Approach to Clarification of Oil Film Behavior in Hot Rolling by Numerical Analysis

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In hot rolling, lubrication oil plays an important role in reducing rolling force and protecting the work roll surface. However, the oil behavior in hot rolling has not been clarified sufficiently. In this work, a numerical analysis of the introduced oil film was attempted. There are no previous reports on numerical analysis of hot rolling lubrication. The analytical results of the introduced oil film thickness showed a good correlation with the experimental results. The numerical analysis of hot rolling lubrication clarified the following points: The introduced oil film did not become saturated even if the oil film thickness increased. The reason for this phenomenon is thought to be because the oil viscosity remains high on the work roll side. It was also found that the gradient of the oil velocity in the thickness direction is not constant and changes greatly on the strip side.

KEY WORDS: hot rolling; lubrication; oil film; numerical analysis.

1. Introduction

In hot strip mills, lubrication oil is supplied to the work rolls in order to reduce electric power consumption, protect the work roll surface and improve the quality of the hot-rolled sheet.1) The role of lubrication in hot rolling is increasingly important for the production of high-tensile steel. However, the oil behavior at the interface between the work roll and the sheet is complicated due to fracture of the oxidation scale on the sheet surface and combustion of the oil. Methods for estimating the oil film thickness analytically from the rolling conditions have been reported for cold rolling.2–4) However, only a few reports5–7) have examined the behavior of the lubricant oil in hot rolling, and the mechanism of lubrication has not been clarified sufficiently.

In examining this problem, hot rolling experiments in which both the specimens and the work roll were polished to a mirror surface were carried out with Type 316 stainless steel, as oxidation scale does not tend to form at high temperatures with this material.8) The oil film introduced in the interface was estimated by measuring the remaining amount of oil on the work roll after rolling. The oil-pits of the rolled sheet were also observed. Generally, it has been thought that the oil film introduced in the interface in hot rolling decreases in comparison with that in cold rolling because the oil temperature increases and oil viscosity decreases as a result of contact with the hot sheet. However, in the results of these rolling experiments, the oil introduced in hot rolling was almost the same as that in cold rolling. Moreover, the introduced oil film increased as the initial oil amount increased, and clear oil-pits were not observed. These results were different from the case of cold rolling. Thus, questions concerning the behavior of the lubricant oil in hot rolling remain to be clarified.

There are no reports on the distribution of the oil velocity or oil temperature at the interface in hot rolling. Therefore, in the present study, a numerical analysis of the introduced oil film was carried out and calculations of the distribution of the oil velocity and oil temperature were attempted in order to clarify the lubricant oil behavior in hot rolling.

2. Analysis Method

Figure 1 shows a schematic illustration of the numerical analysis in this study. The aim of this analysis is to calculate the introduced oil film thickness \( t_1 \) against the initial oil film thickness \( t_0 \) on the work roll.

![Fig. 1. Schematic illustration of a numerical analysis in this study. (Online version in color.)](http://dx.doi.org/10.2355/isijinternational.ISIJINT-2016-626)
oil film thickness \( (t_0) \) in hot rolling. The oil film thickness at the point where the oil film pressure equals the yield stress is regarded as the introduced oil film thickness. In this analysis, the initial oil film thickness was set to 0.1, 1.0 and 10 \( \mu \text{m} \). Other analysis conditions, such as the work roll diameter and sheet thickness, are shown at Table 1. These conditions are the same as the rolling experiments in our previous report.\(^3\)

Figure 2 shows the analytical procedure. Under each initial oil film condition, the oil film thickness at the entry side is set, and then the oil film temperature and pressure are calculated. When the oil film pressure equals the yield stress, the oil film thickness at the entry side is determined as the introduced oil film thickness \( (t_1) \).

2.1. Thermal Analysis of Oil Film

The analytical procedure for the oil film temperature in hot rolling is as follows. The analysis was carried out by the dynamic implicit method with Abaqus Standard 6.14-1. In this analysis, the change of the oil film temperature was calculated from the time the oil film contacts the hot sheet to the time the oil pressure reaches the yield stress.

Figure 3 shows the divided elements for the case where the initial oil film thickness is 1.0 \( \mu \text{m} \). The work roll is 100 \( \mu \text{m} \) in thickness and is divided into 29 by 1 to 10 \( \mu \text{m} \) in thickness. The oil film is 1.0 \( \mu \text{m} \) in thickness and is divided into 46 by 0.01 to 0.04 \( \mu \text{m} \) in thickness. The sheet is 100 \( \mu \text{m} \) in thickness and is divided into 29 by 1 to 10 \( \mu \text{m} \) in thickness.

Here, \( q \) is temperature (K), \( y \) is position (m), \( t \) is time (sec.), \( \lambda \) is thermal conductivity (W/m K), \( C_p \) is specific heat (J/kg K), \( \rho \) is density (kg/m\(^3\)) and \( \alpha \) is the heat transfer coefficient (W/m\(^2\) K). \( w \) is the sheet temperature and \( O \) is the oil film temperature at the interface.

