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Abstract: A roll-bending process that minimizes the flat areas on the leading and trailing ends of formed plates will produce more accurate and easier assemble final shapes. There are several methods of minimizing flat areas, but they are costly or difficult to apply for thick plates. This study proposes a new, simple approach that reduces these flat areas. This approach includes moving the bottom roll slightly along the feeding direction and adjusting the bottom roll location. Sensitivity analyses were performed using a developed 3D dynamic FE (finite element) model of an asymmetrical roll-bending process in the Ansys/LS-Dyna software package. Simulations were validated by experiments run on an instrumented roll-bending machine. The FE results indicate that this new approach not only minimizes the flat areas but also reduces the forming forces.

Key words: Roll-bending process, flat end areas, dynamic FEM simulation, Ansys/LS-Dyna.

1. Introduction

Roll bending is an efficient metal forming technique, where plates are bent to a desired curvature using forming rolls. This type of sheet forming process is one of the most widely used techniques for manufacturing axisymmetric shapes. Moreover, this process is beginning to be taken into serious consideration by industries for producing large, thick parts such as the thick, conically shaped crown of a Francis turbine runner or of a wind turbine tower [1].

Over the past few decades, several bending machines were developed to adapt to various forming production specifications. However, these can be classified into two major types of roll-bending machines in the current market: three-roll models and four-roll models. For three-roll models, depending upon the setup location of the forming rolls, they can be arranged in two groups: three-roll pyramidal models and three-roll asymmetric models. The roll-bending process is a continuous type of three-point bending, where the basic principles and operations can be found in Refs. [2-4]. Although the roll-bending process can be performed for a wide range of cylindrical parts, for heavy to extremely thick plate applications, there are several issues that limit its application more widely in metal forming. One of them is the flat areas that are left at the leading and trailing edges of the final shape when the process is completed as shown in Fig. 1.

Forming parts with minimal flat areas on the leading and trailing ends are easier to assemble by welding and obtain a more accurate final shape. However, studies on the mechanisms that produce flat areas are still limited in the literature. Typical studies focus mainly on analyzing the bending mechanism. Hua et al. [5-11] conducted a considerable amount of research studying the four-rolls bending process to understand the bending mechanism. Hu et al. [12] applied an FEM (finite element model) to the study of the mechanism of

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Fig. 1 Flat areas left by a roll-bending machine.

the roll-bending process. Analyses of the pyramidal three-roll-bending process and the asymmetrical three-roll-bending process can also be found in Refs. [13-15]. Zeng et al. [16], Feng et al. [17-19] and Tran et al. [20-24] developed FE (finite element) models using Ansys/LS-Dyna to simulate the three-roll-bending process. However, an analysis of the flat lengths that remain at both ends of the final shape has not been addressed.

The mechanism of the roll-bending process inherently produces a certain amount of flat area at the leading and trailing edges of the part. It is observed that this amount of unbent area depends on the machine type. Usually, a three-roll asymmetric model leaves a smaller flat area at the leading and trailing ends of the final shape relative to a pyramid-type model because the workpiece is held more firmly in Ref. [3]. Zhong et al. [25] analyzed the straight-end problem in a thin-plate, pyramid-type machine through the development of an analytical method. However, the authors did not discuss the flat areas produced by a three-roll asymmetric machine and did not propose a method to reduce these. Therefore, Tran et al. [24] expanded to study in additional detail the effect of the rolls setup on the length of the flat areas in this study. To reduce or even eliminate the unbent areas, a number of methods can be applied such as: (1) forming a small amount of extra length at each end and subsequently cutting them off or (2) hand hammering the flat end. However, these techniques are costly or difficult to apply for thick plates made of high-strength steel.

Therefore, to obtain a better circularity for the final shape, the most common method used is to pre-bend both ends of the workpiece using the roll-bending machine. This is done by inserting the leading end of the workpiece into the machine. A short section of the plate is fed for pre-bending, and subsequently, the rotation of the rolls is reversed to remove the part. The pre-bending operation is then repeated at the other end of the blank. However, this is a drawback because the plate must be handled twice for pre-bending and requires more intensive labor at the production stage and additional safety measures.

The effect of moving the bottom roll to the left hand side by a distance d_i as shown in Fig. 2a and adjusting the bottom roll to a "gap" value g_i (Fig. 2b) on the flat ends length is presented in this paper. The goal is to propose a new approach to minimize the apparent flat ends and to reduce the forming forces.

