Optimization of Work Roll Taper for Extremely-thin Strip Rolling

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A simulation model was developed for analyzing the “roll-kiss” phenomenon, i.e., a situation where the upper and lower work rolls contact each other in the roll barrel. As a result of the analysis, a theoretical method of providing taper on the work rolls was found. The applicability of the method was experimentally confirmed in a laboratory mill, and the following findings were obtained:

1. The accuracy of the load of roll-kiss calculation by Hertz’s equation proved satisfactory for the practical use.
2. Analysis using the simulation model revealed two different configurations of roll-kiss.
3. The experimental results showed that for both configurations of roll-kiss, it is possible to prevent roll-kiss, by giving work rolls the optimum taper predicted from the simulation model.

KEY WORDS: cold rolling; simulation model; extremely-thin strip; roll-kiss

1. Introduction

The demand for extremely thin cold-rolled strips having a precisely controlled shape is rapidly increasing in relation to recent improvements in electric and electronic appliances; smaller, lighter and more precise materials. Most of extremely thin strips are produced in a cold rolling mill which is equipped with a set of work rolls being capable of precise control. In the relevant technology the phenomenon of “roll-kiss” is a main disadvantage which limits the minimum strip thickness.

Shimotsuchibashi reported a simulation model of strip rolling which took roll-kiss into consideration. He calculated the distribution of the roll gap and the load of roll-kiss along the roll length. In his report, however, the model was not validated in experiment and the method for preventing roll-kiss was not given.

This report describes a new simulation model for predicting roll-kiss which was found to appear in two ways on the basis of the analysis of a roll-kiss phenomenon. A suitable profile of tapered work roll to prevent each type of the roll-kiss was found by using the model. Its applicability was experimentally confirmed in a laboratory mill.

2. Simulation Model

2.1. Outline of the Model

The specifications of a 4-Hi mill of laboratory scale used in this study are shown in Table 1. As the structure and the force system of the mill (Fig. 1) can be regarded as symmetrical with respect to its center, the calculations were performed for the rolls of the upper set on the right-hand side. The deflection of roll axis was calculated by modeling the roll as a beam supported at its center. The distribution of loads along the beam was evaluated with a dividing method suggested by K. N. Shohet. The shear stress and bending stress were superimposed in the calculation of the roll deflection. The distribution of contact load between the work roll and backup roll, and that between the upper and lower work rolls (referred to as the load of roll-kiss hereafter) were calculated from Hertz’s equation by assuming the modulus of elasticity.

Table 1. Specifications of the laboratory mill.

| Roll dimension (mm) | Backup roll | Work roll |
|---------------------|-------------|-----------|
| φ400×350 l          | φ80×350 l   |
| Distance between cylinders (mm) | Backup roll | Work roll |
|                      | 560         | 680       |
| Maximum roll separating force (tf) | 120 |

Fig. 1. Forces acting on the upper work roll.
and by calculating the amount of roll-flattening in both cases. By adding the load of roll-kiss to the total roll separating force, the calculation was repeated until the values of contact loads and those of roll deflections along the roll length converge to reasonable values.

Only the distribution of front tension in the strip direction was counted in the calculation. The distribution of back tension was assumed to be uniform.

The thermal crown was calculated on the basis of the heat conduction equation and heat transfer equation with a finite difference method. Details of the procedure are described in the next section.

2.2. Calculation Procedures

2.2.1. Elastic Deformation of Rolls

The work roll is subject to the contact, rolling and bending forces as shown in Fig. 1. Its deflection was calculated by integrating Eqs. (1) and (3) with the boundary conditions of Eqs. (2) and (4), respectively. Deflection \( \delta \), by bending stress

\[
E \cdot I \cdot \frac{d^2\delta}{dx^2} = M \quad \text{...............(1)}
\]

\( x = 0, \ \frac{d\delta}{dx} = 0, \ \delta = 0 \quad \text{...............(2)}
\]

Deflection \( \delta \) by shear stress

\[
G \cdot A \cdot \frac{d\delta}{dx} = \frac{4}{3} \cdot S \quad \text{...............(3)}
\]

\( x = 0, \ \delta = 0 \quad \text{...............(4)}
\]

Here, \( E \): Young’s modulus

\( I \): Moment of inertia of area

\( S \): Shearing force

\( A \): Area of cross section of roll

\( M \): Bending moment

\( G \): Modulus of rigidity.

The positive direction of deflection was taken to increase the roll gap.

