ISSN 0543-5846
METABK 60(1-2) 51-54 (2021)
UDC – UDK 621.771/539.378:387:669.15:629.11.012.1:(041)=111

FORMATION MECHANISM AND CONTROL OF THE SPIRAL MARKS OF THREE-ROLL SKEW-ROLLED HOLLOW AXLES

Received – Primljeno: 2020-07-11
Accepted – Prihvaćeno: 2020-10-25
Original Scientific Paper – Izvorni znanstveni rad

The spiral marks is one of the main surface quality defects of the three-roll skew rolled hollow axles. In order to eliminate the spiral marks, it is necessary to clarify the cause of the spiral marks on the surface of the rolled piece. Based on the analysis of the kinematics of the three-roll skew rolled hollow axles, the spiral marks is caused by the spiral pitch of the rolled piece being larger than the width of the finishing section of the roller. Increasing the rotation speed of the roller can reduce the spiral pitch of the rolled piece, thereby avoiding the appearance of spiral marks. The correctness of the proposed condition for preventing the defect of spiral marks is verified by simulation.

Key words: three-roll skew rolling, 30CrMoA steel hollow axles, spiral marks, simulation

INTRODUCTION

Three-roll skew rolling is one of the advanced forming methods for hot-rolled hollow axles. Defects such as spiral marks, ovalization of rolled pieces and uneven wall thickness may occur in the three-roll skew rolling of hollow axles, which affects the further application of this technology on hollow axles. Therefore, many scholars are studying the three-roll skew rolling technology. Hwang et al. [1] discussed the effects of various rolling conditions, such as inclined angle, offset angle, roll shape, etc., upon the depth of spiral marks on the surface of the rolled product and rolling force through the finite element method. Three different types of roller-shaped work rollers were tested using a self-designed three-roller planetary rolling test machine. And measured the depth of the spiral marks. Pater et al. [2] described a three-roll skew rolling process for hollow Ti6Al4V alloy shafts used in light truck drive systems. Through the numerical simulation, the product shape changes, wall thickness distribution, effective strain, temperature, load and torque changes during the rolling process were analyzed. Zhang et al. [3] simulated the process of three-roll skew rolling hollow axles. The effect of different process parameters on the wall thickness uniformity of the rolled piece was studied, and the combination of process parameters that minimized the deviation of the wall thickness of rolled piece was obtained. In the simulation process, it is found that the surface of the rolled piece has serious spiral marks, but there is no in-depth study on the cause of the spiral marks. Pater et al. [4] introduced the CNC 3-roll mill of Lublin University of Technology, and conducted an experimental study on the process of three-roll skew rolling rail car axles with this mill. The study found that shallow helical grooves will appear on the surface of the rolled pieces. It is believed that the relationship between the process parameters and the helical groove defects should be further studied to prevent the occurrence of helical grooves defects. The above research only introduced the phenomenon of spiral mark defects on the surface of the three-roll skew rolled shafts. The formation mechanism of spiral marks has not been studied. In this paper, through the kinematic analysis of the three-roll skew rolling hollow axles, the formation mechanism of spiral marks on the surface of the rolled piece is expounded. The process parameters that affect depth of the spiral marks are pointed out. And through the simulation, the correctness of the above analysis has been verified.

KINEMATICS ANALYSIS OF THREE-ROLL SKEW ROLLED HOLLOW AXLES

The principle of three-roll skew rolling is that the three rollers rotate in the same direction to drive the rolled piece to rotate. And at the same time, the chuck pulls the rolled piece forward. Because the roller axis is inclined at a feed angle β relative to the rolling line (the rolling line in the three-roll skew rolling generally coincides with the axis of the rolled piece), the rolled piece advances while spirally rotating. And the rolling process is gradually completed. The principle of three-roll skew rolling hollow axle is shown in Figure 1.

