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Determination of Oil Film Thickness in Rolling
from the Relationship between Surface Roughness of Strip and Roll
(Investigation into Friction and Lubrication in Cold Rolling)*

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Author proposes a method of determination of the oil film thickness from the contact behaviors between the rolls and the strip. The oil film thickness at the contact h_{con} is written as

$$h_{con} = (\text{the surface roughness of roll}) \times 1/2 + (\text{the surface roughness of strip}) \times 1/2$$

The oil film thickness in rolling is measured by means of a similar method to that proposed by Saeki et al. The measured values are in good agreement with the calculated values. When the oil film thickness is greater than h_{con} , the reflection in the rolling direction R agrees with that in the transverse direction R_{90} . When that is smaller than h_{con} , the reflection in the rolling direction is higher.

Consequently, a parameter which can represent the lubrication mechanism in cold rolling is derived as

$$\alpha = R/R_{90}$$

When $\alpha = 1$, the lubrication mechanism is hydrodynamic and when $\alpha > 1$, that is boundary.

1. INTRODUCTION

The behaviors of lubrication between the rolls and the strip should be understood in order to account for the mechanism of lubrication. Since it is not possible to observe the behaviors of lubrication in rolling, these behaviors have been studied by means of measuring the rolling force and the surface qualities of strip after rolling.^{1),2)}

This paper purports to measure the oil film thickness in rolling and to consider the lubrication mechanisms from the relationship between the measured oil film thickness and the surface roughness of the roll and the strip after rolling.

2. OIL FILM THICKNESS IN ROLLING

2.1 Preliminary Discussion

There have been several studies,³⁾⁻⁶⁾ which presented the oil film thickness and the lubrication characteristics, when a hydrodynamic lubrication film exists between the rolls and the strip. In one³⁾ of these studies, the oil film thickness is calculated from the hydrodynamic lubrication theory. When a lubricant builds up a thick film at the entrance between the rotating cylinders set in parallel and the Reynolds equation is expressed as

$$\frac{dP}{dx} = 6\eta U \left(\frac{1}{h^2} - \frac{C}{h^3} \right) \dots\dots\dots(1)$$

the minimum oil film thickness can be written as

$$h_{min} = 1.225 \eta (U_1 + U_2) R / P_1 \dots\dots\dots(2)$$

where η : viscosity of lubricant
 P : pressure
 U : velocity
 h : oil film thickness
 U_1, U_2 : peripheral velocities of cylinders
 R : radius of cylinder
 P_1 : pressure per unit width
 C : constant

The equation (2) shows qualitatively that the oil film thickness in cold rolling increases with an increasing viscosity and rolling speed, and decreases with an increasing rolling pressure.

In cold rolling, Mizuno calculated the oil film thickness at the entrance between the rolls and the strip using Reynolds equation and derived the equation of the oil film thickness, t_d .⁴⁾ This can be written as

$$t_d = \frac{\eta(U_0 + U_1)}{\alpha P} \dots\dots\dots(3)$$

where U_0 : velocity of roll
 U_1 : velocity of strip
 α : contact angle
 P : mean roll pressure

The oil film thickness t_d in the equation (3) is regarded as a parameter which represents the characteristics of lubrication as well as h_{min} in the equation (2).

Whetzel, Rodman⁵⁾ and Saeki, Hashimoto⁶⁾ measured the oil film thickness in rolling. Whetzel et al. dipped a strip into the solvent after rolling and dissolved the adhered lubricant into the solvent. Then they vaporized the solvent, and measured the volume of lubricant. They calculated the oil film thickness, assuming that the lubricant adhered uniformly on the surface of strip after rolling. Saeki et al. measured the weight of the strip before rolling and measured again the weight of the strip after

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adhering a drop of lubricant on the surface of the strip. The weight of lubricant was calculated from the difference between the measured weights. They rolled the strip and then measured the area where the lubricant adhered. They determined the oil film thickness by dividing the volume of lubricant obtained from the weight by the area.

