Emulsion Effect on Energy Consumption of Cold Strip Rolling Lubricated in Mixed Regime

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Abstract

Emulsions are popular lubricants in cold strip rolling. Application of emulsion which are mostly consist of oil and water, makes the products with higher quality, meanwhile keeps the friction low and reduces the unwanted heat generation due to friction. High production of steel companies makes the efficiency of production a prominent issue. In the present study, a model based on mixed film lubrication is used to find the effect of oil content of emulsion on the energy consumption of cold strip rolling process.

1. Introduction

Steel manufacturing is one of the most pollutant industries in the world by producing enormous amount of greenhouse gases [1]. The optimized design of the lubrication system can effectively reduce both the cost of production and energy usage in rolling section in steel manufacturing process and consequently reduce the contaminations from the steel manufacturing industry [2, 3]. Strip rolling with emulsion is widely used in the steel production companies. Oil/water emulsions has this capability to reduce the friction and keep the heat low due to the high specific heat parameter of water and lubricity of oil. In other hand, using O/W emulsion is cost effective in a term because it needs to use lower amounts of oil which is the main expense of lubrication. Fig. 1 shows the cold strip rolling which is lubricated with oil. [4]

Lubrication with emulsion has been investigated by Yan and Kuroda [5]. In their model, emulsion is considered as a two-phase fluid with continuous phase (water) and disperse phase (oil). Kosasih et. al. [6] applied this model to cold strip rolling.

Emulsion as lubricant behavior is mainly dependent on the velocity of the sliding surfaces where emulsion is lubricating. Fig. 2 shows this behavior.
In low speed region, the oil particles have sufficient time to stick to the surfaces and form an oil pool. In this case, most of the lubrication region is occupied by oil. As the sliding speed increases, more water is strained between the surfaces. When speed is high enough, most of the lubrication is carried out by the continuous phase (water). This behavior makes emulsion unique in its behavior when it is used for lubrication. [7, 8].

In other terms, lubrication is generally divided into different regimes. According to fig. 3, when the load on the two lubrication surfaces is not high, the two surfaces are separated by a thick film of lubricant [9, 10]. This regime is called full-film regime. On the other side, if load increases, the two sliding faces get into direct contact and the lubricant continuity is interrupted by direct contact of asperities of the surfaces.

This regime of lubrication is more serious in journal bearings [11].

2. Model description
2.1. Slab method

Fig. 4 shows the slab method used for cold strip plastic behavior. The plastic stress on the element of the strip is shown on the two faces of the element. Using the force equilibrium in x and y direction and considering the small plastic region under the rolls, Eq. 1 is found.
\[ \sigma_y \frac{dy}{dx} + y \frac{d\sigma_y}{dx} - \gamma \frac{dp}{dx} - 2\tau = 0 \]  \hspace{1cm} (1)

In this equation, \(\sigma_y\), \(y\), \(\tau\) and \(p\) are the yield stress, thickness of the strip, shear stress on the friction surface of element and pressure from the rolls on the surface of strip[12]

### 2.2. Mixed film regime

The flow in micro scale is attracting researchers’ interest from many different fields due to its extended applications including heat transfer, multiphase flows, Nano particles movement, etc [13-17]. One of the main applications of the micro fluidic equations is in mixed film regime. Cold strip rolling mostly evolves high pressure from the rolls on the plates. This means that lubrication regime is mixed regime. In the mixed regime, contacts of asperities are the dominant friction mechanism. It is also important to take the viscous effect of lubricant into account. The relation which is widely used for describing lubrication in mixed regime is the modified Reynold’s equation.

\[
\frac{d}{dx} \left( \frac{\varphi_x h^3 dp}{\xi} \frac{dp}{dx} \right) = - \frac{d}{dx} \left( (u_w + u_r)h_t \right)
\]  \hspace{1cm} (2)

\(p_f\) is the lubricant pressure. The work piece and roll speed are given by \(u_w\) and \(u_r\). \(h_t\) represents the average film thickness. This equation is corrected for the effect of emulsion by applying the equivalent viscosity (\(\xi\)) concept.

\[
\xi = \frac{\eta_c \eta_d}{\lambda_d \eta_d + \lambda_c \eta_c}
\]  \hspace{1cm} (3)

where \(\lambda_c\) and \(\lambda_d\) are the water and oil content of emulsion \((\lambda_d + \lambda_c = 1)\). In Eq. 3, \(\eta_d\) stands for viscosity of oil.

### 2.3. Plastic deformation of the asperities

Fig. 5 shows the asperity contact of two sliding surfaces. Due to the pressure on the asperities, the deform plastically. This flattening behavior is the contributor to higher friction force due to increasing of the contact ratio \(A = \frac{a}{L}\). The parameter \(a\) is half of the contact area in half pitch of asperity contact \((L)\).