The velocity vector analysis of any point in the deformation zone of the rolled piece during three-roll skew rolling hollow axles is shown in Figure 2. The O

S. Zhang, X.D. Shu, Y.X. Xia J.T. Wang. Ningbo University, School of Mechanical Engineering and Mechanics, Ningbo, China; X.D. Shu (Email: shuxuedao@nbu.edu.cn)

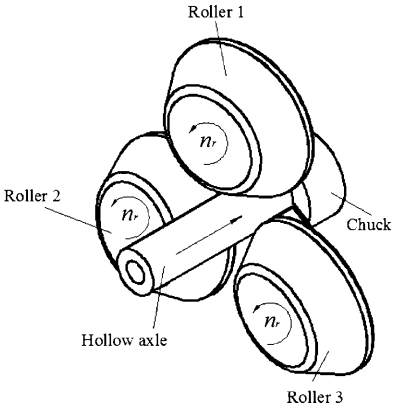

Figure 1 Principle of three-roll skew rolling hollow axles

point is defined as the center of rotation around the roller when adjusting the feed angle. The rotation axis is perpendicular to the rolling line at point O. The plane formed by the rotation axis and the rolling line is the principal plane of the rolling. The plane formed by the rotation axis and the roller axis is the principal plane of the roller. Take any point P in the deformation zone of the rolled piece as the origin of coordinates. The x-axis passes through the point P in the rolling direction. The y-axis passes through the point P along the tangential direction of the rolled piece. The z-axis is perpendicular to the rolling line passing through point P. View A-A is a projection perpendicular to the principal plane of the rolling along the rolling direction. View B-B is a projection perpendicular to the principal plane of the roller along the roller axis. β is the feed angle. γ is the angle between the z-axis and the principal plane of the rolling. j is the angle between the radius of the roller passing through point P and the principal plane of the roller.

Each point on the roller has the same angular velocity ω_r:

$$\omega_r = \frac{2\pi n_r}{60} \tag{1}$$

Where n_r is the rotational speed of the roller.

The linear velocity v_r of any P point on the roller is:

$$v_p = \omega_r \rho_p \tag{2}$$

Where ρ_p is the radius of gyration at point P on the roller.

The linear velocity of any point P on the roller in the deformation zone of the rolled piece is v_p. By analyzing the velocity vector at any point P in the deformation zone of the rolled piece, the components of the linear velocity v_p at the point P on the roller in the axial and tangential directions of the rolled piece are:

Axial: $u_{px} = \eta_x v_{px}$ (5)

Tangential: $u_{py} = \eta_y v_{py}$ (6)

Where u_{px} and u_{py} are the components of the movement speed of any point P in the deformation zone in the axial and tangential directions; h_x and h_y are the slip coefficients of any point P in the deformation zone in the axial and tangential directions, respectively.

The slip coefficient is generally taken from the actual measured value or empirical value of the existing equipment.

The tangential movement speed of any point P in the deformation zone can be expressed by the rotational speed of the rolled piece and the radius of the point:

$$u_{py} = \frac{2\pi n_b r_p}{60} \tag{7}$$

Where n_b is the rotational speed of the rolled piece; r_p is the radius of point P on the rolled piece.

With the equations (1), (2), (4), (6) and (7), the rotational speed of the rolled piece is:

$$n_b = \frac{\rho_p}{r_p} n_r \eta_y (\cos\phi \cos\beta \cos\gamma - \sin\phi \sin\gamma) \tag{8}$$

The distance traveled in the rolling direction for each revolution of the rolled piece is the lead Z_x:

$$Z_x = \frac{60}{n_b} u_{px} = 2\pi r_p \frac{\eta_x}{\eta_y} \frac{\cos\phi \sin\beta}{\cos\phi \cos\beta \cos\gamma - \sin\phi \sin\gamma} \tag{9}$$

Each time the rolled piece is processed by the roller, the distance along the rolling direction is the pitch z_x:

$$z_x = Z_x / 3 = \frac{2\pi r_p}{3} \frac{\eta_x}{\eta_y} \frac{\cos\phi \sin\beta}{\cos\phi \cos\beta \cos\gamma - \sin\phi \sin\gamma} \tag{10}$$

