Experimental Study of Roll Flattening in Cold Rolling Process

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Precise control of the sheet thickness in cold rolling process is becoming more and more important. Sheet thickness after cold rolling, depends on the initial thickness, the initial roll gap as well as the elastic deformation of the rolling mill including rolls. As production amount of high-strength materials increases, the elastic deformation of rolls becomes larger and more important. In cold rolling of high-strength steel sheets, it is reported that the rolls show non-circular deformation and the rolling load predicted by Hitchcock’s equation does not agree with experiments. In this study, stainless steel sheets were cold-rolled and the profiles of the partly rolled specimen were measured by a laser profilometer. Meanwhile, data processing method to reveal the sheet profiles in the roll bite is developed. Flattened radius $R_F$ calculated from the measured profile is smaller than the radius $R_H$ estimated by Hitchcock’s equation. In addition, the contact length $L_M$ estimated with consideration of elastic deformation of the sheet is in good agreement with $L_P$ measured by a laser profilometer under three lubrication conditions.

KEY WORDS: cold rolling; profiles of partly rolled sheets; flattened roll radius; contact lengths; non-circular deformation.

1. Introduction

Precise control of the sheet thickness in cold rolling process is becoming more and more important. The sheet thickness is not only influenced by initial thickness and initial roll gap, but also by the elastic deformation of the rolling mill including rolls. As production amount of high-strength materials increases, the elastic deformation of rolls becomes larger and more important in industries.

In the past, numerous researchers have undertaken a serious of works on elastic deformation of rolls. In the well-known cold rolling theories provided by Bland and Ford,1) it was assumed that the roll maintained circular profile, however, with increased radius. The increased roll radius was estimated by Hitchcock’s equation2) as follows.

$$R_H = R \left[1 + \frac{16(1-v^2)}{\pi E} \frac{P}{b\Delta h}\right]$$ .......................... (1)

where $R$ and $R_H$ are the initial and the increased roll radius respectively, $E$ and $v$ are the Young’s modulus and the Poisson’s ratio of the rolls, $P$ is the rolling load, $b$ is the average sheet width, and $\Delta h$ is the decrease in the thickness, i.e., the thickness draught. Equation (1) means radius of the flattened rolls $R_F$ increases linearly with increasing rolling load $P$. The equation has been widely used because it generally gives reasonable contact length ($L = \sqrt{R_H \cdot \Delta h}$) for prediction of rolling load.

However, in some limited cases, for example in cold rolling of high-strength steel sheets or foils, it is known that the rolling load predicted with Hitchcock’s equation (Eq. (1)) does not show good agreement with experiments. Jortner et al.3) and Fleck et al.4) pointed out that the rolls do not maintain circular profile during rolling, and proposed that roll profile was flat around the central of the roll bite in cold rolling of thin foils. Meanwhile, both elastic non-circular deformation of rolls and elastic deformation of foils or strips were taken into account in numerical simulation by Kainz et al.5) and Hao et al.6) On the other hand, only few experimental results were reported by Matsumoto et al.7) and Sun et al.8) As far as the authors know, non-circular profiles of the flattened rolls during rolling process is vital and it is still not observed clearly in metal rolling experiments. Only Sutcliffe et al.9) reported the experimental profiles of partly rolled plasticine clay sheets.

In order to investigate the roll profile in the roll bite experimentally, stainless steel sheets were cold rolled in this study. Profiles of the sheets partly rolled were measured by a laser profilometer and processed. Contact lengths were calculated and discussed.

This paper is organized as follows. The cold rolling experiments of stainless steel sheets are described in Chapter 2. Thickness after rolling, rolling load, flattened roll radius estimated by Hitchcock’s equation and contact length are shown. Then the profiles of the partly rolled stainless steel sheets are presented in Chapter 3, where the profiles were measured by a laser profilometer. In Chapter 4, contact lengths detected from measured profiles are compared with those by rolling theory. Finally the concluding remarks are made in Chapter 5.
2. Cold Rolling Experiments

2.1. Workpiece

Type 304 austenitic stainless steel sheets 1.91 mm thick, 15.00 mm wide and 150 mm long were used. The uniaxial flow stress of the sheets is expressed by Eq. (2).

\[ \bar{\sigma} = 298.3 + 901.1 e^{-0.48 \varepsilon} \] ................................ (2)

Where \( \bar{\sigma} \) is the equivalent stress (MPa) and \( \varepsilon \) is the equivalent strain.

In order to determine the flow stress, tensile tests were performed with sheets pre-strained by cold rolling. 0.2% proof stress was plotted against the equivalent strain of the prior cold rolling. The curve was regressed as Eq. (2).

