Modeling and computation of the three-roller bending process of steel sheets

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Abstract

Sheet metal bending processes are some of the most commonly used industrial manufacturing operations. The development and optimization of these processes are time consuming and costly. Therefore, finite element simulations may aid the design and quality assurance of sheet metal products. In the present study, a commercial finite element package was used to analyze the three-roller bending of a steel sheet. A two-dimensional finite element model of this process was built under the ABAQUS/Explicit environment based on the solution of several key techniques, such as contact boundary condition treatment, material property definition, meshing technique, and so on. Maps with desired curvature radii were established by varying the distance between the two bottom rollers and the position of the upper one. The developed maps made the rolling process easier and less time consuming. An industrial experiment using optimized numerical results was carried out to validate the numerical model. Residual stress and equivalent plastic strain distributions were also studied. The numerical spring back phenomenon was compared with analytical results.

Keywords: Cylindrical bending; Finite elements analysis; Residual stress; Spring back

1. Introduction

Cylindrical sections or ferrules are used in many engineering applications like pressure vessels, heat-exchanger shells, and boiler chambers. They also form the major skeleton of oil and gas rigs. Rolling machines with both three and four rolls are indispensable to the production of ferrules with various curvatures [1-3]. To date, research on the cold cylindrical bending process has been done using only analytical and empirical models. Yang and Shima [4] have discussed the distribution of curvature and calculated bending moment in accordance with the displacement and rotation of rolls by simulating the deformation of a workpiece with a U-shaped cross-section in a three-roller bending process. Hua et al. [3] have proposed a formulation to determine the bending force on rollers, the driving torque, and the power in the continuous single-pass four-roll bend of thin plate. Gandhi and Raval [5] have developed analytical and empirical models to estimate explicitly the top roller position as a function of the final radius of curvature for the three-roller cylindrical bending of plates.

In the present paper, the three-roller bending process parameters were studied using two-dimensional dynamic explicit finite element (FE) analysis. As schematically shown in Fig. 1, the sheet metal was fed by two side rollers from point A, bent to an arbitrary curvature by adjusting the position of the top roller, and then exited at point B. Afterwards, the workpiece was welded together to produce a ferrule. The rolling process always began with the crucial operation of pre-bending both ends of the workpiece (Fig. 2). This operation eliminated flat spots when rolling a full cylindrical shape and ensured better closure of the seam.

The success of the three-roller bending process heavily depends on the experience and skill of the operator. The work-
piece bend is generally produced via the multi-pass method, also named “trial and error” to optimize the bending capacity of the roller benders. Nevertheless, the multi-pass method suggests high costs owing to material wastage and loss of production time. The repeatability, precision, and productivity of the process require the use of a single-pass production method [5].

However, the latter method has always been a challenge because an operator must have knowledge of the different machine parameters to obtain ferrules with desired diameter. The parameters include the position of the top roller (U), distance between the bottom rollers (a), and thickness of the sheet metal (e).

2. FE modeling

The rolling process is complicated from an FE modeling perspective. Its common features with other forming processes include large strain plasticity, large displacements, and contact phenomena. However, this process seems to be more complicated than other forming processes. For instance, the workpiece is pulled into the roll gap by friction due to the motions of the upper and lower rollers.

To model the rolling process using Abaqus FEs code and to ensure the accuracy and efficiency of computation, many key techniques were taken into account, such as geometry modeling, assembling, treating of contact boundary conditions, definition of material properties, mesh, and so on [6]. These techniques are detailed in the following sections.

2.1 Modeling problem

Both implicit and explicit solution methods were tried to run successful simulations. The implicit method is favorable in models where large time increments can be used. Several attempts using the implicit method were made, but simulations were interrupted after a few rotation degrees. Given the nonlinearity of the problem and the severe contact conditions, using large time increments was not possible. Consequently, the explicit solution method seemed more suitable because very small time increments were needed in the problem. This choice of the dynamic explicit procedure has been confirmed by Han and Hua [7] using a model of the cold rotary forging process of a ring workpiece. The explicit dynamic analysis procedure was based on the implementation of an explicit integration rule using diagonal element mass matrices. The equations of motion for the body were integrated using the explicit central-difference integration rule [8], as shown in the following:

\[
\begin{align*}
\dot{u}_N^i(t + \frac{1}{2}) &= \frac{1}{2} \left( u_N^i(t) + u_N^i(t + \frac{1}{2}) \right) + \frac{1}{2} \left( \Delta t_{i+1}^N \right) \cdot \ddot{u}_i^N, \\
\dot{u}_N^i(t + 1) &= \Delta t_{i+1}^N \cdot \ddot{u}_i^N(t + \frac{1}{2}) 
\end{align*}
\]

where \( u_N^i \) is a degree of freedom and the subscript \( i \) refers to the increment number in an explicit dynamic step.

The different steps are detailed in the following sections.

2.2 Modeling problem

The entire three-roller bending process model was made up of a workpiece and rollers. The sheet steel was defined as a deformable body, and the rollers, which were not deformable, were defined as discrete rigid bodies. Each of these rigid bodies was assigned to a reference point (RP) to represent its rigid motion in all degrees of freedom.

2.3 Material properties

The rollers were made from C46-forged carbon steel, and were presumed to be rigid bodies. A steel sheet was assigned as a deformable body. The material properties of S275JR steel were defined using Young’s modulus \( E \), density \( \rho \), and Poisson’s ratio \( \nu \). To determine the plastic behavior of the steel, a conventional stress-strain curve was obtained from a uniaxial tensile test (NF A 03-151), as presented in Fig. 3. Isotropic elasticity behavior was assumed, with Young’s modulus of 210 GPa and Poisson’s ratio of 0.3. Strain hardening was described using several points of tensile stress versus plastic strain over the yield strength (290 MPa) and below the tensile strength (489 MPa). The dynamic explicit method was used in the computation, and the weight of the sheet was taken into account. The steel density used was 7800 kg·m⁻³. Mass scaling greatly affects computational results; a greater is the mass scaling the shorter is the computation time. However, very high mass scaling can lead to an unstable solution. In the present work, the optimized mass scaling parameter was found to be 3000 times.

2.4 Contact definition

The finite element code Abaqus uses surfaces to describe contacts and interactions between different parts of a rolling machine. A master–slave contact approach is used in an analysis where the rollers are considered as the master surfaces, and the sheet surfaces facing the rollers constitute the