Prediction of effect of rolling speed on coefficient of friction in hot sheet rolling of steel using sliding rolling tribo-simulator

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1. Introduction

In the 1970s, lubricants were used in hot sheet rolling of steel in order to reduce the rolling force and the roll wear. Mase (1979) reviewed that the rolling force with lubricant became 10–30% lower than those without lubricant in industrial mill. Lenard (2000) similarly reviewed that the tribological properties in hot rolling. Sato et al. (1978) examined the effect of the composition of rolling oils on the coefficient of friction laboratory hot rolling mill. Recently, hot/warm rollings with severely high reduction, such as a continuous warm rolling (Nagai, 2003) and a super short interval multi-pass rolling (Kiuchi, 2005) have been developed to make the ultra-fine grained steels. The high reduction causes some troubles such as the increase of the rolling force, the occurrence of friction pick up and so on. To solve these problems, the new tribological system of lubricant and roll must be developed. For this development, the lubrication behavior at the interface between roll and workpiece in hot sheet rolling of steel must be quantitatively evaluated. Therefore it is desired that the data of the coefficient of friction under the wide range of tribological conditions are obtained. In order to measure the coefficient of friction, the authors (Azushima et al., 2006) developed a new simulation testing machine in the laboratory instead of the small scale hot rolling mill, the two disks testing machine (Inoue et al., 2003), the hot Timken test (Ikeda, 1999) and so on. From these coefficients of friction, the lubrication model at the interface between roll and workpiece in hot sheet rolling of steel was proposed by the authors (Azushima et al., 2007a,b). Moreover, Azushima et al. (2008) discussed about the effect of surface roughness on coefficient of friction in hot rolling using the proposed lubrication model.

In this paper, using the new simulation testing machine developed by the authors, the coefficients of friction are measured changing the rolling speed and the surface roughness of roll. From these coefficients of friction, the effect of rolling speed on coefficient of friction in hot sheet rolling of steel is predicted and the developed lubrication model is proposed.

2. Experimental

2.1. Simulation testing machine

Fig. 1 shows the schematic representation of the simulation testing machine for the evaluation of the lubrication behavior in hot sheet rolling. This testing machine consists of a main-stand with 2-high, a sub-stand, a furnace and a tension device. An infrared image furnace is set between the main and the sub-stands. The specification of the simulation testing machine is summarized in Table 1. The rolling speed of the main-stand can be continuously changed up to 207 m/min using 37 kW DC motor, the timing belt and the electrical operated friction clutch. The rolling speed of the sub-stand
becomes from one-sixth to one-twentieth of the rolling speed of the main-stand using the timing belt and the reducing gear. The workpiece strip moves at speeds from one-sixth to one-twentieth of the rolling speed of the main-stand using the sub-stand.

2.2. Measurement of coefficient of friction

Since the neutral point moves out of the exit point in the upper roll of the main-stand, the strip begins skidding. This simulation rolling is close to the slip rolling with the back tension. Fig. 4 shows the schematic representation of the simulation method. As shown in Fig. 2(a), the strip is first set on the table and a load of about 26 kN is applied at the sub-stand. Then, the strip edge is clamped with the chuck part of the tension device and a load of about 0.9 kN is applied. The strip is heated at a given temperature during a constant time using the infrared image furnace. As shown in Fig. 2(b), the heated zone of the strip with a front tension secondly moves to the main-stand by rolling in the sub-stand. Next, as shown in Fig. 2(c) as the heated zone of the strip comes to the main-stand, the heated strip is compressed at a given rolling reduction by the upper roll and the strip is rolled at a constant sliding speed. Under these conditions, the rolling force \( P \) and the torque of the upper roll \( G \) are measured. The coefficient of friction can be calculated from \( P \) and \( G \) using the following equation:

\[
\mu = \frac{G}{PR}
\]

where \( R \) is the roll radius. The coefficient of friction is used in order to understand the lubrication behavior at the interface between roll and workpiece.