The deflection is given by

\[
y_{\text{WR}(0)} = (\delta_{\text{WR}(0)} + \delta_{\text{WR}(0)})_p - (\delta_{\text{WR}(0)} + \delta_{\text{WR}(0)})_o
\]

\[+ (\delta_{\text{WR}(0)} + \delta_{\text{WR}(0)})_r. \quad \text{...............(5)}
\]

The deflection of backup roll \( \delta_b \) was calculated in the same way. The surface profiles of the deflected work roll and backup roll were obtained by considering the terms of initial crown and thermal crown of the rolls. The distribution of roll rigid body motion between the rolls is determined from their surface profiles as shown by

\[
y_{\text{WR}(0)} = y_{\text{WR}(0)} + C_{\text{WR}(0)/2} - \left( y_{\text{WR}(0)} - C_{\text{WR}(0)/2} \right) + \delta_b. \quad \text{...............(6)}
\]

Here, \( \delta_b \): The roll rigid body motion at the roll center which is to be determined by the repetitive calculation

\( C_{\text{WR}(0)} \): The crown of work roll consisting of the mechanically ground crown (the initial crown) and the thermal expansion of roll (the thermal crown)

\( C_{\text{BR}(0)} \): The crown of backup roll.

The distribution of contact load \( q_{\text{WR}} \) between the rolls is given by Eq. (7) in terms of constant elastic modulus \( K_{\text{WR}} \) between these rolls.

\[
q_{\text{WR}} = K_{\text{WR}} \cdot J_{\text{WR}} \quad \text{...............(7)}
\]

\( K_{\text{WR}} \) in Eq. (7) is given by Eq. (8), i.e., the theory of rigid body motion between two cylinders suggested by Hertz.

\[
K_{\text{WR}}^2 = B_{\text{WR}}(0.1182 + \ln(d_{\text{WR}} + d_{\text{WR}}))
\]

\[- \ln B_{\text{WR}} - \ln Q)/\pi \quad \text{...............(8)}
\]

Eqs. (9) and (10) give \( B_{\text{WR}} \) and \( Q \), respectively, necessary for numerical calculation of Eq. (8).

\[
B_{\text{WR}} = (1 - \nu_{\text{WR}}^2)/E_{\text{WR}} + (1 - \nu_{\text{WR}}^2)/E_{\text{WR}} \quad \text{...............(9)}
\]

\[
Q = \sum P_{\text{WR}}/l_{\text{WR}} \quad \text{...............(10)}
\]

Here, \( \nu \): Poisson’s ratio

\( d \): Diameter of roll

\( l_{\text{WR}} \): Contact length between work roll and backup roll.

The deviation of roll gap between the upper and lower work rolls is given by Eq. (11) when roll rigid body motion can be neglected.

\[
\theta_{\text{WR}} = 2.2 B_{\text{WR}} - C_{\text{WR}} \quad \text{...............(11)}
\]

In actual rolling, however, the rigid body motion of work roll takes place where the work roll contacts the strip. The actual deviation of roll gap is the summation of \( \theta_{\text{WR}} \) and the deviation of roll rigid body motion \( V_{\text{WR}} - V_{\text{crown}} \), where \( V_{\text{crown}} \) is the roll rigid body motion at the mill center. The distribution of the roll gap \( G_{\text{WR}} \) was calculated from Eq. (12) by giving the value of roll gap at the mill center \( h_b \).

\[
G_{\text{WR}} = h_b + \theta_{\text{WR}} + V_{\text{WR}} - V_{\text{crown}} \quad \text{...............(12)}
\]

In this study, it is postulated that the rigid body motion of work roll takes place only where the work roll contacts the strip. It is also postulated that the value of \( k_{\text{WR}} \) agrees with that of \( G_{\text{WR}} \) in the above mentioned region.

2.2.2. The Distribution of Rolling Load and the Load of Roll-kiss

The distribution of rolling load is given by Eq. (13) suggested by Orowan.

\[
P'_{\text{WR}} = (K_{\text{WR}}^2 - l_{\text{WR}}/J_{\text{WR}}) \cdot f_{\text{WR}} \quad \text{...............(13)}
\]

\( K_\star \): is the weighted average flow stress of the strip shown by

\[
K_\star = (K_\star + 2K_\star^2)/3, \quad \text{...............(14)}
\]

where, \( K_\star, K_\star^2 \): the flow stress before and after rolling, respectively.

The unit tension \( t_{\text{WR}} \) in Eq. (15) is the average of front \( t_{\text{WR}} \) and back \( t_{\text{WR}} \) tension.

\[
t_{\text{WR}} = (t_{\text{WR}} + t_{\text{WR}})/2 \quad \text{...............(15)}
\]

As the calculation in this study deals with the rolling of extremely thin strips, the following Roberts’ equation was used as the rolling force function \( f_{\text{WR}} \).
where $\mu$ is the friction coefficient.

$$f_{\rho(0)} = (1 - 5r_{10}/4 + \mu L_{10}/2H_{10}) (1 - r_{10})$$

...............(16)

The reduction in thickness $r_{10}$ is defined as Eq. (17) by using the strip thickness before and after rolling, $H_{10}$ and $h_{10}$, respectively.

$$r_{10} = (H_{10} - h_{10})/h_{10}$$

...............(17)

The projected length of contact $L_{10}$ is calculated from the following Roberts’ equation,

$$L_{10} = (K_w^* - t_{10})/2R[E_{ww} + \sqrt{P_{10}'(H_{10} - h_{10})}]$$

...............(18)

where, $R$: The radius of work roll

$R_{10}'$: The radius of curvature of flattening work roll.