Table 2 shows the thermo-physical property values of each of the elements. The specific heat of the oil film depends on the oil film temperature. The heat transfer coefficient between the oil film and the sheet was assumed to be 60 kW/m\(^2\) K when the oil film thickness was 1.0 \( \mu \text{m} \) and was inversely proportional to the oil film thickness. Figure 4 shows an enlarged view of the analysis area. The setting of the initial oil film thickness \( (t_0) \) and oil film thickness at the entry side \( (t_1) \), and the oil film length L is determined by Eq. (3). Here, \( R \) is the work roll radius. The contact time was calculated from the roll speed and the oil film length.

\[
Q = \alpha (w - O) = -\lambda \frac{\partial \theta}{\partial y} \quad \ldots \ldots \ldots \ldots \ldots \ldots \text{(1)}
\]

\[
\frac{\partial \theta}{\partial t} = \frac{\lambda}{C_p \rho} \frac{\partial^2 \theta}{\partial y^2} \quad \ldots \ldots \ldots \ldots \ldots \ldots \text{(2)}
\]

Table 1. Analysis conditions.

| Condition                                    | Value         |
|----------------------------------------------|---------------|
| mill                                         | 2Hi \( \varnothing \) 340 mm |
| work piece size                              | 2 mm \( \times \) 100 mm\(^3\) |
| rolling velocity                             | 50 m/min.     |
| reduction                                    | 6.0%          |
| oil viscosity                                | 110 mm\(^2\)/sec. |
| rolling temp.                                | 973 K         |

Fig. 2. Flow chart of the numerical analysis in this study.

Table 2. Thermophysical property values in this analysis.

|                 | thermal conductivity (W/m K) | specific heat (kJ/kg K) |
|-----------------|-------------------------------|-------------------------|
| oil             | 0.16                          | 0.0012 \( \times \) T + 1.2 |
| strip           | 25                            | 0.8                      |
| work roll       | 50                            | 0.4                      |

Fig. 3. Divided elements in the case of \( t_0 = 1.0 \mu \text{m} \).
2.2. Fluid Analysis of Oil Film

A 2D fluid analysis was performed with Abaqus CFD 6.14. This fluid analysis includes thermal analysis. The analysis area was limited to only the entry side of rolling. In this analysis, Navier-Stokes equations in consideration of viscosity, as shown in Eq. (4), an equation of continuity, as shown in Eq. (5), and an energy equation, as shown in Eq. (6), are solved simultaneously.

\[
\frac{d}{dt} \int_{V} \rho \mathbf{v} dV + \int_{S} \rho \mathbf{v} \cdot \mathbf{n} dS = - \int_{V} \nabla p dV + \int_{S} \mathbf{r} \cdot \mathbf{n} dS + \int_{V} f dV
\]

\[\nabla \cdot \mathbf{v} = 0 \] ...........................(4)

\[
\frac{d}{dt} \int_{V} \rho C_p \theta dV + \int_{S} \rho C_p \theta (\mathbf{v} - \mathbf{v}_m) \cdot \mathbf{n} dS = \int_{V} q dV - \int_{S} \mathbf{q} \cdot \mathbf{n} dS ... (6)
\]

Here, S is the surface area, \( V \) is an inspection volume having area S, n is the outward normal of S, p is pressure, \( \mathbf{v} \) is a velocity vector, \( \mathbf{v}_m \) is the velocity of the moving mesh, \( f \) is buoyancy caused by natural convection, \( \tau \) is viscous shear stress, q is the heat movement by heat conduction and r is the heat capacity per unit volume to be supplied to the object from outside.

The oil film is divided into 8 in the thickness direction. For example, the oil film is divided into 505 in the rolling direction, and the total number of elements is 4040 in the case where the initial oil film thickness (t₀)/oil film thickness ratio at the entry side (t₁) is 10/0.39, 1.0/0.25 or 0.1/0.085 μm. The average temperature of the oil film is low and the gradient of the oil temperature in the thickness direction is large because the oil film is thick. It is difficult to measure the heat transfer coefficient between an oil film and hot sheet in a very short time experimentally. However, while the heat transfer coefficient used in this analysis is not a well-grounded value, it is thought that these results of the temperature distribution of the oil film and the change of the temperature distribution with oil film thickness are appropriate qualitatively.

\[
\eta = 2020 \times \exp \left( -0.407 \times (\theta - 273)^{0.534} \right) \] ...........................(7)

3. Analytical Results

3.1. Results of Thermal Analysis

Figure 6 shows the oil film distribution at the entry side of rolling under the condition that the initial oil film thickness (t₀)/oil film thickness ratio at the entry side (t₁) is 10/0.39, 1.0/0.25 or 0.1/0.085 μm. The average temperature of the oil film is low and the gradient of the oil temperature in the thickness direction is large because the oil film is thick. It is difficult to measure the heat transfer coefficient between an oil film and hot sheet in a very short time experimentally. However, while the heat transfer coefficient used in this analysis is not a well-grounded value, it is thought that these results of the temperature distribution of the oil film and the change of the temperature distribution with oil film thickness are appropriate qualitatively.

