

Development of Cluster Mill Simulator for Thin Strip and Foil Rolling (I)

— Outline of Simulator —

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A rolling simulator for the Cluster Mill, especially the 6Hi X and 10Hi X type mills besides the conventional 4-high mill, has been developed for evaluation of rolling thin strips and foils. The evaluation includes roll deflection, pressure of rolls in contact, roll exit thickness distribution, and so on. Characteristics of kiss rolling (edge parts of work rolls are in contact, except material width) was clarified with this simulator, and the effect of roll actuators on mill delivery thickness distribution was estimated. The outline of the simulator is described.

1. Introduction

There have been many reports on rolling load characteristics, roll deflection and other characteristics of thin and foil rolling. Most of the reports presented analyses of just one type of mill and just one type of rolled material in each case. For example, for rolling loads, no uniform formula has been established for calculating foil rolling loads, and this is one of the areas not clarified yet.

The current thin and foil rolling mainly rolls steel type hardening steel sheets, stainless steel materials and nonferrous materials, such as aluminum alloys, copper alloys and titanium, and adopts 4-high, 6-high, 10-high, 12-high, 20-high and other cluster mills. Generally, foil products are manufactured in multiple paths by reducing the rolling load per path for harder materials by using small-diameter work rolls in cluster mills.

Our company has many actual achievements in thin and foil rolling mills. However, the type of mill varies depending on the rolled materials and we had no simulator for uniform analyses.

To enable uniform analyses of thin and foil rolling mills, the authors developed a simulator targeting some of our proven mills. This simulator is applicable not only to rolling thin and foils but also to ordinary flat rolling with larger thickness, and it is easy to modify it for mill types other than the target mills of this study.

The important simulator functions for determining the main mill specifications in designing thin strip and foil rolling mills include:

- (1) The capability to simulate the kiss rolling state in which the edges of upper and roller work rolls elastically come into contact with each other for rolling with reduced thickness; in other words, a capability to simultaneously and accurately analyze the rolling pressure distribution of rolled materials and the elastic contact pressure distribution of work rolls.
- (2) The capability to analyze the contact and non-contact states of each cluster roll and a capability to accurately analyze the contact surface pressure distribution and the roll deflection distribution.
- (3) The capability to calculate the strip profile (strip thickness distribution in the width direction) in combination with an actuator, and especially, a capability to quantitatively determine the effect of a roll bender on the strip crown during kiss rolling.
- (4) The capability to process many analysis cases in a minimized calculation time and produce results with a high degree of accuracy.

In this study, we adopted aluminum alloys, copper alloys and steel materials as rolled materials, and adopted a 4-high rolling mill for aluminum alloys and a 6Hi X type mill and a 10Hi X type mill for copper alloys and thin steel sheets.

The formula we used to calculate foil rolling loads, was Stone's formula, which is conventionally used for flat rolling, and Hill's formula (which was expanded and corrected by Misaka for rolling with tension)⁽¹⁾ as mentioned above. By using these formulas, we compared the data obtained from production machines

and the analysis values from the rolling region of thin sheets to the rolling region of foil, and thereby conducted studies to determine which formula worked better for simulating production situations.

2. Details of simulator

2.1 Outline of calculation methods

This simulator calculates the rolling loads and roll deflection of cluster rolling mills; a 4-high mill, a 6Hi X type mill and a 10Hi X type mill. **Figure 1** shows the mills used for calculation.

The rolling mills have the backup rolls (BUR), intermediate rolls (IMR) and work rolls (WR) of the same size and the same materials. These components are positioned symmetrically to the $Y = 0$ plane and to the $Z = 0$ plane. The upper backup roll chock is supported and the lower backup roll chock is subject to a load in the Z direction.

Figure 1 shows the target rolls for calculation in solid lines, with consideration for this symmetry. The common section W in the X -axis direction of the target rolls is divided into NX equal intervals and the divided models are used for calculation. The X coordinate of the midpoint of each interval is expressed as X_i ($i = 1$ to NX) and the physical quantities at X_i are calculated. The physical quantities include the outlet thickness, the rolling load distribution, the roll axis's deflection of target rolls, the contact surface pressure between rolls and the roll displacements in the Y and Z directions.

To calculate the surface deformation of rolls direct contact area, Herz's analytical solution for the contact between cylinders is used at each section of $x = X_i$. For

the rolling contact area where some rolled material is in contact with work rolls, the solution of rolling by infinite cylinders is used at each section of $x = X_i$. Stone's formula or Hill's formula with expanded rolling theory with tension is used as the rolling load formula.

Roll deflection is calculated by the formula for beam deflection with shear deformation. The distribution of forward tension σ_f varies depending on the distribution of delivery thickness in the strip width direction. This effect (tension feedback) is taken into consideration.

With regard to thin materials, the upper and lower work rolls may directly come into contact with each other at edges as shown in **Fig. 2**. This calculation is enabled by determining whether the rolls are in the non-contact area, the direct contact area or the rolling contact area each time at each $x = X_i$ section, and by using the iteration method. Solving simultaneous equations is somewhat troublesome, as classification of these areas must be assumed in advance.