2.2. Rolling Experiments

All the cold rolling experiments were conducted on a 2-high rolling mill with rolls 310 mm in diameter of tool steel JIS SKD61. Stainless steel sheets were rolled by one-pass operation at roll peripheral speed of 5 m/min. The rolling loads were measured by two load cells and recorded by a portable data logger during each operation. Initial roll gap 1.8 mm, and then varied as 1.7 mm, 1.5 mm, …, 0.1 mm, 0 mm.

Three lubrication conditions were employed: (a) un lubricated, (b) lubrication with Tetrafluoroethylene (TFE) coating and (c) lubrication with commercial rolling oil. Before each operation of rolling experiments, the surfaces of the rolls were carefully polished with emery papers and degreased with acetone. The TFE coatings in (b) were formed on the stainless steel sheet by spraying from an aerosol can of New TFE coat by Fine Chemical Japan Co. Ltd. The thickness of TFE coating was 15 \( \mu \)m, which was estimated from the mass change and the density of TFE (0.88 Mg/m\(^3\)). Previous study\(^{10}\) showed TFE coating can follow rolling deformation without breakage up to heavy reduction of 60%. Mineral-oil based lubricant FX-80 by Idemitsu Kosan Co. Ltd. was used for (c). The kinematic viscosity of the oil was 15.29 mm\(^2\)/s at 40\(^\circ\)C.

2.3. Results of Rolling Experiments

2.3.1. Thickness after Rolling

The thicknesses of the rolled sheets are shown as a function of the initial roll gap in Fig. 1. When initial roll gap is wider than 1.0 mm, the sheets thickness decreases linearly with decreasing the roll gap. When the initial roll gap is narrower than 1.0 mm, the thickness of the rolled sheet is sensitive to lubrication conditions. For TFE coating, the sheet thickness continues to decrease linearly with a decrease in initial roll gap. The thickness of the rolled sheet with zero gap was 0.86 mm. For rolling oil lubrication, the thickness after rolling decreases with decreasing initial roll gap more gradually and the thickness with zero gap was 1.14 mm. The thickness of the unlubricated sheet does not decrease with initial roll gap when the initial roll gap is smaller than 0.7 mm. The thickness after the rolling were around 1.47 mm. The change in width, i.e., lateral spread, under lubricated condition was less than 12%. Lateral spread under unlubricated condition is smaller.

2.3.2. Rolling Load

Rolling loads are shown as a function of reduction in thickness in Fig. 2. Rolling loads under TFE coating lubrication are the lowest and those under unlubricated conditions are the highest for the same reduction in thickness. Rolling loads are sensitive to lubrication conditions when reductions are higher than 10%. It is notable that under TFE coating lubrication, increase in rolling load with reduction is still linear even at very heavy reduction \( (r > 50\% ) \). It means TFE coating is a good lubrication even at heavy reduction and high pressure. On the other hands, rolling loads under unlubricated condition show steep increase with reduction.

2.3.3. Flattened Roll Radius

Flattened roll radius \( R_H \) calculated with Hitchcock’s equation from measured rolling loads is shown as a function of reduction in thickness in Fig. 3. Flattened roll radius \( R_H \) under lubricated condition is around 300 mm. \( R_H \) under unlubricated condition shows steep increase with increasing reduction in thickness \( r \), when \( r > 10\% \).

2.3.4. Contact Length

Contact lengths \( L \) was calculated geometrically from the initial roll radius \( R \) and the draught \( \Delta h \) under assumption of rigid roll as Eq. (3).

\[ L = \sqrt{R \cdot \Delta h} \] .............................. (3)

Contact lengths \( L_H \) was calculated from the flattened
radius $R_H$ and the draught as Eq. (4).

$$L_H = \sqrt{R_H} \cdot h \quad \text{(4)}$$

$L_M$ is the contact length with considering of elastic deformations of the sheet before and after the roll bite proposed. $L_M$ is given by Matsumoto \cite{11} as Eq. (5). Figure 4 shows the contact lengths as a function of reduction in thickness and lubrication conditions.

$$L_M = \sqrt{R_H} \left( h_0 - h + \frac{1 - \nu^2}{E} \cdot h_1 \cdot \frac{2}{\sqrt{3}} Y_1 \right) + \sqrt{R_H} \cdot h_1 \quad \text{(5)}$$

where $h_0, h_1$ are the thickness of sheets before and after rolling, $Y_1$ is the yield stresses of the rolled sheets. The Poisson’s ratio $\nu = 0.3$ and the Young’s modulus $E = 197$ GPa were assumed for the calculation. All the contact lengths increase with an increase in the reduction in thickness, which is similar trend with the numerical results reported by Hao et al. \cite{6} and Sun et al. \cite{8} The contact lengths $L_M$ of unlubricated conditions are around twice of that of rigid roll $L$ at reduction of 20%. Both contact lengths $L_H$ and $L_M$ are sensitive to lubrication conditions. Contact lengths $L_H$ and $L_M$ of TFE coating are the shortest among all lubrication conditions, due to the lowest rolling loads. The increase in contact lengths by the elastic deformation of sheets are less than 20% at $r > 5\%$ for all the lubrication conditions.

