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DEVELOPING A WORK ROLL MODEL BY ANALYZING THE MECHANISM INFLUENCE THROUGH ANALYTIC CALCULATION

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This paper presents a novel approach to developing a work roll prediction model that takes into account the impact both the mechanism and conditions on the work roll wear. This was accomplished by conducting an analytic calculation of work roll mechanism influence, constructing a work roll wear model, and combining the wear mechanism with actual wear data. The resulting model is applicable to both symmetric and asymmetric wear of the work roll. Experimental results showed that the relative error between measured and predicted values was less than *5%*, with a maximum error of below *15%*. This level of accuracy is sufficient for predicting roll wear and lays the foundation for improved strip shape control and roll design. Furthermore, this approach has the potential to generate significant economic benefits and has wide-ranging applications.

Key words: wear, mechanism, developing model, work roll.

1. Introduction

The manufacturing industry has been developing rapidly in recent years and demands higher prediction accuracy for cold rolled strip and coated products. The prediction accuracy for work roll wear depends on various factors such as the actual roll type, roll gap shape with load, roll deformation calculation precision, roll bending force setting and subsection cooling compensation system usage. It directly influences the shape quality of a finished product [1]. Roll wear is a gradual and complex process that varies under different conditions. Previous studies on the cold rolling process paid less attention to the roll wear model. The correlation model mainly concentrated on hot rolling [2-3]. Many researchers have tried to measure roll wear and obtain more wear curves but no accurate calculation model of roll wear has been established yet. Therefore, based on a lot of field tests and theoretical research studies, considering the equipment and production craft features in cold rolling, combining the wear mechanism and actual wear data measurement results, a work roll prediction model that considers both mechanism and conditions was developed. The model was suitable for both symmetric and asymmetric work roll wear. It was applied to 1220 Five-stand Tandem Cold Mill of Baosteel in China and significantly improved the prediction accuracy of work roll wear. It laid foundation for flatness control and roll design, effectively ensured product shape quality stability and generated greater economic benefits.

2. Basic mathematical model

2.1. Structure of work roll wear mode

Taking into account the extensive impact of both the mechanism and actual conditions, the prediction model for roll wear can adopt the following structure:

$$R(x_i) = G(x_i) \cdot J(x_i) \tag{2.1}$$

where: $R(x_i)$ is the wear value of work roll, $G(x_i)$ is the conditions influence equation in work roll wear for correcting the mechanism model, $J(x_i)$ is the mechanism influence equation in work roll wear, x_i is the horizontal coordinate of *i* point, as the origin in the middle of work roll.

2.2. Structure of working conditions influence equation

Based on practical experience and data regression results, the equation for condition influence in work roll wear is constructed as follows:

$$G(x_i) = \sum_{k=0}^{6} a_k x_i^k \tag{2.2}$$

where: a_k is the conditions influence coefficient, which is closely linked to equipment, process characteristics, and rolling conditions. A detailed solution of this topic can be found in section 2.6 of this article.

2.3. Structure of mechanism influence equation

In accordance with the process characteristics in a four-high cold rolling mill, the equation for mechanism influence in work roll wear is formulated as follows:

$$J(x_i) = \sum_{m=1}^{n} \left[J_{1m}(x_i) + J_{2m}(x_i) + J_{3m}(x_i) + J_{4m}(x_i) \right] \tag{2.3}$$

where: n is the total number of rolling rolls in work roll changing period.
$J_{1m}(x_i), J_{2m}(x_i), J_{3m}(x_i)$, and $J_{4m}(x_i)$ are, respectively, the value of sliding wear between work roll and strip, the value of rolling wear between work roll and strip, the value of sliding wear between work roll and supporting roll and the value of rolling wear between work roll and supporting roll, in the m^{th} roll strip rolling process in work roll changing period.