The obtained values of oil film thickness at the entrance between the rolls and the strip in cold rolling change from $0.1\text{ }\mu\text{m}$ to $10\text{ }\mu\text{m}$. These values are a hundred times as large as the values calculated from the equation (3) for a lubricant of the viscosity at an ambient pressure. Mizuno found that the calculated values were in good agreement with the measured values, considering the dependence of viscosity of lubricant on pressure.⁷⁾

2.2 Surface Roughness of Strip after Rolling and Oil Film Thickness

Author⁸⁾ proposed a method for determination of the film thickness. The unevenness of surface roughness in the rolling direction is obtained by means of graining of the roll. It is assumed that the roll is rigid and the strip undergoes plastic deformation. If the lubricant builds up a thick film at the entrance between the roll and the strip, the strip undergoes plastic deformation in rolling without touching the roll. Consequently, the surface roughness of the strip rolled at the conditions and at an ambient pressure is similar to that of a tensile sample which has undergone plastic deformation.

If the oil film built up at the entrance becomes thinner as shown in Fig. 1 (b), the top of asperity on the surface of roll begins to touch the surface of strip. If the lubricant does not build up a thick film at the entrance as shown in Fig. 1 (c), the strip touches the roll and the surface roughness of the strip after rolling is similar to that of the roll.

Fig. 1 Schematic representation of the contact behavior between the rolls and the strip

In order to make clear the contact behaviors of the surface between the rolls and the strip, the relationships between the reflection of strip surface and the rolling speed are shown in Fig. 2. The results are obtained from previous experiments.⁸⁾ If the groove in the rolling direction is formed by the contact with the roll on the surface of strip, the reflection in the rolling direction is higher than that in the transverse direction.

Fig. 2 Effect of the rolling speed on the reflections in the rolling direction and in the transverse direction

When the reflection in the rolling direction agrees with that in the transverse direction at a higher rolling speed, the strip undergoes free deformation. It is seen that there are three types of contact models (a), (b) and (c) in Fig. 1 from the photographs of the surface of the strip as shown in Fig. 3. The oil film thickness between the rolls and the strip can be determined, considering the three models (a), (b) and (c).

The profiles of the surface roughness of roll are assumed as shown in Fig. 4 and the surface of strip is flat. When the top of asperity of the roll touches the strip, the oil film thickness is $h/2$, where h is the surface roughness of roll. However, considering that the strip undergoes deformation, the oil film thickness at the contact, h_{con} ($h_{contact}$) can be written as

$$h_{con} = (\text{the surface roughness of roll}) \times 1/2 + (\text{the surface roughness of strip}) \times 1/2 \quad \dots\dots\dots(4)$$

When the lubricant builds up a thick film as shown in Fig. 1 (a), the oil film thickness h_a can be written as

$$h_a > h_{con} \quad \dots\dots\dots(5)$$

When the lubricant does not build up a thick film as shown in Fig. 1 (c) the oil film thickness h_c can be

Fig. 3 Photographs of the surface of strip after rolling corresponding with contact models of (a), (b) and (c)

Fig. 4 Schematic representations of the surface roughness curve of roll.

written as

$$h_c < h_{con} \dots\dots\dots (6)$$

The oil film thickness can be determined by measuring

the surface roughness of roll before rolling and that of strip after rolling.

In this paper, in order to compare the oil film thickness h_{con} calculated from the equation (4) with that in rolling, the oil film thickness in rolling is determined by a similar method to the one proposed by Saeki et al. At the same time, the discussion about the model in Fig. 1 and the equation (4) is carried out from results of the surface roughness and the reflection of the strip. Consequently, a parameter which can represent the mechanism of lubrication in cold rolling is derived.

3. EXPERIMENTAL METHOD

Rolling tests were carried out using a high speed test mill described elsewhere (1). The roll radius is 50 mm and the peripheral speed ranges from 0.6 m/min to 1000 m/min. The surface of roll is grained in the rolling direction using the No. 400 emery paper and the following surface roughness can be established
Maximum roughness $R_{max} = 0.8 \mu\text{m}$

Fig. 5 shows the profile of surface roughness of the roll. The roll is cleaned with benzine before rolling.

