Simulation of a Two-Roll Straightening Process and Analysis of Residual Stress After Straightening

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Abstract — Residual stress was an important factor for subsequent machining accuracy of bar. Two-roll straightening process in a roll mill was simulated by large commercial finite element software. The change of stress in two-roll straightening process and the distribution of residual stress after straightening was revealed. The surface residual stress of bar after straightening was tested by blind-hole method. The result of test was compared to the simulation result, and they were approximated.

Keywords - Two-roll straightening; Residual stress; Numerical analysis; Blind-hole method

I. INTRODUCTION

Two-roll straightening is an important step for bar straightness and it decides the final production accuracy and quality of bar [1]. The distribution of residual stress after straightening has an important influence on subsequent processing. But two-roll straightening is a complex process with repeated elastic-plastic deformation [2]. Each elastic-plastic deformation would cause stress changing and would have an influence on the final residual stress. Two-roll straightening process involves multiple nonlinear problems including geometry, material and contact [3]. Traditional straightening theory and analytical method can not accurately calculate stress changing during two-roll straightening, so it is difficult to grasp the residual stress distribution of bar.

Many scholars studied on two roll straightening. Cui Fu[4] held that the straightening roll shape was consisted of three arcs with different curvatures; A.M.Максимов [5] simplified roll shape as a double-arc shape; Du Xiaozhong [6] solved the roll shape by conjugate surface theory; Das Talukder, N.K. [7-8] proposed an analytical procedure that predicted the evolution of bar straightness; Kuboki et al [9] investigated the straightening of tubes, for which stamping plays a major role.

With the development of computer and finite element method (FEM), many complex issues can be effectively solved. FEM simulation is not only with less investment and short period, but also obtains a lot useful information that can not be got by experiment. Many scholars at home and abroad simulated the two-roll straightening process, and a lot of analysis works on force parameters and process parameters during straightening have been done. For example, A. Mutrux [10-13] simulated two-roll straightening by LS-DYNA. Then a model with a small slice of bar was set up for simulation two-roll straightening process, the softening process of bar during the straightening process was analyzed. The deformation was also be studied with strain tensor methods by FEM. Asakawa. M [14] studied the maximum deflection of bar before and after it was straightened by simulation and experiment, and the bar with large curvature could be well predicted, but the prediction for the bar with small curvature was still not well. Liu yong [15-16] simulated two-roll straightening process by LS-DYNA and the influence of different straightening parameters on the straightening force and plate force was analyzed with the nonlinear finite element analysis technique. Zhang Zi-qian [17] used ANSYS/LS-DYNA for visual simulation of straightening process, the key parameters of straightening force model under different conditions were determined. Yanagihasi et al. [18] used a three-dimensional static explicit FEM approach of two-roll straightening in which only the deformation in bending was taken into account. But study on residual stress of big bar after straightening is very rare and the residual stress has an important influence on the subsequent machining precision.

The structure of two-roll straightener in this paper is shown in Fig.1. The straightening rolls include a concave roll and a convex roll. There is a device to adjust roll gap at the top and there is a protection device to prevent overload at the bottom. There are two guides at both sides of roll gap. The guide spacing can be adjusted by the adjustment device. In this paper, the FEM model is created based on Figure 1.

![Figure 1](image-url)

Figure 1. Structure of two-roll straightener

In following chapter, stress change of different points during straightening is analyzed, and the distribution of residual stress is studied. The surface residual stress of bar is tested by blind-hole method. The Mises stress of test points is computed. The results of test are compared to the FEM computed results, and they coincide. So the finite element model is reliable and the results can be referenced for future analysis.

II. FEM MODEL

Geometric Model

FEM model is as close as possible to the work site by referring to actual straightening in a mill. But in order to shorten the calculation time, 2m bar is created and the actual length is 6m. The diameter of bar is 120mm. There are sleeves near inlet and outlet of straightener in order to mitigate the impact of drift. Guides on both sides of straightener are used to prevent bar instability during straightening. Roller, sleeve and guide are assumed to be discrete rigid body. Overall mesh of model is shown in Fig.2. There are 20082 discrete rigid elements R3D4 and 29200 hexahedral elements C3D8R.