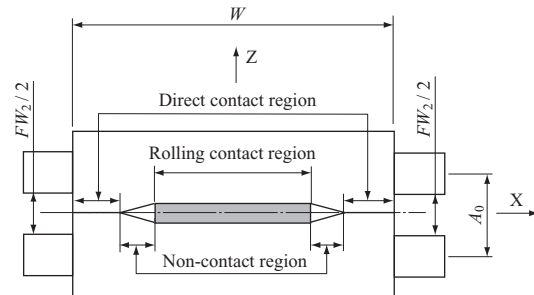
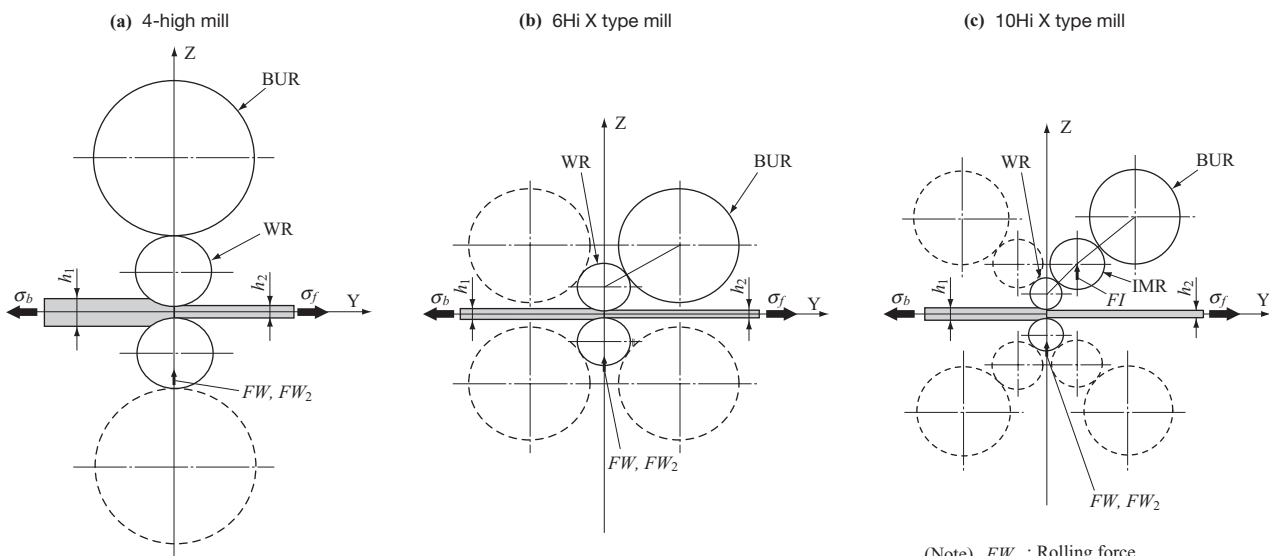


Fig. 2 Contact between work rolls



- (Note) FW : Rolling force
- FW_2 : Work roll bending force
- FI : Intermediate roll bending force
- h_1 : Entry thickness
- h_2 : Delivery thickness
- σ_f : Front tension
- σ_b : Back tension

Fig. 1 Calculated multi-rolls

2.2 Calculation of reaction force caused by work roll flattening

Work rolls are locally flattened under a rolling load as shown in Fig. 3 and the following Hitchcock's formula (2) is assumed to be true.

$$R' = R \cdot (1 + C_0 \cdot q_E / \Delta h) \dots\dots\dots (1)$$

$$L = \sqrt{R' \Delta h} \dots\dots\dots (2)$$

$$L_0 = \sqrt{R(h_1 - A + 2R)} \dots\dots\dots (3)$$

$$L - L_0 = C_0 \cdot q_E \cdot R / (2L) \dots\dots\dots (4)$$

$$C_0 = 16(1 - \nu^2) / (\pi E) \dots\dots\dots (5)$$

$$\Delta h = h_1 - h_2 \dots\dots\dots (6)$$

where

- R, R' : Roll radius before and after roll flattening
- L, A : Projected contact arc length and distance of two rolls center axes
- h_1, h_2 : Entry and delivery thickness
- q_E : Rolling load per unit width
- E, ν : Young's modulus and Poisson's ratio of rolls
- $L - L_0$: Difference of curvature radius center, before and after roll flattening

Equations (1) and (2) make the following formula true.

$$q_E = (L^2 - R\Delta h) / (RC_0) \dots\dots\dots (7)$$

When A, R, h_1, h_2 and L are given, q_E can be derived from equation (7).

2.3 Calculation of rolling loads

Some rolled material is rolled from thickness h_1 to h_2 . When Stone's formula (3) is used, the rolling load per unit width q_S is given as follows.

$$q_S = k_m \cdot L [1 - (\sigma_b + \sigma_f) / (2 k_m)] \cdot [\exp(c) - 1] / c$$

$$c = \mu L / h_m, h_m = (h_1 + 2h_2) / 3 \dots\dots\dots (8)$$

When Hill's formula expanded by Misaka for rolling with tension (1) is used, q_S is given as follows.

$$q_S = k_m \cdot L \cdot [1 - (0.7\sigma_b + 0.3\sigma_f) / k_m] \cdot f$$

$$f = 1.08 + 1.79 \cdot a \cdot r \cdot \sqrt{1 - r} - 1.02 \cdot r$$

$$r = (h_1 - h_2) / h_1, a = \mu \cdot \sqrt{R' / h_2} \dots\dots\dots (9)$$

where

- k_m : Two dimensional deformation resistance
- σ_f, σ_b : Front and back tension
- μ : Rolling friction coefficient

When A, R, h_1, h_2 and L are given, q_S can be derived from equation (8) or (9).

