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Effect of Shear Strength of Oil on Lubrication of Cold Strip Rolling in Full-Fil Regime

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Abstract. Cold strip rolling is a major deformation process in industry. The need for high quality products and increased production speed, makes the application of the lubricant important. In the present study, oil property effect is investigated in cold rolling using oil lubricant in full-film lubrication regime. The model predicts decisive role of oil property in rolling parameters.

Keywords : Cold Rolling, Shear Strength, Non-Newtonian Fluid

1. INTRODUCTION

Cold strip rolling has been one of the most used metal deformation methods for production of metal sheets which has widespread application in most industries. There is always a need to make this process optimized in order to make it cost efficient and increase the final product quality. Cold strip rolling consists of several thickness reduction passes to make the final plate with desirable thickness. Fig. 1 shows the schematic illustration of cold rolling with 4 stands of reduction [1].

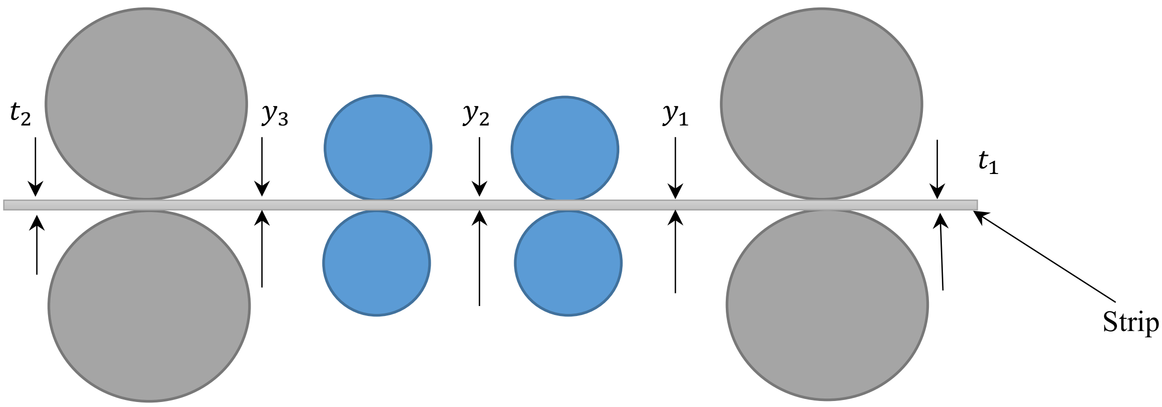

Figure 1. Schematic of a 4 stand tandem mill of lubricate cold rolling

Wilson et. al. [2] developed one of the earliest models for cold strip rolling followed by Yuen et. al.[3] who considered mixed lubrication in their model.

In recent years, cold strip rolling with emulsion has been subject of study. Hajshirmohammadi et. al.[4] developed a model for cold strip rolling with oil and water emulsion.

Recently porous material are being used in the rolling lubrication [5].

For the purpose of reduction in energy consumption, oil is sprayed on the contact line of rolls and strips. Depending on the rolling speed and normal force applied on the rolls, different lubrication regimes prevails. If a thick layer of oil forms between the rolls and the strips, the regime of lubrication would be full-film. This regime is more common in high speed rolling or rolling with high viscosity lubricants. Fig. 2 shows this type of lubrication regime.

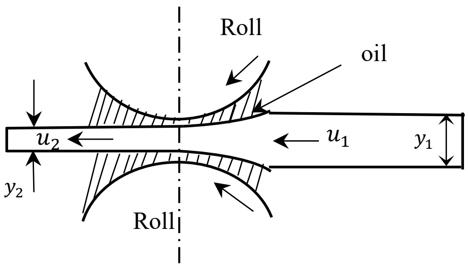

Figure 2. strip rolling in full-film regime

It can be seen in Fig. 2 that the strip goes under the rolls with the initial thickness of y1 and speed u1 and after reduction, thickness is y2 and the strip speed is u2. As it is depicted, the oil forms as a barrier between the rolls and the strip. The thickness of this layer of oil decides on the properties including the friction and consequently torque on needed to be applied on the rolls. This film thickness is affected by both rolling properties and the oil characteristics. The following model is used to study the oil viscosity effect on the properties of rolling.