The paper is divided in six sections. The content is as follows: Section 2 introduces the asymmetrical roll bending machine setup and flat areas definition; Section 3 details the FE model of the asymmetrical roll bending process; Section 4 presentes experimental study to validate the FE model; Section 5 is the discussion about the results; and Section 6 summarizes key conclusions of this research.

2. Asymmetrical Roll-Bending Machine and Flat Areas Definition

In this study, an asymmetrical roll-bending machine is used to shape a plate of thickness *t* as shown in Fig. 3.

The radius R of a formed cylindrical shape depends on the position of the lateral roll [19] and can be expressed in Eq. (1):

$$R = \frac{a}{2} \left[\frac{a \sin^2 \theta}{2r + t \cdot a \cos \theta} - \cos \theta \right]$$
(1)

where,

a: center location of lateral roll along action line;

r: radius of the rolls;

t: thickness of workpiece; and

 θ . operating action line angle of offset cylinder.



Fig. 2 Varying the location of the bottom roll: (a) offset d_i , and (b) "gap" value g_i .



Fig. 3 Three-roll asymmetric bending machine.

The top roll is in a fixed position, while the bottom roll has an adjustable up and down displacement to pinch the workpiece and to allow for the removal of the finished workpiece. The workpiece is fed and "pinched" between the top roll and the bottom roll; the lateral roll location can be adjusted to achieve the desired radius of the final shape. At the end of the forming process, a cylindrical shape with a radius R is obtained if the length of the blank equals the developed length of the cylindrical shape and if the lateral roll is properly positioned. However, the workpiece must remain supported at all time by the rolls as mentioned previously. The process continually produces flat areas along the leading and trailing edges of the workpiece where the plate cannot be completely bent as shown in Fig. 4.

3. FEM of the Asymmetrical Roll-Bending Process

To study the flat areas produced by the roll-bending process, a 3D numerical FE model of an asymmetrical roll-bending machine described in the above section was developed in the Ansys/LS-Dyna software package. The FE model consists of four main components: three rigid rolls and one flexible plate, which are illustrated in Fig. 5. The rolls are considered to be rigid in comparison with the deformable workpiece.

To describe the nonlinear behavior of the stress-strain curve of the workpiece, a material model obeying the Ludwik-Hollomon equation is used for this nonlinear analysis. Ludwik-Hollomon's equation relates the stress to the amount of plastic strain as a power law.

$$\sigma = K\varepsilon^n \tag{2}$$

where,

 σ : the stress;

K: material constants;

 ε : the strain;

n: study hardening exponent.



Fig. 4 Flat ends definition.



Fig. 5 FE model of the asymmetrical roll-bending process.



Fig. 6 Stress-strain curve.

The constants K and n are approximated by a curve fitting based on the results from a tensile specimen. Fig. 6 shows the stress-strain curves for the tensile testing model and the approximation model obtained by Ludwik-Hollomon's equation. The rate sensitive PLAW (power law) plasticity model in Ansys/LS-Dyna applied determine is to the stress-strain behavior of the workpiece.

The interaction between the rigid and flexible components is characterized through contact surfaces. In this roll-bending model, the surface of the roll is smaller than the surface of the blank. Although in the explicit analysis, Ansys/LS-Dyna supports a large number of contact options to define the interaction between the surfaces. The automatic node-to-surface algorithm was used for the interaction between the rolls and the plate because this type of surface contact is efficient when a smaller surface comes into contact with a larger one. In addition, the static friction coefficient (μ s) between the plate and the rolls is directly measured via experiments.

For the boundary conditions, the top and bottom rolls are driven in rotation and fixed in translation. The lateral roll is constrained in translation and experiences no self-rotation to press the forming plate against the top roll.

4. Experimental Study to Validate the FE Model

To validate the FE model developed in Ansys/LS-Dyna, experiments are conducted using the same parameters on an asymmetric roll-bending machine. This instrumented roll-bending machine has three rolls with diameters of 100 mm, roll length of 1,500 mm and an operating action line angle of the lateral roll (i.e., θ) of 600 is shown in Fig. 7.

The final shape radius from the experiments obtained by the roll-bending machine is measured by an EXAscan laser scanner. This device is a hand-held laser system that allows for quick and accurate geometry data acquisition for verifying the characteristics of a formed plate.

Fig. 8 shows the flat ends at the leading and trailing edges of the cylinder shape in Ansys/LS-Dyna when the roll-bending process is completed.