2.3.5. Mean Roll Pressure

Mean roll pressures ($\bar{p} = P/(L_M \cdot b)$, b: mean width) are shown as a function of reduction in thickness in Fig. 5. All the mean roll pressures increase with increasing the reduction in thickness. For TFE coating, mean roll pressures are the smallest among all the lubrication conditions, which are less than 1.95 GPa.

2.4. Discussion on Experimental Results

Friction coefficients were calculated from the mean rolling pressure in Fig. 5 and the flow stresses in Eq. (2). For pressure multiplier factor, Hill’s equation \cite{12} in Eq. (6) and Stone’s equation \cite{13} in Eq. (7) were used. Hill’s equation is an approximate solution of Bland and Ford’s theory, while Stone’s equation was derived under assumption of uniform compression between flat platens. Friction coefficients are shown as a function of reduction in thickness in Fig. 6.

$$Q_H = 1.08 + \frac{1.79 \mu \sqrt{r}}{\phi} - 1.02 r \quad \text{(6)}$$

Where $\mu$ is the friction coefficient and $\phi$ is the contact angle (radian).

$$Q_S = \frac{\exp(\mu L_H/h_m) - 1}{\mu L_H/h_m} \quad \text{(7)}$$

where $h_m$ is the mean thickness $(h_m = (h_0 + 2h_1)/3)$, $L_H$ is the contact length.

As shown, friction coefficient of TFE coating is the lowest among all the lubrication conditions. For friction coefficient calculated by Hill’s equation, the values under TFE coating lubrication are less than 0.07 until $r = 55\%$ and it shows very small increment with increase in reduction in thickness especially at $r > 20\%$. For rolling oil lubrication, friction coefficient increases gradually with reduction in thickness and keep less than 0.11 until $r = 40.3\%$. In addition, friction coefficient of unlubricated sheets increases rapidly from 0.01 at $r = 2\%$ to 0.22 at $r = 25.1\%$. Addition-
ally, both friction coefficients calculated by Hill’s equation and Stone’s equation give similar values at heavy reduction where elastic deformation of rolls is large.

2.5. Summary

(1) The sheets thicknesses after rolling are very sensitive to the lubrication conditions and the thickness of the unlubricated sheet does not decrease with initial roll gap when the initial roll gap is less than 0.7 mm.

(2) Flattened radius $R_H$ estimated by Hitchcock’s equation is around 300 mm under TFE coating condition.

(3) Contact lengths $L_H$ and $L_M$ are sensitive to the lubrication conditions. $L_M$ under unlubricated conditions is around twice of that of rigid roll $L$ at reduction of 20%.

(4) Friction coefficient under TFE coating lubrication shows the lowest values among all the lubrication conditions. Friction coefficients calculated by Hill’s equation and Stone’s equation show the similar values at higher reduction in thickness ($\mu = 0.21$ under unlubricated conditions, $\mu = 0.07$ for TFE coating and $\mu = 0.11$ for rolling oil).

3. Profiles of Partly Rolled Specimen

3.1. Partly Rolled Specimen

During the cold rolling processes, revolution of the rolls was stopped when around a half of sheet length was rolled. Then a partly rolled sheet was taken from the mill after opening the roll gap.

3.2. Profiles Measurement of Partly Rolled Sheets

The partly rolled sheets were fixed to a substrate horizontally by oil clay and the profiles of partly rolled sheets were scanned along the center of the width using a laser profilometer (Keyence Corporation LK080) as shown in Fig. 7. The light source of the sensor was red semiconductor laser and spot diameter 70 $\mu m$. The measurement pitch in the rolling direction was 50 $\mu m$. The resolution of the sensor in the thickness direction was 1 $\mu m$. After turning over the sheets, the profile of the opposite side was scanned in the same way.

