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Effect of Lubrication on a Surface parameter of Strip in Cold Rolling with Oil in Water Emulsion

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Abstract

Cold rolling is one of the major metal forming processes used in industry. Surface properties play an important role in the quality of products used and controlling the rolling parameters in order to maintain preferable quality of surface is important. The lubrication is essential in this regard. The regime of lubrication is often mixed-film where strips and rolls have asperity contact because of high pressure between the two contacting surfaces. This contact is favorable for quality of trip surface. The surface characteristic of product depends directly on the value of contact ratio between roll and sheet. In this study a model is presented to describe strip rolling lubricated with oil in water (O/W) emulsion. In the present research, the plastic flattening of asperities during the process in mixed regime of lubrication is taken into account. The Reynolds equation is solved for emulsion and slab method is implemented to take the bulk plastic deformation of strip into consideration. This study confirms higher film thickness and lower contact ratio for higher oil content of emulsion. Furthermore, results show higher dependence of asperity contact and film thickness on oil percentage of emulsion in high speeds.

1. INTRODUCTION

Oil in water (O/W) emulsions are widely used in cold strip rolling for the sake of its lubrication properties and coolant effect due to presence of water. Being non-inflammable and easy to spray, emulsions make a perfect choice when heat reduction and surface property qualities are important. There have been many studies in recent years to propose a realistic approach for the process of cold rolling. There are three major view point for describing lubrication with two components (emulsions). Plate out theory, dynamic concentration and starvation [1-3] are the three most studied of all.

Dynamic concentration theory, which is used in this research, assumes that concentration of disperse phase (oil) changes due to being drown into the contact zone of roll and strip preferentially compared to water part. The increase of oil concentration leads into an oil-rich region between two contacting surfaces (roll and strip) and a concentrated lubricant which has oil as major part, comes out from the outlet zone (Fig.1)

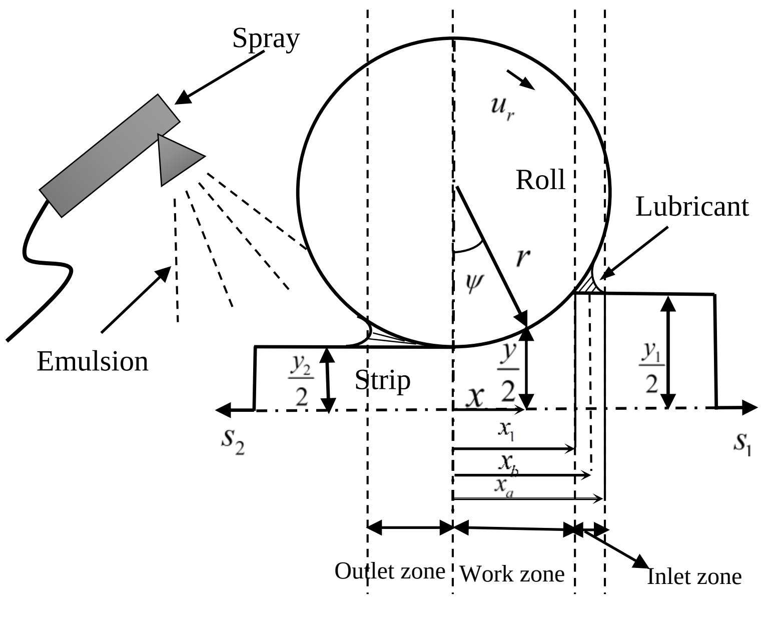

Fig. 1: Schematic of cold strip rolling being lubricated with emulsion

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Recently Chen *et al* [4] studied the lubrication in cold rolling process of B443NT stainless steel. Sun *et al* [5] explore the regularities of distribution on oil film and Li *et al* [6] A theoretical model for cold-rolling copper alloy in mixed lubrication regime indicated that lubrication plays a decisive role in vibrations, surface quality, torque and load capacity of tandem mills. Mixed-film lubrication happens when there is direct contact between lubricating components [7-14].

Xie *et al* [15] studied the surface roughness of SUS 304 stainless steel by considering effect of lubricant and future size effect. Wu *et al* investigated rolling with random surface asperity and multi-scale plastic deformation using a statistical model. In some studies, the thermal effect was considered as well. Wu *et al* used a computational analysis of interfacial heat transfer which was based on heat transfer theory Singh *et al* [6] proposed an analysis for prediction of minimum film thickness in the inlet zone. Lee *et al* [17] considered adhesive layer of oil on both rolls and strip. Lo *et al* [18]studied the lubricity of oil in water emulsions in different zones of lubrication. Tieu *et al* [19]showed the effect of emulsion in cold rolling both numerically and experimentally. Shen *et al* [20]studied the speed in rolling characteristics. Hajshirmohammadi *et al* [21] considered the interstand tension using O/W emulsion in the tandem rolling mills. Thermal investigation is considered by[22].