2.4. The analysis calculation of work roll mechanism influence

The solution to the work roll mechanism influence equation, as specified in Eq.(2.3), actually involves the calculation of $J_{1m}(x_i), J_{2m}(x_i), J_{3m}(x_i)$, and $J_{4m}(x_i)$.
Synthesizing related literature, [4-6] $J_{1m}(x_i)$ can be calculated as:

$$J_{1m}(x_i) = k_1 \cdot p_m(x_i) \cdot \frac{L_m \cdot \left(f_{vm} + C_{um} \cdot \left(\dfrac{x_i}{0.5B_\mathrm{m}} \right)^4 \right)}{\left(1 + f_{qm}\right) \cdot \pi \cdot D_1} \tag{2.4}$$

where: k_1 is the sliding wear coefficient of contact between work roll and strip. D_1 is work roll diameter. $p_m(x_i), L_m, f_{qm}, f_{vm}, C_{um}$, and B_m are respectively the transverse distribution of rolling pressure in unit width, the rolling length of strip, the rolling forward slip coefficient, the relative sliding distance of each contact

between roller surface and strip, transverse flow influence coefficient, and strip width, in the $m\hat{}th$ roll strip rolling process in work roll changing period.
Synthesizing related literature [4-6]. $J_{2m}(x_i)$ can be calculated as:

$$J_{2m}(x_i) = k_2 \cdot p_m(x_i) \cdot \frac{L_m \cdot l_m^{'}}{(1+f_{qm}) \cdot \pi \cdot D_1} \tag{2.5}$$

where: k_2 is the rolling wear coefficient of contact between work roll and strip l'_m is the contact arc length of deformation zone in the m^{th} roll strip rolling process in work roll changing period.
Correspondingly, synthesizing related literature [4-6], $J_{3m}(x_i)$ can be calculated as followed model [6]

$$J_{3m}(x_i) = 2b_m \cdot \frac{L}{\pi D_1} k_3 \cdot Q_m(x_i) \cdot \left| 1 - \frac{R_{2m}(x_i)\omega_{2m}}{R_{1m}(x_i)\omega_{1m}} \cdot \frac{R_2}{R_1} \right| \tag{2.6}$$

where: k_3 is the sliding wear coefficient of contact between work roll and strip.
$Q_m(x_i)$, $R_{1m}(x_i)$, $R_{2m}(x_i)$, ω_{1m}, ω_{2m}, and b_m are respectively the transverse distribution of pressure between work roll and supporting roll in unit width, the load radius distribution value of work roll, the load radius distribution value of supporting roll, the circumferential speed of work roll rotation, the circumferential speed of supporting roll rotation, and half width of contact flattening between work roll and supporting roll, in the m^{th} roll strip rolling process in work roll changing period. R_1 and R_2 are nominal radii of work roll and supporting roll, respectively.
Similarly, synthesizing related literature, [4-6,10]. $J_{4m}(x_i)$ can be calculated as [6]:

$$J_{4m}(x_i) = k_4 \cdot Q_m(x_i) \cdot \frac{L_m \cdot 2b_m}{\pi \cdot D_1} \tag{2.7}$$

where: k_4 is the rolling wear coefficient of contact between work roll and supporting roll.
At last, integrating Eqs (2.3)-(2.7), the general equation of work roll mechanism influence can be constructed.

$$\begin{aligned} J(x_i) = \sum_{m=1}^{n} \Bigg\{ & \frac{p_m(x_i) \cdot L_m}{(1+f_{qm}) \cdot \pi \cdot D_1} \left(k_1 \cdot \left(f_{vm} + C_{um} \cdot \left(\frac{x_i}{0.5B_m} \right)^4 \right) + k_2 \cdot l_m^{'} \right) + \\ & +2b_m \cdot \frac{L_m \cdot Q_m(x_i)}{\pi D_1} \left(k_3 \left| 1 - \frac{R_{2m}(x_i)\omega_{2m}}{R_{1m}(x_i)\omega_{1m}} \cdot \frac{R_2}{R_1} \right| + k_4 \right) \Bigg\}. \end{aligned} \tag{2.8}$$

2.5. Measure and collect of the actual data of wear

To fully account for the equipment state in the roll wear model, we selected N (where $N > 15$ for adequate reflection of equipment and technology conditions in the rolling process) typical roll cycles as the background conditions. Subsequently, we obtained the actual roll wear data of each roll cycle $R_j^*(x_i)$ for $j = 1, 2, \cdots, N$.