3.3. Data Processing

Processing method of measured profiles is shown in the flow chart in Fig. 8. $f(x, y)$, where $x$ and $y$ are coordinates in the rolling and the normal direction. Procedure is consisted with (1) rotation, (2) determination of the minimum roll gap positions, (3) averaging of the upper and the lower profiles and (4) smoothing, as described below.

3.3.1. Rotation of the Profiles

The partly rolled sheet is placed with slight inclination as shown in step (1). The measured profiles on both upper and lower surfaces should be rotated so that the unrolled part is exactly parallel to the horizontal axis. 2 points $A(x_A, y_A)$ and $B(x_B, y_B)$ are chosen arbitrarily in the unrolled left straight portion on the measured profile $f(x, y)$ and the angle of inclination $\alpha$ is calculated by Eq. (8).

$$\alpha = \tan^{-1} \frac{y_B - y_A}{x_B - x_A} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldOTS
adjustments of the profiles in the rolling direction are needed. It was assumed that the points of the minimum roll gap are same in the rolling direction on both upper and lower surfaces. The minimum roll gap points $G'(x_1', y_1')$ on both upper and lower profiles $f'(x', y')$ were moved to the same position according to Eq. (10) for superposition of the upper and lower profiles. In addition, the position of the minimum gap was treated as the origin $C'(0,0)$.

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} x_1' \\ y_1' \end{pmatrix}$$ 

Then without reversing both profiles of upper and lower surfaces were superposed as shown in Step (3). If the sheet has curling, the rolled portions of both upper and lower profiles on the same sheet are symmetrical to the horizontal axis. The rolled portion of profiles on both upper and lower profiles $f''(x'', y'')$ were averaged by Eq. (11) to obtain the profile without curling.

$$y''_{ave} = (y''_{u} + y''_{l})/2$$

3.3.4. Smoothing of the Profiles

As the measured profiles contain noise, the processed profiles were smoothed by a convolution smoothing method (Savitzky-Golay smooth). The method is effective in denoising stochastic noise with ensuring the profiles shape constant. Different smooth conditions were compared as shown in Fig. 9 and the smoothing conditions with points of window 50 and the 1st order polynomial were used in this study.

3.3.5. Contact Length

Contact lengths $L_P$ measured from profiles directly from contact arc are shown as a function of reduction in thickness in Fig. 10. The contact lengths increased with increasing reduction in thickness are steep under unlubricated condition and the mild with TFE coating. It is due to the better lubrication of TFE coating which lead to small rolling loads and the small non-circular deformation of rolls.

3.3.6. Calculation the Flattened Roll Radius $R_P$

Flattened radius $R_P$ was calculated by choosing three points in the contact arc on the measured profiles of partly rolled sheets as shown in Fig. 11. First, point $D(x_D, y_D)$ near the entry of the bite, $E(x_E, y_E)$ near the middle of the vertical reduction and $F(x_F, y_F)$ near the exit of the bite were selected. Then the center of the circle $O(x_0, y_0)$ and $R_P$ could be obtained by the set of Eq. (12) on account of the distances are equal for each point on the arc to the center. So the regressed circular profiles as well as its radius could be obtained.

$$x_0 = \frac{(y_F - y_0)(y_E - y_0)(y_E - y_F) + (y_E - y_0)(y_F - y_0) + (y_F - y_0)(y_E - y_0) + (y_E - y_0)(y_F - y_0)}{2(x_E - x_0)(y_E - y_0) - 2(x_F - x_0)(y_F - y_0)}$$

$$y_0 = \frac{(x_F - x_0)(y_E - y_0)(y_F - y_0) + (x_E - x_0)(y_F - y_0) + (x_F - x_0)(y_E - y_0) + (x_E - x_0)(y_F - y_0)}{2(y_E - y_0)(y_F - y_0) - 2(y_E - y_0)(y_F - y_0)}$$

$$R_P = \sqrt{(x_0 - x_D)^2 + (y_0 - y_D)^2}$$

3.4. Analyzed Profiles

3.4.1. Obtained Profiles

Non-circular roll profiles compared with its regressed circular profiles with radius of $R_P$ under (a) unlubricated, (b) lubrication with TFE coating and (c) lubrication with rolling oil are shown in Fig. 12. Flattened roll non-circular profiles show similar shapes with the profiles of plasticine reported by Sutcliffe et al. Profiles in (a) under unlubricated condition change from nearly circular to non-circular at $r = 16\%$ with increasing the reduction in thickness. In (b), profiles show nearly circular at $r = 4\%$–$32\%$ and show non-circular deformation at $r = 52\%$ owing to the excellent lubrication of TFE coatings which reduces the rolling loads considerably. In (c), profiles are nearly circular at $r = 31\%$ and non-circular at $r = 35\%$–$38\%$. It is found the transition from the circular to the non-circular deformation with increasing reductions.

