporting process due to external or internal force or temperature variation, so straightening, especially continuous rotary straightening, is an important process in order to eliminate the tube's undesirable geometric imperfections[1,2]. However, during the initial stage of straightening operation, the thin-walled tube is usually subjected to a large plastic bending in order to unify its non-uniform initial curvature along its longitudinal axis. This plastic bending creates large nonlinear plastic deformation, causing the tube cross-sectional ovalization, known as the Brazier effect. The amount of ovalization, defined as maximal cross section flattening, which is a major technical parameter for straightening process, should be controlled under a tolerable limit, to ensure no buckling occurrence. Therefore, it is very important to analyze the Brazier effect response and to predict maximum cross-section flattening accurately in straightening process of thin-walled circular steel tube.

Since Brazier[3] firstly described and modelled this highly nonlinear cross section flattening phenomenon observed by tube bending experiments with simplified method in 1927, numerous studies investigating the responses of circular steel tubes under bendings have been published. Reissner[4] generated nonlinear equations by applying the small-strain bending theory in 1959. His equations were solved by Fabian[5] using numerical method in 1975. Levyakov[6] proposed another numerical method to solve Reissner's nonlinear equations in terms of two unknown functions and two unknown parameters. However, the studies mentioned above were all assuming that the material was in elastic range. Ades[7] firstly proposed an iterative numerical method, and analyzed the tube's ovalization in plastic range by applying the energy principle in 1957. Prinja and Chitkara[8] derived a theoretical solution for tube cross section flattening, by modeling the initially circular section subjected to static compression using four stationary hinges in 1984. Similar methods were discussed by Mentella and Strano[9] in 2012, as well as Arabzadeh and Zeinoddini[10] in 2013, to analyze the tube's ovalization. Elchalakani et al.[11] employed Mamalis kinematic model and developed a closed-form solution for moment-rotation response of the tube under pure bending using two local plastic mechanisms (star and diamond shapes). But all models mentioned above were used to predict the post-buckling response, and the tube's cross-sectional shape observed in the buckling experiment did not resemble the real shape during the continuous straightening process. Furthermore, Tatting et al.[12] established governing equations for nonlinear bending response of finite length composite tube by using semi-membrane constitutive theory in 1997. Similar equations were proposed by Adam and Rotter[13] in 2013 and Hiroyuki[14] in 2014. But these equations were too complicate to be used in straightening machine routine design.

There is no established method available for prediction of maximum cross section flattening of thin-walled circular steel tube in its straightening process. The maximum section flattening obtained from the experimental charts sometimes causes that the design curvature of working roll is so sufficiently large that the tube's localized buckling takes place during straightening operation. Thus, a quantitative prediction of maximum section flattening is very important. In this paper, an analytical model was formulated that accounted for the cross-sectional ovalization and predicted the maximum section flattening, and then its validation was investigated.

1 Brazier Effect in Tube's Straightening Process and Assumptions

Currently, the multiple cross roll straightening machine is usually used to straighten thin-walled tubes. It employs a set of roll system, consisting normally of four or five pairs of working rolls placed along the longitudinal axis, as illustrated in Fig. 1 (a). Each paired rolls have the same circular profile of a single curvature radius rather than the hyperbolic profile, one with a convex surface and the other with a concave surface, and are mounted at an oblique angle, as illustrated in Fig. 1 (b). During straightening operation, thin-walled tube is moved forward whilst being rotated in a spiral direction. It is straightened by alternating bendings applied by the roll system. At the initial stage of straightening operation, just as shown in Fig. 1(b), the tube undergoes a large plastic bending in the paired rolls' gap, to unify its non-uniform axial curvature. It is the very plastic bending that may cause the ovaliza-