Material

Tensile test is done with bar specimen to obtain stress-strain curve. The material is elastic-plastic and Von Mises yield criterion is adopted. The Elastic modulus is 210GPa, poisson’s ratio is 0.3 and yield strength is 930MPa. Yield data obtained by tensile test is shown in table 1.

TABLE I. YIELD DATA OF TESTING

<table>
<thead>
<tr>
<th>Plastic strain</th>
<th>0</th>
<th>0.005</th>
<th>0.01</th>
<th>0.02</th>
<th>0.03</th>
<th>0.05</th>
<th>0.07</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength</td>
<td>930</td>
<td>990</td>
<td>1020</td>
<td>1060</td>
<td>1075</td>
<td>1100</td>
<td>1120</td>
</tr>
</tbody>
</table>

A. Boundary

Roller speed is computed based on actual straightening speed 10m/min. Angular speed is applied to the rollers in the model. An initial speed field is applied to the bar, so that bar can smoothly enter roller gap. The angle between concave roll and bar is 13.2°, the angle between convex roll and bar is 16.8°. The value of roll gap is 121mm. It is assumed that there is no friction between bar and guides, sleeves. But friction between bar and rollers is considered, and friction coefficient is 0.2.

III. ANALYSIS OF FEM RESULTS

The Mises stress contour of bar after straightening is show in Fig.3. Stress distribution shown in Fig.3(a) at both ends of bar is irregular because of impact, straightening blind area and taile-flick. For easy analysis, stable straightening region shown in Fig.3(b) is chosen. It is shown that surface stress distribution of bar is spiral and circular in stable area, and this is consistent with actual straightening process.

A. Change of Stress during Straightening

The cylindrical coordinate system is established at the center of bar cross-section. The changes of all stress components during straightening in this system are analyzed. Two points are chosen on the surface of stable straightening area. One is chosen with indentation and the curve of stress vs. time of this point is shown in Fig.4. The other one is chosen with no indentation and the curve of stress vs. time of this point is shown in Fig.5. S11, S22, S33 in Fig.4 and Fig.5 represents hoop stress, radial stress and axial stress respectively.
Through Fig.4 and Fig.5, it is shown that the stress of points is not changed before they enter roll gap or after they leave roll gap because there is no external force. During straightening, the values of stress change greatly due to the action by two rollers. When the two points are in roll gap, the tension-compression stress is main stress state due to bending. When bar is in the exit, there is line contact in some area between concave roller and bar, so there is a great compressive stress in this area, and spiral indentation emerges. The pressure of concave roll to the bar has little influence on the point with no indentation, so the value of radial stress of point with no indentation is much smaller than that of point with indentation. Through both Fig.4 and Fig.5, it can be shown that axial compressive stress is slightly larger than axial tensile stress when the two points are subject to continuous bending in the roll gap. After straightening, axial stress of the two points is compressive stress. This indicates that axial stress on the upper surface and lower surface is not symmetrical, so neutral layer is not in the center of bar during straightening and the migration of neutral layer should be considered in the theoretical calculation process.

B. Distribution of residual stress

The distribution of internal stress and surface stress of bar is analyzed respectively in order to fully grasp the stress state after straightening. Through above analysis, it can be seen that the stress state of points on the surface is mainly axial stress and radial stress, so followed that, the axial stress and radial stress of points on different paths inside and outside of bar is mainly analyzed.

C. Distribution of surface residual stress

The points of four lines on the surface are chosen as four paths. These four lines are evenly distributed in circumferential direction. Radial stress and axial stress curves of points in these four paths are shown in Fig.6 and Fig.7 respectively.
Through Fig.6, it can be seen that the distribution of radial surface residual stress is very regular and the radial stress cyclically changes by lead. This is because the bar is continuous rotating and bending in the straightening process, and there is line contact between bar and concave roll at the exit. So the spiral indentation on the surface of bar is generated and this is consistent with the actual production in a steel plant. The radial stress exists at the bar surface indentation after straightening, and the value of stress is about 250MPa. Through Fig.7, it can be shown that the axial surface residual stress is all compressive stress and the values of compressive stress are between 200MPa and 400MPa, the average value is probably around 300MPa. The curve of axial stress on different paths presents a certain periodicity and the periodic coincides with the radial stress, but amplitude of each cycle largely changes.