2. MODEL DESCRIPTION

The surface quality of rolling products is closely related to the regime of lubrication. Hydrodynamic lubrication without surface asperity contact is not favorable in this regard. This means that the when there is not direct contact between the lubricating surfaces, there will be a relatively thick layer of oil separating the two sliding metals (roll and strips). The packets of oil which form between the surfaces during deformation process leads to reduction of quality of surface characteristics. Therefore; mixed lubrication is the regime which can produce high quality surface. In mixed regime lubrication, asperities of two metal surfaces get into contact and cause deformation of these pikes. Fig. 2 shows this regime of lubrication

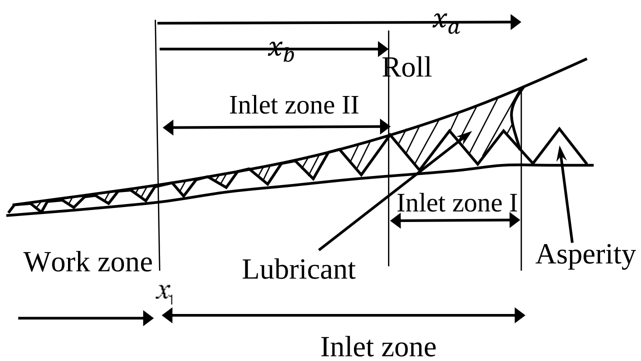


Fig. 2: Different parts of the inlet zone.

As it is seen in Fig. 2. Inlet zone is divided into two sub-zones. In inlet zone I, there is not a direct contact between the asperities and the lubricant fills the gap between the surfaces. The asperities get into direct contact at the end of inlet zone I and start deformation in the inlet zone II. Finally, the strip goes into work zone where deformation takes place and noticeable change in surface roughness happens.

In the inlet zone the Eq. 1 is valid proposed by Tieu *et al* [19] which Reynolds relation for emulsion made of continues phase (water) and disperse phase (oil).

$$\frac{d}{dx}\left(\frac{\phi_x h_t^3}{\xi}\frac{dp_f}{dx}\right) = -\frac{d}{dx}\left((u_w + u_r)h_t\right) \tag{1}$$

In which, p_f is pressure of lubricant, h_t stands for average film thickness. Roll and strip speed are shown by u_r and u_w. ϕ_x is flow factor which makes the mixed lubrication comparable with hydrodynamic lubrication. Since the lubricant has two component (oil and water), equivalent viscosity ξ is used. The relation between equivalent viscosity and the two components of the lubricant is defined by Eq. 2.

$$\xi = \frac{\eta_c \eta_d}{\lambda_c \eta_d + \lambda_c \eta_c} \tag{2}$$

where η_c is continues phase (water) viscosity and η_d is disperse phase (oil) viscosity. The concentration of oil and water is shown by λ_d and λ_c respectively.

The change of strip thickness happens in the work zone where a relatively large amount of force is applied on the work piece. In this zone asperity flattening takes place and the roughness of surface changes. To account for the deformation of strip, slab method is used as the following:

$$\sigma_y \frac{dy}{dx} + y\frac{d\sigma_y}{dx} - y\frac{dp}{dx} - 2\tau = 0 \tag{3}$$

where σ_y is the strip yield stress and p is the total interface pressure. The shear stress τ is composed of two components, the friction related to viscose lubricant (q_f) and the one because of asperity contact (q_a)

The total shear stress is found using the contact ratio (A).

$$\tau = Aq_a + (1 - A)q_f \tag{4}$$

The two components of shear stress are found according to the following relations.

$$q_a = \frac{c}{2}\sigma_y sign(u_w - u_r) \tag{5}$$

$$q_f = \frac{\eta(u_w - u_r)}{h_t} + \frac{h_t}{2}\frac{dp_f}{dx} \tag{6}$$

in which c is the adhesion coefficient between strip and rolls and $sign$ denotes the sign function.

