Research on Mathematical Model of Strip Slip during Speed Increase of the Bridle Roll of SPM

Yong-qiang WANG¹²*, Yang-long LI¹², Jie WEN¹², Meng YU¹² and Gong-yin LI¹²

¹ Research Institute of Technology of Shougang Group Co., Ltd., Beijing 100043, China
² Beijing Key Laboratory of Green Recyclable Process for Iron and Steel Production Technology, Beijing 100043, China
*Email: wangyq@shougang.com.cn

Abstract. When the strip slip occurs during the speed-up process of SPM, there is the relative slippage between the strip and the bridle roll. It will cause the fluctuation of rolling force, elongation and tension of SPM, which are harmful to the strip surface quality and stable operation. For the sake of researching the mechanism of relative slipping happens between the bridle roll and strip when the speed of the skin pass mill (SPM) is increased, a mathematical model for relative sliding between the strip steel and the bridle roll was built. At the same time, a quantitative parameter named “the strip slip risk ratio” was proposed. On the basis of this model, a lot of factors that affect the slip were analyzed, such as friction coefficient, front and rear tension, velocity, acceleration, coiling angle and etc. The results show that increasing friction coefficient, decreasing tension difference, decreasing velocity and acceleration will reduce the slip risk of sliding strip. According to the calculation results, the controllable influencing factors for strip slipping were optimized. The roughness of bridle roll was increased from 4 to 5 microns. The tension difference of bridle assembly at the outlet of SPM was decreased by 50% and the strip acceleration of SPM was reduced from 0.6 to 0.5 m/s². After application of measures, the monthly incidence of strip slipping is obviously reduced. The incidence of strip slipping per month is reduced from about 3.33% to 0.17%, which prevents the slip between strip and the bridle roll during the speeding process of SPM.

1. Introduction

The group of bridle rolls is an important equipment of skin pass mill. The slipping problem of the strip on bridle roll has been concerned by many operators [1-3]. When the strip slip occurs during the speed-up process of SPM, there is the relative slippage between the strip and the bridle roll [4]. It will cause the fluctuation of rolling force, elongation and tension of SPM, which are harmful to the strip surface quality and stable operation. In recent years, the strip slipping problems on bridle roll have been found frequently on site. It prompts us to focus on the mechanism of the strip slipping to solve these problems.

At present, the mechanism of strip slipping is mainly based on mechanical model [5-7], and some mathematical methods such as statistics [8] and optimization algorithm [9-10] are used to analyze and prevent strip slipping phenomenon. However, there are few reports on the strip slipping problems on the bridle roll of skin pass mill during speeding process. How to establish a mathematical model for studying strip slipping on the bridle roll during speed-up process is worth studying.
In this paper, a mathematical model of the movement between strip and the bridle roll during the speeding process of SPM is built. A quantitative parameter named “the strip slip risk ratio” is advanced to analyze the main influencing factors of strip slipping. Through on-site optimization, the strip slipping was successfully suppressed and reduced.

2. Mathematical model

2.1 Model simplification

Figure 1 shows the layout of the skin pass mill, which is a single stand 6-roll CVC (continuous variable crown) rolling mill. It is installed at the exit section of the continuous annealing line for temper rolling the annealed strip. Two assemblies of bridle rollers are installed on both sides (entry and exit) of the skin pass mill in order to achieve the required tension of strip.

![Picture of the skin pass mill](image1)

![Diagram of the skin pass mill](image2)

**Figure 1.** Layout diagram of the skin pass mill

For the sake of studying the slipping principle between strip and bridle roll, a mathematical model for the movement of strip and the bridle roll in the process of speeding up should be established and simplified. Therefore, taking No. 1 bridle roll of the exit bridle assembly as the research object, the force of strip and the bridle roll in the process of speeding up of the skin pass mill is analyzed.

Figure 2(a) shows the force model of strip on the bridle roll. The wrap angle of the strip is $\theta$ and the acceleration is $a$. $T_1$ and $T_2$ are the strip tension before and after No. 1 tension roll at the exit of skin pass mill, while $T_3$ and $T_4$ are the strip tension before and after No. 1 bridle roll corresponding to the actual wrap angle.

