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Strip layer method for simulation of the three-dimensional deformations of large cylindrical shell rolling

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ABSTRACT

A strip layer method is presented for analyzing the three-dimensional deformations and stresses of large cylindrical shell rolling process. In this approach, the different radii and velocities of upper and lower rolls, the uneven distributions of deformations and stresses at the roll gap, are taken into account. The rolling deformation zone is divided into a number of strip and layer elements along the width and thickness directions, respectively. In order to reduce the optimization parameters and improve the computation efficiency, the exit lateral displacement distribution is expressed as polynomial function. Based on the fundamental principles of plasticity, the three-dimensional deformations and stresses of the deformation zone are formulated. The simulation results can be obtained quickly and easily. The fishtail spread is predicted satisfactorily on the free side, and the rolling pressure distribution is quite different from that of a conventional strip rolling. The predicted rolling force and average spread of the proposed method are in agreement with the experimental and FEM results.

1. Introduction

Large cylindrical shell is the basic component of heavy pressure vessel, which is widely used in nuclear power, petrochemical and coal chemical industries et al. In the past, large cylindrical shells were typically produced by forging. In order to improve productivity efficiently, the rolling forming as a near net shape process has been introduced. Compared with the conventional forging process, large cylindrical shell rolling is an advanced plastic forming technique with its obvious advantages including good quality, high efficiency, and considerable cost-saving in energy and material. In the rolling process, the upper and lower driving rolls move toward each other to cause the cylindrical shell's thickness to decrease and its diameter to increase continuously.

As a rotary forming technology, large cylindrical shell rolling is a specific ring rolling technique. Many studies have been performed on the aspects of theory and experiment of ring rolling. Mamalis et al. [1,2] performed the earlier ring rolling experiments to measure the pressure distribution and spread, and found that fishtail spread is heavily influenced by the feed speed. However, the experiment study has a few limitations. Hawkyard et al. [3] proposed the slip line field method to analyze the ring rolling force and torque, and the calculated results were in good agreement with the experimental results. Apart from the slip line field method, some other methods have also been used for analyzing ring rolling. Parvizi et al. [4] presented an analytical solution of ring rolling employing the slab method, in which non-uniform normal and shear stresses were considered. The constant shear friction was applied between the main roll and the ring. Ryoo et al. [5] utilized the upper bound method to investigate the torque and load in the ring rolling process, even though the method has a limitation in handling with complex shapes. Although some assumptions and simplifications were made in the above studies, an important basis could be supplied for understanding large cylindrical shell rolling process.

Apart from the above methods, numerical methods have also been widely used for analyzing the ring rolling process. FEM is one of the popular methods for simulating ring rolling [6–8]. In ring rolling process, a large number of ring rotations are required to finish the product, which is different from the conventional rolling process. Each of these rotations must be divided into a large number of deformation increments, hence the number of increments is several times more than that in other metal forming simulation. Yang et al. [9] first proposed the rigid-plastic finite element method to simulate the plane strain ring rolling. Despite that the two-dimensional finite element method is efficient, accuracy is not satisfying and lateral spread cannot be obtained. Subsequently, Yang et al. [10] extended the early model to employ

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rigid-plastic 3D FE model to analyze T-section profile ring rolling process, and Xu et al. [11] presented the metal flow, strain and spread with 3D finite element analysis. In order to further reduce the calculation time, the dualmesh technology was adopted in the FE method, which was reported by Yea et al. [12]. Then, explicit FEM [13,14] was adopted to simulate the hot ring rolling instead of the implicit approach, so as to greatly accelerate computation speed.