2.4 Calculation of delivery thickness

The reaction force caused by roll flattening of work rolls must be equal to the reaction force caused by rolling some material. When A, R, h_1 and L are given, h_2 is determined to satisfy the following formula.

$$q_E(h_2) = q_S(h_2) = q(h_2), 0 \leq h_2 \leq h_1 \dots\dots\dots (10)$$

2.5 Calculation of projected contact arc length

Equation (4) makes the following equation true.

$$2L(L - L_0) = C_0 \cdot q \cdot R \dots\dots\dots (11)$$

The following equation is obtained by assigning equation (1) to equation (2), assigning equation (3) to equation (4), deleting C_0 and solving the quadratic equation.

$$L = L_0 + \sqrt{L_0^2 - R\Delta h} \dots\dots\dots (12)$$

This gives the following inequality.

$$L_0 \leq L \leq 2L_0 \dots\dots\dots (13)$$

L is adjusted to make equation (11) true in the range of equation (13).

2.6 Calculation of the load per unit width when the distance between two roll centers is given

When the distance between two roll centers A is given, the load per unit width q is calculated in the following three different cases as shown in Fig. 4. The radii of the upper and lower rolls are expressed as R_1 and R_2 , considering the shape of crowning at $x = X_i$. For work rolls in contact, $R_1 = R_2 = R$. h_1 is the entry thickness and is assumed to be zero ($h_1 = 0$) where there is no material between the rolls.

(1) When $A \geq R_1 + R_2 + h_1$ is true as shown in Fig. 4-(a)

The load q is zero ($q = 0$) since the rolls do not contact each other.

(2) When $A < R_1 + R_2 + h_1$, $h_1 = 0$ is true as shown in Fig. 4-(b)

The rolls come into direct contact with each other. From Herz's analytical solution, the following equation becomes true.

$$R_1 + R_2 - A = 2q / \pi \cdot (1 - \nu^2) / E^2 \cdot \{ 2/3 + \log [2\pi (R_1 + R_2) / q \cdot E / (1 - \nu^2)] \} \dots\dots\dots (14)$$

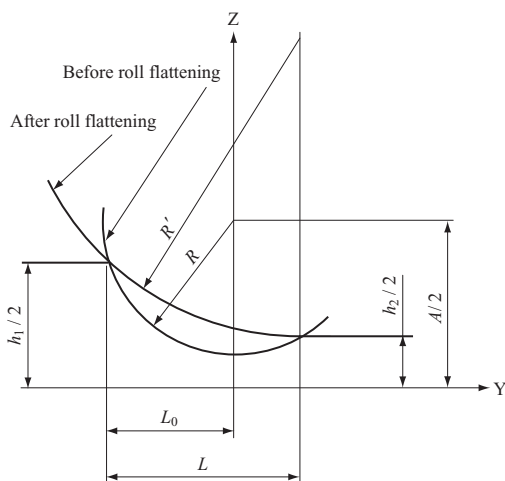


Fig. 3 Roll flattening of work rolls

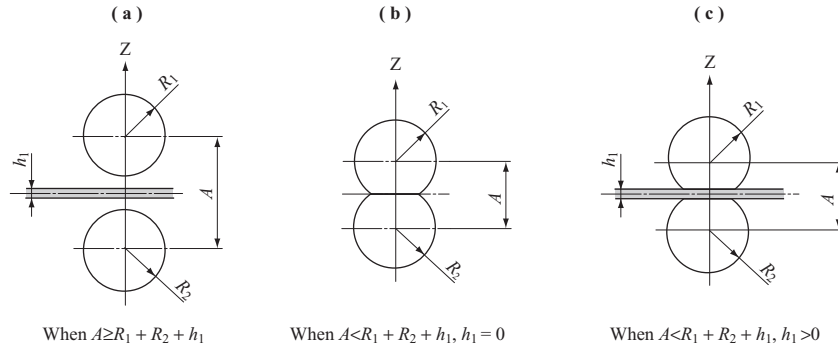


Fig. 4 Calculation of load q

It is difficult to analytically solve this equation and thus q is derived by numerical calculation.

(3) When $A < R_1 + R_2 + h_1$, $h_1 > 0$ is true as shown in Fig. 4-(c)

The rolls come into contact with each other with some rolled material in between. The load q is determined by following procedure.

- (a) Assume L in the range of equation (13).
- (b) Assume h_2 in the range of $0 \leq h_2 \leq h_1$.
- (c) Derive q_E from equation (7) and derive q_S from equation (8) or (9).
- (d) Adjust h_2 to satisfy equation (10).
- (e) Adjust L to satisfy equation (11).

Iterate steps (c), (d) and (e) until the values converge.