2.3. Experimental procedures

The workpiece material used is SPHC. The strip with the dimensions of a thickness of 9 mm, a width of 22 mm and a length of 2750 mm is used. The roll material of the upper roll of the main-stand is SKD61 and the diameter is 100 mm. The surface roughness are \( Ra = 0.05 \mu m, 0.2 \mu m \) and 0.8 \( \mu m \). The strip is set on the table as shown in Fig. 4(a). The strip edge is clamped with the chuck part of the tension device and the strip is compressed by the rolls of the sub-stand. The strip is heated at a constant temperature of 800 °C using the infrared image furnace. The atmosphere in the infrared image furnace is controlled with Ar gas.

The experiments are carried out at constant sliding rolling conditions of a velocity ratio of 20, a rolling reduction of 0.3 mm and a furnace temperature of 800 °C, changing the rolling speed from 15 m/min to 70 m/min. The colza oil is used as a base oil. The emulsion concentrations are 0.1% and 3%. The emulsion temperature is controlled at 40 °C. The emulsion amount of 1.4/l/min is supplied at the exit side of roll surface using the flat nozzle. The separating rolling force and the torque are measured in order to measure the coefficient of friction.

In order to measure the oil film thickness introduced in the interface between roll and workpiece when the rolling speed changes, the colza base oil with a calcium sulfonate of 30% is used and the emulsion concentration of the lubricant is 1%. In order to measure the oil film thickness introduced, the amount of Ca on the surface of the rolled workpiece is measured using an energy-dispersive X-ray fluorescence analyzer.

Table 1

<table>
<thead>
<tr>
<th>Specification of simulation testing machine for hot rolling.</th>
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<tr>
<td>Velocity of main roll, ( U )</td>
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<tr>
<td>Ratio of velocity, ( r_U )</td>
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<tr>
<td>Velocity of sub roll, ( V )</td>
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<tr>
<td>Rolling load, ( P )</td>
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<tr>
<td>Rolling torque, ( G )</td>
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<td>Temperature of furnace, ( T_F )</td>
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<td>Forward tension, ( T_F )</td>
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Fig. 3 shows the relationship between coefficient of friction and rolling speed at emulsion concentrations of 0.1% and 3% for the colza oil using the roll with a surface roughness of \( Ra = 0.05 \mu m \). The coefficients of friction are independent on the rolling speed at an emulsion concentration of 3.0% and the values are around 0.1. On the other hand, at an emulsion concentration of 0.1% the coefficient of friction decreases with increasing rolling speed.

Fig. 4 shows the relationship between coefficient of friction and rolling speed at emulsion concentrations of 0.1% and 3% for the colza oil using the roll with a surface roughness of \( Ra = 0.2 \mu m \). The coefficients of friction are also independent on the rolling speed at an emulsion concentration of 3.0% and the values are around 0.1. On the other hand, at an emulsion concentration of 0.1% the coefficient of friction decreases with increasing rolling speed up to a rolling

speed of 50 m/min and the values are slightly larger than those of the roll with a surface roughness of \( Ra = 0.05 \mu m \). Over 50 m/min, it increases slightly with increasing rolling speed.

Fig. 5 shows the relationship between coefficient of friction and rolling speed at emulsion concentrations of 0.1% and 3% for the colza oil using the roll with a surface roughness of \( Ra = 0.8 \mu m \). The coefficients of friction are also independent on the rolling speed at an emulsion concentration of 3.0% and the values are larger than those of the rolls with surface roughnesses of \( Ra = 0.05 \mu m \) and \( 0.2 \mu m \) and are around 0.125. On the other hand, at an emulsion concentration of 0.1% the coefficients of friction at rolling speeds of 30 m/min and 50 m/min are independent on the rolling speed and the values are larger than those the rolls with surface roughnesses of \( Ra = 0.05 \mu m \) and \( 0.2 \mu m \). Over 50 m/min, the coefficient of friction increases with increasing rolling speed and the value at a rolling speed of 70 m/min becomes higher compared with those of other rolls at 70 m/min. In the experiment at a rolling speed of 15 m/min, the scale on the workpiece surface was broken during rolling.