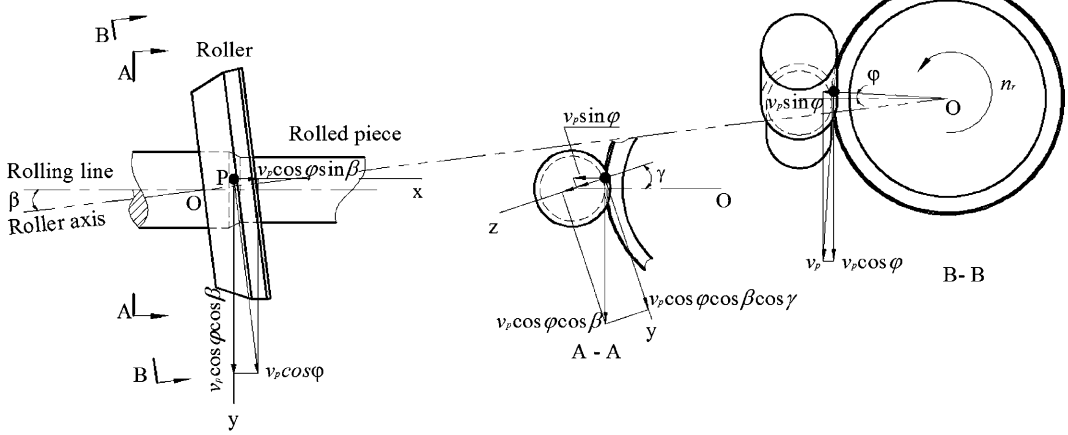

Figure 2 Velocity vector analysis of any point in the deformation zone of the rolled piece

DISCUSSION ON THE FORMATION MECHANISM OF SPIRAL MARKS ON THE SURFACE OF ROLLED PIECE

When three-roll skew rolling hollow axles, the O point of the rotation center is set at the interface between the conical part and the cylindrical part of the roller. And the P point is located on the axis of rotation. At this time, ρ_p is the maximum radius of the roller. r_p is the radius of the exit profile in the deformation zone of the rolled piece. Both γ and j are 0. Then the rotational speed of the rolled piece can be expressed as:

$$n_b = \frac{\rho_{\max}}{r_a} n_r \eta_y \cos\beta \tag{11}$$

Where ρ_{max} is the maximum radius of the roller; r_a is the radius of the exit profile in the deformation zone of the rolled piece.

The lead and pitch of the rolled piece along the rolling direction are:

$$\text{Lead } Z_x\text{: } Z_x = 2\pi r_a \frac{\eta_x}{\eta_y} \tan\beta \tag{12}$$

$$\text{Pitch } z_x\text{: } z_x = \frac{2\pi r_a}{3} \frac{\eta_x}{\eta_y} \tan\beta \tag{13}$$

According to equations (11), (12), and (13), when ρ_{max}, r_a, n_r, and β are constant, increasing the tangential slip coefficient can increase the rotational speed of the rolled piece, but it also increases the rolling time. Increasing the axial slip coefficient can not only shorten the rolling time, but also reduce the number of repeated rolling in the deformation zone of the rolled piece. The condition for preventing the formation of spiral marks is: $z_x<B$. B is the width of the finishing section of the roller.

In this paper, the axial speed of the rolled piece is set to a constant value. According to equations (8), (9) and (10), when point P is located on the axis of rotation, the lead and pitch of the rolled piece in the rolling direction are:

$$\text{Lead } Z_x\text{: } Z_x = \frac{60 u_x r_a}{\rho_{\max} n_r \eta_y \cos\beta} \tag{14}$$

$$\text{Pitch } z_x\text{: } z_x = \frac{20 u_x r_a}{\rho_{\max} n_r \eta_y \cos\beta} \tag{15}$$

According to the above equations and the condition for preventing the formation of spiral marks, when other parameters are fixed, the larger the rotation speed of the roller is, the less likely the spiral marks will appear on the surface of the rolled piece.