2. METHODS

2.1 Strip plastic behavior

Plastic deformation in the work zone under the rolls is the reason for thickness reduction. To model the plastic respond of the strip, an element of the plate in the direction of rolling is isolated under the rolls as it is shown in Fig. 3.

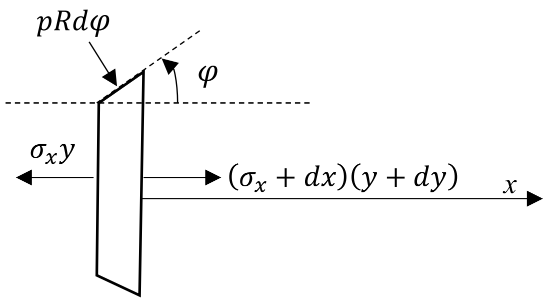

Figure. 3. An element of strip and the stresses acting on it

The strip element is subjected under back and forward tensions as shown by $\sigma_x$in Fig. 3. The equilibrium of the forces on the element is given by Eq. 1.

$$(\sigma_x + d\sigma_x)(y + dy) - \sigma_x y - 2\tau \cos\varphi \, Rd\varphi + 2p \sin\varphi \, Rd\varphi = 0 \quad (1)$$

where p is pressure on the strip, τ denotes the shear stress, the normal stress on the strip is given by $\sigma_x$and R. is the rolls radius.

$$ydx + \sigma_x dy - 2\tau dx + pdy \quad (2)$$

If the force equilibrium is considered in y direction the results would be:

$$-\sigma_z dx - (p\cos\varphi + \tau\sin\varphi)Rd\varphi \quad (3)$$

In which σ_z is the vertical stress. Because $Rd\varphi \cos\varphi = dx$, Eq. 3 will be in the following form.

$$p + \tau \tan\varphi = -\sigma_z \tag{4}$$

For most cases of rolling the angle of plastic zone is small which means $\tan\varphi \cong 0$ thus $p = -\sigma_z$
Using von Mises criterion leads to the following relation.

$$\sigma_x - \sigma_z = \sigma_k \tag{5}$$

The final relation used for quantifying plastic behavior will be as:

$$\sigma_k \frac{dy}{dx} + y\frac{d(\sigma_k - p)}{dx} - 2\tau = 0 \tag{6}$$

2.2. Shear stress

In the case of full-film lubrication, the shear force between the rolls and the strip is only due to the viscosity of the oil. This means that there is no direct contact between the two metal surfaces [6].
The relation between the shear stress and speed gradient in a Newtonian fluid is linear and described as:

$$\tau = \frac{\mu(u_r - u_w)}{h} \tag{7}$$

In this relation, u_r and u_w represent the roll and work piece velocity and h is the film thickness between the roll and strip. Plastic flow rule is used to make a relation between the inlet and outlet thickness and velocity of the strip. This is given by the following equation.

$$u_w y = u_{w1} y_1 = u_{w2} y_2 \tag{8}$$

The index 1 and 2 in the last relation denote the inlet and outlet.

2.3. Oil condition in the inlet and outlet

To solve the relation of oil lubrication, this is needed to find the oil pressure in the inlet and outlet.
The assumption is that oil pressure increases from the ambient pressure to the what is imposed on it in the work zone. This means that the pressure is zero in the inlet. If the elastic deformation of the strip is neglected in the outlet, the pressure of the oil will be zero in the outlet as well.

$$x = x_1 \qquad p = \sigma_y - s_1 \tag{10}$$

$$x = 0 \qquad p = \sigma_y - s_2 \tag{11}$$

2.4. Viscosity-pressure relation

Oil viscosity is directly related to its pressure. This means that shear force of oil and consequently the rolling parameters are largely affected by the oil pressure. Specially in cold rolling, due to this fact that oil pressure increases rapidly from zero to a considerable value under rolls, it is needed to consider the viscosity as the function of the oil pressure. In this regard, several empirical relations have been proposed. One of the most well-known relations was given by Baruse.