Although FEM is powerful in solving complex problems and many ideas are proposed to speed up the computation, it still suffers excessive runtime, especially for large workpiece. Thus, there have been efforts to formulate the efficient strip element method. Liu and Achenbach [15,16] proposed the strip element method in the stress analysis and elastrodynamics problems. Subsequently, Wang et al. [17] developed the strip element method for static bending analysis of orthotropic rectangular plates. Xi et al. [18,19] presented the strip element method for analyzing wave scattering by a crack. Also, the strip element method is widely used to investigate the three-dimensional deformation of metal rolling. Liu and Lian [20] firstly proposed the third power B-spline finite strip method to simulate cold strip rolling. In this method, a new lateral displacement function, which makes the lateral flow velocity continuous at the entry and the exit of the roll gap, was developed. The experiment of strip rolling was carried out on a four-high mill and the computed results of the transverse distributions of front and back tension stresses were close to the experimental results. Then, Liu et al. [21] proposed the third power spline function strip element method to simulate the three-dimensional deformations of cold strip rolling. Assuming the deformations and stresses of the thin strip along the thickness direction are uniform, the rolling deformation zone was divided into a number of strip elements, and the lateral displacement was constructed to be third-power spline function. In order to improve this method and develop the basic theory of the strip element method, Liu et al. [22] put forward the streamline strip element method, in which the rolling deformation zone was divided into a number of streamline strip elements along metal flow traces. Subsequently, Peng and Liu [23] extended the streamline strip element method, in which the initial value of the exit lateral displacement was determined by strip element variation method, in order to increase the calculation precision and convergence speed of this method. Further, Liu et al. [24,25] proposed stream surface strip element method for simulation of plate and strip rolling. The uneven stresses and deformations along the thickness direction were considered. Although many studies have used the strip element method to investigate the conventional strip and plate rolling, there is little research work concentrating on large cylindrical shell rolling.

Consequently, in this paper, considering different roll diameters and velocities, as well as uneven deformations and stresses at the roll gap, a strip layer method is presented to analyze large cylindrical shell rolling. The rolling deformation zone is divided into a number of strip and layer elements along the width and thickness directions, respectively. Based on fundamental principles of plasticity, three-dimensional deformations and stresses of the deformation zone are formulated. The spread, metal flow and rolling pressure can be predicted. The calculated rolling force and average spread are compared with the experimental and FE results.

2. Strip layer method

The schematic illustration of large cylindrical shell rolling is shown in Fig. 1. In the rolling process, the upper and lower rolls are driven to compress the cylindrical shell radial thickness, consequently leading to the expansion of its radius. In the development of the mathematical model, the workpiece is assumed to be the rigid-plastic material at the roll gap, and the elastic material outside the roll gap. The rolling process is considered to be steady and the cross sections at the entrance and exit of roll gap are vertical.

2.1. Strip layer division and lateral displacement model

Taking into account the uneven deformations of large cylindrical shell rolling, the deformation zone is divided into m layer elements and n strip elements along the radial thickness and the width directions, respectively, as shown in Fig. 2. The horizontal distance from the exit point in the deformation zone is taken as the x-axis, and the width direction is set to the y-axis, and the origin of coordinates is at the center of the exit cross section. The exit node coordinates are expressed as y_i and z_j ($i=0,1,\ldots n$; $j=0,1,\ldots m$). m and n are even numbers.

In the deformation zone, considering the large thickness and uneven deformations in the thickness direction, the lateral displacement function of the metal flow is supposed to be:

$$W(x,y,z)=f(x)U(y,z) \tag{1}$$

where $f(x)$ is the longitudinal distribution function of lateral displacement. From Ref. [21],

$$f(x)=1-4(x/L)^3+3(x/L)^4 \tag{2}$$

where L is the length of the deformation zone.

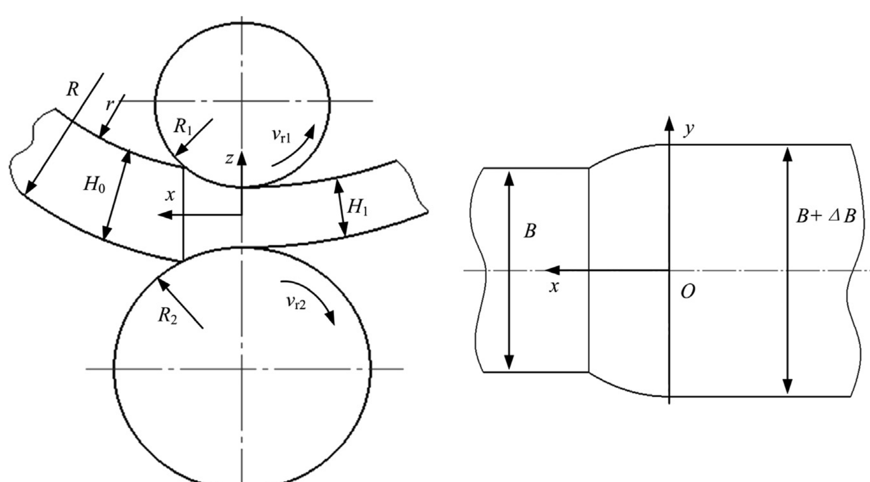

Fig. 1. Schematic illustration of large cylindrical shell rolling.