Rolling Force Prediction of Hot Strip based on Combined Friction

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Abstract. Rolling force of hot strip was predicted in which slipping and sticking friction were adopted on the contact arc between work roll and hot strip. Karman equation was applied to slipping friction and Orowan equation was applied to sticking friction. Predicted rolling forces of hot strip agreed with measured ones from a seven-stand hot strip mill. Friction stress distributions of one classical hot rolled strip on contact arc were analysed at each pass. From pass 1 to 3, sticking friction dominated while from pass 4 to 7 slipping and sticking friction coexisted. It proved that the applicability and superiority of rolling force model based on combined friction for rolling force prediction of hot strip.

1. Introduction
Rolling force is an important parameter that influences thickness precision and strip shape quality in the control of hot strip rolling. A lot of researchers [1-5] have been involved with simulation of rolling force in hot strip rolling with different methods. Chai X J [1] et al. computed transverse distribution of rolling force of hot strip by finite element and artificial neural network. Considering deformation rate on deformation resistance, Li Z J [2] et al. developed a rolling force predicting model on the basis of SIMS model. Chun S Y [5] calculated rolling force distribution based on improved Karman equation for hot strip rolling.

Karman equation had been widely used to predicting rolling force of cold strip where friction stress is not large and smaller than shearing yield limit of rolled strip. But in computing rolling force of hot strip when friction was large and nearly equal to shearing yield limit, Karman equation had a deviation from measured rolling force in reason that friction was ignored in plastic condition equation. Orowan equation had been widely used to predicting rolling force of hot strip. However, in the past passes of hot tandem rolling mill, rolling force predicted by Orowan equation had a deviation from measured rolling force.

In this paper, friction on the contact arc between work roll and hot strip was adopted as slipping and sticking friction. The models for computing unit rolling force with slipping and sticking friction conditions were developed based on Karman and Orowan unit pressure differential equation respectively, and then the model were developed for predicting the total rolling force. A lot of total rolling force simulations were conducted with collected data from a seven-stand rolling mill to assess the validity of the roll force models based on combined friction. The applicability and superiority of rolling force model in this paper was shown by analyzing the friction stress distribution of one classical hot rolled strip on contact arc.
2. Predicting model of rolling force of hot strip

In this paper, contact arc surface between hot rolled strip and work roll were divided into backward slipping, sticking and forward slipping zones, and point _n_ was neutral plane, as shown in figure 1.

From point _a_ to _b_ , friction stress increased and was less than shearing yield limit of rolled strip. Within this zone, it was named backward slipping zone. The zone from point _d_ to _c_ was similar to that from point _a_ to _b_ , and it was named forward slipping zone. From point _b_ to _c_ , absolute value of friction stress was equal to shearing yield limit of rolled strip and remains unchanged. Within this zone, it was named sticking zone.

![Figure 1. Friction condition in contact arc surface.](image)

2.1. Derivation of rolling forces per unit area \( p_x \)

In backward and forward slipping zone, contact arc was adopted as straight line and friction was adopted as dry friction. Friction coefficient \( \mu \) is unchanged, and friction stress \( t_x \) is

\[
 t_x = \mu p_x \tag{1}
\]

Based on Karman differential equation of unit pressure, rolling forces per unit area \( p_{dc} \) in forward slipping zone is

\[
p_{dc} = 2k \left(1 - \sigma_1 \left(2k\right)^{-1} + tg \theta_{dc} \mu^{-1} \right) h_x h^{-1} \left(\frac{1}{\theta_{dc}}\right)^{\mu tg \theta_{dc}} - 2k \mu^{-1} \mu \theta_{dc} \tag{2}
\]

where \( k \) , \( \sigma_1 \) denote shear yield limit of rolled strip, exit tension respectively; \( h_x \) denotes strip thickness at point _x_ and \( \theta_{dc} \) denotes angle between chord \( dc \) and center line of the rolling.

Similar to forward slipping zone, rolling forces per unit area \( p_{ba} \) in backward slipping zone is

\[
p_{ba} = 2k \left(1 - \sigma_0 \left(2k\right)^{-1} - tg \theta_{ba} \mu^{-1} \right) H(h_x) \left(\frac{1}{\theta_{ba}}\right)^{\mu tg \theta_{ba}} + 2k \mu^{-1} \mu \theta_{ba} \tag{3}
\]

where \( \sigma_0 \) denotes entrance tension and \( \theta_{ba} \) denotes angle between chord \( ba \) and center line of the rolling.

In sticking zone, friction stress was equal to shearing yield limit of rolled strip. Contact arc was adopted as

\[
h_x = h + R \theta_x^2 \tag{4}
\]

where \( R \) , \( \theta_x \) denote radius of work roll and central angle at point _x_ respectively.
Based on Orowan differential equation of unit pressure, rolling forces per unit area $p_{cn}$ in forward sticking zone is

$$p_{cn} = 2k \left\{ \frac{\pi}{4} \ln \left( \frac{h_c}{h} \right) + \frac{\pi}{4} \left( \frac{R}{h} \right)^{\frac{1}{2}} \arctan \left[ \left( \frac{R}{h} \right)^{\frac{1}{2}} \theta_x \right] + \frac{1 - 2 \mu}{2 \mu} \left( \frac{R}{h} \right)^{\frac{1}{2}} \arctan \left[ \left( \frac{R}{h} \right)^{\frac{1}{2}} \theta_c \right] \right\}$$

where $h_c$, $\theta_c$ denote strip thickness and central angle at point $c$ respectively.