In order to ensure precision, four conditions had to be met while measuring the actual wear data: (1) the roll must be maintained cold for 24 hours or more to ensure that the roll temperature on the surface, inside, and outside is essentially the same, thereby effectively eliminating the effect of thermal deformation on roll wear data and temperature change on roller front diameter; (2) the measurement data after rolling must be taken twice in the directions of maximum and minimum, and the average value must be taken to reduce data deviation; (3) before measuring the roll wear, we must carefully remove any oxide and other adhesions from the roller surface; (4) the level roller bearings at both ends must be adjusted to ensure that the measurement center line and the roll axis are coinciding [7, 12, 13].

2.6. Calculate the conditions influence coefficient a_k

To determine the conditions influence coefficient a_k , the measurement data of actual wear quantity and the calculation results of the mechanism influence on roll wear should be fully utilized [8].

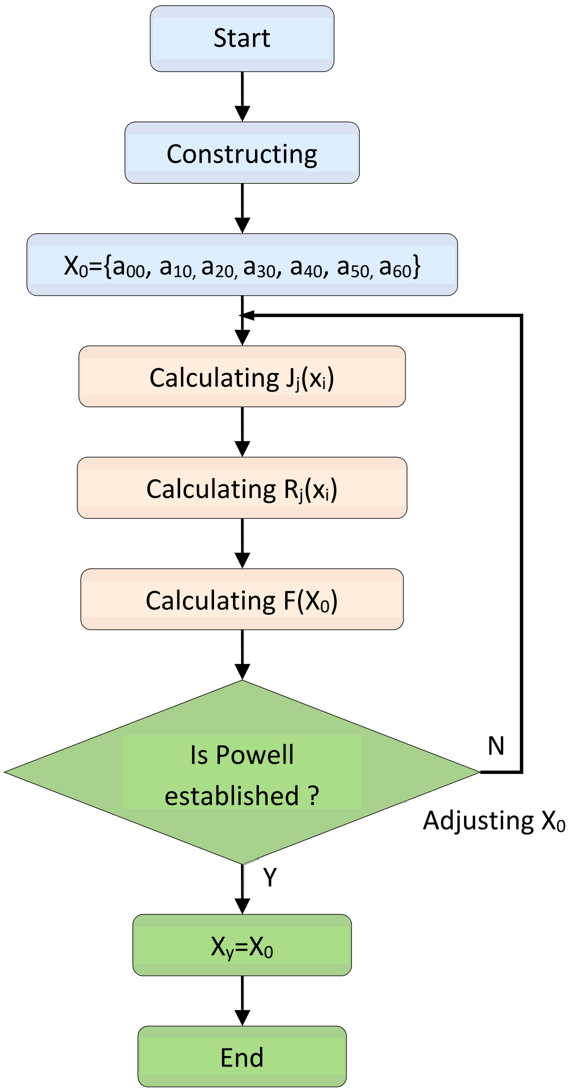


Fig.1. Calculation diagram of conditions influence coefficient.

The basic steps, illustrated in the calculation diagram of Fig.1, are as follows:

(a) Construct the objective function. In order to ensure the predicted value is as consistent as possible with the measured value, the objective function of conditions, $F(X)$, is formulated as follows:

$$F(X)=\sum_{j=1}^{N}\sqrt{\sum_{i=1}^{n}\left[R_j(x_i)-R_j^*(x_i)\right]^2} \tag{2.9}$$

where: $X=\{a_0,a_1,a_2,a_3,a_4,a_5,a_6\}$; $R_j(x_i)$ is the predicted value of work roll wear prediction model. Obviously, the smaller $F(X)$ is, the more realistic the roll wear model will be.

(b) Given the initial value of conditions influence coefficient $X_0=\{a_{00},a_{10},a_{20},a_{30},a_{40},a_{50},a_{60}\}$.

