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RESEARCH ON LOGARITHMIC SPIRAL ROLL PROFILE IN HOT ROLLING

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Presented is a new logarithmic spiral roll profile for 2-high hot rolling,and successfully establishing the logarithmic spiral roll profile equation.The inherent benefits over traditional sine curve roll profile include control of rolling force and optimization of strip profile.Comparison of rolling force and strip profile produced by logarithmic spiral rollers with that produced using traditional sine curve rollers through three-dimensional finite element simulation also verifies the new roll profile is more prominent in reducing rolling force and optimizing strip profile than traditional sine curve roll profile.

Key words: hot rolling, strip profile, speed, logarithmic spiral roller, rolling force

INTRODUCTION

The research on initial roll profile can be traced back to the 1970s,scholars at home and abroad have done a lot of research on exponential curve,parabolic function curve and sine curve,on this basis,continuing to optimize and design the CVC(Continuously variable crown) roll profile[1]and smart crown roll profile[2]. The research results show the roll profile is one of the most direct and effective technologies to control the strip profile[2]. In recent years,with the increasing variety of strip products,not only more and more complex problems appears in the rolling process,but also more and more strict requirements for strip profile are being put forward,which results in the existing roll profile design methods have gradually failed to meet the production needs,it is necessary to explore a new roll profile.

Logarithmic spiral has equiangular characteristics, that is beneficial to make the pressure distribution more uniform between the contact surfaces,this feature just meets the selection requirements of the initial roll profile. Moreover, based on this characteristic, logarithmic spiral has been fully applied to the fields of industry and agriculture,construction,medicine, aerospace and other fields,and all achieving good application results[3,4].

Therefore, based on equal angle characteristics of logarithmic spiral, a new logarithmic spiral roll profile is proposed to compare with the traditional sine curve roll profile[5] in terms of control of rolling force and optimization of strip profile through three-dimensional finite element simulation method.The results obtained can be used to explore the feasibility of applying logarithmic spiral to hot rolling field.

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ESTABLISHMENT OF SINE CURVE EQUATION

Usually, the initial roll profile in hot rolling is designed as a concave roll profile. Based on the roll body length L = 1 450 mm, roll body diameter D = 500 mm and original crown C = -0,04 mm,it can be got A (0,-0,04) and B (725,0) in Figure 1.

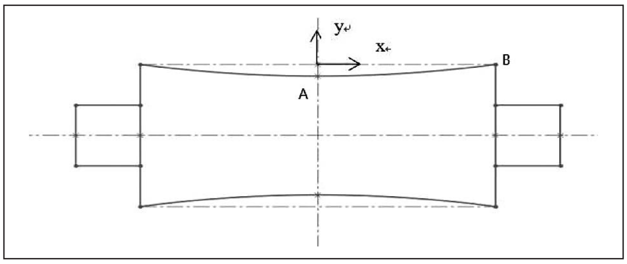

Figure 1 Schematic diagram of roll coordinate system

Bringing the points A and B into the sine curve roll profile equation formula[5]:

$$y = D + 2C\left[\cos\left(\frac{x\alpha}{L} + \pi\right) - \cos\left(\pi - \frac{\alpha}{2}\right)\right]$$

Where: *D* - roll body diameter, D = 500 mm.
C - original crown, C = -0,04 mm.
L - roll body length, L = 1 450 mm.
a - Sine function wrap angle, $a = \pi$.
It can obtain the sine curve equation:

$$y = 500 + 0,08\cos\left(0,002167x + \pi\right), x \in \left[-725, 725\right]$$

ESTABLISHMENT OF LOGARITHMIC SPIRAL EQUATION

The logarithmic spiral equation needs to be established according to the coordinate system of sine curve equation.As shown in Figure 2, the XOY rectangular coordinate system where the logarithmic spiral is located can be obtained by translating the X´O´Y´ rectangular coordinate system where the sine curve is located. So through three points A(0,-0,04), B(300,-0,0335) and C(725,0) on the X´O´Y´ coordinate system,it can be got the points A(x_0, y_0-0,04), B(x_0+300, y_0-0,0335) and C(x_0+725, y_0) on XOY coordinate system.

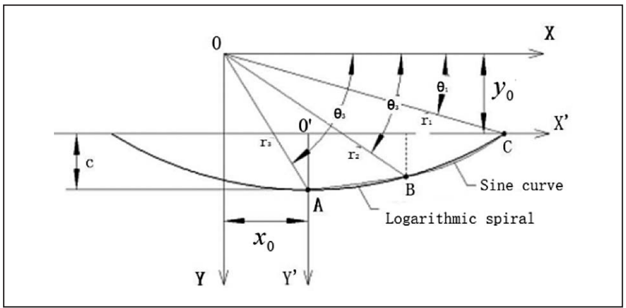

Figure 2 Coordinates of roll profile

Based on the polar equation of logarithmic spiral:

$$r = a \cdot e^{k\theta} \tag{1}$$

It can be got the polar coordinates of points A, B and C are (r_3,θ_3), (r_2,θ_2) and (r_1,θ_1).

