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EFFECT OF PROCESS PARAMETERS ON THE SURFACE FORMING ACCURACY OF STEP OF HOLLOW STEP SHAFT FORMED BY THREE-ROLL SKEW ROLLING

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This paper adopts a three-roll skew rolling technology with rolls that can either converge or move apart to form shafts with variable cross-section dimensions. Based on the rolling pitch, the effect of rollers' rotation speed, radial speed, axial speed of chuck on the forming accuracy of the hollow shaft surface is analyzed. Increasing the rotation speed of rollers, reducing the radial speed of rollers and the axial speed of chuck can obtain higher surface forming accuracy. The finite element simulation results verified the correctness of the conclusion.

Keywords: alloy steel, three-roll skew rolling, hollow step shaft, forming accuracy, simulation

INTRODUCTION

The current production process of variable cross-section shaft parts is mostly forging or cross wedge rolling. Forging can be applied to blanks of different shapes, but with slow production efficiency and high cost. Cross-wedge rolling ensures production efficiency but the versatility of the mold is poor, and large-size mold is needed when producing a long axis. The three-roll skew rolling process is a new process for the near forming of shaft parts, which has the advantages of high efficiency, strong versatility and low investment. Pater et al. [1] described a skew rolling process forming a hollow Ti6Al4V alloy shaft. Shape progression, wall thickness distribution, effective strain, temperature and variations in loads and torques were analyzed. Zhang et al. [2] 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. Pater [3] presents a comparative analysis of skew rolling in 3- and 4-roll CNC rolling mills, an innovative concept of calibrating hollow axles by the rotary compression technique developed is presented. In summary, the research on the forming quality of three-roll skew rolling is relatively rare. This paper research the surface forming accuracy of the step of the hollow shaft in the three-roll skew rolling, the mechanism of surface defects in three-roll skew rolling is explained, the effect of process parameters is analyzed and verified by simulation.

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VELOCITY ANALYSIS OF THREE- ROLL SKEW ROLLING PROCESS FOR STEPPED SHAFT

The principle of three-roll skew rolling hollow axle is shown in Figure 1. The hollow piece is fixed in a freely rotatable chuck, and the three rolls are evenly distributed in the circumferential direction of 120°. Meanwhile, there is an angle β between the axis of the roll and the axis of the hollow billet, which make the rolling piece rotates and moves in the axial direction at the same time, and the workpiece is radially compressed and axially extended under the traction of the chuck. During rolling, each point on the roller has the same rotation speed n_r, the speed of the any surface point P in the deformation zone of the rolled piece can be decomposed into the axial speed and the tangential speed:

$$u_{px} = \eta_x v_{px} = \eta_x \frac{2\pi n_r}{60} \rho_p \cdot \sin\beta \tag{1}$$

$$u_{py} = \eta_y v_{py} = \eta_y \frac{2\pi n_r}{60} \rho_p \cdot \cos\beta \tag{2}$$

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; η_x and η_y are the slip coefficients in the deformation zone in the axial and tangential directions, respectively. ρ_p is the radius of gyration at point P on the roller. β is the angle between the axis of the roll and the axis of the hollow billet.

In the traditional three-roll skew rolling process, when the roll is processed with the finishing section, the radius of the end section of the deformation zone of the rolling is r_p, and the maximum movement distance in the axial direction of the rolling one revolution is the lead Z_x [4]:

$$Z_x = 2\pi r_p \frac{\eta_x}{\eta_y} \tan\beta \tag{3}$$

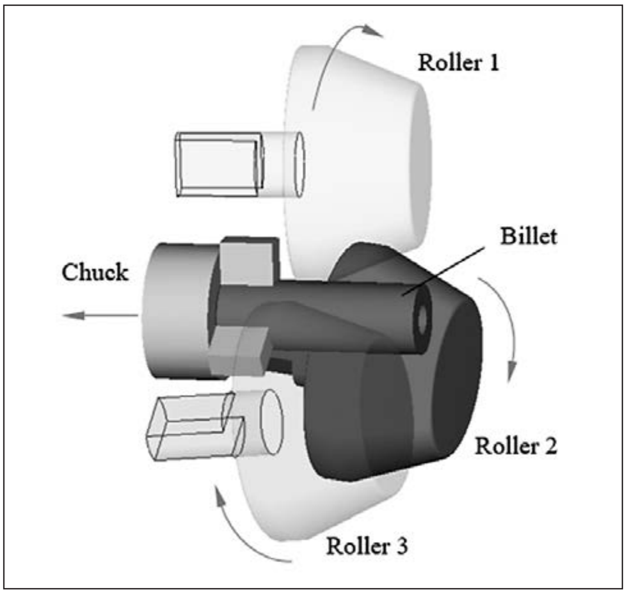


Figure 1 Principle of three-roll skew rolling hollow stepped shaft

As shown in Figure 2, in the rolling process of the long shaft section, the rolling piece is drawn by the chuck in the axial direction, so the axial velocity of any point of the rolled piece during the rolling is V_1, T is the rolling time for one revolution of shaft, so the lead Z_x:

$$Z_x = V_1 T = V_1 \cdot \frac{2\pi\rho_p}{u_{py}} = \eta_y \frac{60V_1}{n_r \cos\beta} \quad (4)$$

In the stage of forming step. The angle of steps is α. The chuck speed needs to be matched with the rolls' radial speed to form a step with a fixed angle α, V_2 is the radial speed of rollers. so V_1 and V_2 need to meet a certain proportional relationship:

$$V_1 = V_2 \tan\alpha \quad (5)$$

It can simplify the lead Z_x' of the three-roll skew rolling in the forming stage:

$$Z_x' = V_2 \tan\alpha \frac{2\pi\rho_p}{u_{py}} = \eta_y \frac{60V_2 \tan\alpha}{n_r \cos\beta} \quad (6)$$

In the axial direction, the maximum pitch z_x' processed by the three rollers can be expressed as:

$$z_x' = Z_x'/3 = V_2 \tan\alpha \frac{2\pi\rho_p}{3u_{py}} = \eta_y \frac{20V_2 \tan\alpha}{n_r \cos\beta} \quad (7)$$

The essence of the three-roll skew rolling process is the rollers' spiral movement to the rolled piece. The smaller the roll pitch is equivalent to the smaller the processing gap, the more precise the surface is. When the rolling pitch is greater than the length of the roller finishing section, spiral marks or surface defects with incomplete rolling may appear. According to equation (7), when the other parameters of three-roll skew rolling are fixed, a higher rotation speed of rollers, smaller axial speed of the chuck, and the radial speed of rollers will let rolling pitch smaller. The smaller the gap between the rolls' each processing, the smaller the possibility of spiral marks, the higher the forming accuracy of the shaft surface.

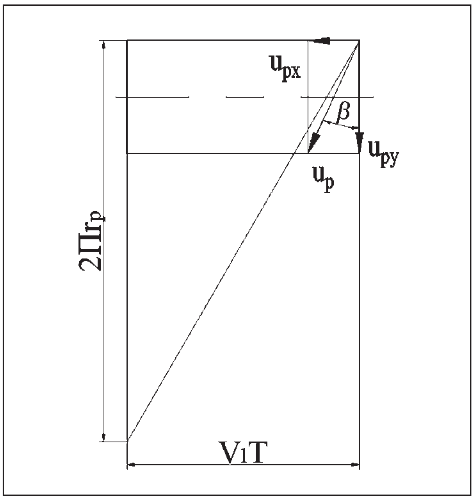


Figure 2 Analysis of rolling lead in three-roll skew rolling

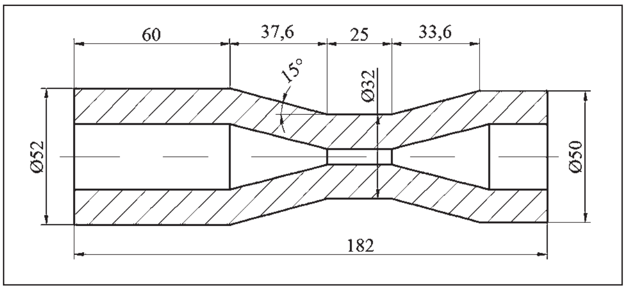


Figure 3 Stepped shaft used in the analysis

MATERIAL AND FE MODEL OF THREE-ROLL SKEW ROLLING

The three-roll skew rolling process can be used to manufacture train axles, pressure vessels, aircraft structural parts. Moreover, 30CrMoA steel has sufficient strength and toughness. Therefore, the 30CrMoA steel is selected for hollow stepped shaft material for finite element simulation. According to the existing research, the empirical constitutive equation for 30CrMoA steel at 950 -1 150 °C is as follows [5,6]:

$$\dot{\varepsilon} = 3{,}67\times10^{9}[sinh(0\ 011\sigma_p)]^{4{,}403} exp(-\frac{261850}{RT}) \quad (8)$$

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.

A single factor simulation experiment is designed with the rotation speed of rollers, the axial speed of the chuck, and the radial speed of rollers as variables. The designed hollow stepped shaft is shown in the Figure 3. The rolling process defines the following variables: the rotation of rollers n_r, axial speed of chuck V_1, radial speed of rollers V_2. Set constant conditions: the initial temperature of the shaft is 1 100 °C, the mold temperature is 150 °C, and the friction coefficient is 0,8. The 15 groups of single factor experiment parameters are shown in Table 1.

Table 1 **The process parameters selected in simulation**

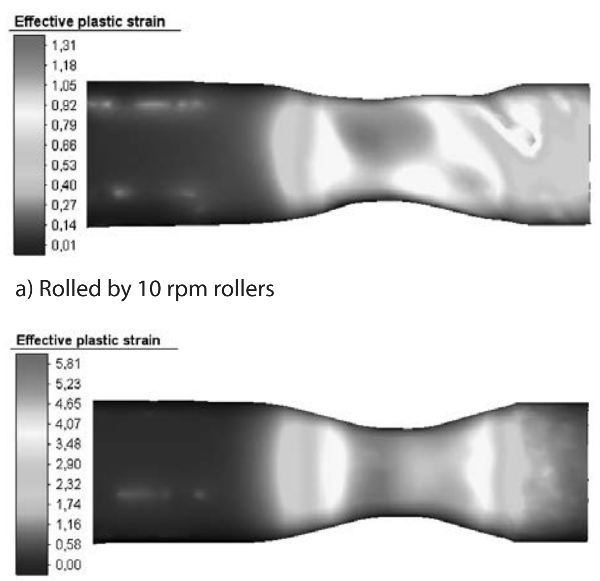
	Reference	Change
n/rpm	30	10 / 20 / 40 / 50
V_1/mm s^{-1}	30	10 / 20 / 40 / 50
V_2/mm s^{-1}	7,5	2,5 / 5 / 10 / 12,5

DISCUSSION ON THE EFFECT OF PROCESS PARAMETERS ON FORMING QUALITY

As shown in Figure 4, when the rotation speed of rollers is 10rpm, the rolling pitch is much higher than the length of the finishing section of the roller, and the rolled shaft has serious spiral marks. When the rotation speed of rollers is 50 rpm, the rolling pitch becomes significantly smaller, and there is basically no spiral pattern defect. Use Simufact.Forming to establish the surface streamline, take points every 2mm on the outer surface along the 4 quadrant directions, When the rotation speed of rollers is 10 rpm, as shown in Figure 4(a), obvious spiral patterns appear on the surface of the rolled piece, especially on the outward step. When the rotation speed of rollers is increased to 50rpm, as shown in Figure 4(b), there is basically no spiral marks on the surface of the rolled shaft. This shows that increasing the roll speed can effectively reduce the spiral marks defect and improve the surface accuracy.

Figure 5 shows the average deviation of surface dimensional accuracy of different forming sections under five rotation speeds of rollers. Whether it is an inward step or an outward step, within a certain range, with the increase of the rotation speed of rollers, the average precision deviation of the rolled shaft surface decreases, and the surface becomes more accurate. Therefore, a higher rotation speed of rollers should be selected during rolling.