4. Discussions

4.1. Lubrication model in hot rolling

The authors measured the coefficient of friction and the introduced oil film thickness, and they proposed the lubrication model at the interface between roll and workpiece (Azushima et al., 2007a). The colza oil with a calcium sulfonate of 30% was used as lubricant, in order to measure the oil film introduced in the interface between roll and strip. The amount of Ca on the surface of rolled strip was measured using an energy-dispersive X-ray fluorescence analyzer. In order to change the oil film introduced, the emulsion concentration was changed from 0.1% to 3% in sliding rolling experiments. After rolling, the distributions of the X-ray intensity for the emulsion concentration were measured and the integral intensities were estimated. Fig. 6 shows the relationship among integral intensity of X-ray, coefficient of friction and emulsion concentration. The integral intensity increases with increasing emulsion concentration. Consequently, it is estimated that the oil film thickness introduced increases with increasing emulsion concentration. On the other hand, the coefficient of friction becomes constant over an emulsion concentration of 1.0% in spite of the increase of the oil film thickness introduced. Up to an emulsion concentration of 1.0%, the coefficient of friction increases with decreasing emulsion concentration or oil film thickness introduced.

From the experimental results, it can be understood that the coefficient of friction becomes constant in the region that the oil film thickness introduced in the interface between roll and workpiece exceeds a certain value. On the other hand, in the region that it is lower than the certain value, the coefficient of friction increases with in decreasing oil film thickness introduced.

Fig. 7 shows the schematic representation of the lubrication model at the interface between roll with smooth surface and workpiece. In the lubrication model in Fig. 7(a), the lubrication film covers all of contact interface under a mean contact pressure. It is estimated that the lubrication film consists of a sub-micrometer boundary film. In Fig. 7(b), the contact interface consists of the region covered with the lubrication film and the region without the lubrication film. In the former model, the coefficient of friction becomes constant and is independent on the oil film thickness introduced in the interface. In the latter model, the coefficient of friction increases with increasing ratio of the region without the lubrication film, and is depend on the oil film thickness.
4.2. Effect of rolling speed on coefficient of friction

The effect of rolling speed on coefficient of friction is discussed using the lubrication model proposed by the authors as shown in Fig. 7 (Azushima et al., 2007a). Fig. 8 shows the photographs of workpiece surface after rolling at emulsion concentrations of 0.1% and 3% for the colza oil using the roll with a surface roughness of $R_a = 0.05 \mu m$, changing the rolling speed. The scale on the all workpiece surfaces and the fracture crack are observed. At an emulsion concentration of 3.0%, the appearances of the workpiece surface after sliding rolling at rolling speeds of 15 m/min, 30 m/min, 50 m/min and 70 m/min are observed as similar. On the other hand, at an emulsion concentration of 0.1%, the color uneven of the workpiece surfaces after sliding rolling at rolling speeds of 15 m/min and 30 m/min is observed.

Fig. 8. Photographs of workpiece surface after rolling at emulsion concentrations of 0.1% and 3% for the colza oil using the roll with a surface roughness of $R_a = 0.2 \mu m$.

Fig. 9 shows the photographs of workpiece surface after sliding rolling at emulsion concentrations of 0.1% and 3% for the colza oil using the roll with a surface roughness of $R_a = 0.2 \mu m$, changing the rolling speed. The scale on the all workpiece surfaces and the fracture crack are also observed. At an emulsion concentration of 3.0%, the appearances of the workpiece surfaces after sliding rolling at rolling speeds of 15 m/min, 30 m/min, 50 m/min and 70 m/min are also observed as similar as those of the roll with a surface roughness of $R_a = 0.05 \mu m$. On the other hand, at an emulsion concentration of 0.1%, the ploughing tracks on the workpiece surfaces after sliding rolling at all rolling speeds are observed and it can be obtained that the surface appearance at a rolling speed of 50 m/min is smooth.

