Lubrication Analysis of Strip Rolling with Oil-in-Water (O/W) Emulsions

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Abstract— An Isothermal analysis of lubrication mechanism of strip rolling with oil-in-water emulsion, have been carried out. In this analysis, condition viz. smooth roll and strip as well as roughness are considered. Numerical study on the oil concentration effects of O/W emulsion on parameters viz. pressure and film thickness are found out and discussed. The dynamic concentration theory and extended Reynolds equation based on effective viscosity for binary medium are adopted and a co-relation between both theories is derived. The numerical results for the pressure variation towards inlet zone at different operating parameter like variation in concentration of emulsion supplied and variation in mean roll and strip speeds are found out and compared.

Key Words— Lubrication, Emulsion, Cold Rolling, Inlet Zone, Dynamic Concentration Theory

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1 INTRODUCTION

TO obtain the high quality sheet at high roll speeds in cold rolling process, the presence of continuous lubricating film at the roll-sheet interface is essential. The primary purpose of lubrication in rolling is to reduce the friction and roll wear. Secondarily, it acts as coolant too. It removes excessive heat generated during plastic deformation of metallic sheets.

It has been evident by the present authors that the sufficient amount of work is available in open literature using oil as the lubricant. However, it is now felt that, the emulsion can be the alternate of the mineral oil and can provide sufficient lubrication during process. The minimum film thickness obtained with the emulsion is almost of the same order as the mineral oil.

Applying oil in water (O/W) emulsions during cold rolling of metal strips helps achieve the objectives of the industry: dimensional accuracy, satisfactory surface finish and improved mechanical properties. The additional benefits include reduced mill loads, minimized roll wear, cooling of the surfaces and prevention of rusting.

Oil in water (O/W) emulsion is a lubricant composed of oil suspended in water in droplets form and it generally contains 1-10% of natural, mineral, or synthetic oil generally with droplet diameter ranges from 2 to 20 µm.

Minimizing the oil content in the emulsion may reduce the overall cost of the process, however the quality of the tribological conditions required for successful rolling should not be affected. Use of less oil would also have beneficial environmental effects. So, due to its reduced cost, inflammable characteristic, good lubrication and cooling capability and less adverse environmental effects, Oil-in-Water (O/W) Emulsion is adopted as a common lubricant in cold rolling process. Oil-in-water emulsions have been used by many investigators in their cold rolling studies with the twin objectives of cooling the surfaces and to provide sufficient amounts of oils at the roll-strip interface.

When the O/W Emulsion is used as lubricant, sufficient lubrication film can be developed due to droplet capture and oil concentration process in inlet zone. The concentration process invert the oil-in-water (O/W) Emulsion into Water-in-oil (W/O) at the end of inlet zone and this concentration Emulsion provide the lubrication pure oil in the work zone.

In-spite of emulsions use as a common lubricant for lubrication in strip rolling processes, the mechanism of film formation by O/W emulsions at the entrance region of the roll gap is still not very clear.

The lubricating mechanism with emulsion has attracted many researchers and directed them to focus on the concentration process of disperse phase and oil droplets capture. Various theories such as plate-out theory [1], mixture theory [2], dynamic concentration model [3], and extended Reynolds equation with effective viscosity [4,5] have been proposed. The dynamic concentration model was firstly introduced by Wilson et al. [3], which describes emulsion concentration in the gap between the roller and strip surfaces when droplets are captured in the conjunction. The basic assumption of dynamic concentration model was that the oil is preferentially entrained into the inlet zone due to its relatively high viscosity. Nevertheless, at high speed, it is supposed that some water is entrained in the contact since is not able to escape when it approaches close to the inlet of the contact. This model includes a capture coefficient, which is a combination of droplet entrainment probability and flattening. However, the droplet capture process is not yet fully understood.

Yan and Kuroda [4] have proposed a simplified model based on the continuum theory of mixture to derive the extended Reynolds equation for lubrication with emulsions. The pressure distribution and the concentration of disperse phase (oil) in Emulsion can be obtained by solving the equation. On simplification of the Extended Reynolds equation, it is evident that the velocity difference between two phases (oil as disperse phase and water as continuous phase) exists and this causes the oil concentration and inversion of O/W Emulsion into W/O. This inverted Emulsion behaves into the same manner as the neat oil.