So we can obtain:

$$\begin{cases} r_1 = \sqrt{\left(x_0 + 725\right)^2 + {y_0}^2} \\ r_2 = \sqrt{\left(x_0 + 300\right)^2 + \left(y_0 - 0,0335\right)^2} \\ r_3 = \sqrt{{x_0}^2 + \left(y_0 - 0,04\right)^2} \end{cases} \tag{2}$$

and

$$\begin{cases} \theta_1 = \arctan\left(\dfrac{y_0}{x_0 + 725}\right) \\ \theta_2 = \arctan\left(\dfrac{y_0 - 0,0335}{x_0 + 300}\right) \\ \theta_3 = \arctan\left(\dfrac{y_0 - 0,04}{x_0}\right) \end{cases} \tag{3}$$

Converting Eq.(1) to rectangular equation,it can be cast in the form:

$$\begin{cases} x(\theta) = a \cdot e^{k\theta} \cdot \cos\theta \\ y(\theta) = a \cdot e^{k\theta} \cdot \sin\theta \end{cases} \tag{4}$$

Point A is the lowest point on the roll profile curve in Figure 2, so its slope is 0.Therefore, we can get the partial derivative of Eq.(4):

$$\frac{dy}{dx} = \frac{dy}{d\theta} \Big/ \frac{dx}{d\theta} = \frac{1 + k \cdot \tan\theta}{k - \tan\theta} = 0 \tag{5}$$

Bring θ_3 (Eq.(3)) into it.It can be obtained:

$$1 + \frac{k \cdot \left(y_0 - 0,04\right)}{x_0} = 0 \tag{6}$$

Inputting Eq.(2), Eq.(3) and Eq.(6) into the 1stOpt software, it can fit the best parameters:

$$\begin{cases} a = 815,4530 \\ k = 13\ 969,5573 \\ x_0 = 300,0011 \\ y_0 = -0,0198 \end{cases} \tag{7}$$

Thus, it can obtain polar equation of logarithmic spiral:

$$r = 815,413 \cdot e^{13\ 969,573\theta}, \quad \theta \in \left[-5,78 \times 10^{-5}, 2,07 \times 10^{-5}\right] \tag{8}$$

MATERIAL PARAMETERS AND MODELING

Low carbon steel with carbon content of 0,05 % is selected as rolling material,and the high-chromium-content alloy cast iron is used as roll material. In order to make the roll expand rapidly in the short simulation process and enter the rolling stable state as soon as possible, the linear expansion coefficient and thermal conductivity coefficient are enlarged by 10 times.

Considering the symmetry of rolling model, it can be simplified to 1/4 model. The roll body length L = 1 450 mm, the roll body diameter D = 500 mm, the strip length L´= 5 000 mm, the strip width B = 1 000 mm, the strip thickness H = 10 mm. The finite element model of rolling based on ABAQUS is shown in Figure 3.

In order to obtain accurate analysis data, we fully consider the boundary condition parameters such as applying tension to strip, contact friction and contact heat

Figure 3 The finite element model of hot rolling

Table 1 **Boundary conditions**

Parameter	numeric
Fore-pulling force / σ_0	1,3 MPa
Post-pulling force / σ_1	1,0 MPa
Contact heat transfer coefficient /h_c	8 000 W/m²·K
Radiant heat transfer coefficient /h_r	150 W/m²·K
Contact friction coefficient /f	0,3
Initial temperature of strip steel /T	900 °C
Ambient temperature /T_f	25 °C

transfer coefficient between roller and strip and radiation heat transfer coefficient between strip and surrounding environment. Boundary condition parameters are shown in Table 1.

ROLLING FORCE

Figure 4 shows the comparison of rolling force between two types of roll profiles when the rolling speed is v = 600 mm/s, the reduction amounts are Δh= 2,4 mm, Δh= 3,0 mm and Δh= 3,6 mm, respectively.