Fig. 5 Surface roughness curve of roll

The materials used are 17 % Cr stainless steel of 32 kg/mm² yield stress and 0.22 strain. The surface roughness of the strip is $R_{max} 0.25 \mu\text{m}$ and the profile is as shown in Fig. 6. The strip is also cleaned with benzine before rolling. The dimensions of the strip are 1 mm thick, 35 mm wide and 300 mm long. The lubricants used are No. 120 machine oil and two paraffinic base oil. Table 1 contains the description of these lubricants.

Fig. 6 Surface roughness curve of strip

The strips are rolled at rolling speeds of 4 m/min, 20 m/min, 70 m/min, 460 m/min and 850 m/min. The effect of viscosity on oil film thickness is examined at a constant rolling speed of 460 m/min. The rolling reductions are chosen from 5 % to 30 % and these rollings are carried out at a room temperature. A constant volume of lubricant is dropped on the surface of strip, using micro-pipettes of 0.01 ml volume and 0.02 ml volume in order to measure the oil film thickness in rolling. The volume of lubricant changes from 0.002 ml to 0.01 ml with the rolling speed, the rolling reduction and the viscosity. The volume is measured by means of a micro-pipette and the measured values will give 90 % accuracy. A lubricant which drops on the surface of strip extends the bounds of the adhered area of lubricant after rolling.

Table 1 Properties of lubricants

Lubricant	Viscosity η cSt			Viscosity Index
	10 °C	38 °C	99 °C	
No. 120 machine oil	484	61	7	5
Paraffinic base oil A	—	30	5	65
Paraffinic base oil B	—	4	1.5	115

Figure 7 shows an adhering behavior of lubricant on the surface of the strip after rolling. In order to measure the adhered area of lubricant, that is cut off from the paper. The weight of the paper is measured and the area of the paper can be calculated. The mean oil film thickness can be measured by dividing the dropped volume of lubricant by the area. Moreover, the surface roughness and the reflection in the adhered area of lubricant are measured.

Fig. 7 Surface of strip adhered the lubricant after rolling

Consequently, the relationship between these results and the mean oil film thickness is discussed and the mechanism of contact model is considered.

4. RESULTS

Figure 8 shows the relationship between the mean oil film thickness and the rolling reduction at rolling speeds of 850 m/min, 460 m/min, 70 m/min, 20 m/min and 4 m/min, using No. 120 machine oil as a lubricant. The experiment is carried out at a room temperature (12 °C) and the viscosity of lubricant is 380 cSt. The mean oil film thickness decreases with a decreasing rolling speed and with an increasing rolling reduction. The mean oil film thickness at a rolling speed of 460 m/min is similar to that at a rolling speed of 850 m/min. It is shown that the mean oil film thickness becomes a constant value at a higher rolling speed.

Fig. 8 Mean oil film thickness for rolling reduction at various rolling speeds

Figure 9 shows the relationship between the mean oil film thickness and the rolling speed at a rolling reduction of 0.1. The mean oil film thickness is 0.4 μm at a rolling speed of 4 m/min and 4 μm at 850 m/min.

Fig. 9 Mean oil film thickness for rolling speed at a rolling reduction of 0.1

Figure 10 shows the relationship between the surface roughness in the adhered area of lubricant on the surface of strip after rolling and the rolling reduction at rolling speeds of 4 m/min, 20 m/min, 70 m/min, 460 m/min and 850 m/min. At the three rolling speeds of 70 m/min, 460 m/min and 850 m/min, the surface roughness increases linearly with an increasing rolling reduction and the change of the surface roughness is similar to that of the tensile sample which has undergone free deformation. At rolling speeds of 20 m/min and 4 m/min, the strip is in contact with the roll and it is seen that the surface roughness of strip after rolling agrees with that of roll.

Fig. 10 Surface roughness for rolling reduction at various rolling speeds

Figure 11 shows the relationships between the reflection and the rolling speed at a rolling reduction of 0.2. At a lower rolling speed, there is a relative difference between the reduction in the rolling direction and that in the transverse direction. The

reflection in the rolling direction is higher than that in the transverse direction by the groove on the surface of strip in the rolling direction.