Schmid and Wilson [6] have applied the dynamic concentration model to strip rolling to derive a relatively simple equation for inlet film thickness. They have shown experimentally that the predictions made in their new model were in good agreement with the experimental result. It was suggested that the efficiency of oil droplet capture increases with increasing rolling speed.

All the theories proposed for lubrication with Emulsion are based on smooth surface but Strip rolling processes are generally performed in mixed lubrication in which load capacity is generated by hydrodynamic pressure of lubricant generated in between the roughness asperity of the contacting surfaces.

Many researchers have done the work to model the mixed film lubrication. The developed models are focused on asperity-flattening model relating the plastic and surface asperity deformation [7]. This relation, developed for roughness with lay parallel to rolling direction, is capable to calculate the actual contact area and total friction between roller and strip. Wilson and Chang [8] have done the analysis for the lubrication of saw-tooth surfaces with longitudinal lay under conditions of high fractional contact area is developed. This analysis is then coupled with Wilson and Sheu's [7] asperity flattening model to treat the mixed lubrication of a rolling process. It shows that, even under low speed conditions where the inlet zone does not generate significant hydrodynamic pressures, relatively high hydrodynamic pressures can be generated in the work zone. This explains the persistence of hydrodynamic effects noted in low speed experiments.

A numerical study of on oil concentration effect of O/W emulsion in the mixed film lubrication regime has been done by Kosasih and Tieu [9]. Their study mainly focused on effects of variation of concentration of emulsion on other parameter viz. pressure, film thickness, and variation in disperse phase in IZ and WZ during a cold rolling process.

Recently, Azushima et al. [10] have developed a model to calculate the plating-out film thickness. Their estimating method of the plating-out film thickness was investigated using the numerical method of the inlet oil film thickness under the starvation condition of emulsion.

Though, the available theories for lubrication with O/W Emulsion are significantly contributing to understand the mechanism, the detailed analysis of lubricating parameters is proposed in this paper keeping the mixed film lubrication into consideration. The numerical study has been proposed in this work which shows the significant pressure building occurs in the inlet zone. The effect of variation of different input parameters (i.e. concentration of supply emulsion, roll velocity, reduction ratio, etc) on the output parameters (i.e. peak pressure, film thickness, concentration of emulsion at the end of inlet zone, etc) has been shown and discussed.

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2 ISOTHERMAL ANALYSIS OF LUBRICATION MECHANISM

The schematic diagram of the cold rolling along with coordinate system is shown in Fig.1a where various zones of the contacts have been indicated. Analysis of lubrication in rolling process is generally divided into two zones viz. inlet zone (IZ) and work zone (WZ). In the lubrication of cold rolling, the pressures of the film in the inlet zone vary from atmospheric to yield strength (deformation of strip is only possible if film pressure reaches yield strength of strip material) of the work piece and remains approximately constant in work zone (WZ). Therefore, inlet zone (IZ) is chosen for the analysis of lubrication. The zoomed view of the inlet zone (IZ) (xb ≤ x ≤ xa) is shown in fig. 1b which is further divided into three region viz. supply region, concentration region and pressurization region. Supply region is the non-contact region where the concentration region and pressurization regions are contact regions where the asperity on strip starts to make contact with roll surface. Since the viscosity of the lubricant is strong function of pressure and temperature, therefore use of proper viscosity model in the analysis is essential.

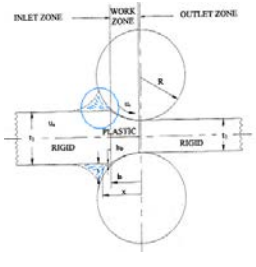


Fig. 1a. Schematic diagram of cold rolling along with coordinate system

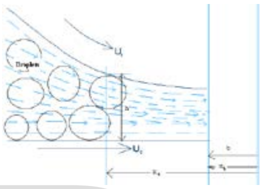


Fig.1b Zoomed view of selected section of fig. 1(a)

In this analysis, it has been assumed that the viscosity is independent of temperature. Such situation may occur in case of rolling of soft metallic materials at low speeds.