2.7 Consideration for tension feedback

It is assumed that some rolled material is cut out to a length of S_0 and then cut into strips with a width of ΔX (Fig. 5), and as a result, the strips shrink to a length of S_i . Strips longer than the average length S_A are subject to compression stress increment, while strips shorter than S_A are subject to tension stress increment. (4)

Variation in strip length is caused by the delivery thickness distribution. The average of h_{1i} is expressed as h_{1A} , while the average of h_{2i} is expressed as h_{2A} . Δh_{1i} and Δh_{2i} are defined as follows.

$$h_{1i} = h_{1A} + \Delta h_{1i}, h_{2i} = h_{2A} + \Delta h_{2i} \dots\dots\dots (15)$$

Δh_{1i} and Δh_{2i} are assumed to be smaller enough than the

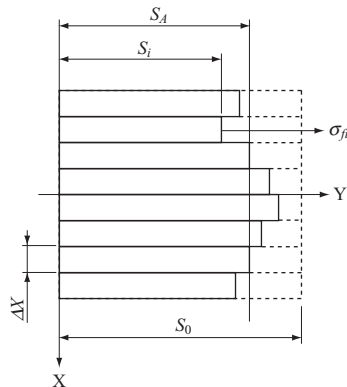


Fig. 5 Illustration of tension feedback

average values as given below.

$$|\Delta h_{1i}/h_{1A}| \ll 1, |\Delta h_{2i}/h_{2A}| \ll 1 \dots\dots\dots (16)$$

When the equation is transformed by taking into consideration that the plastic deformation is a volume conserving process, the front tension is given by the following equation.

$$\sigma_{fi} = \sigma_f + E \cdot (\Delta h_{2i}/h_{2A} - \Delta h_{1i}/h_{1A}) \dots\dots\dots (17)$$

where σ_f is the average front tension and E is the Young's modulus of the sheet with the assumption of $\sigma_f \ll E$.

2.8 Calculation of load distribution between rolls

Hereinafter, the physical quantity $f(X_i)$ ($i = 1$ to NX) is expressed as $f(x)$. When the bender external force applied to work rolls FW_2 (see Fig. 2) and the external loads distribution from the contact rolls other than work rolls in the Y and Z-directions, $q_{OZ}(x)$ and $q_{OY}(x)$ are given, the following equation becomes true with the load distribution between work rolls $q(x)$ (see Fig. 2).

$$\int q(x) dx + FW_2 = \int q_{OZ}(x) dx \dots\dots\dots (18)$$

The calculation procedure is as follows.

- (1) Assume the distance between two roll centers at edges A_0 .
- (2) Assume $q(x)$.
- (3) From the given loads distribution $q(x)$, $q_{OZ}(x)$ and $q_{OY}(x)$, calculate the roll deflection using the formula for beam deflection with shear deformation, and determine the distribution of distance between two roll centers $A(x)$.
- (4) Determine $q(x)$ according to the procedure described in Section 2.6.
- (5) Correct $\sigma_f(x)$ according to the procedure described in Section 2.7.
- (6) Repeat steps (3), (4) and (5) until $q(x)$ converges.
- (7) Adjust A_0 to satisfy equation (18).

When there is no material between rolls, the same procedure can be used to calculate the load distribution between the rolls.

2.9 Calculation of cluster rolls

Taking the 10-high rolls shown in Fig. 1-(c) as an example, the calculation procedure for cluster rolls is described below.

- (1) Assume the load distribution between rolls $q_{WL}(x)$ for the upper work roll and the lower work roll.
- (2) Assume the load distribution between rolls $q_{IW}(x)$ for the intermediate roll and the upper work roll.
- (3) Calculate the load distribution between rolls $q_{BI}(x)$ for the backup roll and the intermediate roll according to the procedure described in **Section 2.8**.
- (4) Calculate the load distribution between rolls $q_{IW}(x)$ for the intermediate roll and the upper work roll according to the procedure described in **Section 2.8**.
- (5) Calculate the load distribution between rolls $q_{WL}(x)$ for the upper work roll and the lower work roll according to the procedure described in **Section 2.8**.

Repeat steps (3), (4) and (5) until $q_{BI}(x)$, $q_{IW}(x)$ and $q_{WL}(x)$ converge.

The proximity between the backup roll and the intermediate roll is converted to the Z-direction displacement of the intermediate roll. The proximity between the intermediate roll and the upper work roll is converted to the Z-direction displacement of the upper work roll. The proximity between the upper work roll and the lower work roll is converted to the Z-direction displacement of the lower work roll.

3. Analysis results

3.1 Comparison between the data obtained from actual machines and the analysis results for the delivery thickness of rolling mills for thin strips (including foils)

Figure 6 shows a comparison between the data obtained from actual machine operations and the results of analyzing the delivery thickness of rolling mills under the same conditions as those for the data on rolling with the prototype.

Table 1 shows the type of mill and roll dimensions at each customer. **Table 2** shows the material, dimensions and rolling reduction of each rolled material. In the actual rolling operations at each company, the rolls have roll crowns that are appropriate for the rolling conditions, and this is considered in the analysis.

As with the actual machines, the rolling force was applied by the lower push-up cylinder, the operation values are used for the entry and delivery tension values and work roll bender values, and the deformation resistance value is taken into consideration to calculate the strip thickness in a gap between rolls in the analysis.

Companies A and B rolled aluminum alloy thin strips (including foils) using an ordinary 4-high rolling mill, while company C rolled mild steel thin strips using a 10Hi X type mill.⁽⁵⁾ **Figures 6-(a)**, **-(b)** and **-(c)** show the cases of rolling aluminum alloy thin strips (including foils) using an ordinary 4-high rolling mill. The results are described below.

- (1) **Figures 6-(a)** and **-(b)** indicate that analysis

values agree well with the data obtained from actual machines when the aluminum alloy materials are changed from the softer 1 100 material to the harder materials in the 5 000s.