(c) Using Eq.(2.7), we can compute the mechanism influence factors of work roll wear for each roll cycle of N typical roll cycles, and the fundamental expression is as follows:

$$\begin{aligned} J_j(x_i)=\sum_{m=1}^{n_j}\Bigg\{&\frac{p_{mj}(x_i)\cdot L_{mj}}{\left(1+f_{qmj}\right)\cdot\pi\cdot D_{1j}}\left(k_1\cdot\left(f_{vmj}+C_{umj}\cdot\left(\frac{x_i}{0.5B_{mj}}\right)^4\right)+k_2\cdot l_{mj}'\right)+\\ &+2b_{mj}\cdot\frac{L_{mj}\cdot Q_{mj}(x_i)}{\pi D_{1j}}\left(k_3\left|1-\frac{R_{2mj}(x_i)\omega_{2mj}}{R_{1mj}(x_i)\omega_{1mj}}\cdot\frac{R_{2j}}{R_{1j}}\right|+k_4\right)\Bigg\} \end{aligned} \tag{2.10}$$

where: n_j is the total number of steel coils.

(d) By utilizing Eqs (2.1), (2.2), and (2.10), the theoretical value of work roll wear in the present typical roll cycle can be computed as follows:

$$\begin{aligned} R_j(x_i)=G(x_i)\bullet J_j(x_i)=\sum_{k=0}^{6}a_{k0}x_i^k\bullet\sum_{m=1}^{n_j}&\Bigg\{\left(k_1\cdot\left(f_{vmj}+C_{umj}\cdot\left(\frac{x_i}{0.5B_{mj}}\right)^4\right)+k_2\cdot l_{mj}'\right)+\\ &+\ 2b_{mj}\cdot\frac{L_{mj}\cdot Q_{mj}(x_i)}{\pi D_{1j}}\left(k_3\left|1-\frac{R_{2mj}(x_i)\omega_{2mj}}{R_{1mj}(x_i)\omega_{1mj}}\cdot\frac{R_{2j}}{R_{1j}}\right|+k_4\right)\Bigg\}. \end{aligned} \tag{2.11}$$

(e) According to Eq.(2.8) and Eq.(2.11) ,the value of the objective function $F(X_0)$ can be calculated.

(f) Judge whether the condition of Powell is established or not [9]. If it is established, the optimal value of conditions influence coefficient $X_y=X_0$ is obtained, ending the cycle, and then go to step(g); If it is not established, adjust the value of X_0, then go to step(c) to find the optimal value.

(g) Output the optimal value of conditions influence coefficient $X_y=\{a_{0y},a_{1y},a_{2y},a_{3y},a_{4y},a_{5y},a_{6y}\}$.

2.7. Roll wear prediction model based on the combination of the working mechanism and conditions.

Substitute the optimal conditions influence coefficient $X_y=\{a_{0y},a_{1y},a_{2y},a_{3y},a_{4y},a_{5y},a_{6y}\}$ into the correlation equations. We will develop a work roll wear prediction model by combining the working mechanism and conditions [11].

$$R(x_i)=\sum_{k=0}^{6} a_{ky}x_i^k \bullet \sum_{m=1}^{n}\left\{\frac{p_m(x_i)\cdot L_m}{(1+f_{qm})\cdot\pi\cdot D_1}\left(k_1\cdot\left(f_{vm}+C_{um}\cdot\left(\frac{x_i}{0.5B_m}\right)^4\right)+k_2\cdot l_m'\right)+\right.$$
$$\left.+2b_m\cdot\frac{L_m\cdot Q_m(x_i)}{\pi D_1}\left(k_3\left|1-\frac{R_{2m}(x_i)\omega_{2m}}{R_{1m}(x_i)\omega_{1m}}\cdot\frac{R_2}{R_1}\right|+k_4\right)\right\}. \tag{2.12}$$

By utilizing the model based on Eq.(2.12), we can obtain the rolling parameters of each coil strip rolling in a particular work roll changing period, such as the transverse distribution of rolling pressure, rolling length, and rolling forward slip coefficient, among others. Substituting these parameters into Eq.(2.12), we can generate the curve of work roll wear in a specific roll cycle, thereby completing the prediction of work roll wear.