Fig. 10 shows the photographs of workpiece surface after sliding rolling at emulsion concentrations of 0.1% and 3% for the colza oil using the roll with a surface roughness of $R_a = 0.8 \mu m$, changing the rolling speed. The scale on the all workpiece surfaces and the fracture crack of the scale are also observed except the workpiece at a rolling speed of 15 m/min. At an emulsion concentration of 3.0%, the ploughing tracks on the workpiece surface after sliding rolling at all rolling speeds are observed similar to those after rolling at an emulsion concentration of 0.1% using the roll with a surface roughness of $R_a = 0.05 \mu m$. On the other hand, at an emulsion concentration of 0.1%, the ploughing tracks on the workpiece surface after rolling at all rolling speeds are observed and in the surface at a rolling speed of 70 m/min, the failure on the track surface is observed.

In the schematic representation of the lubrication model at the interface between roll with randomly rough surface and workpiece as shown in Fig. 11, the two main factors of the friction force acting at the interface between roll and workpiece must be considered. The first is the adhesion which occurs at the contact regions, and the second is the ploughing in which the asperities of the harder roll plough a path through the softer workpiece.

The friction force $F$ is given as follows:

$$F = F_b + F_p$$

\[ (2) \]
where the suffixes \( b \) and \( p \) denote the adhesion and the ploughing terms respectively. Dividing by the load \( P \), the corresponding equation is written in terms of coefficients of friction as follows:

\[
\mu = \mu_b + \mu_p
\]  

(3)

From the coefficients of friction obtained in Figs. 3–5 and the photographs of workpiece surface observed in Figs. 8–10, the effect of the rolling speed on the coefficient of friction is discussed. The coefficients of friction at an emulsion concentration of 3.0% as shown in Figs. 3–5 are independent on the rolling speed and become constant. The values increase with increasing surface roughness of the roll. In these conditions, the lubrication film covers all of contact interface as shown in Figs. 7(a) and 11(a) and the values do not depend on the lubrication film thickness. At a roll surface roughness of \( \text{Ra} = 0.05 \, \mu\text{m} \), the coefficient of friction is only due to the adhesion and it is given as follows:

\[
\mu = \mu_b
\]  

(4)

It is estimated that the lubrication mechanism is boundary region as shown in Fig. 7(a). At a roll surface roughness of \( \text{Ra} = 0.8 \, \mu\text{m} \), it is understood that the friction consists of the adhesion and the ploughing as shown in Fig. 11(a). The coefficient of friction is given by Eq. (3).

On the other hand, the lubrication models at an emulsion concentration of 0.1% are shown in Figs. 7(b) and 11(b). The coefficients of friction at an emulsion concentration of 0.1% using the roll with a surface roughness of \( \text{Ra} = 0.05 \, \mu\text{m} \) decrease with increasing rolling speed as shown in Fig. 3. From the photographs of workpiece surface after sliding rolling, the ploughing track cannot be observed. In this emulsion concentration, the contact interface consists of the region covered with the lubrication film and the region without the lubrication film as shown in Fig. 7(b). It can be estimated that the region covered with the lubrication film increases with increasing rolling speed, so that the coefficient of friction decreases with increasing rolling speed. It may be understood that the patches observed on the workpiece surface increases with decreasing rolling speed. The coefficient of friction in this region is given by

\[
\mu = \alpha \mu_b + (1 - \alpha) \mu_w
\]  

(5)

where \( \mu_b \) is the coefficient of friction in the region covered with the lubrication film, \( \mu_w \) the coefficient of friction in the region with the water and \( \alpha \) the ratio of the region with the lubrication film. The ratio \( \alpha \) depends on the rolling speed and it increases with increasing rolling speed.