$$\eta = \eta_0 e^{\alpha p} \tag{12}$$

The pressure coefficient is shown by α and η_0 is the oil viscosity in ambient condition.
Another relation which is widely used is the Roeland's equation.

$$\eta(p,T) = \eta_0 \exp\left((\ln(\eta_0) + 9.67)\left\{\left(1 + \frac{p}{p_r}\right)^z - 1\right\}\right) \tag{13}$$

in this relation, p_r is a constant given as 1.963×108 and z stands for the viscosity-pressure power that has the following relation with α as:

$$\alpha = z\left[\frac{1}{p_r}(\ln\eta_0 + 9.67)\right] \tag{14}$$

The other important property of the lubricant is its shear strength (τ_{max}). Shear strength is the maximum shear stress that a fluid can stand. This means that any higher velocity gradient cannot produce a higher shear stress in the oil after it reaches its strength.

2.5 Numerical Procedure

A MATLAB code is written to solve the equations of lubrication and plasticity of the strips. The procedure of solution is comprised of several steps to find the pressure distribution of oil as a function of location I the work zone under the rolls. In each step, the boundary conditions are satisfied for plastic flow of strip and the oil pressure in both inlet and outlet of the work zone. Fig. 4 shows the flow-chart of the solution. One dimensional differential equation of lubricant is solved by applying shooting method and Runge-Kutta approach.

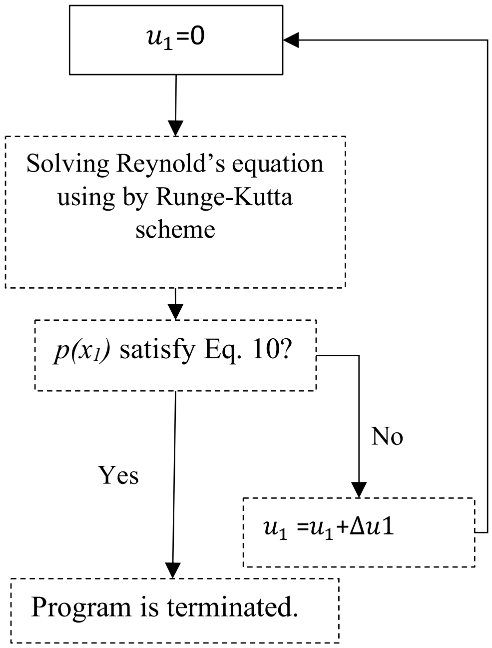

Figure 4. Numerical procedure flow chart for full-film regime.

3. RESULTS AND DISCUSSION

Fig. 6 shows the present study solution for rolling parameters listed in Table.1

Table 1. Rolling parameters used for simulation of cold rolling

Parameter	η_0 (mm)	α(1/Pa)	R(mm)	σ_y(MPa)	y_1(mm)	y_2(mm)
Value	0.02	6.2e-8	0.126	97.75	1	0.8

The maximum pressure in Fig. 6 corresponds to the neutral point where the roll speed is equal to the strip speed. Before this point, the rolls circumferential speed is more than the trip speed. After the neutral point, the rolls speed is lower than the strip's. This notion is seen in the shear stress plot of Fig. 6 which shows that at the neutral point the sign of shear stress changes due to change of sign of relative speed.