2.1 Dynamic Concentration Theory

In the supply region, the oil droplets are in disperse form and isolated from each other as well as from strip and roll surfaces. Then emulsion moves towards the concentration region where the film thickness get reduces and oil droplets are captured between the strip and roll surface gap due its higher diameter than the film thickness. It is assumed that this happens when the film thickness is some fraction C of the mean droplet diameter of disperse phase in supplied emulsion [6].

$$h_s = Cd_s \tag{1}$$

where h_s is the film thickness at the inlet of concentration region. C is referred as the Capture Coefficient and it varies from 0.33 to 1. As it is assumed that the pressure remains at ambient approximately [11], the concentration of emulsion ϕ (volume fraction of disperse phase) and the film thickness h are related in this region by equation (2).

$$\phi h = Const. \tag{2}$$

Equation (2) shows that as the gap between the roll and strip surface reduces, the Emulsion gets concentrated in the concentration region because the oil droplets are being captured between the roll and strip surface while water gets left behind. The pressure gradient is controlled by the relatively low viscosity water so that no significant pressure buildup occurs. At the end of the concentration region, where the film thickness is

h_i, the emulsion will reach the concentration ϕ_i at which oil-in-water gets inverted into water-in-oil. Applying equation (2) between the conditions at the boundaries of the concentration region yields:

$$\phi_i h_i = \phi_s h_s \tag{3}$$

And substituting for h_s from equation (1) gives:

$$h_s = Cd_s \frac{\phi_s}{\phi_i} \tag{4}$$

Equation (4) can be used to calculate the film thickness at the boundary between the concentration and pressurization region. To match the assumptions used in the development of the interacting flow model, it is assumed that the inversion occurs when the concentration reaches 0.907 [6]. Further concentration of Emulsion is not possible whet it enters into the pressurization region. It is because the water is trapped within the oil film. The viscous properties of this invert (water-in-oil) are same as the neat oil. The viscosity variation into pressurization region is according to the Barus equation.

$$\eta = \eta_0 e^{\gamma p} \tag{5}$$

Where η_0 is the viscosity at atmospheric pressure and γ is the pressure coefficient of viscosity of the oil. In the pressurization region the film thickness h is given by:

$$h = h_0 + \theta\, x \tag{6}$$

where h_0 is the film thickness entering the work zone, θ is the inlet angle and x is distance from the virtual intersection of the roll and incoming strip surfaces. As it was mentioned at the earlier section of this paper that the pressure is approximately constant and so pressure gradient can be neglected in the work zone. Now, the Reynolds equation may be written as:

$$\frac{1}{\eta}\frac{dp}{dh} = \frac{6(u_r + u_s)}{\theta}\left(\frac{h - h_0}{h^3}\right) \tag{7}$$

Equation (7) can be used to determine the pressure distribution as well as the film thickness in the inlet zone of a cold rolling process.

2.2 Extended Reynolds Equation Considering Smooth Roll and Strip Surfaces

As discussed earlier, the Emulsion is the mixture of oil and water and to derive the extended Reynolds equation the continuum theory of mixture is used. While using the continuum theory to derive the extended Reynolds equation, it is assumed that a mixture is considered as superposition of all single continua and each obeys its own motion. The oil-in-water Emulsion is the superposition of volume fraction of disperse phase (oil) and volume fraction of continuous phase (water) and their volume fractions are related as

$$\phi_d + \phi_c = 1 \tag{8}$$

On the basis of continuum theory of mixture, Yan and Kuroda [4] developed the Extended Reynolds equation for lubrication with emulsion which is applicable in all zone i.e. Inlet zone and work zone. It is expressed as

$$\frac{\partial}{\partial x}\left(\frac{h^3}{12\xi}\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{h^3}{12\xi}\frac{\partial p}{\partial y}\right) = \frac{\partial}{\partial x}\left(\frac{(u_r + u_s)}{2}h\right) + \frac{\partial h}{\partial t} \tag{9}$$

Equation (9) is in the same form as the conventional Reynolds equation. Only difference is that, in this equation the equivalent viscosity (ξ) is used which has the effect of oil concentration during the lubrication process. Equivalent viscosity (ξ) is derived under the condition that two phases (oil and water) have different velocity and due to this concentration of Emulsion increases. While deriving the expression of equivalent viscosity, it is assumed that shearing stress of disperse phase has its effect not only on its own velocity gradient but also on the velocity gradient of continuous phase.

$$\xi = \frac{\mu_d \mu_c - \mu_{dc}\mu_{cd}}{\phi_c^2 \mu_d - \phi_d \phi_c (\mu_{dc} + \mu_{cd}) + \phi_d^2 \mu_c} \tag{10}$$

The equivalent viscosity (ξ) can be calculated by calculating the four viscosity coefficient μ_d, μ_c, μ_{dc} and μ_{cd}. Yan and Kuroda [5] derived the values of these coefficients for thick film and thin film. For thin film, the vales are as follows

$$\mu_d = \phi_d\, \eta_d \tag{11}$$

$$\mu_c = \phi_c\, \eta_c \tag{12}$$

$$\mu_{dc} = \mu_{cd} = 0 \tag{13}$$

3 RESULTS AND DISCUSSION

The input data used during analysis are given in Table 1. The results have been presented in graphical form at various rolling speeds, reduction ratios, and emulsion concentration. Roll speeds have been varied between 0.1 m/s to 15 m/s.