- (2) **Figure 6-(c)** shows a case of aluminum foils and the calculated values basically agree with the data obtained from the actual machine.
- (3) **Figure 6-(d)** shows a case of rolling mild of steel thin strips using a 10Hi X type mill and the analysis results agree well with the data obtained from the actual machine again.
- (4) There is little difference between the results of calculating rolling loads using Stone's formula and Hill's formula. Particularly, in **Fig. 6-(d)**, the results of two formulas agree well with each other with no difference for the mild steel thin strips. In the comparison for aluminum alloys shown in **Figs. 6-(a)** and **-(b)**, the results of Stone's formula have smaller variation on the whole and it seems better than the other formula.
- (5) One of the reasons why even thinner materials can be analyzed at a relatively high degree of accuracy is that the entire rolling force is divided into the real rolling load and the kiss rolling load at the width edges with a high degree of accuracy.

3.2 Examples of analysis results for cluster rolls

This simulator was used to analyze the roll deflection and the distribution of contact pressure between rolls on the 6Hi X type mill and the 10Hi X type mill, and produced the results as described below.

3.2.1 Example of analysis on the 6Hi X type mill

Table 3 shows the analysis conditions. The analysis was conducted for a hypothetical mill with a work roll (WR) diameter of $\phi 140$ mm, a backup roll (BUR) diameter of $\phi 320$ mm, a roll body length of 900 mm and a work roll bender force of ± 9.8 kN/chock. **Table 4** shows the analysis results. The delivery thickness was 0.05 mm and the rolling reduction was 29%. In this case, when the increase bender is provided (INC) and when no bender is provided (0), the work roll contact load is zero, in other words, this is the ordinary rolling with gaps at edges of work rolls. When the decrease bender is provided (DEC), the rolls are in the kiss rolling state. The degree of contact between the rolls was low and the contact load was 1.0 kN.

Figure 7 shows the roll axis's deflection and rolling pressure distribution of the 6Hi X type mill. **Figure 7-(a)** shows the roll axis's deflection of the backup rolls and the values are plotted on the same curve in all the cases because of a small bender load.

Figure 7-(b) shows the roll axis's deflection of the work rolls and indicates that the work roll axes also deflect in each bender setting direction.

When no bender is provided, the work roll axis is slightly bent to the increase side. This occurs under the influence of the initial crown given to the backup rolls.

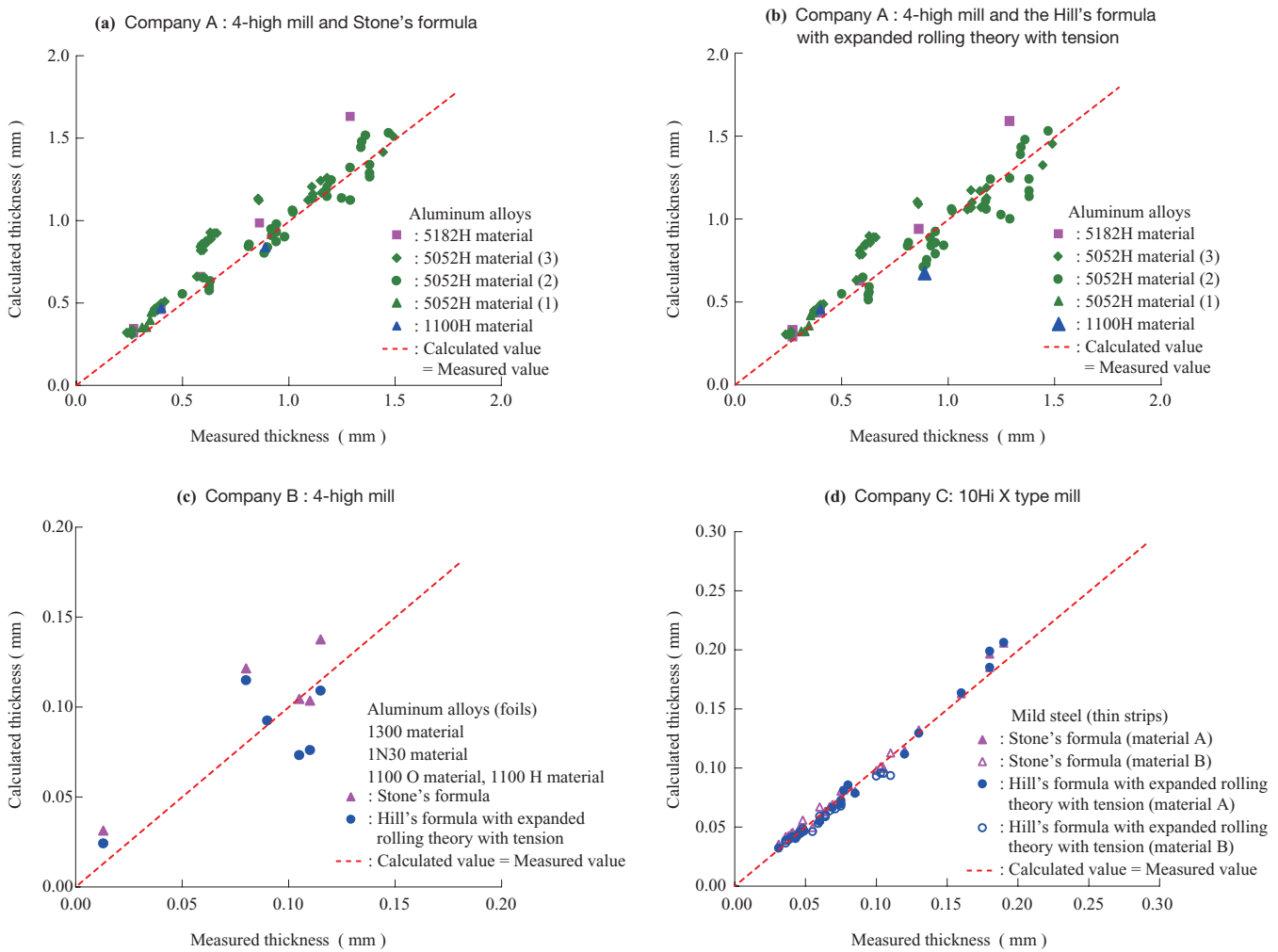


Fig. 6 Delivery strip thickness comparison between measured values and analysis results