Figure 7 shows the temperature changes of the oil film interface when t₀ and t₁ are 1.0 and 0.25 μm, respectively. The temperature change with time was converted to the rolling direction. The oil film temperature increases rapidly on the side in contact with the hot sheet. These results of the oil film temperature were regarded as the boundary conditions of the fluid analysis.

3.2. Results of Fluid Analysis

Figure 8 shows the change of the oil pressure in the rolling direction at the entry side when t₀ and t₁ are 1.0 and 0.25 μm, respectively. The oil pressure increases as the oil film becomes thinner. This is the result of the “wedge effect,” in which pressure occurs when oil is introduced into a tapered space, and the “diaphragm effect,” in which pressure increases when oil is pressed by the sheet and work...
Figure 6. Temperature distribution on thickness direction on each conditions. (Online version in color.)

Figure 7. Analysis results of temperature distribution ($t_0 = 1.0 \text{m}$, $t_1 = 0.25 \text{m}$).

Figure 8. Change of oil film pressure in the case of $t_0 = 1.0 \text{m}$, $t_1 = 0.25 \text{m}$.

Figure 9. Relationship between oil film thickness and oil film pressure. (a) $t_1 = 10 \text{m}$, (b) $t_1 = 0.1 \text{m}$.

Figure 10 shows the relationship between the oil film thickness and the oil film pressure at the entry side of rolling when the initial oil film thickness is 1.0 μm. The oil film pressure increases as the oil film becomes thinner. In this analysis, when the oil film pressure equals the yield stress, the oil film thickness at the entry side is determined as the introduced oil film thickness. Since the yield stress of Type 316 steel at 973 K is 61 MPa, the introduced oil film thickness was determined to be 0.25 μm.

Figure 11 shows the velocity distribution of the oil film, which is the result of the fluid analysis in the case where $t_0$ and $t_1$ are 1.0 and 0.25 μm, respectively. The oil temperature increases as the oil film approaches the roll bite, and the oil temperature of the side in contact with the high temperature sheet is high.

Figure 12 shows the relationship between oil film thickness and oil film pressure. (a) $t_1 = 10 \text{m}$, (b) $t_1 = 0.1 \text{m}$. 
extruded from the roll bite.

The relationship between the oil film thickness and the oil pressure was also calculated for the cases of initial oil film thicknesses of 0.1 and 10 μm. The introduced oil film thickness for each initial oil film thickness was determined as shown in Fig. 12. Figure 13 shows the comparison between the results of this analysis and the experimental results in our previous report.3) The introduced oil film calculated by this analysis method was substantially consistent with the experimental results. Therefore, this method is judged to be an effective numerical model for discussing the behavior of the lubricant oil in hot rolling.

4. Discussion

Figure 14 shows the oil viscosity distribution in the thickness direction for each of the cases of initial oil film thicknesses of 0.1, 1.0 and 10 μm. As the initial oil film thickness increases, the oil viscosity on the low temperature
roll side also increases. In cold rolling, it is well known that the introduced oil film becomes saturated when the initial oil film is increased beyond a certain level.\(^{11}\) On the other hand, in hot rolling, it is thought that the introduced oil film is not saturated but increases because the oil viscosity increases as the initial oil film increases.

For the purpose of comparison with cold rolling, a similar analysis was carried out for the case of cold rolling. In the analysis of cold rolling, the oil temperature was fixed at 293 K, the yield stress of the sheet was set to 215 MPa and the initial oil film thickness was set to 1.0 \(\mu\)m. As shown in Fig. 15, the oil film pressure reached 215 MPa when the introduced oil film thickness was 0.36 \(\mu\)m.

Figure 16 shows the oil velocity distribution in cold rolling. Compared with the distribution in hot rolling in Fig. 11, the gradient of the oil velocity in hot rolling is steeper than in cold rolling. This was thought to be due to the large oil viscosity distribution in hot rolling. Figure 17 shows the oil velocity distribution in the thickness direction at the points where the oil pressure reached the yield stress in hot and cold rolling. In cold rolling, the gradient of the oil velocity in the thickness direction is constant. However, in hot rolling, the gradient changes greatly, and the velocity difference becomes large on the strip side.

Summarizing the above, this research clarified the fact that the gradient of the oil velocity in the thickness direction is not constant, and the velocity difference becomes large on the strip side in hot rolling.

5. Conclusions

In order to discuss the behavior of the lubricant oil in hot rolling, a numerical analysis of the introduced oil film was attempted. The following points were clarified.

(1) As the result of a fluid analysis including thermal analysis, the introduced oil film thickness increases as the initial oil film thickness increases. This calculation result is substantially in agreement with the experimental results.

(2) In hot rolling, the viscosity of the oil on the low temperature roll side remains high when the initial oil film is thick. Therefore, the introduced oil film is not saturated but increases when the initial oil film increases.

(3) In hot rolling, the gradient of the oil velocity in the thickness direction is not constant. The oil viscosity becomes low and the velocity difference becomes large on the high temperature strip side.

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