The order of the transition reduction from lower reduction
is: unlubricated, rolling oil, TFE coating lubrications. In other words, it is the easiest for rolls do non-circular deformation under unlubricated condition among all the lubrication conditions. In addition, small thickness increase can be observed clearly near the exit of roll bite owing to elastic recovery of the sheet, similar results are found in the study by Kijima. 14)

3.4.2. Flattened Radius

Flattened roll radiuses \( R_P \) calculated from profiles by Eq. (12) are shown as a function of reduction in thickness in Fig. 13. The flattened radius is 200–300 mm. The dependence on reduction is small. The unlubricated conditions generally give larger radius. It increases with reduction, however, the increase is much smaller than that predicted by Hitchcock’s equation \( R_H \) shown in Fig. 3.

4. Discussion

4.1. Comparison of Flattened Radius

In comparison of the flattened radius \( R_H \) estimated by Hitchcock’s equation in Fig. 3 and the experimental flattened radius \( R_P \) in Fig. 13, \( R_H \) is larger than \( R_P \) under the same lubrication and same reduction in thickness. Hitchcock’s equation is able to consider circular deformation of rolls only. However, rolls do non-circular deformation in the rolling experiments. Domanti et al. 15) also reported that effective radius of the non-circular models in the region of plastic deformation is smaller than that of the circular model.

4.2. Comparison of Contact Length

Figure 14 shows the comparisons of (a) contact lengths \( L_P \) and \( L_M \) and (b) contact lengths \( L_P \) and \( L_{RP} \). In (a), \( L_M \) is close to \( L_P \) under different lubrication conditions. \( L_M \) is slightly longer than \( L_P \) for short \( L \) and then \( L_P \) becomes longer than \( L_M \) for longer \( L \). In (b), \( L_P \) is longer than \( L_{RP} \). The differences increase with increasing the \( L_{RP} \). It means that profile of contact arc deviates from circular profile with increasing contact length.

4.3. Height Difference and the Flattened Non-circular Length

Figure 15 shows the height difference and the flattened non-circular length as a function of reduction in thickness. The largest height difference between the flattened roll non-circular profiles and its approximated circular profiles in Fig. 12 is shown by open symbols. On the other hand, flattened non-circular length, which is defined by the length where two profiles overlap is shown by solid symbols. Both the height differences and the flattened non-circular lengths increase with increasing the reduction in thickness and friction coefficient. At last, the height differences reach to the maximum values near 30 \( \mu \text{m} \). The measured value is similar to those predicted by numerical simulation [8, 14–16].
In addition, flattened non-circular lengths reach nearly 10–12 mm under all the lubrication conditions.

5. Conclusion

1.91 mm thick stainless steel sheet was cold rolled between $\phi$310 mm steel rolls. The profiles of the partly rolled sheets were measured by a laser profilometer. Data processing method to reveal the profiles of partly rolled sheets is presented. The procedure consists with (1) rotation, (2) determination of the minimum roll gap points, (3) averaging of the upper and the lower profiles, (4) smoothing. The obtained contact lengths, flattened radius of rolls have been compared with theoretical values.

(1) With increasing the reduction in thickness, rolls do circular deformations at lower reduction and do non-circular deformations at heavy reduction in thickness.

(2) Flattened roll radius $R_P$ calculated from the profiles is shorter than the prediction by Hitchcock’s equation $R_H$. The transition to non-circular deformation of rolls appears at small reduction under unlubricated conditions.

(3) Contact length $L_M$ is in good agreement with $L_P$ under three lubrication conditions. Therefore, for precise prediction of rolling load, it is recommended to consider elastic deformation of sheets before and after the roll bite.

(4) The maximum height difference between the measured profile and the approximate circular arc is 30 $\mu$m in this experiment.

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Nomenclature

| Quantity | Symbol | Description |
|----------|--------|-------------|
| Radius:  | $R$ | initial roll radius |
|          | $R_H$ | flattened roll radius estimated by Hitchcock’s equation |
|          | $R_P$ | flattened roll radius calculated from three points on measured profiles |
| Contact lengths: | $L$ | calculated from the initial radius (rigid roll) and the thickness draught |
|          | $L_H$ | calculated from $R_H$ and the thickness draught |
|          | $L_M$ | calculated by Matsumoto’s equation from $R_H$ and the thickness draught |
|          | $L_P$ | detected from measured profiles |
|          | $L_{RP}$ | calculated from $R_P$ and the thickness draught |

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