D. Distribution of Internal Residual Stress

By analyzing the FEM result, the radial stress inside bar is very little, so axial stress is analyzed only. Besides the stress along a diameter path is substantially symmetrical, so paths on the half-section are chosen and the paths are shown in Fig.8. The axial stress curve on the paths is shown in Fig.9.
Through Fig. 9, it can be seen that the stress close to the surface is axial compressive stress, but the stress near the axis of bar is axial tensile stress. The values of stress near the axis are smaller than that near the surface. This shows that neutral layer is not in the central position and the migration of neutral layer should be considered in the theoretical calculation of straightening.

IV. BLIND-HOLE TEST

The surface residual stress test of bar after straightening is done by blind-hole test. The procedure of residual stress test is as follows.

1) The lead is calculated according to the calculation formula $p = \tan(\beta)$. Six collinear points are chosen within one lead and they are equally spaced. But the six points within one lead is too close and the residual stress of other measuring points would be affected during drilling process. Therefore, in order to avoid this case, it is assumed that the stress distribution is same in each lead of stably straightening area. So one lead distance is added to the spacing distance between the six points. The new six points are approximate thought that they are equally spaced within one lead. Only the stably straightening area is tested because stress at both ends of bar is irregular due to impact, straightening blind area and taile-flick.

2) The surface around the test points is cleaned and then rosette is pasted. In this test, the rosette type is TJ120-1.5-Φ1.5. Its sensitivity coefficient is $2.07 \pm 0.01$ and its nominal resistance is 120Ω.

3) The wires of rosette are connected to the static strain gauge. The type of static strain gauge is XL2101B5+.

4) The center of rosette is drilled by a professional drill.

5) Strain test data is collected and the stress is calculated by following formula.

$$\sigma = \sqrt{\sigma_1^2 - \sigma_2 \sigma_3 + \sigma_3^2}$$  \hspace{1cm} (2)

Where $\sigma_1$, $\sigma_2$, $\sigma_3$: primary stress; $\varepsilon_1$, $\varepsilon_2$, $\varepsilon_3$: release strain; $A$, $B$: stress releasing factor(MPa-1); $\beta$: the angle between primary stress and 0°, 90° reference axis of strain gauge.

The equivalent stress is calculated based on primary stress by following formula

$$\sigma = \frac{\frac{2}\sqrt{2} \sigma_1 + \sigma_2 + \sigma_3}{4} + \frac{1}{4} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}$$  \hspace{1cm} (1)

V. COMPARISON OF RESULTS BETWEEN FEM AND TEST

The accuracy of residual stress measurement result by blind-hole method is related to many factors such as pasting quality of rosette and hole deviation. The test error caused by some of human factors such as pasting quality can be minimized through careful operation during the test. In the process of extracting data, if the data is too large or significate distortion caused by the damage of rosette during drilling, the data should be removed and this point is considered to be invalid. Because the distribution of residual stress within each lead is basically same, the Mises stress only within one lead is compared between test and FEM. The result is shown in Fig.10.

From Fig.10, it can be shown that the test values of surface Mises stress are within 400MPa and most of them are around 250MPa. The maximum results of FEM is close to 500MPa. This is because the residual stress measured by
blind-hole method is plane stress, while there are radial compressive stress especially in the indentation area.

VI. CONCLUSION

(1) The bar bends in the roll gap due to effect of concave roll and convex roll during straightening and the maximum axial compressive stress of points on the surface is larger than the maximum axial tensile stress. Spiral indentation is generated due to the line contact between bar and concave roll and there is large radial compressive stress in the region of indentation.

(2) The surface axial stress is compressive stress and the center axial stress is tensile stress. The migration of neutral layer appears during bending, and this should be considered in the theory calculations.

(3) The numerical result is close to the test result. However, because there is radial stress on the surface, the numerical result is larger than the test result.

(4) The following work is that measures should be taken to eliminate the surface indentation and minimize the axial residual stress.

Conflict of interest

The authors confirm that this article content has no conflicts of interest.

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REFERENCES