Similar to forward sticking zone, rolling forces per unit $p_{nb}$ in backward sticking zone is

$$p_{nb} = 2k \left\{ \frac{\pi}{4} \ln \left( \frac{h_b}{h} \right) + \frac{\pi}{4} \left( \frac{R}{h} \right)^{\frac{1}{2}} \arctan \left[ \left( \frac{R}{h} \right)^{\frac{1}{2}} \theta_b \right] - \frac{1 - 2 \mu}{2 \mu} \left( \frac{R}{h} \right)^{\frac{1}{2}} \arctan \left[ \left( \frac{R}{h} \right)^{\frac{1}{2}} \theta_x \right] \right\}$$

where $h_b$, $\theta_b$ denote strip thickness and central angle at point $b$ respectively.

2.2. Derivation of total rolling forces

It was assumed that total rolling force acted on the roll by the hot strip was equal to its vertical component. Friction was ignored, total rolling force $P$ is

$$P = B \left( \int_{0}^{x_n} p_{d1} dx + \int_{x_n}^{b} p_{na} dx \right) + BR \left( \int_{0}^{\theta_n} p_{dn} d\theta + \int_{\theta_n}^{\theta_c} p_{mn} d\theta \right)$$

where $\theta_n$ denotes central angle at point $n$.

To solve $P$ with equation (7), $x_n$, $\theta_n$ and $x_c$ must be determined beforehand. $x_c$ and $x_b$ is calculated by iterative method. Total contact arc was assumed straight line. When deviation between the friction stress and shear yield limit of rolled strip at point $b$ was smaller than 0.000001 times the shear yield limit, it was considered that this point was $x_b$. The same method can be used to determine $x_c$. $\theta_n$ was calculated by the intersect method. In the forward and backward sticking zone, both equations (5) and equation (6) can be used to compute rolling forces per unit area at point $n$.

When rolling forces per unit area at point $n$ in two equations was equal, the position was neutral point $n$. The central angle at the neutral point $n$ was the neutral angle $\theta_n$.

3. Validation and discussion

In order to verify the validity of rolling force model in this paper, many simulations were made with the experimental data collected from a seven-stand finished hot rolling mill. Errors, this is equal to the difference between rolling force of predicted and measured divided by measured rolling force, are shown in figure 2.

As shown in figure 2, at stands 1, 2, and 3, errors were within 2%, and at stands 4, 5, 6 and 7 the errors which were bigger than those at stands 1, 2 and 3 were within 5%. As a whole, errors of rolling force predicted by combined friction model in this paper were within 5%. It can be used to predict rolling force of hot strip for hot strip plant.

Taking one classical hot rolled strip in this plant as example, strip thickness at entrance of rolling mill is 40 $mm$ and strip thicknesses at exit of each pass successively are 21.03, 12.97, 8.45, 5.48, 3.72, 2.74, and 2.36 $mm$. Strip width is 720 $mm$ and work roll diameters of each pass successively are 824.3, 757.1, 781.8, 617.1, 588.3, 597.1, 638.2 $mm$. Rolling forces measured and predicted by combined friction model and SIMS model are shown in figure 3.
Figure 2. Errors between rolling force of predicted and measured.

Figure 3. Comparison of rolling force among measured, combined friction and SIMS model.

As shown in figure 3, rolling forces predicted by combined friction model and SIMS model were a little larger than measured ones at pass 1 and rolling forces predicted by combined friction model and SIMS model were nearly equal to measured ones at pass 2 and 3. At pass 4, 5, 6 and 7, rolling forces predicted by combined friction model were smaller than measured ones, while rolling forces predicted by SIMS model were larger than measured ones. This is because of the ratio of slipping zone on the contact arc. Friction stress distribution of the above rolled strip on contact arc between hot strip and work roll at each pass are shown in figure 4.

Figure 4. Friction stress on contact arc of each pass.
As shown in figure 4, at pass 1 the length of slipping zone that is small can be ignored because of large friction coefficient and rolling reduction. With the decease of rolling reduction at pass 2 and 3, the length of slipping zone increased, but against the length of contact arc, it is relatively small. Therefore, at pass 1, 2 and 3, sticking friction dominated the contact arc, SIMS model was fitted to predicting rolling forces and rolling forces predicted by combined friction model are close to ones by SIMS model. At pass 4, 5, 6 and 7, with the decease of friction coefficient and rolling reduction, the length of slipping zone visibly increased. The contact arc consisted of slipping and sticking friction. Rolling forces predicted by SIMS model were bigger than measured ones because it assumed the entire contact arc was sticking friction. Rolling force predicted by combined friction model was fitted and errors were smaller than those by SIMS.

4. Conclusions
It was assumed that friction on contact arc between work roll and hot strip consisted of slipping and sticking friction. Within slipping friction zone, friction stress is equal to the coefficient of friction multiplied by the unit rolling force and smaller than or equal to absolute value of shearing yield limit of rolled strip. Within sticking friction zone, friction stress was equal to shearing yield limit of rolled strip. The unit rolling force equation within slipping friction zone was derived based on the principle of Karman equation, and equation within sticking friction zone was derived based on the principle of SIMS equation. Then, total rolling force model was constructed and made to simulate rolling force with the process data collected from a seven-stand hot strip rolling mill. The simulated rolling force agreed with the measured ones. By analyzing the friction stress distribution on contact arc, it showed that from pass 1 to 3 it was close to SIMS friction assumption, while from pass 4 to 7 it consisted of slipping and sticking friction on contact arc. It provides a better applicability method for predicting the rolling force in hot strip rolling.

5. References
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