3. Application results

To enhance the precision of flatness control for products produced by the 1220 Five-stand Tandem Cold Mill, Baosteel collaborated with Yanshan University to develop a software called the Online Prediction Model of Work Roll Wear for 4-hi Tandem Cold Mill, based on the mathematical model proposed in this paper. On-site testing yielded favorable results.

a)

b)

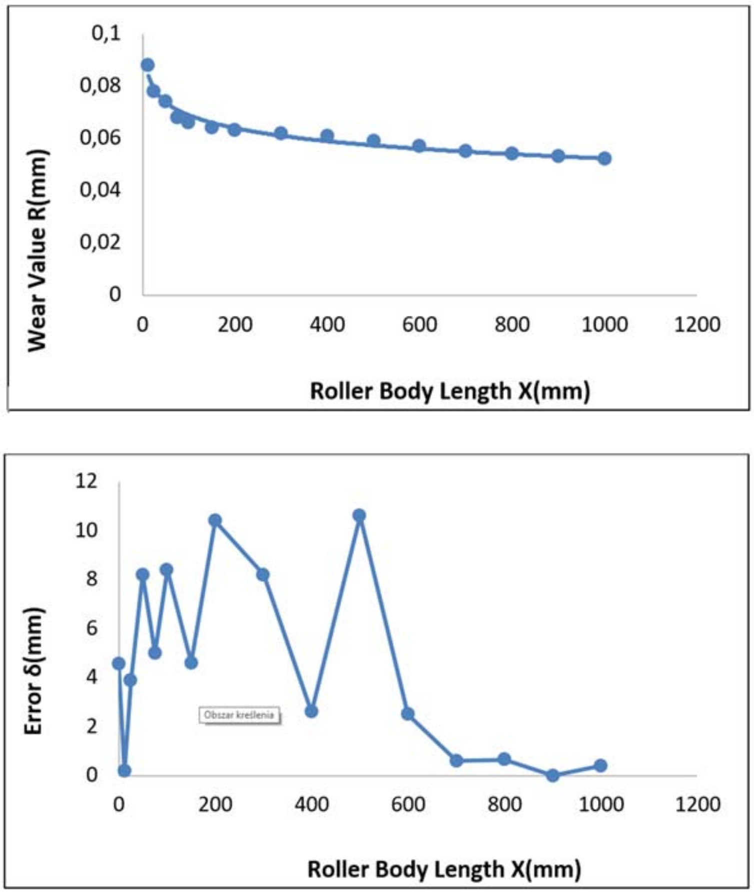
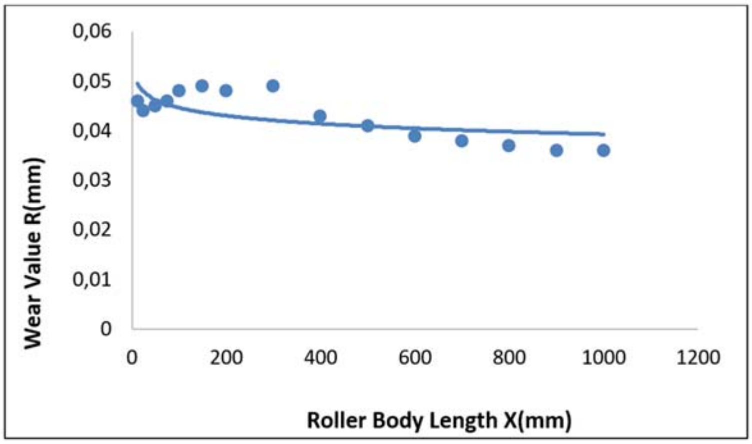


Fig.2. Comparison of measured and model predicted value of work roll 1 (a: Measured and predicted value of work roll 1, b: Relative error of measured and predicted value of work roll 1).