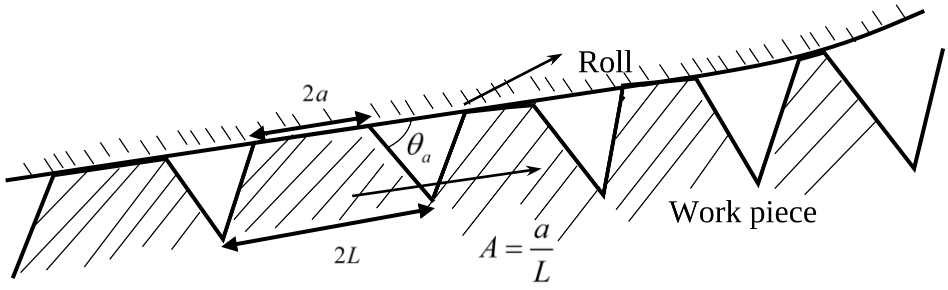


Fig. 3: Contact of strip and roll surfaces and asperity flattening

For the purpose of investigating asperity flattening, Chang and Wilson [23] relation is utilized as follows:

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

where, L and θ_a are asperity half-pitch and asperity slope shown in the Fig.3. E_s and f_1 and f_2 are defined as:

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

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

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

Procedure for solution of equation have to be carried out using the appropriate boundary conditions. Lubricant pressure is zero at the beginning of the work zone and it increases rapidly during the deformation of strip.

$$x=x_1 \qquad p_f=0 \quad (11)$$

The that non-dimensional strain rateE_s, is zero at *x=0*

$$x=0 \quad E_s=\frac{2A-(p-p_f)f_2}{(p-p_f)f_1}=0 \quad p_f=p-\frac{A}{f_2} \quad (12)$$

Since thickness reduction of the strip takes place in the work zone, at the both ends of this zone, yield criteria has to be satisfied. Which means:

$$x=x_1 \qquad P=\sigma_y-s_1 \quad (13)$$

$$x=x_2 \qquad P=\sigma_y-s_2 \quad (14)$$

where s_1 and s_2 are forward and backward pressure applied on the strip from front and back due to the inter-stand tensions.

Lubricant viscosity is affected noticeably with temperature and pressure. Increasing the temperature normally leads to a reduction in viscosity and high pressure makes the lubricant more viscos.

When emulsion is used, most of heat produced during the deformation process is spent on increasing water temperature and this temperature rise is normally small due to high heat capacity of the water. Therefore, heat effect on the lubricant can be neglected. The well-known Barus equation which gives the relation between viscosity and pressure is:

$$\eta=\eta_0e^{\alpha p} \quad (15)$$

in which η_0 is the viscosity in ambient condition and α is pressure coefficient which is a lubricant property. The average separation of strip and rolls are given by Eq. 16.

$$h(x)=h_1+\frac{x^2-x_1^2}{2R}+y_1-y_2 \quad (16)$$

Using Barus relation in Eq.
2 yields:

$$\xi=\frac{\eta_c\eta_0e^{\alpha p_f}}{\eta_c\eta_0e^{\alpha p_f}+\eta_c\lambda_d} \quad (17)$$

which is the equivalent viscosity of emulsion.

3. NUMERICAL PROCEDURE

An iterative procedure is taken to solve the Reynolds equation alongside with slab equation and asperity flattening relation. The procedure starts by guessing x_a and x_b in the inlet zone and solving Reynolds in the inlet. After that, the Reynolds is solved in the work zone. In each step solution is stopped after convergence achieved after the relative error of consecutive solutions are less than 10^{-6}. Reynolds equation is solved using central difference method of discretization and Runge-Kutta approach is implemented to solve asperity flattening equation. In this regard, a MATLAB code is prepared with 4 functions for one dimensional integration of Runge-Kutta method.