CONTROL THE ROTATION SPEED OF THE ROLLER TO OPTIMIZE THE SPIRAL MARKS

In order to verify that when the other parameters are constant, the larger the rotation speed of the roller is, the less likely the spiral mark defects appear on the surface of the rolled piece. In Simufact Forming software, the three-roll skew rolled hollow axles is simulated. The maximum diameter D of the roller is 176 mm. The width B of the finishing section of the roller is 10 mm. The rolling angle α of the roller is 20 °. The feed angle β is 5 °. The rolling temperature T is 1 050 °C. The axial velocity v_c of the chuck is 20mm/s. The test sample of the three-roll skew rolled hollow axles is shown in Figure 3. The billet diameter is 50 mm. The length is 210 mm. The material of the billet is 30CrMoA steel, and its constitutive relationship is as follows [5]:

$$\dot{\varepsilon} = 3,67\times10^9 \left[\sinh\left(0,011\sigma_p\right)\right]^{4,403} \exp\left[-261\ 850/RT\right]$$

Where $\dot{\varepsilon}$ is the strain rate /s^{-1}; σ_p is the peak stress; R is the gas constant (8,314 J·mol^{-1}·K^{-1}), and T is the temperature /K;

The friction model on the contact surface is shear friction. The friction factor m is 0,8. The heat transfer

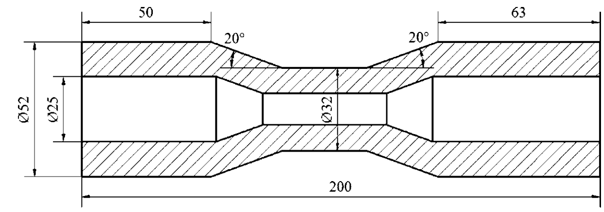

Figure 3 Test sample of three-roll skew rolled hollow axles

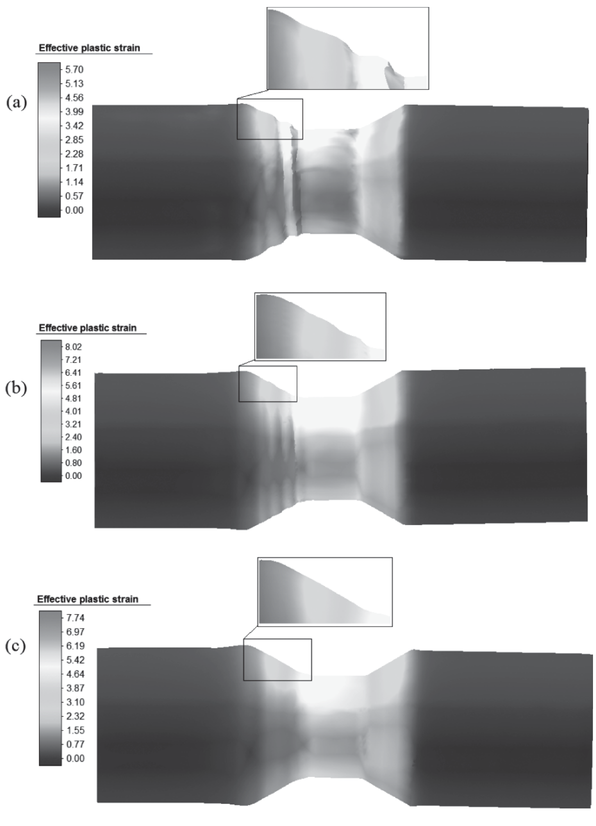

Figure 4 Spiral marks on the surface of the rolled piece at different rotation speeds of the roller (a) n_r = 20 rpm; (b) n_r = 30 rpm; (c) n_r = 40 rpm