To compute the flat-end lengths of the formed plate from the FE simulations in Ansys/LS-Dyna, a numerical procedure is applied as summarized in Fig. 9.



Fig. 7 Instrumented roll-bending machine.



Fig. 8 Final shape obtained by the FEM.



Fig. 9 Flat end and radius computational procedure.

Because the nodes of the formed plate are distributed along a cylindrical geometry, the coordinates of the center of the cylinder x_C , y_C and its radius R_0 are determined using the least-squares method:

min F(x_c, y_c, R_0) with F = $\Sigma (R_0 - R_i)^2$ (3)

where,

$$R_i = [(x_i - x_c)^2 + (y_i - y_c)^2]^{1/2}$$

with $x_i = x_i^{(0)} + u_{xi}$ and $y_i = y_i^{(0)} + u_{yi}$.

With grad (F) = 0, three nonlinear equations are simultaneously solved for x_c , y_c and R_0 . Only the initial coordinates $x_i^{(0)}$, $y_i^{(0)}$ and the displacements u_{xi} and u_{yi} of the nodes located at the mid-width of the plate are imported into MatLab® for numerical processing. A Newton-Raphson scheme is subsequently applied to determine the circle's parameters.

We assume that the nodes at the mid-width and at the trailing or leading edges of the formed plate in Fig. 8 are distributed along a geometry as shown in Fig. 10.

To determine which nodes at the leading or trailing ends belong to a straight line, based on a number of flatness criteria, a least-squares method was applied to compute the constants p_i and b of the best straight line y= $p_i x + b$ passing through nodes [1, 2, 3, ..., i + 1].

With $\Delta = 0.2 t/R$, the criterion for flatness, a node i + 1 is considered to belong to the flat end if and only if the new slope p_{i+1} satisfies Eq. (4):

$$|p_{i+1} - p_i| \le \Delta \tag{4}$$

The procedure is terminated when adding a new subsequent node does not satisfy Eq. (4). The final shape radius R is then recomputed following Eq. (3) with the remaining nodes, i.e., by removing the flat-end nodes from the initial node list.

It is costly to run a large number of experiments to study how the flat areas are related to the setup. Therefore, the idea is to compare the final shape radius *R* obtained by both the FE model and the experiment under the same forming conditions. The FE model is used to study the parameters affecting the extent of the flat areas. Fig. 11 shows comparisons of the final shape radius *R* for various plate thicknesses, i.e., t = 1.0, 1.5 mm, 2.0 mm or 2.5 mm for four different locations of



Fig. 10 Flat end lengths computational procedure.



Fig. 11 Final radius dependence of the plate thickness and the location of the lateral roll.

the lateral roll, i.e., a = 110.0 mm, 115.0 mm, 120.0 mm or 125.0 mm. The final shape radii *R* obtained by the FE simulations (solid lines in Fig. 11) are slightly smaller than those obtained through experiments (dotted lines in Fig. 11). However, a deviation is observed with a highest difference of less than 8.0%, showing that the developed FE model is capable of accurately predicting the geometry of the formed plate.

5. Results and Discussion

The flat-end length for any given final shape obtained by the roll-bending process depends on the machine type, workpiece thickness, final radius, roll positions and even the operators' skills. In this study, correcting the position of the bottom roll of the roll-bending machine is considered as a method to reduce the forming forces and flat ends on the leading and trailing edges of the final shape. Correcting the positions of the bottom roll involves moving this roll in the horizontal plane and lowering it vertically. Although it is not possible to eliminate the flat areas inherent to the process, the challenge for future roll-bending machine designs is to minimize these areas.

5.1 Moving the Bottom Roll in the Horizontal Plane

To study the flat areas' dependence on the bottom roll positions, the FE simulations were performed using plates 2.0 mm thick, 100.0 mm wide and having a center to center distance "*a*" (Fig. 3) from the top roll to the lateral roll of 115.0 mm. While keeping the same input parameters, i.e., the roll radii, material properties, mesh, etc., the position of the bottom roll was moved to the left hand side for various distances d_i . Fig. 12 shows the values of the forming forces' dependence on d_i , which is expressed as a function of r, ranging from 10.0% to 70.0% of the bottom roll radius.