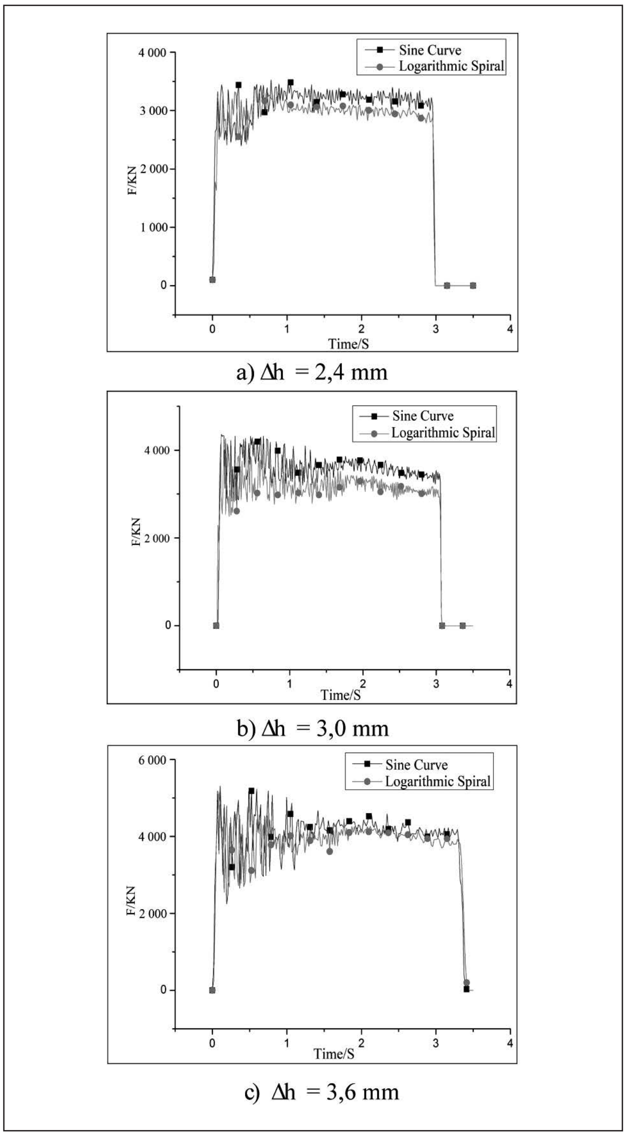

Figure 4 The comparison of rolling force curve

The Figure 4 shows that the curve representing the sine curve is almost above the curve representing the logarithmic spiral, that indicates at the same speed and different reduction amounts, the rolling force produced by logarithmic spiral roller is less than that produced by sine curve roller. In order to make the comparison results more obvious,we extract the maximum and minimum values of rolling force in the rolling stability stage within 1,5 s - 2,5 s from the simulation results,and calculate the average value in this time period, as shown in Table 2.

Table 2 **The comparison of average Rolling force**

Reduction amount / mm	Average value / KN	
	Sine curve	Logarithmic spiral
2,4	3 237,85	2 998,88
3,0	3 642,69	3 275,75
3,6	4 264,36	4 087,50

Table 2 shows the average rolling forces produced by logarithmic spiral roller is 7,38 %, 10,07 % and 4,15 % lower than that produced by sine curve roller.

STRIPE PROFILE

In this chapter, we made contrastive analysis of strip profile between two types of rollers by analyzing plate crown and strip flatness.

As shown in Figure 5, it set six paths in the transverse and longitudinal directions of the strip.Path1, path2 and path3 are transverse paths, the distance between two adjacent transverse paths is 500 mm, the length of each transverse path is 400 mm, 8 points are extracted from each transverse path. Path4, path5 and path6 are longitudinal paths, the distance between two adjacent longitudinal paths is 50 mm, the length of each longitudinal path is 1 000 mm, 12 points are extracted from each longitudinal path. So the strip thickness values of 24 points on three transverse paths and the strip thickness values of 36 points on three longitudinal paths can be extracted to calculate the average plate crown and the average strip flatness.

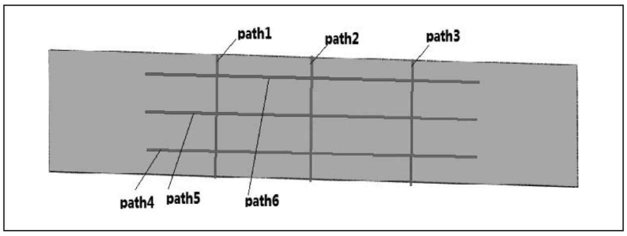

Figure 5 Transverse and longitudinal paths

Tables 3 and 4 show the comparison of the plate crown and strip flatness between two types of roll profiles when the rolling speed is v = 600 mm/s, the reduction amounts are Δh= 2,4 mm, Δh= 3,0 mm and Δh= 3,6 mm, respectively.

It can be seen from Tables 3 and 4 that under three kinds of reduction amounts, the average plate crowns produced by logarithmic spiral roller is 31,5 %, 33,3 % and 8,3 % lower than that by sine curve roller respectively and the average strip flatness produced by loga-

Table 3 **The comparison of average plate crowns**

Reduction amount Δh / mm	Average plate crown C/μm	
	Sine curve	Logarithmic spiral
2,4	19	13
3,0	15	10
3,6	12	11

Table 4 **The comparison of average strip flatness**

Reduction amount Δh / mm	average strip flatness λ/×10^{-5}	
	Sine curve	Logarithmic spiral
2,4	0,471	0,437
3,0	0,671	0,625
3,6	0,526	0,520

rithmic spiral roller is 7,2 %, 6,8 % and 1,1 % lower than that by sine curve roller respectively.

CONCLUSION

- In this paper, a new logarithmic spiral roll profile is proposed.
- Successfully establishing the logarithmic spiral roll profile equation.
- Under the same rolling conditions, the rolling force and stripe profile (plate crown and strip flatness) produced by logarithmic spiral roller is almost less than that produced by sine curve roller.
- Based on the simulation results, it can be seen that the logarithmic spiral roller for hot rolling mill is feasible,that also lays a theoretical foundation for the follow-up experimental research,even for the research of the logarithmic spiral roller for 4-high mill.

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Note: The responsible for English language is F. B. Lian.