Fig. 11 Reflections in the rolling direction and in the transverse direction for rolling speed at a rolling reduction of 0.2

Figure 12 shows the relationship between the mean oil film thickness and the rolling reduction at a rolling speed of 460 m/min using lubricants of 380 cSt, 117 cSt and 8 cSt viscosity. The mean oil film thickness decreases with a decreasing viscosity. In particular, the mean oil film thickness using a paraffinic base oil of 8 cSt viscosity as a lubricant at a rolling speed of 460 m/min is 0.5 μm , similar to that using No. 120 machine oil as a lubricant at a rolling speed of 4 m/min.

Fig. 12 Mean oil film thickness for rolling reduction using lubricants with viscosities of 380 cSt, 117 cSt and 8 cSt

The relationship between the surface roughness and the rolling reduction is shown in Fig. 13 and the relationship between the reflection and the rolling reduction is shown in Fig. 14. The reflection of strip in the rolling direction is higher than that in the transverse direction and the strip is in contact with the roll.

Fig. 13 Surface roughness for rolling reduction using lubricants with three viscosities

Fig. 14 Reflections for rolling reduction using lubricants with three viscosities

5. DISCUSSION

The lubrication behaviors in cold rolling can be classified as hydrodynamic lubrication when the mean oil film thickness is greater than h_{con} and as boundary lubrication when that is smaller than h_{con} .

In the case of the hydrodynamic lubrication, the groove on the surface of strip is not observed from the photography and the reflection in the rolling direction agrees with that in the transverse direction. In the case of the boundary lubrication, the groove is observed and the reflection in the rolling direction is higher than that in the transverse direction.

In this way, the lubrication mechanism is discussed qualitatively and quantitatively from the relationship between the oil film thickness and the surface qualities. From the results on the surface roughness of strip as shown in Fig. 10, the mean oil film thickness can be calculated from the equation (4) when the top of asperity of the roll touches the strip at a rolling reduction of 0.2. The value is obtained as

$$\begin{aligned} h_{con} &= (\text{the surface roughness of roll}) \times 1/2 \\ &\quad + (\text{the surface roughness of strip}) \times 1/2 \\ &= 0.8 \times 1/2 + 1.3 \times 1/2 \\ &= 1.05 \mu\text{m} \end{aligned}$$

The mean oil film thickness measured from Fig. 8 in the same contact condition is $1.10 \mu\text{m}$ and the measured value agrees with the calculated value. Therefore, the mean oil film thickness can be calculated from the contact condition between the roll and the strip, and the surface roughness of roll and strip, using the equation (4).

It is necessary to make clear the contact condition between the rolls and the strip. When the roll touches the strip, the groove on the surface of strip in the rolling direction is observed and when the roll does not touch the strip, the unevenness of the surface roughness of strip is observed. In the former case, the reflection in the rolling direction is higher than that in the transverse direction and in the latter case, the reflection in the rolling direction agrees with that in the transverse direction.

Consequently, a parameter is derived as

$$\alpha = \frac{R}{R_{90}} \dots\dots\dots(7)$$

where R : reflection in the rolling direction
 R_{90} : reflection in the transverse direction

From the α values, the contact conditions are classified as follows;

- 1) $\alpha > 1$, the sample is in contact with the tool
- 2) $\alpha = 1$, the sample is not in contact with the tool

When $\alpha = 1$, the lubrication mechanism in cold rolling is a hydrodynamic lubrication and when $\alpha > 1$, that is a boundary lubrication. Consequently, the contact condition can be made clear.

6. CONCLUSIONS

From results of the mean oil film thickness in various rolling conditions, the conclusions obtained are as follows:

- 1) The mean oil film thickness depends on the rolling speed and the viscosity of lubricant and the measured values range from $0.4 \mu\text{m}$ to $5 \mu\text{m}$.
- 2) The mean oil film thickness can be calculated from the relationship between the surface roughness of the roll and that of the strip. When the top of asperity of the roll touches the strip, the mean oil film thickness is written as

$$h_{con} = (\text{the surface roughness of roll}) \times 1/2 + (\text{the surface roughness of strip}) \times 1/2$$

- 3) A parameter which can represent the lubrication mechanism in cold rolling is written as

$$\alpha = \frac{R}{R_{90}}$$

When $\alpha = 1$, the lubrication mechanism is hydrodynamic and when $\alpha > 1$, that is boundary.

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