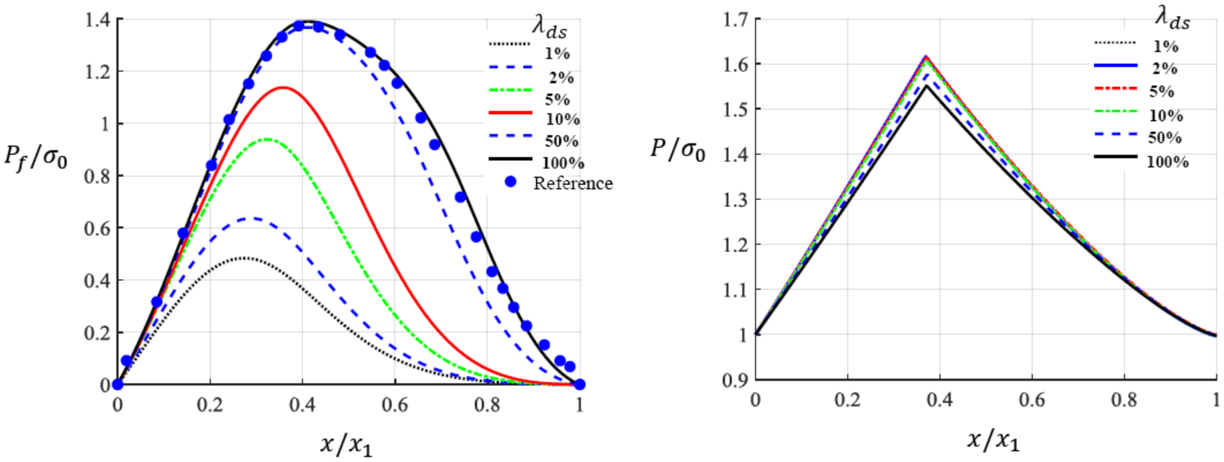
4. RESULTS AND DISCUSSION

The solution of the present study is validated with Yuen *et al.* [24] for pure oil ($\lambda_{ds} = 1$). The rolling parameter used are shown in Table 1. It is seen that the present results are in good agreement with the reference (Fig. 4.). The results are illustrated for different oil concentration of emulsion. The oil percentage is 1%, 2%, 5%, 10%,50% and 100%.

It is seen from the graphs that by increasing the oil percentage of emulsion, lubricant pressure increases and the total pressure drops. This was predictable because of the fact that lubrication become more prominent as the oil content of emulsion increases and consequently the amount of pressure needed to deform the strip decreases. This behavior is the same for the case where frictional force is considered. In Fig.5 the shear stress is depicted which decreases with the oil content of lubricant. As it is expected, there is a discontinuity in the shear stress that represents the neutral point. This point is where the relative speed of the roll and the strip changes sign.

Table 1: Parameters of rolling

Parameter	$\boldsymbol{\eta_0}$ (mm)	$\boldsymbol{\alpha}$(1/Pa)	$\boldsymbol{R}$(mm)	$\boldsymbol{c}$	$\boldsymbol{y_1}$(mm)	$\boldsymbol{y_2}$(mm)	$\boldsymbol{\sigma_y}$(MPa)	$\boldsymbol{\theta_a}$	L(μm)	$\boldsymbol{\delta}$(μm)
Value	0.02	15.8e-9	0.2	0.2	1	0.8	97.75	0.2	35	1



(a) (b)

Fig. 4: (a) Non-dimensional lubricant pressure and (b) non-dimensional total pressure in work zone