Figure 6 shows the average deviation of the surface dimensional accuracy of the inward and outward steps at five axial velocities of chuck. Although the axial speed has a smaller effect on the average accuracy deviation of the shafts' surface, the average accuracy deviations of the inward and outward steps increase with the increase of the axial speed of the chuck. It shows that increasing the axial speed of check will increase the surface accuracy deviation and reduce the forming accuracy. So in the rolling, a lower axial speed of the chuck should be adopted to improve the surface accuracy of the shafts.



a) Rolled by 10 rpm rollers

b) Rolled by 50 rpm rollers

Figure 4 Rolled shafts at different rotation speeds of the rollers

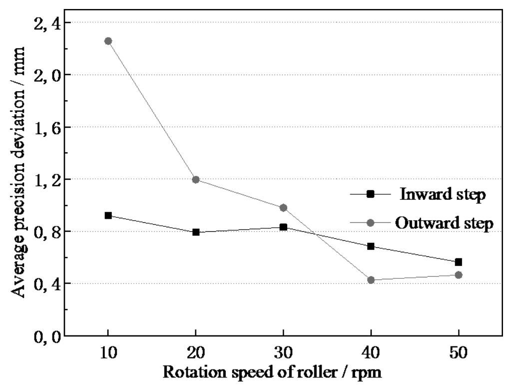


Figure 5 Effect of rotation speed of rollers on shafts' average precision deviation

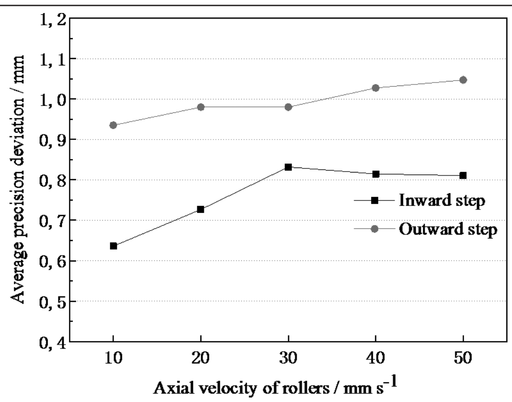


Figure 6 Effect of axial speed of the roller on shafts' average precision deviation

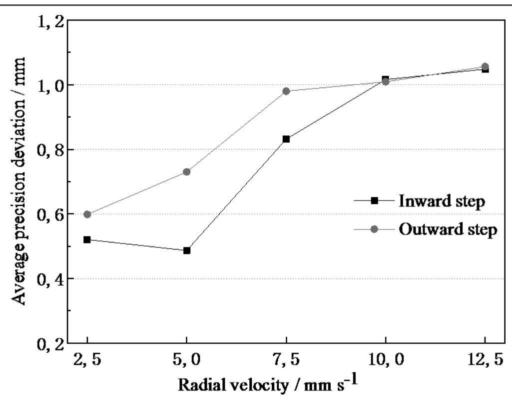


Figure 7 Effect of radial speed of the rollers on shafts' average precision deviation

Figure 7 shows the average accuracy deviation of the surface of the inward and outward steps at five radial speeds of rollers. The average accuracy deviation of the inward, outward steps increases with the increase of the radial speed of the rollers, which shows that increasing the axial speed of the chuck will increase the contour accuracy deviation, and reduce the surface forming accuracy. So in actual rolling, a lower roll radial speed should be used to improve the surface accuracy of the shafts.

CONCLUSIONS

The surface forming accuracy of the step section will be affected by the rolling pitch. For the pitch determined by the process parameters, the smaller the pitch, the higher forming accuracy of the shafts.

The rotation speed of rollers, axial speed of chuck, and radial speed of rollers will all have an impact on the surface forming accuracy. The higher the rotation speed of rollers, the smaller the axial speed of rollers and radial speed of the chuck, the smaller the deviation of the surface accuracy of the step section, and the higher the forming accuracy. In the actual rolling process, in order to obtain a shaft with better surface accuracy, a rollers' rotation speed not less than 50rpm, a small radial speed of rollers, and a chuck axial speed should be selected for hollow shaft parts.

Acknowledgments

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Note: The responsible translator for English language is J. N. Shi, Ningbo, China