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Analysis of wrinkling limit of rotary-draw bending process for thin-walled rectangular tube

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ABSTRACT

The rotary-draw bending process for thin-walled rectangular tube of aluminum alloy may produce a wrinkling phenomenon if processing parameters are inappropriate, especially for tubes with thin wall and small bending radius. To predict this wrinkling rule rapidly and accurately, here, a wrinkling wave function was proposed and a wrinkling prediction model was developed based on the deformation theory of plasticity combined with the energy method, and then the minimum bending radius without the occurrence of wrinkling in the process was obtained. Furthermore, the effects of geometrical parameters and the material properties of the tube on the minimum bending radius were analyzed. The results show that larger thickness-to-width ratio (t/b) and thickness-to-height ratio (t/h) are beneficial to improve the wrinkling limit of the tube. The minimum bending radius becomes smaller with an increase in strain-hardening exponent of the tube, whereas with the strength coefficient decreasing. And the Young's modulus has little effect on the wrinkling limit. These achievements are helpful to develop the bending technique and provide a guideline in rotary-draw bending process for thin-walled rectangular aluminum alloy tube.

1. Introduction

Thin-walled rectangular tube bent parts of aluminum alloy possess a combination of light weight, less loss pulsing signal and good vibration absorbability, which have attracted many applications in aviation, aerospace, radar and various other industries. This type of tube bending can be done using several different methods, such as rotary-draw bending, stretch bending and press bending (Vollertsen et al., 1999). Among these methods, the rotary-draw bending method is the most versatile, cost-effective, and precise method for tight bending radii and thin-walled tubes (Stange, 1997). However, wrinkling may occur on the compression flange of the tube if the processing parameters are inappropriate, which will lead to failure, even die damage if wrinkling is severe. As a result, how to predict this winkling rule rapidly and accurately, and improve the wrinkling limit has become urgent for the development of the rotary-draw bending process for thin-walled rectangular tube.

Researches on the prediction of wrinkling during sheet forming processes have been made for a long time. The energy method has been a widely used approach to obtain the critical condition of wrinkling in these processes. Yossifon and Tirosh (1985) applied the energy method to the analysis of the buckling phenomena. The buckling mode can be predicted under particular pressure and strain, and the general solution can be obtained under particular conditions. Cao and Wang (2000) presented an analytical model for the onset of the sheet wrinkling under normal constraints and transverse tension, based on the wrinkling criterion. The critical buckling stress and wavelength as functions of normal pressure are calculated using a combination of energy conservation and plastic bending theory. Therefore, energy method is adopted for the development of the wrinkling prediction of thin-walled rectangular tube in bending due to its simplicity and above success in predicting flange wrinkling.

Wang and Cao (2001) studied the wrinkling limit of circular tube bending process by wrinkling analysis. The critical conditions of the onset of wrinkles can be obtained through energy equality by defining appropriate boundary conditions. Yang and Lin (2004) improved this method and introduced a new wave function, and then established a simplified analytical wrinkling prediction model for thin-walled circular tube bending. However, it appears that the wrinkling wave function and shell model they proposed are not suitable to study the wrinkling limit for rectangular tube bending process because the wrinkling characteristic and the wrinkling waveform of rectangular tube are different from that of circular tube, nevertheless the achievements of their studies can provide a guideline for our research.

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Corona and Vaze (1996) had done comprehensive theoretical and experimental analysis of buckling of rectangular hollow sections in pure bending. They also discussed the effect of deformations prior to buckling on post-buckling behavior based on the bifurcation theory, and found that the effect of pre-deformations on buckling is usually small for slender, square hollow sections. The prediction method based on bifurcation condition can effectively track the post-buckling behavior. When it is used to predict the critical condition of wrinkling, however, the predicted results greatly depend on the treatment of the key problems in FE simulation. This defect combined with the complex algorithm and the inefficiency cause a limited application of bifurcation method in the practice forming process. Yoshida and Fujwara (1997) studied the wrinkling of rectangular tube in draw bending process and obtained the critical compressive strain using theoretical method. But their studies are not concerned with the minimum bending radius which does not yield wrinkling in the bending process. Paulsen et al. (2001) presented an analytical model for the determination of local post-buckling and suck-in deformations in bending based on the deformation theory of plasticity combined with the energy method. However, the model is not suitable to predict large local deformation and the large displacement in the rotary-draw bending process because of the localization of post-buckling deformation. Zhao et al. (2009) developed a three-dimensional finite-elements model for rotary-draw bending of thin-walled rectangular tube based on ABAQUS/explicit environment and discussed the effect of bending process on the maximum tangent stress. It is found that the effect of bending angle on the maximum tangent stress is negligibly small. The results can provide theoretical basis for the energy analytical model.

In the present paper, a wrinkling prediction model of the rotary-draw bending process for thin-walled rectangular 3A21 aluminum alloy tube is established based on the deformation theory of plasticity combined with the energy method. This model is then used to predict the onset of wrinkling in the process. The effects of the geometrical parameters and the material properties of the tube on wrinkling limit are discussed.