The forming forces, for both the top and bottom rolls, quickly decrease when the bottom roll is moved away to the left hand side by a distance d_i of 20% of r. The forces then slowly decrease when the bottom roll is moved to a distance d_i that is larger than 20% of r. Meanwhile, the forming force on the lateral roll (q_1) remains unchanged for every distance d_i . Fig. 13 shows the instantaneous free-body diagram of the system's roll-bending process, including the contact forces q_i and their respective angles θ_i . The equilibrium of the moments at point P_2 leads to Eq. (5):

$$\sum M_{(P_2)} = 0$$

leading to $q_3 s_3 = q_1 s_1$ (5)

where, s_1 and s_3 are the arc lengths of P_1P_2 and P_2P_3 , respectively.

The contact angle between the rolls and the plate varies when the bottom roll is moved to the left hand side. However, the value of s_1 remains quasi-constant. This may explain why the forming forces of the lateral roll do not change in Fig. 12.

The flat ends for various positions d_i of the bottom roll are shown in Fig. 14. Knowing that the larger flat end is usually left at the leading end of the final shape [3], only the flat-end length at this edge is studied in this research.



Fig. 12 Forming forces on the rolls versus the values of d_i of the bottom roll.



Fig. 13 Free body diagram of the roll-bending process.



Fig. 14 Flat-end length at the leading end versus the distance d_i of the bottom roll.

The value of the flat-end length of the final shape was determined to be monotonically decreasing when the bottom roll is moved to the left hand side by a distance d_i of 10% of r. This is because at this position, the bottom roll is not only used to "pinch" the plate but,



Fig. 15 Plate configuration when the bottom moves horizontally.

it is also used to support the plate at the contact line c (Fig. 15). The plate is therefore more efficiently bent with the lateral roll.

5.2 Moving the Bottom Roll in the Vertical Plane

The bottom roll of the three-roll asymmetric model was adjusted (up or down) in the vertical plane to compensate for the various plate thicknesses and to provide the pressure needed for "pinching". Therefore, choosing the matching "gap" between the top and the bottom roll is very important when using the roll-bending process. For example, if the bottom roll pressure is too tight, the final shape obtained may be a bell-mouthed shape. To avoid this defect, the bottom roll should leave a gap that is equal to or greater than the plate thickness.

To study the "gap" effect on the flat ends and the forming forces, a series of FE simulations were performed for various values of the "gap" g_i . These "gap" values range from 10.0% to 30.0% of the plate thickness. The center locations of the top and bottom rolls were placed on the same vertical axis. For this FE simulation, the forming parameters and the material conditions held constant were the 2.0 mm plate thickness, 100.0 mm plate width and 115.0 mm center-to-center distance "a" from the top roll to the lateral roll. The forming forces versus the "gaps" g_i are shown in Fig. 16.

The top and bottom forces tend to decrease when the

value of g_i increase. A rapid decreasing tendency is observed when the "gap" is set to 5.0% of the plate thickness. The forming forces then slowly decrease when the "gap" value continually increases, up to 30% of the plate thickness. The forming force of the lateral roll remains nearly constant for all the values of g_i .

Fig. 17 shows the flat-end length variation's dependence on the "gap" value g_i . The flat-end length monotonically increases when g_i is less than 15% of the plate thickness. Over this last value, the flat-end length is nearly unaffected when the "gap" continues to open.

This interesting phenomenon can be explained with the help of Fig. 18. The plate is held less firmly when the "gap" in-between the top and bottom rolls is larger than the plate thickness. For these cases, the plate tilts with an angle ε (dotted lines in Fig. 18), leading to a less bent plate.





Fig. 16 Forces of the rolls versus the "gaps" values $g_{i.}$

Fig. 17 Flat end versus the opening "gap" values g_i .



Fig. 18 Varying plate contact lines with rolls when moving the bottom roll downward.

Because the plate cannot be bent sharply, a larger amount of the blank at the leading edge remains flat.

6. Conclusions

A dynamic FE model was developed in the Ansys/LS-Dyna environment and was validated satisfactorily through experiments. In this study, we show how the flat-end lengths and forming forces are affected by the bottom roll setup. It is seen that by moving the bottom roll to the left hand side, the flat areas can be minimized, and the forming forces will be reduced on the top and bottom rolls. However, by adjusting the bottom roll with a "gap" value greater than the plate thickness in the vertical plane, the forming forces on the top and bottom roll are also reduced, but the flat area increases slightly. Therefore, in conclusion, maintaining the bottom roll at a gap close to the plate thickness and moving it laterally will produce the best results: lower forming forces and shorter flat-end lengths.

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