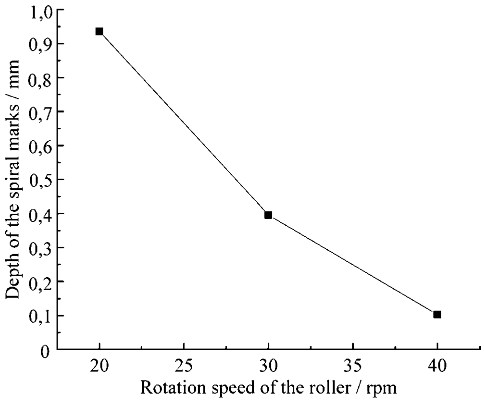

Figure 5 Effect of rotation speed of the roller on depth of the spiral marks

coefficient between the billet and tools is 1 × 104 W/($m^2 \cdot K$).

The spiral marks at different rotation speeds of the roller are shown in Figure 4. When the rotation speed of the roller is 20 rpm, severe spiral marks appear on the surface of the rolled piece. When the rotation speed of the roller is increased to 30 rpm, the spiral marks are alleviated. When the rotation speed of the roller rose to 40 rpm, there were no obvious spiral marks on the surface of the rolled piece. This shows that the rotational speed of the roller has a decisive influence on the formation of spiral marks on the surface of the rolled piece. The higher the rotational speed of the roller, the less likely the spiral marks to appear on the surface of the rolled piece.

The height difference between the lowest point and the highest point of the spiral marks on the surface of the rolled piece is defined as the depth of the spiral marks. The effect of rotation speed of the roller on depth of the spiral marks is shown in Figure 5. As the rotational speed of the roller increases, the depth of the spiral marks decreases significantly.This verifies the correctness of the proposed condition for preventing spiral marks. Therefore, in the three-roll skew rolling hollow axles, the largest rotation speed of the roller should be selected as much as possible.

CONCLUSIONS

The spiral marks of the three-roll skew rolling hollow axles is caused by the helical advancement of the rolled piece due to the deflection of the roller relative to the rolling axis by an angle. The formation condition of the spiral marks is that the spiral pitch of the rolled piece is larger than the width of the finishing section of the roller.

The rotation speed of the roller has a great influence on the formation of the spiral marks on the surface of the rolled piece. The higher rotation speed of the roller, the less likely the surface of the rolled piece to have spiral marks. In the actual rolling process, the rotation speed of the roller should be as large as possible according to the working conditions.

Acknowledgments

This research was supported by the National Natural Science Foundation of China [No. 51975301], and The Natural Science Foundation of Zhejiang [No. LZ17E050001].

REFERENCES

[1] Hwang Y. M., Tsai W. M., Tsai F. H., Her I.. Analytical and experimental study on the spiral marks of the rolled product during three-roll planetary rolling processes. Int. J. Mach. Tools Manuf. 46(2006)12, 1555-1562.

[2] Pater Z., Tomczak J., Bulzak T. Numerical Analysis of a Skew Rolling Process for Producing a Stepped Hollow Shaft Made of Titanium Alloy Ti6Al4V. Arch. Metall. Mater. 61(2016)2, 677-682.

[3] Zhang S., Shu X., Xu C., Wang J., Li Z. Research on wall thickness uniformity of hollow axles by three-roll skew rolling. ASME Int. Mech. Engineering Congress and Exposition, Proceedings (IMECE) (2019), 2A-2019.

[4] Pater Z., Tomczak J., Lis K., Bulzak T., Shu X. Forming of rail car axles in a cnc skew rolling mill. Archiv. Civ. Mech. Eng. 20(2020), 69.

[5] Shu X.D., Zhang S., Wang J.T., Shi J.N., Xia Y.X. Flow stress behavior of 30CrMoA steel under high temperature compression. Metalurgija 59(2020)3, 313-316.

Note: The responsible translator for English language is S. Zhang, Ningbo, China