Eq. (19) suggested by Hitchcock gives the value of

$$P_{10}' = R(1 + 16(1 - \nu_{ww}^2) P_{10}/(\pi E_{ww}(H_{10} - h_{10}))$$

...............(19)

Subsequently, the load of roll-kiss, i.e., the contact load between the upper and lower work rolls is calculated according to the note of $G_{10}$.

i) $G_{10} > 0$; the rolls do not contact each other in this case.

ii) $G_{10} < 0$; the rolls contact each other resulting in roll-flattening to the amount of $G_{10}$.

Shimotsuchibashi’s method is complicated, because he divided the region of roll-kiss into many rectangular finite elements, calculated the load of roll-kiss of each portion, and finally obtained the total load of roll-kiss.

Therefore, we predicted that the following simple equation is applicable to calculate the load of roll-kiss and tried to confirm its applicability experimentally.

$$P_{10}' = K_{ww} G_{10}$$

...............(20)

Here, $K_{ww}$ is the elastic modulus between the upper and lower work rolls and written by

$$K_{ww} = B_{ww}(0.1182 + \ln (2d_{ww}) - \ln B_{ww} - \ln Q)/\pi$$

...............(21)

The following equation (22) gives the value of $B_{ww}$ necessary for calculating Eq. (21).

$$B_{ww} = 2(1 - \nu_{ww}^2)/E_{ww}$$

...............(22)

The theory of roll-flattening suggested by Hitchcock is usable to estimate the rigid body motion of work roll at the exit of roll bite as written by

$$V_{10} = (C/2) P_{10} \ln [2d_{ww}/(H_{10} - h_{10} + CP_{10})]$$

...............(23)

where, $C$: A constant value determined by

$$C = 16(1 - \nu_{ww}^2)/(\pi E_{ww})$$

...............(24)

2.2.3. The Distribution of Tension

Eq. (25) suggested by Kohno et al. gives the deviation of front tension, where $E_{p}$ is Young’s ratio of the rolled material.

$$\Delta t_{10} = E_{p} \cdot \gamma \left[ \frac{h_{10}}{H_{10}} \cdot \sum_{i=1}^{n} \frac{h_{10}}{(L_{10} + \sum_{i=1}^{n} h_{10})} - 1 \right]$$

...............(25)

The distribution of front tension per unit area is given by,

$$t_{10} = t_{10} + \Delta t_{10}$$

...............(26)

where, $t_{10}$: The front tension per unit area at the strip center.

The coefficient $\gamma$ in Eq. (25) is defined by the following equation,

$$\gamma = \frac{J_{10}}{J_{20}}$$

...............(27)

where, $J_{10}$: The deviation of longitudinal strain at $i$-portion compared with that at strip center

$J_{20}$: The deviation of thickness strain.

It is necessary to determine the value of $t_{10}$ by the repetitive calculation so that the summation of the front tension for each portion may be equal to the total front tension. The front tension for each portion $t_{10}$ is determined by

$$T_z = \sum t_{10} \cdot dx$$

...............(28)

where, $dx$: The length of each divided portion.

A sequence of calculations mentioned above was performed in the procedures shown in Fig. 2.

3. The Prediction of Roll-kiss Configuration by Simulation Model

The configuration of roll-kiss was predicted from the newly developed simulation model for the pass schedule, shown in Table 2, in the laboratory mill, the specifications of which are shown in Table 1. The strip used in Simulation 1 was SUS 301 steel of 180 mm in width and 0.2 mm in thickness. The strip was annealed at the gauge before first rolling. Simulation 1 was carried out for the straight work rolls according to the pass schedule shown in Table 2.

Fig. 3 shows the calculated roll gap for each pass. The negative value of roll gap means that the upper and lower work rolls flatten by the same amount.

The roll-kiss starts at the 6th pass at the both roll edges. The region of roll-kiss expands at the 7th pass as shown in Fig. 3. This type of roll-kiss is referred to as type A in this study.

The following three reasons were considered for the type A roll-kiss;

1. The profile of work roll is straight.
2. The deflection of work roll axis is very large because the diameter of work roll is small and the rolling force is comparatively large owing to the high flow stress of rolled material (SUS 301 steel).
3. The strip thickness at which the roll-kiss starts is larger than the rigid body motion of the work roll.