To verify the accuracy of the model, a simulation test was conducted on the fifth stand work roll over two roll cycles, using the process parameters of Baosteel's 1220 5-stand tandem cold rolling mill. The model was used to calculate the work roll wear value, and the results indicated that the average relative error between the predicted and measured values of work roll wear was less than *5.0%*, and the maximum relative error was less than *15%*, which met the accuracy requirements of roll wear prediction. The findings are presented in Figs 2 and 3.

a)



b)

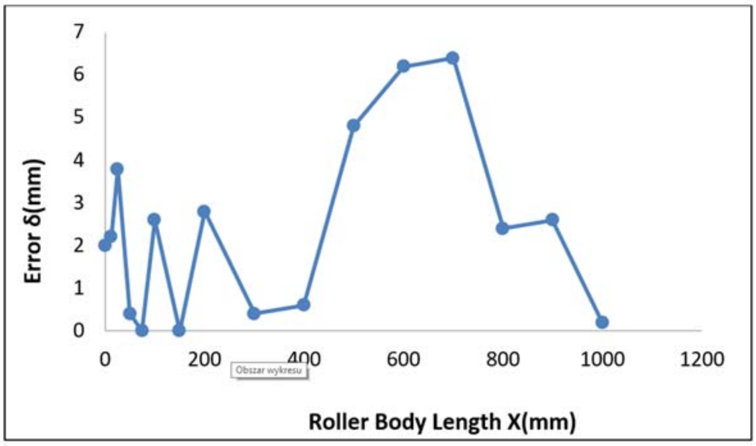


Fig.3. Comparison of measured and model predicted value of work roll 2 (a: Measured and predicted value of work roll 2, b: Relative error of measured and predicted value of work roll 2).

4. Conclusions

After conducting numerous field tests and theoretical research, we developed a wear model that combines actual wear data and takes into account the equipment and production characteristics of cold rolling. This model considers both the mechanism and conditions of wear, making it suitable for both symmetric and asymmetric wear. Using this model in the production of Baosteel's 1220 5-stand tandem cold rolling mill has ensured accurate prediction of work roll wear and provided a sound theoretical basis for roll contour design and flatness control techniques. As expected, the flatness of products has significantly improved, resulting in substantial economic benefits.

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Nomenclature

a_k – condition influence coefficient
B_m – strip width
b_m – half width of contact flattening between work roll and supporting roll
C_{um} – transverse flow influence coefficient
D_1 – work roll diameter
f_{qm} – rolling forward slip coefficient
f_{vm} – relative sliding distance of each contact between roller surface and strip
$F(X)$ – objective function
$G(x_i)$ – conditions influence equation in work roll wear
$J(x_i)$ – mechanism influence equation in work roll wear
$J_{1m}(x_i)$ – value of sliding wear between work roll and strip
$J_{2m}(x_i)$ – value of rolling wear between work roll and strip
$J_{3m}(x_i)$ – value of sliding wear between work roll and supporting roll
$J_{4m}(x_i)$ – value of rolling wear between work roll and supporting roll
k_1 – sliding wear coefficient of contact between work roll and strip
k_2 – rolling wear coefficient of contact between work roll and strip
k_3 – sliding wear coefficient of contact between work roll and strip.
k_4 – rolling wear coefficient of contact between work roll and supporting roll
L_m – rolling length of strip
l'_m – contact arc length of deformation zone under considering the flattening
m^{th} – roll strip rolling process in work roll changing period
n_j – total number of steel coil
$p_m(x_i)$ – transverse distribution of rolling pressure in unit width
$Q_m(x_i)$ – transverse distribution of pressure between work roll and supporting roll in unit width
$R(x_i)$ – wear value of work roll.
ω_{2m} – circumferential speed of supporting roll rotation
R_1 – nominal radius of work roll
R_2 – nominal radius of supporting roll
$R_{1m}(x_i)$ – load radius distribution value of work roll
$R_{2m}(x_i)$ – load radius distribution value of supporting roll
x_i – horizontal coordinate of *i* point
ω_{1m} – circumferential speed of work roll rotation

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