Table 1 Mill specifications

Customer	Type of mill	Roll dimension			
		Maximum roll diameter (mm)			Body length (mm)
		BUR	IMR	WR	BUR/WR
Company A	4-high	1 220	—	470	1 850/1 900
Company B	4-high	820	—	280	1 950/1 950
Company C	10Hi X	250	70	36	284/300

Figure 7-(c) shows the contact surface pressure distribution between the backup roll and the work roll at that time. Figure 7-(d) shows the average rolling pressure distribution in the rolling direction between the work roll and a strip in the roll gap and the contact surface pressure distribution between the work rolls.

3.2.2 Example of strip crown analysis on the 10Hi X mill

Figure 8 shows examples of analyzing the roll axis's deflection and rolling pressure distribution and strip thickness distribution for the 10Hi X type mill. The roll dimensions and other rolling specifications were based

Table 2 Rolling conditions

Customer	Rolled material							Rolling load formula	
	Material	Strip width (mm)	Strip thickness (mm)		Rolling reduction (%)	Tension (MPa)			Bender application range (kN/chock)
			Entry	Delivery		Entry	Delivery		
Company A	Aluminum alloy	800 - 1 350	0.37 - 2.10	0.24 - 1.50	17.5 - 47.0	16 - 29	28 - 37	510 - -157	Stone's formula
Company B	Aluminum alloy	950 - 1 670	0.03 - 0.17	0.03 - 0.11	35.0 - 60.0	20 - 48	18 - 36	608 - -29	Hill's formula with expanded rolling theory with tension
Company C	Mild steel	100 - 250	0.06 - 0.21	0.03 - 0.19	9.5 - 45.6	76 - 204	114 - 235	—	

Table 3 6Hi X type mill analysis conditions

Case	Color coding	Roll diameter		Roll body length	Rolling load	Bender	Tension		Strip width	Entry thickness (mm)	Rolling load formula	Image of load
		BUR (mm)	WR (mm)	BUR/WR (mm)	Pr (kN)	FW (kN/chock)	Entry (MPa)	Delivery (MPa)	W (mm)			
1 (INC)	Blue	320	140	900	785	9.8	74	177	700	0.07	Stone's formula	
2 (0)	0											
3 (DEC)	-9.8											

Table 4 6Hi X type mill analysis results

Case	Delivery thickness	Rolling reduction	WR Contact load (kN)	Real rolling force (kN)
	Center (mm)	Center (%)		
1 (INC)	0.0497	29.0	0.0	775
2 (0)	0.0499	28.7	0.0	785
3 (DEC)	0.0496	29.2	1.0	793

on various reference data.⁽⁵⁾ This is a small mill with a work roll diameter of $\phi 36$ mm, an intermediate roll diameter of $\phi 70$ mm, a backup roll diameter of $\phi 250$ mm and a body length of 300 mm for each roll.

No bender was provided in the mill described in the references,⁽⁵⁾ but a bender was provided in the mill analyzed in this study. The work rolls were small in diameter, and a bender was provided for the intermediate rolls. The bending force was 9.8 to -9.8 kN/chock from the increase side to the decrease side. The analysis conditions are shown in **Table 5**. As described in the references,⁽⁵⁾ the rolled material was mild steel strips. The entry thickness was 0.209 mm, the strip width was 200 mm, the set rolling load was 211 kN, and the