The strip used in Simulation 2 was SUS 304 steel of 205 mm in width and 0.080 mm in thickness. The
Fig. 2. Flow chart of the main calculation program.

Table 2. Pass schedules.

| Gauge H/h (mm) | Tension f/ (kgf/mm²) | Average static flow stress (kgf/mm²) |
|---------------|----------------------|-------------------------------------|
| 0.200/0.160  | 24.4/42.7            | 121.9                               |
| 0.160/0.130  | 30.4/53.1            | 151.8                               |
| 0.130/0.120  | 34.0/59.6            | 170.2                               |
| Simulation 1  |                      |                                     |
| 0.120/0.110  | 35.9/62.8            | 179.4                               |
| 0.110/0.100  | 37.5/65.6            | 187.5                               |
| 0.100/0.090  | 39.1/68.4            | 195.5                               |
| 0.090/0.080  | 40.0/70.0            | 200.1                               |
| Simulation 2  | 0.080/0.065          | 33.0/20.4                           | 72.5                               |

The calculated roll gap for each pass through the straight work rolls for SUS301 having an initial crown of 0.070 mm according to the pass schedule in Simulation 1.

The calculated roll gap for the work rolls having an initial crown of 0.070 mm according to the pass schedule shown in Table 2. The roll-kiss in this case starts at immediately next to the strip edge and the roll gap decreases as the distance from the roll center increases as shown in Fig. 4. The latter is mainly due to the roll crown of the work roll. This type of roll-kiss is referred to as type B in this study. The following reasons were considered for type B:

1. The rigid body motion of the work roll is larger than the strip thickness at which the roll-kiss starts.
2. The deflection of the work roll axis is very small when the diameter of the work roll is relatively large or the rolling force is comparatively small.
3. The work roll has a relatively large positive crown.
4. Method to Determine the Optimum Taper of Work Roll and Experimental Result

4.1. Roll-kiss of Type A

The authors assume that the roll-kiss for the 7th pass in Fig. 3 can be prevented by giving a taper whose size is equal to the maximum roll gap between the upper and lower work rolls. Simulation 1 was carried out again by using the above tapered work roll. Fig. 5 shows that the roll-kiss can be prevented until the 7th pass. In order to confirm the applicability of the results of this simulation, experiments were carried out under the same conditions as those of the calculation. Visual observation of the coolant flow at the roll bite from the delivery side revealed that the experimental results agree comparatively well with the simulation results.

4.2. Roll-kiss of Type B

In order to prevent the roll-kiss of type B, the authors assume that it is necessary to determine the taper size and its start point from the geometrical relation expressed by the following equation.

\[
\frac{D_T - D_E}{L/2 - (W/2 - X)} = \frac{G_{\text{max}}}{X}
\]

where, \( D_T \): Diameter of work roll at strip edge
\( D_E \): Diameter of work roll at roll edge
\( L \): Barrel length (=350)
\( W \): Strip width (=205)
\( G_{\text{max}} \): Maximum roll gap (=0.030)
\( X \): Distance between strip edge and taper start point.

Substitution of \( D_T - D_E = 0.200 \) (mm) in Eq. (29) gives \( X = 12.8 \) (mm). The roll-kiss is perfectly prevented with this tapered work roll. The effect of taper start point on the extent of the roll-kiss was examined under the same conditions as Simulation 2. In this case taper size was fixed constant. As shown in Fig. 6, when the taper start point was 80 mm apart from the roll center, the roll-kiss was perfectly prevented. Visual observation in the experiment supported this simulation result. When the taper start points were 110 and 130 mm apart from the roll center, on the contrary, the roll-kiss at strip edge still remained though the degree of roll-kiss was much decreased. Fig. 7 compares the calculated and measured load of roll-kiss. The value of friction coefficient is necessary for calculating the load of roll-kiss. The authors obtained the coefficient by using the simulation model from the roll separating force experimentally measured for the case when the taper start point was 80 mm apart from the roll center. Assuming that the friction coefficient obtained in this way was applicable to the other cases where the taper start points were 110 and 130 mm apart from the roll center, the load of roll-kiss and the roll separating force were calculated for these cases.

The experimental results agree fairly well with those of calculated even though this simulation model involves a simple calculation method suggested by Hertz.

It can be said from these results that the accuracy of the load of roll-kiss calculated by this model proved to be satisfactory for the practical use.

5. Conclusions

In order to analyze the "roll-kiss" phenomenon, a simulation model was developed. On the basis of the analyses the authors found a theoretical method to determine the taper of the work rolls. Its applicability was tested with a laboratory mill and the following points were clarified.

(1) The well known Hertz's equation was experi-
mentally confirmed to be applicable to calculate the load of roll-kiss with a satisfactory accuracy for the practical use.

(2) Two types of roll-kiss were found by the analysis and they can be prevented by giving the work rolls a suitable straight taper predicted from the simulation model.

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