2. Shell wrinkling criterion

Energy principle is a main and effective approach to establish the wrinkling criteria for thin shell workpieces in the forming processes. If the internal energy (U) for every possible assumed deflection is larger than the work (T) produced by the external force, the shell workpieces are considered in a stable equilibrium condition (Liu, 1987). The critical condition of wrinkling onset can be

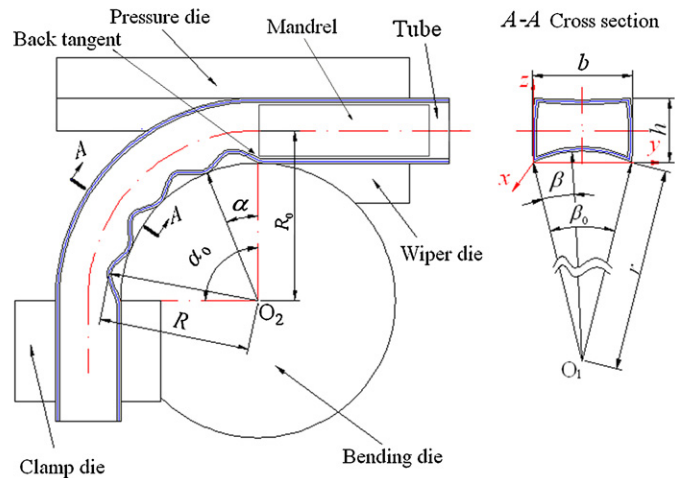

Fig. 1. Schematic diagram of rectangular tube rotary-draw bending process.

expressed by

$$U = T \tag{1}$$

3. Establishment of wrinkling prediction model

3.1. Shell model

In shell bending process, the strain of the shell middle surface, the curvature change of the shell, and the moment of torque (Liu, 1987) can be expressed by

$$\left.\begin{aligned}
\varepsilon_\alpha &= \frac{1}{A}\frac{\partial u}{\partial \alpha} + \frac{v}{AB}\frac{\partial A}{\partial \beta} + \frac{w}{R_1}\\
\varepsilon_\beta &= \frac{1}{B}\frac{\partial v}{\partial \beta} + \frac{u}{AB}\frac{\partial B}{\partial \beta} + \frac{w}{R_2}\\
\gamma_{\alpha\beta} &= \frac{B}{A}\frac{\partial}{\partial \alpha}\left(\frac{v}{B}\right) + \frac{A}{B}\frac{\partial}{\partial \beta}\left(\frac{u}{A}\right)\\
k_1 &= \frac{1}{A}\frac{\partial}{\partial \alpha}\left(\frac{u}{R_1}\right) + \frac{1}{AB}\frac{\partial A}{\partial \beta}\frac{v}{R_2} - \frac{1}{A}\frac{\partial}{\partial \alpha}\left(\frac{1}{A}\frac{\partial w}{\partial \alpha}\right) - \frac{1}{AB^2}\frac{\partial A}{\partial \beta}\frac{\partial w}{\partial \beta} - \frac{\varepsilon_\alpha}{R_1}\\
k_2 &= \frac{1}{B}\frac{\partial}{\partial \beta}\left(\frac{v}{R_2}\right) + \frac{1}{AB}\frac{\partial B}{\partial \alpha}\frac{u}{R_1} - \frac{1}{B}\frac{\partial}{\partial \beta}\left(\frac{1}{B}\frac{\partial w}{\partial \beta}\right) - \frac{1}{A^2B}\frac{\partial B}{\partial \alpha}\frac{\partial w}{\partial \alpha} - \frac{\varepsilon_\beta}{R_2}\\
\chi &= \frac{1}{R_1}\frac{A}{B}\frac{\partial}{\partial \beta}\left(\frac{u}{A}\right) + \frac{1}{R_2}\frac{B}{A}\frac{\partial}{\partial \alpha}\left(\frac{v}{B}\right) - \frac{1}{AB}\left(\frac{\partial^2 w}{\partial \alpha \partial \beta} - \frac{1}{A}\frac{\partial A}{\partial \beta}\frac{\partial w}{\partial \alpha} - \frac{1}{B}\frac{\partial B}{\partial \alpha}\frac{\partial w}{\partial \beta}\right)\\
&\quad -\frac{1}{2}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\gamma_{\alpha\beta}
\end{aligned}\right\} \tag{2}$$

where α and β are the curve coordinates along the shell, u, v and w are the displacements between the tangent direction and the normal direction of the curved surface, A and B are the Lame coefficients, R_1 and R_2, are radii of curvature of the shell, ε_α, ε_β and $\gamma_{\alpha\beta}$ are the strain components on the middle surface, k_α and k_β are the curvature change of the shell, and χ is the moment of torque.

According to rotary-draw bending process of rectangular tube (see Fig. 1), an analytical shell model is built. 0–α_0 is the compressed area along the longitudinal direction of the tube, in which wrinkling may be produced. Moreover, because the middle surface stiffness of the shell is larger than the normal stiffness, it is thought that the shell deformation is only related with the displacement (w) in the normal direction. Accordingly, the shell model due to wrinkling in