The coefficients of friction at an emulsion concentration of 0.1% using the roll with a surface roughness of \( \text{Ra} = 0.2 \, \mu\text{m} \) decrease with increasing rolling speed up to a rolling speed of 50 m/min and over 50 m/min increases slightly with increasing rolling speed as shown in Fig. 4. From the photographs of workpiece surface after sliding rolling, the ploughing tracks are observed. It can also be estimated that the region covered with the lubrication film increases with increasing rolling speed, so that the coefficient of friction decreases with increasing rolling speed up to a rolling speed of 50 m/min. The coefficients of friction are slightly higher than those of the roll with a surface roughness of \( \text{Ra} = 0.05 \, \mu\text{m} \) due to the ploughing. The coefficient of friction in this region as shown in Fig. 11(b) is given by

\[
\mu = \alpha \mu_b + (1 - \alpha) \mu_w + \mu_p
\]  

(6)

At a rolling speed of 70 m/min, it is estimated that the coefficients of friction increase due to the occurrence of the pick up in the region without the lubrication film as shown in Fig. 11(b). If the ratio of the region which the pick up occurred in the region without the lubrication film is defined as \( \beta \), the coefficient of friction in this condition is given by

\[
\mu = \alpha \mu_b + (1 - \alpha) \mu_w + \beta (1 - \alpha) \mu_m + \mu_p
\]  

(7)

where \( \mu_m \) is the coefficient of friction in the region where the friction pick up occurs.

The coefficients of friction at an emulsion concentration of 0.1% using the roll with a surface roughness of \( 0.8 \, \mu\text{m} \) increase with increasing rolling speed as shown in Fig. 5. From the photographs of workpiece surface after sliding rolling, the ploughing tracks are clearly observed. The coefficients of friction are higher than those of the rolls with a surface roughness of \( 0.05 \, \mu\text{m} \) and \( 0.2 \, \mu\text{m} \) due to the ploughing. The coefficient of friction in this region is also given by Eq. (6). At a rolling speed of 70 m/min, it is estimated that the coefficients of friction increase due to the occurrence of the pick up in the region without the lubrication film. In this condition, the coefficient of friction is also given by Eq. (7).
Calcium sulfonate of 30%.

Distribution of the X-ray intensity for emulsion concentration of oil with calcium sulfonate of 30%.

Fig. 12. Distribution of the X-ray intensity for emulsion concentration of oil with calcium sulfonate of 30%.

Fig. 13. Relationship between X-ray intensity and rolling speed.

In order to explain the effect of the rolling speed on the coefficient of friction at an emulsion concentration of 0.1%, the introduced oil film thicknesses were measured changing the rolling speed in rolling conditions at an emulsion concentration of 1.0% using the roll with a surface roughness of Ra = 0.05 μm. Fig. 12 shows the distribution of the X-ray intensity for the emulsion concentration of the colza oil with the calcium sulfonate of 30%. The amount of Ca on the surface of rolled workpiece is analyzed and the peak of the X-ray intensity for Ca is situated at photon energy of 3.69 keV. Since the integral intensity of Ca is proportional to the oil film introduced, the oil film introduced in the interface between roll and workpiece can be qualitatively measured.

Fig. 13 shows the relationship between integral intensity of X-ray and rolling speed. The integral intensity increases with increasing rolling speed. Consequently, it is estimated that the oil film thickness introduced increases with increasing rolling speed. Consequently, the coefficient of friction becomes constant at an emulsion concentration of 3.0% in spite of the increase of the oil film thickness introduced since the lubrication film covered over all of contact region. On the other hand, at an emulsion concentration of 0.1%, it is estimated that the coefficient of friction decreases with increasing rolling speed since the region with the lubrication film increases with increasing rolling speed due to the increase of the introduced oil film with the rolling speed.

From the experimental results, the effect of rolling speed on the coefficient of friction obtained using the tribo-simulator testing machine and the developed lubrication model, the speed dependence of the coefficient of friction at the interface between roll and workpiece in hot sheet rolling can be predicted.

5. Conclusions

(1) The coefficient of friction at an emulsion concentration of 3.0% was independent on the rolling speed and it increased with increasing surface roughness of roll.

(2) The coefficient of friction at an emulsion concentration of 0.1% decreased with increasing rolling speed for the rolls with smooth surface roughness. However, it decreased with increasing rolling speed in the lower range of rolling speed, but it increases in increasing rolling speed in the higher range of rolling speed for the rolls with a rough surface roughness.

(3) The effect of the rolling speed on the coefficient of friction was explained using the proposed lubrication model.

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References