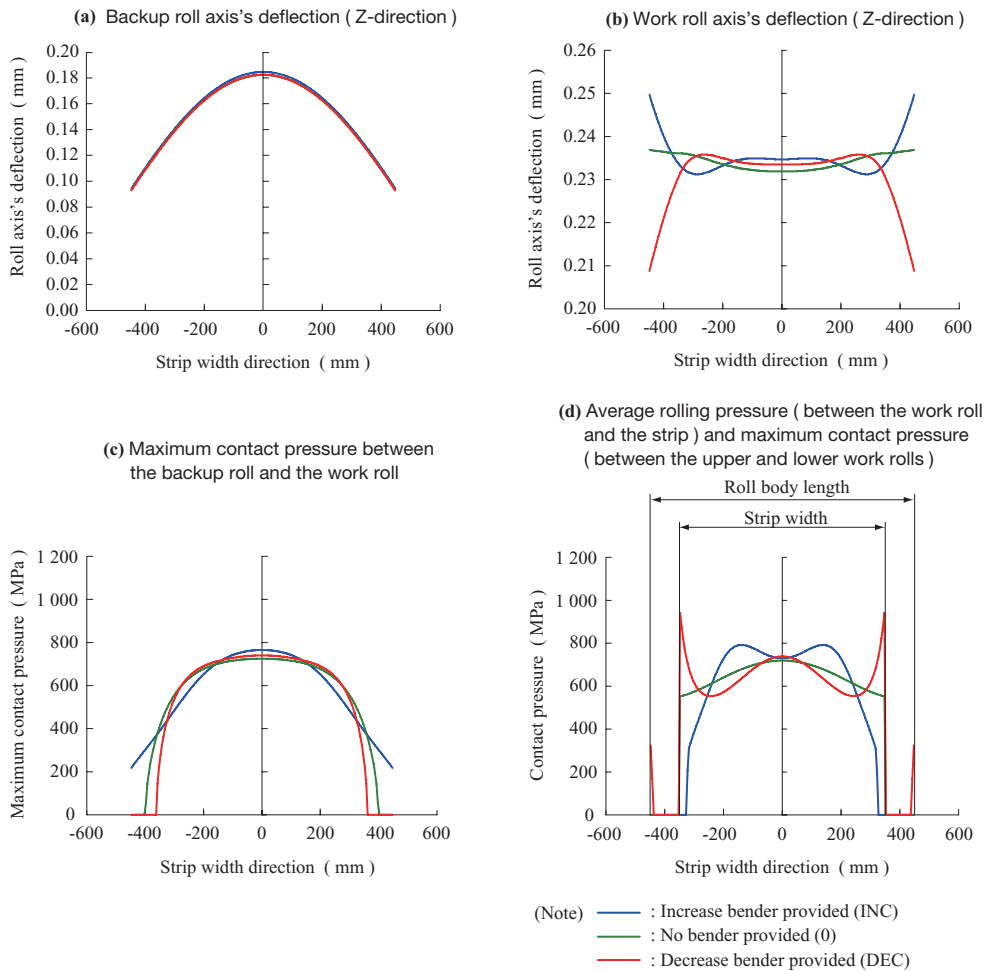


Fig. 7 6Hi X type mill roll deflection and rolling pressure distribution

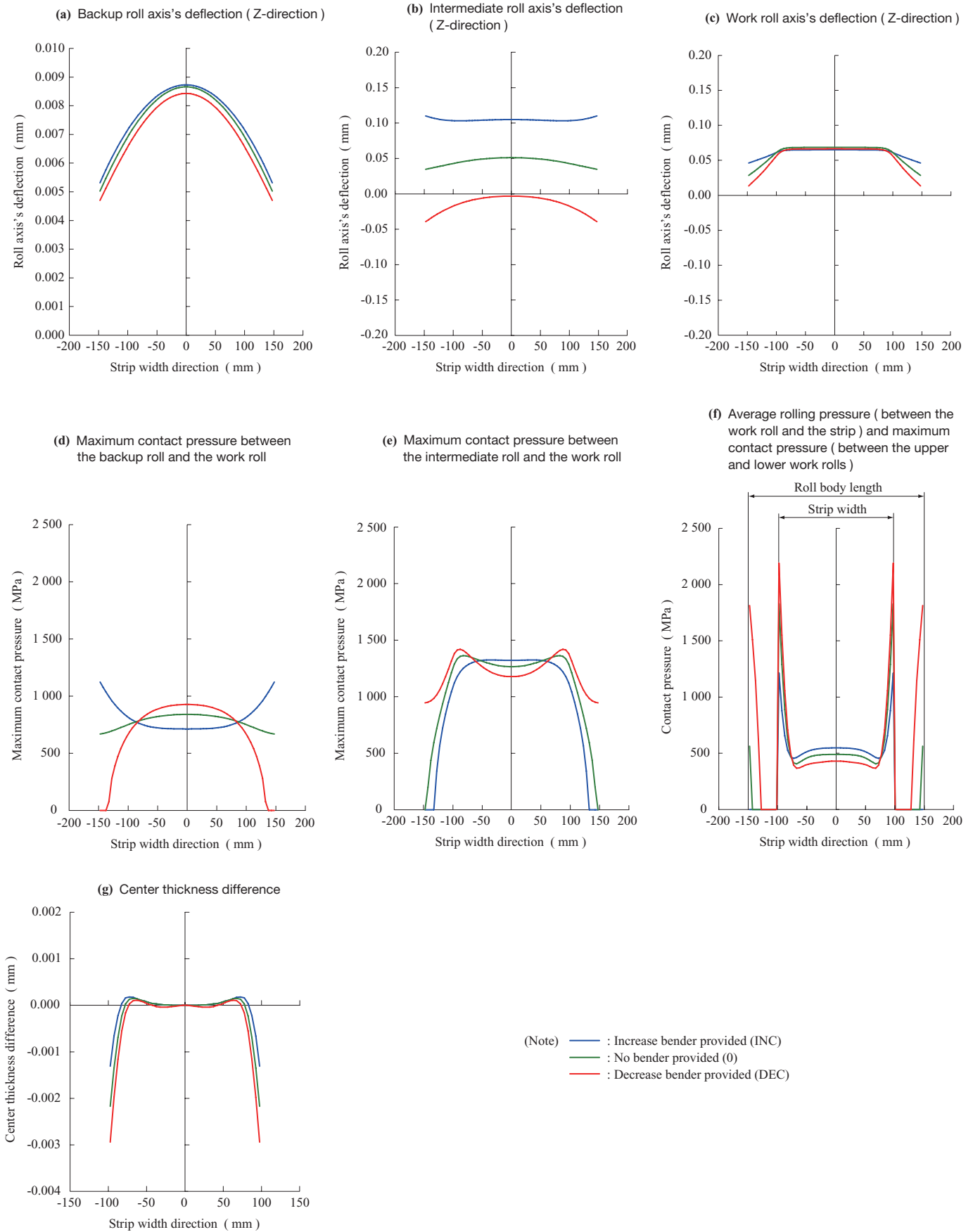
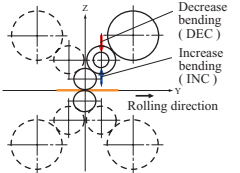