Table 1

Lubricant, strip and roll properties

Strip Material	17 % Cr stainless steel
Oil used in emulsion	No. 120 M/c oil
Roll radius, m	0.05
Viscosity of lubricant (η_0), Pa.s	0.434
Pressure viscosity coefficient, Pa^{-1}	$2.8x10^{-8}$
Density of lubricant (ρ_0), kg m^{-3}	890
Yield strength of strip material, N/m^2	$3.9x10^{+8}$

Inlet strip thickness, m	$1.0x10^{-3}$
Final strip thickness (when RD=0.15),m	$8.5x10^{-4}$

The above equations are solved numerically for pressure distribution, variation of minimum film thickness, variation of volume fraction of disperse phase by varying the different parameters.

A detailed study of the effect of ϕ_{ds} (supply concentration) is carried out for the speed ranges from 10-13 to 10-3 and emulsion supply concentration (ϕ_{ds}) ranges from 5 % to 100 %.

It is seen from the figure 3(a) that the oil concentration increases in the forward direction in inlet zone. There is a sharp increment in the concentration at the exit of inlet zone and the emulsion behaves like pure oil. The concentration process is affected due to change in oil concentration of supplied emulsion. Figure 3(b) shows that due to supply of more oil concentrated emulsion, concentration process starts in early stage and become closer to the neat oil at the exit of inlet zone.

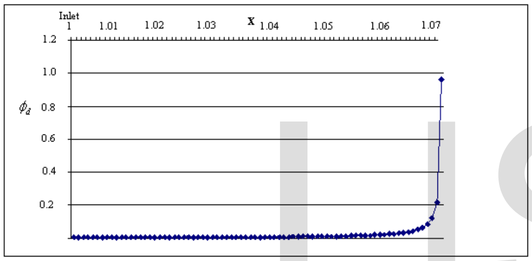


Fig.3 (a).Variation of Volume fraction of disperse phase in forward direction of inlet zone

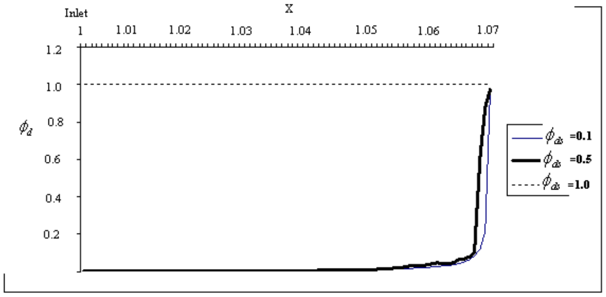


Fig.3 (b).Variation of Volume fraction of disperse phase in forward direction of inlet zone with different supply concentration

Figure 4 shows the variation of film Thickness (H_t) which decreases continuously in forward direction of Inlet zone. Figures 5(a) and 5(b) shows the variation of minimum film thickness (H_{te}) at the exit of inlet zone at different speeds. It is evident that the minimum film thickness increases on increment of speed. The oil concentration supplied emulsion affects the variation of minimum film thickness at different speed and this effect decreases on increment of speed. It increases on increment of oil concentration of supplied emulsion.

