A Simplified Finite Element Simulation for Straightening Process of Thin-Walled Tube

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Abstract. The finite element simulation is an effective way for the study of thin-walled tube in the two cross rolls straightening process. To determine the accurate radius of curvature of the roll profile more efficiently, a simplified finite element model based on the technical parameters of an actual two cross roll straightening machine, was developed to simulate the complex straightening process. Then a dynamic simulation was carried out using ANSYS LS-DYNA program. The result implied that the simplified finite element model was reasonable for simulate the two cross rolls straightening process, and can be obtained the radius of curvature of the roll profile with the tube’s straightness 2 mm/m.

1. Introduction

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 the external or internal force or temperature variation, so straightening is an important process in order to eliminate the tube’s undesirable geometric imperfections [1]. Currently, the two cross rolls straightening machine is usually used to straighten high precise thin-walled tubes. It employs a pair of rotating rolls, one with a convex surface and the other a concave surface, and are mounted at an oblique angle, as illustrated in Fig.1. Each paired rolls have the same circular profile of a single curvature radius [2]. During straightening operation, the thin-walled tube is moved forward whilst being rotated in a spiral direction. It is straightened by alternating bending applied by the roll system. When the tube is in a paired working rolls gap, it is straightened by the roll’s profile, so the radius of curvature of the roll profile is an important technical parameter for tube’s straightness. However, it is usually determined in accordance with the specified charts developed by experienced operators on the basis of experimental data, causing poor straightness.

With the advances in computer technology and plastic forming theory, the finite element (FE) simulation gradually becomes a powerful research tool to study the forming process. So we can simulate the straightening process using FEA to obtain the radius of curvature of the roll profile. Many researchers have worked on simulations for straightening process, and some of them are discussed here.

CHEN Min et al. [3] carried out a finite element for simulating the process of six cross rollers straightening using COSMOS in order to measure the straightening force. Hoon Huh [4] concerned with the optimization of process parameters for a roller leveler by constructing a finite element model of a
multi-staggered 14-roller leveler for numerical analysis. The analysis was carried out with the fractional model and the Taguchi method for evaluation of the effect of process parameters such as the intermesh and the slanted angle of rollers. Yanagihasi et al. [5] used a three-dimensional static explicit FEM approach of the problem in which only the deformation in bending was taken into account. The increase in straightness could be qualitatively predicted but the effect of lateral stamping was neglected. In a first attempt to simulate the cross rolls straightening of bars, Murata et al. [6] built a three-dimensional model of the process. The bar, meshed with solid elements, was driven, bent, and stamped by the rotating rolls. This approach was CPU cost intensive and allowed only for a limited level of accuracy. Aiming to reduce the computation time and to increase the accuracy of the predictions, Mutrux et al. [7] developed a procedure in which only the deformation of a ‘slice’ of the bar was modeled. Based on this method, A.Mutrux et al. [8] focused on the prediction of the softening effect that occurred when straightening SAE 1144 bars 25mm in diameter with a given set of rolls under different process parameters, by simulating the process with a reasonable CPU cost, a suitable set of constitutive equations, and the yield stress values, but it still cost too much time for calculating. To conclude, so many finite element analyses have been carried out to simulate the cross rolls straightening process, but the precision and the computational efficiency are still not high enough, which mainly depend on the modeling techniques, such as meshing, element type, material constitutive model, boundary conditions, etc. So in this paper using the technical parameters of an actual two cross rolls straightening machine, a simplified finite element model is developed to simulate the complex straightening process, and a finite numerical simulation is performed in order to obtain the radius of curvature of the roll profile more precisely.

2. Assumptions
In this paper, it is assumed that the total strain distribution in the steady state during cross roll straightening is similar to the one that develops when the tube is simply bent and stamped between the rolls without rotation and forward feed. So a typical pure bending state can be assumed since the curvature radius of the circular profile is uniform. By using ANSYS LS-DYNA program the finite element model can be constructed as shown in Fig. 2.

3. Finite element model
This model consists of three parts, the upper one is the bending punch, the middle one is the thin-walled tube, and the lower one is the bending die. Both the punch and the die have cylindrical profiles with the bending radius of curvature of deformed tube’s neutral axis $R_w=12.77m$, that is the radius of curvature of the roll’s profile in an actual two cross roll straightening process. On every profile there is a cylindrical
dent with the diameter \( d=21\text{mm} \), which equals the diameter of the thin-walled tube. And the thin-walled tube is located between the punch and the die aiming at the dent.

On the basis of the simulation, the geometry of the specimen is taken as: The tube length \( L=400\text{ mm} \), the tube outside diameter \( d=21\text{mm} \), the tube thickness \( t=1\text{mm} \), the initial radius of curvature of the tube \( R_0=4.92\text{m} \). The material properties of the model are assumed as illustrated in table 1.

**Table 1** The material properties of the parts of FEA model

| Parts | Elastic modulus \( E/\text{GPa} \) | Plastic strain-hardening coefficient \( E_1/\text{MPa} \) | Poisson ratio | Yield stress \( \sigma_y/\text{MPa} \) |
|-------|-----------------|-----------------|--------------|------------------|
| Tube  | 2               | 1070            | 0.3          | 205              |
| Punch | 2.06            | -               | 0.3          | 440              |
| Die   | 2.36            | -               | 0.3          | 440              |

Fig. 3. The numerical simulation for straightening process of thin-walled tube (a) the state before straightening (b) the shape and stress intensity cloud of the tube along the longitudinal direction (c) the state after unloading.
The tube is modeled by the 3D solid element with an elasto-plastic material, and the mesh size of 0.25 × 0.5 × 0.6 mm in the deforming region. The punch and die are modeled as rigid bodies to save computational time.

The analytical surfaces which are probably in contact here are defined as automatic contact (ASTS) with other components, the frictions between the tube and the bending punch, die are all the dry friction. A frictional coefficient of 0.15 are chosen between all the surfaces in contact.

4. Numerical results

During the simulation the tube was placed between the punch and the die, as shown in Fig.3a. Then a uniform displacement in y direction was applied to the upper bending punch. The speed of bending punch was controlled at 40 mm/s. When the tube contacted with the punch completely, the radius of curvature of the tube axis was equal to the punch’s radius. At this moment the shape and stress intensity cloud of the tube along the longitudinal direction was described in Fig.3b. It was shown that the tube was bent reversely and the stress level was much higher. Then the punch moved upward, the springback due to the unloading process occurred. Fig. 3c shown the shape of the tube after unloading, and it was shown that the tube was almost straight.

In order to measure the tube’s straightness at longitudinal direction accurately, the variation in the coordinate values of some key nodes on the tube neutral surface in y direction (shown in Fig.3a) with the deformation time t was described in Fig.4. From the figure the y coordinate values of all the nodes were difference varying from 0.1449m to 0.166014m at the very beginning. Then when the unloading was over they are almost the same, so this model can straighten the tube. And the tube’s straightness is controlled below 2 mm/m. That agrees well with the straightness of the actual two cross roll straightening machine. From the simulation it is concluded that this FEA model can be used to simulate the complex two cross rolls straightening process and simulations can be employed instead of experiments for obtaining the radius of curvature of the roll’s profile.

Fig. 4. The coordinate values of some key nodes on the tube neutral surface in y direction vs. the deformation time t
5. Conclusion
The following conclusions are drawn in this paper:

(1) A simplified finite element model proposed in the paper can be used to simulate the complex two cross rolls straightening process.

(2) This FEA can be used to obtain the radius of curvature of the roll profile, in order to control tube’s straightness under a tolerable limit.

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