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JOURNAL OF IRON AND STEEL RESEARCH, INTERNATIONAL. 2016, 23(7): 669-676

Curvature and Residual Stress Analysis in Rotational Leveling of Bars

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Abstract: Leveling process plays an important role in delivering the desired material properties and product standards. An analytical method for the rotational leveling process of bars was presented. First, each cross section of the bar in the leveling area was discretized with the roller gap-curvature relations established in both planes XY and XZ. Second, a numerical procedure with two steps was developed to simulate both pressing and leveling processes. This approach can be easily implemented to produce simulation results of the curvature and trajectory distributions during the leveling process, as well as the bending and residual stresses. It is found that curvature and trajectory distributions follow a sine-shape due to the characteristic of rotational movement, which also results in a helical pattern of residual stress after leveling. Based on the results obtained, it is also observed that the rotational movement is beneficial for adding the number of bending cycle. This is the reason why there are only a few pairs of rollers on the bar leveler.

Key words: rotational leveling process; bar; curvature; trajectory; residual stress

Symbol List

d_Y—Coordinate increment of the nodes in the Y direction;
d_Z—Coordinate increment of the nodes in the Z direction;
$d\varepsilon_{YZ}^{\mathrm{I}}$—Strain increment due to forward movement;
$d\varepsilon_{YZ}^{\mathrm{II}}$—Strain increment due to rotational movement;
$d\kappa_Y$—Local curvature increment in the Y direction;
$d\kappa_Z$—Local curvature increment in the Z direction;
E—Young's modulus;
J—Elements number between adjacent rollers;
l—Pitch of the helical trajectory of point A;
M—Node number circumferentially;
M_y—Inner moment in the plane XY;
M_Z—Inner moment in the plane XZ;
N—Node number radially;
n—Evolution number of any cross section of the bar between adjacent rollers;
p—Distance between adjacent rollers;
r—Radius of the bar;
T—Periodic time of the helical curve;
v_{T}—Velocity component of the roller tangentially;
v_x—Velocity component of the roller axially;
Y_{ij}—Horizontal coordinate of node ij;
Z_{ij}—Vertical coordinate of node ij;
α—Angle between upper and lower rollers;
δ—Reduction of middle rollers;
θ—Initial bending angle;
θ_i^Y—Contact angle in the XY plane;
θ_i^Z—Contact angle in the XZ plane;
κ_0—Initial curvature;
κ_Z—Bending curvature in Z direction;
κ_i^Y—Bending curvature in the XY plane;
κ_i^Z—Contact angle in the XZ plane;
ρ_0—Initial bending radius;
ρ_Y—Bending radius in the plane XY;
ρ_Z—Bending radius in the plane XZ;
$\sigma_{ij\,\mathrm{Res}}$—Residual stress of node ij;
σ_s—Yield stress of the bar;
σ_{YZ}^t—Stress at current step;
σ_{ij}—Stress of node ij;
ω—Angular velocity.

Due to improper set-up of roller gap during rolling and cooling process, shape deviation in bending often occurs. Such bending defects together with the incurred residual stress affect further manufacturing process. The rotational leveling process is designed for all-dimensional shape improvement of bars. To

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ensure effective correction of the aforementioned defects and improve the quality in the production of bars, it is necessary to develop an effective and robust model to simulate the leveling process and minimize the bending defect.

The leveling process, based on the literature survey, has been used to straighten strips, plates, profile steels, wires, pipes and bars historically. It is easier for strips and plates with regard to the leveling method because there is no rotational movement and rollers contact directly with the surface of the strips and plates during the leveling process. Higo et al.[1] proposed a model using curvature integration method to formulate the relationship between the curvature and reduction of rollers for plate. Xue et al.[2] attempted to use a decoupled method to modify Higo′s model for finding curvature distribution. The leveling method of profile steels is slightly more complicated than those of strips, sheets and plates for profiled components[3-8]. The profile of rollers for bars is not a cylindrical surface anymore but an envelope surface used to achieve the required leveling stability and effectiveness. The profile of a tube-straightening roller can be determined by FEM[9] and the envelope theory[10]. Huh et al.[11] carried out an optimization study of the Al7001T9 pipe leveling process parameter for a multi-staggered-type 14-roller leveler with a finite element model in comparison with the experimental result. The effects of roll inclination and crushing on the roundness of a tube and the leveling of a bar by finite element (FE) analysis were examined by Yoshimura et al.[12] and Liu et al.[13]. Wu et al.[14] developed a mathematical model to study the straightening process of a bar in a two cross-roll straightener. Mutrux et al.[15] simulated the cross-roll leveling process for a bar using LS-DYNA FEM software and predicted the curvature reduction.

Little attempt has been made by analytical method for the bars leveling because of the complexity of 3-D deformation behavior according to aforementioned discussion. This paper presents a detailed analytical model to predict the leveling process for bars.

1 Analytical Model of Leveling Process

1.1 Principle of rotational leveling process

In this paper, the bar leveling process is conducted by a six-roller leveler (2-2-2 rollers), as shown in Fig. 1. The upper and lower rollers are mounted face to face with an angle of inclination, α, to the axis of feed direction. This structure can ensure stability of the leveling process. The two middle rollers move downward together for achieving necessary bending. The bar is forced into elastic-plastic deformation due to the all-around directional bending exerted by the gaps. The rotational movement is driven by the friction between the bar and rollers. The leveling process can be considered as a continuous alternating bending and reverse bending process.

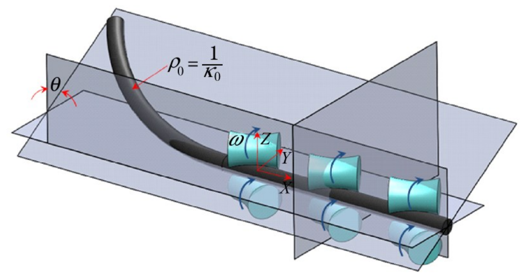

Fig. 1 3-D model of finish-roller leveler (2-2-2 roller system)

A particular characteristic of bar leveling shown in Fig. 2(a) is the rotational movement during the leveling process compared with the leveling process of strips, plates and profile steels. There are two directional bending states even for a bar with a single initial curvature. Taking the bar shown in Fig. 2(b) as an example, the bending bar rotates to the position EFG if there is no constraint of the middle two rollers. However, the reduction of roller 2 in the plane XY and XZ are 0 and δ, respectively. Therefore, point F is pulled to point F' with a distance λ_Y and λ_Z in plane XY and XZ, respectively. The state of bending stress at each section of the bar is a combination of the stresses in planes XY and XZ. The deformation in plane XY is smaller compared to that in plane XZ in general. The trajectory of point P at the surface of the bar presents a bending helical curve during the leveling process shown in Figs. 2(a) and 2(d).

It is not easy to develop an analytical model to capture the main bending characteristic for the complex rotational leveling process with enough details for two reasons. One is that the leveling cannot be idealized as a simple periodic problem since the residual curvature and stresses for each cross section at the previous step are the initial conditions of the current step; the other is that the residual state cannot be superimposed directly because of a small rotational angle from the last step to the current step, as shown in Fig. 3. The positions of the tensile and compressive stress distributions change in the fixed