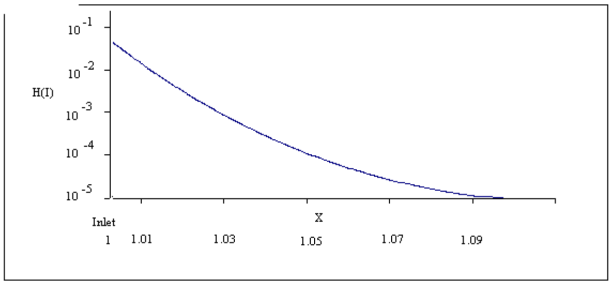


Fig.4. Variation of film thickness in forward direction of inlet zone

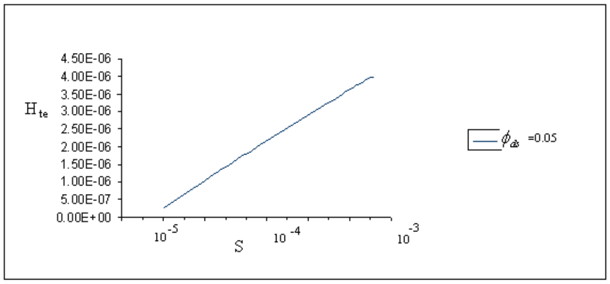


Fig. 5(a).Variation of Minimum film thickness at different non-dimensional speed (S)

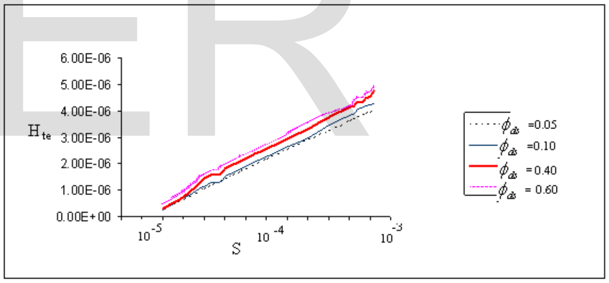
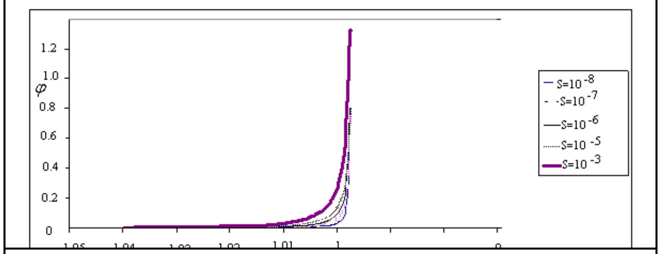


Fig. 5(b).Variation of Minimum film thickness at different non-dimensional speed (S) with different supply concentration

Figures 6(a) and 6(b) shows the clear effect of speed on hydrodynamic pressure distribution. The oil concentration level of supplied emulsion influences the hydrodynamic pressure. There is a significant change in the pressure with the change of concentration of supplied emulsion. The reason of this can be found in the figure 3, where for $\phi_{ds} > 0.5$ the sharp increase of emulsion oil concentration in inlet zone transforms the oil from disperse phase to continuous phase. This effectively produces neat oil lubrication e exit of inlet zone.



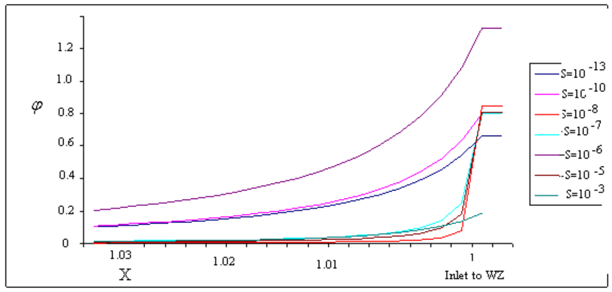


Fig.6(b).Pressure Distribution in Inlet zone at different speeds

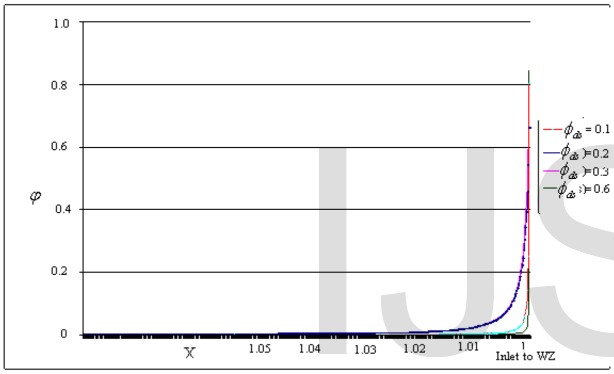


Fig.7. Pressure Distribution in Inlet zone with different supply concentration

5 CONCLUSIONS

A numerical study on the effects of oil concentration and speed variation in O/W emulsion lubricated cold rolling process has been carried out. The key results of the study are as follows:

- The control on minimum film thickness at the exit of inlet zone can be achieved by varying the speed or the oil concentration of supplied emulsion.
- The effect of the oil concentration is predominantly seen in the development of the lubricant pressure.

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