![Fig. 4. Asperity contact and the parameters related](image)

Chang and Wilson [18] suggested the following relation for quantifying the flattening effect of asperities.

\[
\frac{dA}{dx} = \frac{x}{La \theta_a \left( 1 - A + \frac{yE_x}{2L} \right)}
\]  \hspace{1cm} (4)

\(\theta_a\) is shown in Fig. 4. \(E_x\) is the non-dimensional strain rate which is given by Eq. 5.
2.4. Strip speed

The strip thickness changes during the time it is under the rolls and deforms plastically. This decrease of the thickness results in elevation of plate speed. Since the elasticity of strips are small, the plastic condition prevails and the following relation gives the speed based on the thickness of the strip.

\[ E_s = \frac{2A - (p - p_f)}{(p - p_f)f_1} \]  
(5)

\[ f_1 = -0.86A^2 + 0.345A + 0.515 \]  
(6)

\[ f_2 = \frac{1}{2.571 - A - Aln(1 - A)} \]  
(7)

2.5. Film and yield condition of boundaries

Lubricant is not under any pressure before it goes under the rolls and after it come out of the rolls in the outlet.

\[ y_1u_1 = y_2u_2 = yu \]

In this relation, \( y_1 \) and \( y_2 \) are the thickness of the strip in the inlet and outlet of the work zone. \( u_1 \) and \( u_2 \) corresponds to the speed in inlet and outlet.

3. Solution procedure

In order to find pressure and friction force of strip rolling with emulsion, Eqs. 1, 2 and 4, needs to be solved together. The solution involves an iterative method that consists of two ODE problem of Eq. 1 and Eq. 4 and a second order one dimensional differential equation of Eq. 2. The ODE is solved using Runge Kutta approach and Eq. 4 is solved by a discretization based on central difference derivative replacement. The friction force which is the summation of asperity contact and lubricant friction is found according to the following relations.

\[ \tau = Aq_a + (1 - A)q_f \]  
(12)

where \( q_a \) and \( q_f \) denote the asperity contact and lubricant friction force.

4. Results and discussion

To validate the results of the present study, the friction stress of the lubricating surfaces are compared with Hajshirmohammadi et al. The comparison is shown in Fig. 5
The total friction force between the strip and rolls is calculated according to the following relation:

$$ F = \int_0^{x_1} \tau dx $$

Energy consumption of the rolling is the torque applied on the rolls time the angular velocity of rolls. The torque is friction force times roll radius (T = FR) and the angular velocity of rolls is the linear roll speed divided by its radius $$ \omega = \frac{u}{r} $$. The amount of energy consumed to produce one-meter length of strip with unite width is:

$$ E = \frac{F\omega}{u_{w1}} $$

To investigate oil content effect on the energy consumption, non-dimensional speed $$ S $$ is defined as follows.

$$ S = \frac{r\alpha\eta_0(u_r + u_1)}{\sigma_0R_yx_1} $$

Fig. 5 shows $$ E $$ value changing with oil content of emulsion in different speeds $$ S $$.

The oil content varies from 1% to 100% (pure oil) in this figure.
Fig. 6. Energy consumption per unite area of strip for cold rolling as a function of oil percentage for three different non-dimensional speed $S=0.1$, $S=0.01$ and $S=0.001$

It can be inferred from Fig. 5 that as the oil content of emulsion increases, the energy consumption per unite area of strip production reduces. Also production speed makes the manufacturing energy expenditure lower. This is understandable due to this fact that the oil content makes the lubrication easier. However; this reduction of energy consumption is more visible in low percentage of oil content and as the emulsion gets closer to pure oil, $E$ value change is minor.

Table 1. rolling parameters used for simulation of cold rolling

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\eta_0$ (mm)</th>
<th>$a$ (1/Pa)</th>
<th>$R$ (mm)</th>
<th>$\sigma_y$ (MPa)</th>
<th>$y_1$ (mm)</th>
<th>$y_2$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.02</td>
<td>6.2e-8</td>
<td>0.126</td>
<td>97.75</td>
<td>1</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Conclusion

A model for cold trip lubrication of strips is used to evaluate the effect of emulsion properties on the energy consumption. This was found that increasing the oil content of emulsion as lubricant can make the production more cost-effective. In other hand, increasing speed can help reducing the energy needed for production.

Nomenclature

- $\sigma_y$: yield stress
- $\tau$: Shear stress
- $u_1$: Strip speed in the inlet
- $u_2$: Strip speed in the outlet
- $u_w$: work-piece inlet speed
- $u_r$: roll speed
- $p_f$: Lubricant Pressure,
- $p$: interface pressure
- $\xi$: Equivalent viscosity
- $\phi_x$: Flow factor
- $h$: surface separation
- $x$: coordinate along the rolling direction
- $x_1$: Roll contact length
- $y_2$: Strip thickness in the outlet
- $y_1$: Strip thickness in the inlet
- $c$: adhesion coefficient
- $R$: roll radius
- $\eta$: (dynamic) viscosity of oil
- $s_2$: forward tension
- $S$: non-dimensional roll speed
Contact ratio

\[ S = \frac{r \alpha q_\theta (u_r + u_{w1})}{\sigma_0 R_q x_1} \]

\( A \) \quad \text{Contact ratio}
\( \alpha \) \quad \text{viscosity pressure coefficient} \\
\( q_a \) \quad \text{Asperity shear stress} \\
\( q_f \) \quad \text{Lubricant shear stress}

References