For a micro-element of strip, there are mainly four forces acting on it, which are front and back tension, friction and gravity. The forces acting on the micro-element of strip are decomposed along the radial and tangential direction respectively, and the results are shown in Figure 2 (b).

![Strip and bridle roll](image3)

![Strip element](image4)

**Figure 2.** Model diagram of strip and bridle roll
2.2 Model establishment
During the speed-up process of the skin pass mill, it is assumed that there may be the slipping between the strip and the No. 1 bridle roll at the exit of the skin pass mill. The tension loss of the strip during bending through the bridle roll is $T_s$, thus the actual tension of the strip before and after the wrap angle can be calculated by formula (1) [11].

\[
\begin{align*}
T_1 & = T_i + T_s, \\
T_i & = T_2 - T_s
\end{align*}
\]

(1)

Assuming that variation of the tension difference of strip is uniform within the actual wrap angle range, the calculation formula of the front and back tension of the strip ($T$) for arbitrary micro-element of strip is as follows:

\[
\begin{align*}
T & = \frac{T_1 - T_i}{\theta} \alpha + T_i, \\
T + dT & = \frac{T_1 - T_i}{\theta} (\alpha + d\alpha) + T_i
\end{align*}
\]

(2)

Where $\theta$ is actual wrap angle, $\alpha$ is the angle between strip micro-element and normal component of T3 within wrap angle range, which is satisfied with $0 \leq \alpha < \theta$. $T$ is the angle corresponding to the strip micro-element within the wrap angle range. $dT$ is the increased tension for the strip micro-element and $d\alpha$ is the angle corresponding to the strip micro-element within the wrap angle range.

\[
\begin{align*}
T \sin \left( \frac{d\alpha}{2} \right) + (T + dT) \sin \left( \frac{d\alpha}{2} \right) - dF_N + \Delta m \cos \alpha = \frac{dm \cdot v^2}{r} \\
(T + dT) \cos \left( \frac{d\alpha}{2} \right) - T \cos \left( \frac{d\alpha}{2} \right) - df + \Delta m \sin \alpha = dm \cdot a
\end{align*}
\]

(3)

Where $dF_N$ is normal supporting force acting on strip micro-element and $df$ is the tangential friction acting on strip element. $dm$ is the mass of the strip micro-element. $r$ is the radius of the bridle roll. $v$ is velocity of the strip and $a$ is acceleration of the strip.

The mass of the strip micro-element ($dm$) in contact with the bridle roll can be calculated by formula (4).

\[
dm = \rho \cdot w \cdot h \cdot rd\alpha
\]

(4)

Where $\rho$ is density of the strip, $w$ and $h$ are the width and thickness of the strip, respectively.

When there is the relative sliding between the strip and the bridle roll, the relation between $df$ and $dF_N$ can be calculated by formula (5) according to the sliding friction law:

\[
df = \mu \cdot dF_N
\]

(5)

Where $\mu$ is the friction coefficient between strip and bridle roll.

When the angle of the micro-element is very small, it can be considered that $\sin \left( \frac{d\alpha}{2} \right) \approx \frac{d\alpha}{2}$. The normal force and tangential force of the strip element can be integrated and derived as equation (6).

\[
\begin{align*}
F_N & = \frac{T_1 + T_i}{2} + \rho \cdot g \cdot w \cdot h \cdot r \cdot \sin \theta - \rho \cdot w \cdot h \cdot r \cdot v^2 \\
\alpha & = \frac{T_1 - T_i - 2T_s + \rho \cdot w \cdot h \cdot r \cdot \theta \cdot g (1 - \cos \theta) - f}{\rho \cdot w \cdot h \cdot r \cdot \theta}
\end{align*}
\]

(6)

Let $F_{T1} = T_1 - T_i - 2T_s + \rho \cdot w \cdot h \cdot r \cdot \theta \cdot g (1 - \cos \theta)$, which means the tangential force produced by tension and gravity of strip.