Fig. 8 10Hi X type mill roll deflection, rolling pressure distribution and strip thickness distribution

Table 5 10Hi X type mill analysis conditions

Case	Color coding	Roll diameter			Roll body length	Rolling load	Bender	Tension		Strip width	Entry thickness (mm)	Rolling load formula	Image of load
		BUR (mm)	IMR (mm)	WR (mm)	BUR/WR (mm)	Pr (kN)	FI (kN/chock)	Entry (MPa)	Delivery (MPa)	W (mm)			
1 (INC)		250	70	36	300	211	9.8	119	114	200	0.209	Stone's formula	
2 (0)	0												
3 (DEC)	-9.8												

entry and delivery tensions were 119 MPa and 114 MPa respectively, as described in the references.⁽⁵⁾

The analysis results are shown in Table 6 and Fig. 8. Table 6 indicates that no kiss rolling occurs when an increase bender is provided to the intermediate rolls, but kiss rolling occurs when no bender is provided and when a decrease bender is provided.

When no bender is provided, the contact load between the work rolls during kiss rolling is as small as 0.6 kN. However, it increases to 16.1 kN when a decrease bender is provided with the bending force of -9.8 kN.

As shown in Table 6, the strip thickness after rolling varied in a range of 72 to 80 μm (at the center in the width direction). This is because the set rolling load is as small as 211 kN and it is affected by the bender force correction (that reduces the set rolling load by the bender force on the increase side and increases the set rolling load by the bender force on the decrease side). In the kiss rolling zone, the load is also affected by the work roll contact load. Therefore, the real rolling force purely used for rolling is given by further subtracting the work roll contact load from the load already corrected for the bender force. The real rolling force varies in each case, and as a result the delivery thickness varies slightly.

The analysis results of the mill delivery thickness distribution are shown in Fig. 8-(g). In addition to the bender conditions, the tension feedback was taken into consideration in the thickness analysis. The results were obtained by using straight rolls with no crown as the backup rolls and intermediate rolls, and the work roll has a 10 μm parabolic crown. Table 6 shows the strip crown (the difference between the thickness at the center in the width direction and the thickness at the strip edges). This table indicates that the strip crown varies in a range from 1.0 to 2.5 μm when the intermediate roll bender

is changed from the increase side to the decrease side, though the absolute values are small.

From Figs. 8-(f) and -(g), kiss rolling under these conditions shows a tendency differing from ordinary rolling. As the decrease bender is increased, in other words, as the contact load of work rolls during kiss rolling becomes higher, the rolling pressure increases between the work roll and the material at both edges in the strip width direction. It is considered that the work rolls are pushed from the material side under such a high rolling pressure and this produces the effect equivalent to an increase bender that makes the strip edges in the width direction thicker than the center of the strip width. In other words, the strip crown value is smaller than that in ordinary rolling.

In the kiss rolling zone, as the capacity of the decrease bender becomes larger, the bender has an effect equivalent to the increase bender in ordinary rolling. It is thus projected that the inversion phenomenon occurs in the bender according to thickness distribution.

4. Conclusion

- (1) We developed an analysis simulator that can accurately calculate the roll deflection and the strip crown and can be applied universally to 4-high, 6Hi X and 10Hi X type mills for the thin strip and foil rolling that had been conventionally difficult to calculate analytically.
- (2) The simulator enabled accurate and simultaneous analyses of the real rolling load and the work roll contact load during kiss rolling in which both width edges of the upper and lower work rolls elastically contact each other, for thin strip and foil rolling with several types of mills (4-high, 6Hi X and 10Hi X type mills). As a result, it became possible to make detailed examination in zones where it is difficult to determine whether or not kiss rolling occurs, and also to easily determine whether or not the rolls come into contact with each other.
- (3) For thin strip and foil rolling, both the conventional Stone's formula and Hill's formula, expanded by Misaka for rolling with tension, can be used with no difference in adequacy for the delivery thickness calculation. However, in the comparison between the measured thickness values and the analysis values

Table 6 10Hi X type mill analysis results

Case	Delivery thickness	Delivery strip crown (μm)	Rolling reduction	WR Contact load (kN)	Real rolling force (kN)
	Center (mm)		Center (%)		
1 (INC)	0.079 8	1.0	61.8	0.0	191.2
2 (0)	0.072 7	1.8	65.2	0.6	210.3
3 (DEC)	0.074 9	2.5	64.1	16.1	214.4

for aluminum alloys, Stone's formula showed a slightly higher degree of agreement than the other formula.

- (4) From the results of analyzing the strip crown of the 10Hi X type mill, it is projected that, as the roll bender decreasing capacity becomes larger in the kiss rolling zone, the mill delivery strip crown value becomes lower. This produces an effect equivalent to an increase bender in ordinary rolling. In other words, the inverse phenomenon occurs in the bender delivery thickness distribution.

We will effectively utilize this simulator for various kinds of simulations in determining the specifications for actual foil rolling mills.

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