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Research Article

Energy Consumption Optimization of Cold Strip Rolling Lubricated in Mixed Regime

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Abstract

Cold rolling is one of the most popular metal forming methods. Due to mass production of companies which have cold rolling unites, it is essential to make the process optimum to reduce undesirable expense of production. One of the main production expenses is the power which is generally spends in the form of electricity. In the present study, power consumption of rolling is investigated with oil as lubricant

Keywords: *Cold strip rolling, metal forming method, Optimization, Lubrication, Power consumption.*

1. Introduction

Since the beginning of modern era, metal products have been a major commodity with large demand in most of industries including automotive, health care and transportation. The competitive market of these productions has been the incentive to reduce the cost of production in order to be in the safe side of business. This need has made many researchers interested in studying metal forming processes to find methods for reduction of production costs. Cold rolling as a major way of metal sheet forming approach has been the center of studies and there are ongoing efforts to improve it and make it more cost effective (Hajshirmohammadi *et al*).

One of the widely used ways of friction reduction and consequently saving power for production is applying lubricant in the cold rolling. Lubricant are used in various applications (Lijesh *et al*, 2015, 2016, 2019 ; Muzakkir *et al*, 2015; Chaichi *et al*, 2019). It is also essential for high surface quality to use oil during rolling. It is obvious that applying lubricant affects the torque needed on the rolls and as a result, reduces power consumed in this regard. This is also very effective on the reduction of energy consumption in the steel manufacturing industry, which could lead to decreasing the cost of production (Lu, Zhong-wu *et al*, 2000)and air pollution that is emitted to the environment (Isfahani *et al*, 2016).

The first attempts of simulating cold rolling with lubricant was Barker *et.al*. In following years, others investigated rolling (Chang *et al*, 1996). Recently Hajshirmohammadi *et al.* considered inter-stand tension when cold rolling is lubricated with emulsion. Fig. 1 shows the rolling schematic as the oil is sprays on the interface of rolls and strip. It is seen that, the strip goes in between the rolls with thickness y1 and speed u1 and leaves the rolling reduction zone with speed u2 and thickness y2. The area that reduction of thickness takes place is called work zone. As the oil is sprayed on the rolls, due to speed of the strip, it is drawn into the work zone and its pressure increases rapidly from zero to a large value between the two surfaces.

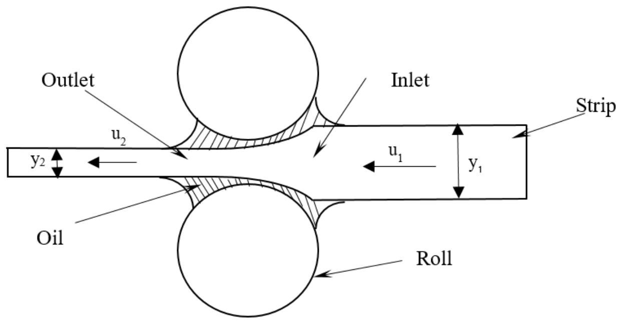

Fig. 1 Lubrication of cold rolling

The power needed for the deformation of plate is applied as the torque on the rolls. This torque is directly related to the friction between the two surfaces. This means that the power is directly related to the friction value between the rolls and strip. In the following section, a model is presented to find the friction and power consumption with the properties of oil and work piece.

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2. Model description

2.1 Strip plasticity

Fig. 2 depicts an element of strip which is under tensions from back and forward. The pressure from the roll is applied with a horizontal angle of φ. When equilibrium of the forces is considered in x and y direction.