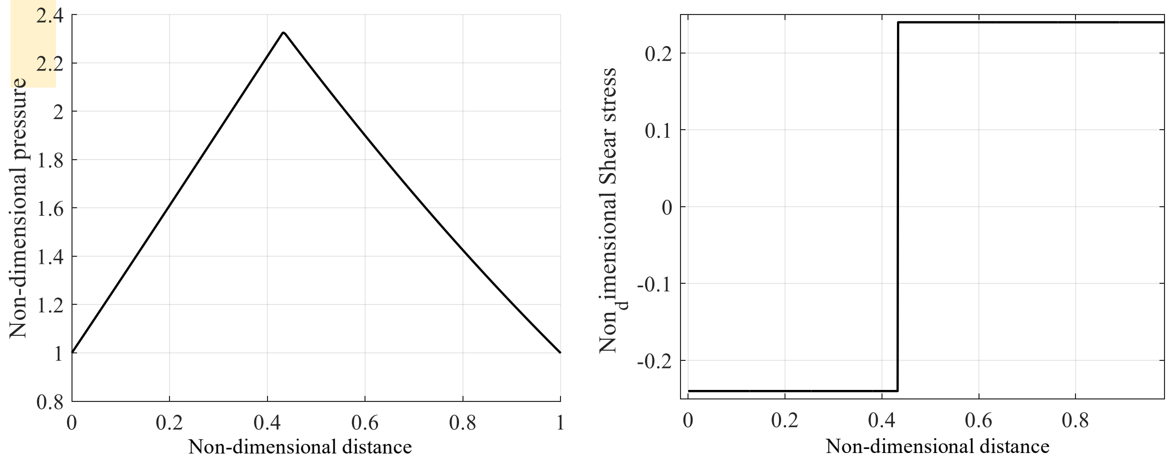

Figure 5. Non dimensional pressure and shear stress in the work zone.

Fig. 6 shows the rolling force and rolling torque for different shear strengths.

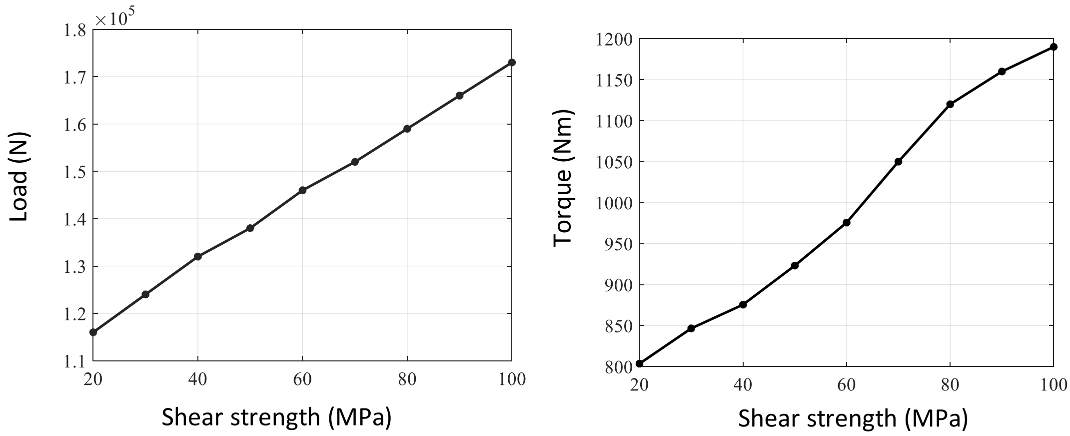

Figure 6. Rolling load and torque in different shear strengths of oil as lubricant.

It is seen that the rolling load and torque is directly affected by lubricant shear strength.

4. CONCLUSION

Effect of shear strength on cold rolling in hydrodynamic full-film regimes is investigated. The solution shows a direct relation between Load and torque needed for rolling. The reduction in torque is favorable for energy efficiency of cold rolling stands.

5. NOMENCLATURE

x	coordinate along the rolling direction	σ_y	yield stress
x_1	Roll contact length	τ	Shear stress

u_{w1}	Strip speed in the inlet	u_{w2}	Strip speed in the outlet
u_w	work-piece inlet speed	c	adhesion coefficient
u_r	roll speed	R	roll radius
y_1	Strip thickness in the inlet	η	(dynamic) viscosity of oil
y_2	Strip thickness in the outlet	S	non-dimensional roll speed $S = \frac{r\alpha\eta_0(u_r + u_{w1})}{\sigma_0 R_q x_1}$
h	surface separation	η_0	oil viscosity at ambient temperature.
α	viscosity pressure coefficient	E	Elastic modulus
p	interface pressure	s_1	backward tension
y, y_1, y_2	inlet, Exit and local strip thickness	s_2	forward tension

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