Define the slip risk ratio as the ratio of $F_{T1}$ and $\mu F_N$, that is:

\[
R = \frac{F_{T1}}{\mu F_N}
\]

(7)
If $R < 1$, the tangential force is smaller than the frictional force so that the slip will hardly occur. Whereas if $R \geq 1$, the tangential force is greater than the frictional force and the slip is likely to occur. By comparison and calculation the slip risk factor ($R$), the influence of various factors on the slip risk of strip can be analyzed.

3. Results and discussion

3.1 Influence of the friction coefficient

Figure 3 shows the Influence of friction coefficient on slip risk ratio. With the increasing of friction coefficient from 0.03 to 0.15, the slip risk ratio obviously decreases form 2.28 to 0.46. Therefore, increasing friction coefficient between strip and the bridle roll can significantly reduce strip slip risk.

![Figure 3. Influence of friction coefficient on slip risk ratio](image)

3.2 Influence of strip tension difference of bridle assembly

Figure 4 shows the Influence of tension difference of bridle assembly on slip risk ratio. If the tension difference of bridle assembly increases, the slip risk ratio will also increase. Although large tension is benefit for preventing strip slipping, it will also lead to large tension difference easily when there is the tension fluctuation. Hence, the tension difference of bridle assembly should be maintained in an appropriate range which is suitable for stable production.

![Figure 4. Influence of tension difference of bridle assembly on slip risk ratio](image)
3.3 Influence of wrap angle
Figure 5 shows the effect of wrap angle on slip risk ratio. The slip factor decreases with increasing the wrap angle of the strip. The small wrap angle can easily lead to strip slip. However, it is not easy to change the wrap angle at normal equipment running condition.

![Figure 5. Influence of wrap angle on slip risk ratio](image)

3.4 Influence of strip velocity
Figure 6 shows the Influence of strip velocity on slip risk ratio. The strip velocity changes from 240 to 720 m/min, the strip slip risk will increase from to 0.98 to 1.03. Therefore, the strip is easy to slip at a large running speed of SPM.

![Figure 6. Influence of strip velocity on slip risk ratio](image)

3.5 Influence of strip acceleration
Figure 7 shows the Influence of strip acceleration on slip risk ratio. Increasing the strip acceleration will increase the strip slip risk. During the speed-up process, the acceleration should be controlled strictly.
4. Application

From the above analysis, it can be seen that the factors affecting strip slipping mainly include friction coefficient of tension roll, strip tension difference, strip velocity and acceleration. Reducing friction coefficient, increasing tension difference, increasing speed and acceleration will increase strip slip ratio.

Figure 8 shows the real production process data of SPM during the speed-up process. During the speed-up process, the rolling force, tension and elongation of SPM fluctuated greatly, which were caused by the strip slipping on exit bridle roll.

Figure 7. Influence of strip acceleration on slip risk ratio

Figure 8. Strip slipping question on bridle roll in speeding up process
In order to prevent the strip slipping, the controllable influencing factors for strip slipping were optimized in practical production as follows.

- The roughness of bridle roll was increased from 4 to 5 microns.
- The tension difference of bridle assembly at the outlet of SPM was decreased by 50%.
- The strip acceleration of SPM was reduced from 0.6 to 0.5 m/s².

Figure 9 shows the incidence of strip slipping before and after optimizing measures. It can be seen from the figure that the monthly incidence of strip slipping is obviously reduced after the optimization measures are taken. The incidence of strip slipping per month is reduced from about 3.33% to 0.17%, which prevents the slip between strip and the bridle roll during the speeding process of SPM.

![Figure 9. Incidence of strip slipping before and after optimizing measures](image)

5. Conclusion

- A mathematical model of the movement between bridle roll and strip during the speed-up process of SPM is established to analyze the mechanism of the strip slipping phenomenon. A quantitative index named “strip slip risk ratio” is proposed to calculate the strip slip risk.
- The main factors affecting strip slipping during the speed-up process are analyzed. Reducing friction coefficient, increasing tension difference, increasing speed and acceleration will increase strip slip ratio between strip and bridle roll.
- In view of the strip slipping problem on site, a lot of effective measures have been taken to reduce the occurrence of strip slipping. The incidence of strip slipping per month decreases from 3.33% to 0.17%, which promotes the stable operation of SPM.

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