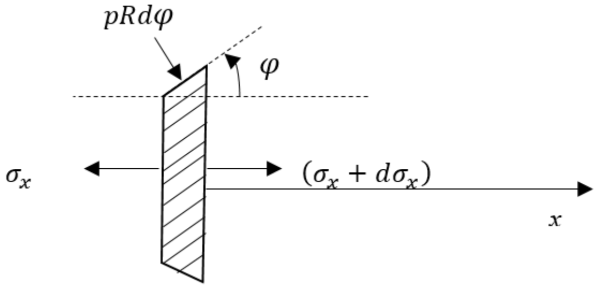

Fig. 2 Strip element in the work zone

Considering force equilibrium in x direction Eq. 1 is found.

$$\sigma_y \frac{dy}{dx} + y\frac{d\sigma_y}{dx} - y\frac{dp}{dx} - 2\tau = 0 \quad (1)$$

2.2 Lubrication regime

When two sliding surfaces are lubricated, different regimes of lubrication might happen based on the sliding speed, lubricant properties and the normal force between the surfaces. When the two surfaces are separated by a considerable layer of lubricant, full film regime takes place. In this regime, the two metal surfaces have no direct contact and all the shear load between them is the fluid shear due to viscosity. If due to low viscosity, speed or contact force, the two metal surfaces get into direct contact, the mixed film regime happens. In this regime, shear force between the surfaces is combination of lubricant and metal friction. Fig. shows this type of lubrication. Mixed regime is the prevalent regime in many real application (Hajshirmohammadi *et al*, 2019).

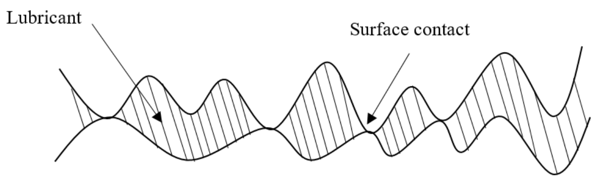

Fig. 3. Mixed film lubrication regime

The friction force in this regime is found according to the following.

$$\tau = Aq_a + (1 - A)q_f \quad (2)$$

where τ is the shear stress on the interface, q_a is the asperity contact and q_f is the fluid shear stress. In this relation A is the contact ratio of asperities which determines what portion of contact is the direct metal contact. Each terms on the RHS of Eq. are given as follows:

$$q_a = \frac{c}{2}\sigma_y sign(u_w - u_r) \quad (3)$$

$$q_f = \frac{\eta(u_w - u_r)}{h_t} + \frac{h_t}{2}\frac{dp_f}{dx} \quad (4)$$

in which c is the adhesion coefficient. u_w and u_r are the strip and roll linear velocity.

To find the pressure distribution between the rolls and strip, Reynolds equation needs to be solved in the proper domain and with reasonable boundary conditions. Reynolds expression has shown the capability for investigation of various type of flow and geometry form micro (Roohani Isfahani *et al*, 2019)to mesoscale (Berthe *et al*, 1974) fluid flow. The following equation gives the modified Reynolds relation for mixed lubrication.

$$\frac{d}{dx}\left(\frac{\phi_x h_t^3}{\eta}\frac{dp_f}{dx}\right) = -\frac{d}{dx}\left((u_w + u_r)h_t\right) \quad (5)$$

where h_t is the average film thickness. p_f is the lubricant pressure ϕ_x stands for flow factor. As it was mentioned, the pressure elevated very rapidly under the rolls (Wu, T., D. Wagner, *et al*, 2016). The viscosity of oil is a direct function of pressure. The exponential relation for this effect is widely used as:

$$\eta = \eta_0 \exp(-\alpha p) \quad (6)$$

where α is the pressure exponent of viscosity and η_0 is the ambient condition viscosity.

2.3 Asperity contact

Due to the interface pressure, the asperities deform and consequently the contact ratio increases. The relation which predicts the flattening effect was proposed by Chang and Wilson.

$$\frac{dA}{dx} = \frac{x}{La\theta_a\left(1 - A + \frac{yE_s}{2L}\right)} \quad (7)$$

in this relation L and θ_a are asperity half-pitch and asperity slope. E_s is given by:

$$E_s = \frac{2A - (p - p_f)}{(p - p_f)f_1} \quad (8)$$

$$f_1 = -0.86A^2 + 0.345A + 0.515 \quad (9)$$

$$f_2 = \frac{1}{2.571 - A - Aln(1 - A)} \quad (10)$$

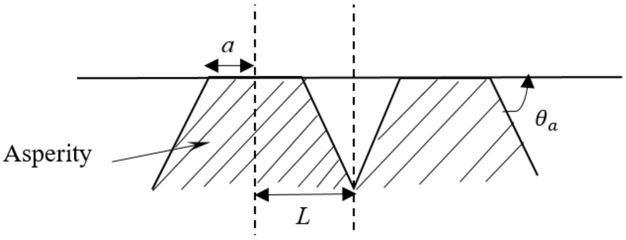

Fig. 4 Asperity contact and the parameters related

2.4 Plastic flow of strip

When the strip enters the work zone interface under the rolls, it deforms plastically. Since the thickness of the strip changes during this deformation, the speed changes. The flow relation which determines the strip speed and thickness is as follows.

$$y_1u_1 = y_2u_2 = yu$$

where y_1, y_2 and y are strip thickness in the inlet, outlet and during deformation under rolls respectively, u_1 , u_2 and u are strip speed in the inlet, outlet and under the rolls.

2.5 Boundary conditions

The pressure of lubricant is zero before and after the work zone because the elastic behavior of strip is considered small.

$$x = x_1 \qquad p_f = 0 \tag{11}$$

$$x = 0 \qquad p_f = 0 \tag{12}$$

The yield condition of strip in the inlet and outlet is found according to von Mises criterion.

$$x = x_1 \qquad P = \sigma_y - s_1 \tag{13}$$

$$x = 0 \qquad P = \sigma_y - s_2 \tag{14}$$

in these relations, σ_y is the yield stress and s_2 and s_1 are the tension applied on the strip in the inlet and outlet.

3. Numerical Procedure

The solution procedure is started with guessing pressure distribution and the value contact ratio in the domain. An iterative scheme is applied to solve Eq. 6 and Eq. 7 in conjunction with Eq. 1. The ODE of Eq. 1 and Eq. 7 is solved using 4th order Rung Kutta approach and a central difference discretization method is applied to solve Reynold's relation of Eq. 5. For this purpose, a MATLAB script is written.

4. Results and discussion

After the solution is achieved, the friction force is found according to Eq. 2. This relation gives the shear stress in the interface. The torque on the rolls for a unite width of strip can be found by integrating this shear stress in the work zone and multiplying it by the radius of the rolls.

$$T = R\int_0^{x_1} \tau dx \tag{15}$$

Energy consumption for manufacturing a unite length of the strip is found by dividing the energy rate applied on the rolls to the inlet speed of the strip.

$$E = \frac{T\omega}{u_1} = \frac{T\frac{u_r}{R}}{u_1} \tag{16}$$

in which ω is the angular velocity of the rolls. Fig. shows E as a function of the non-dimensional speed $S = \frac{r\alpha\eta_0(u_r+u_1)}{\sigma_0 R_q x_1}$

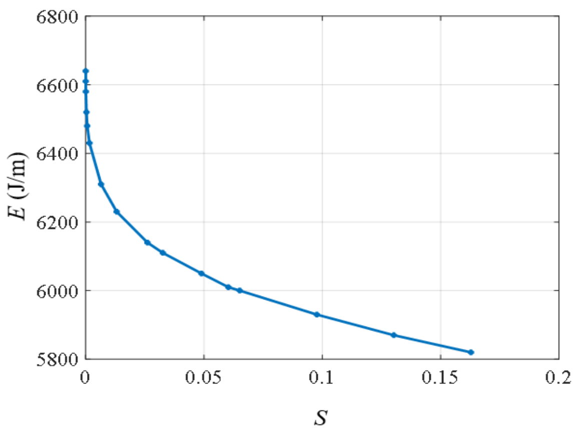

Fig.5 Energy consumed for different speed

This is seen in the figure that energy consumed for production of unite length of strip E decreases with speed. This reduction of energy consumption is more in low speed region compared to high speed.

Table 1. rolling parameters used for simulation of cold rolling

Para-meter	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

Conclusion

A model is presented to find energy consumption for production of strip lubricated in mixed regime under rolling stands. The results show that production is more efficient in high speed and the reduction in energy consumption is more prominent when speed is in low regime compared to high speed regime.

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