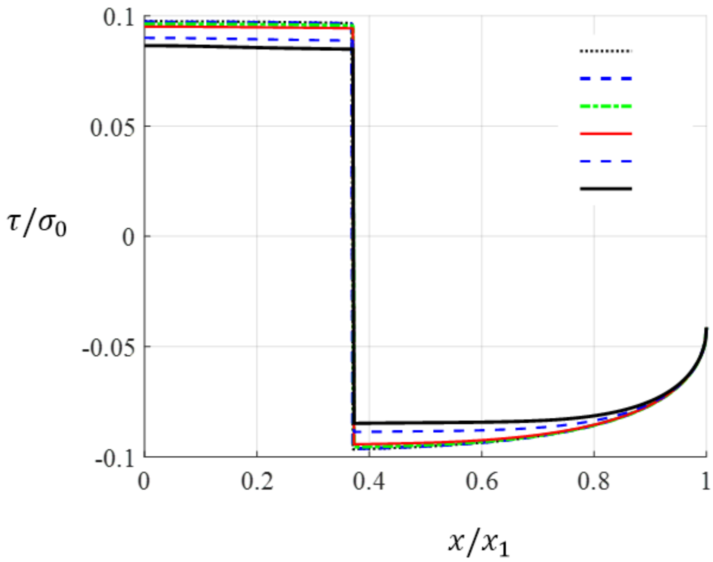


Fig. 5: Non-dimensional shear stress between roll and strip in work zone

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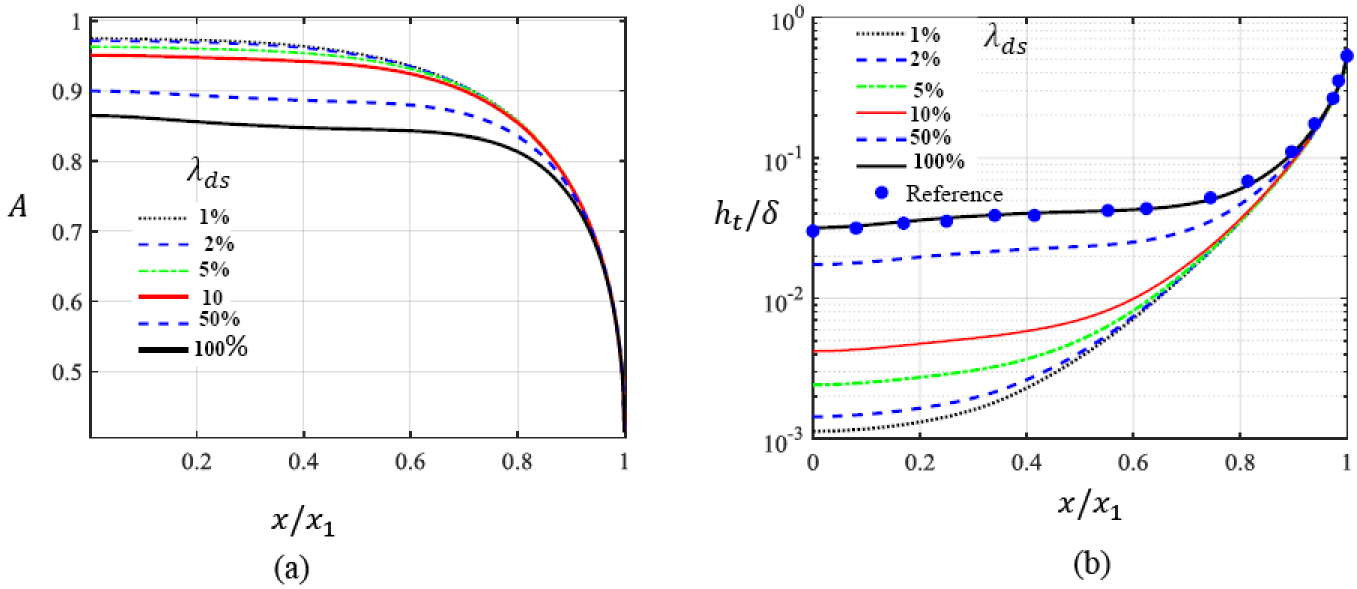

Fig. 6: (a) contact ratio of asperities and (b) non-dimensional film thickness of lubricant in the work zone

In this figure the asperity contact ratio is shown for different emulsion concentrations. It is seen that the contact ratio decreases as the percentage of oil in the lubricant increases. This is due to the higher viscosity of oil compared to water which means that when the oil content increases, the lubricant's viscosity become higher and the film thickness between the roll and strip increases as shown by Fig.6. a. The final result of this change of concentration is separation of roll and strip and reduction in contact ratio (Fig.6 b).

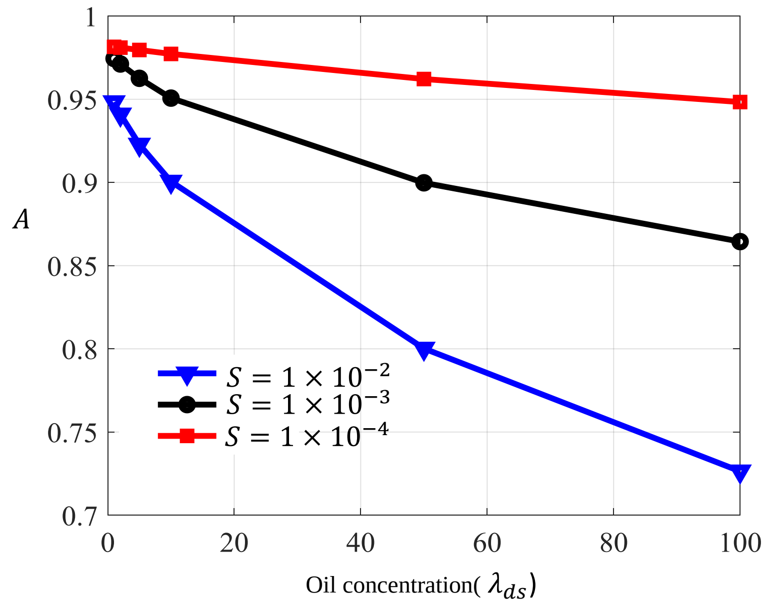

Fig. 7: Comparison between contact ratio of asperities in different oil concentration (λ_{ds}) of emulsion for three rolling speed S.

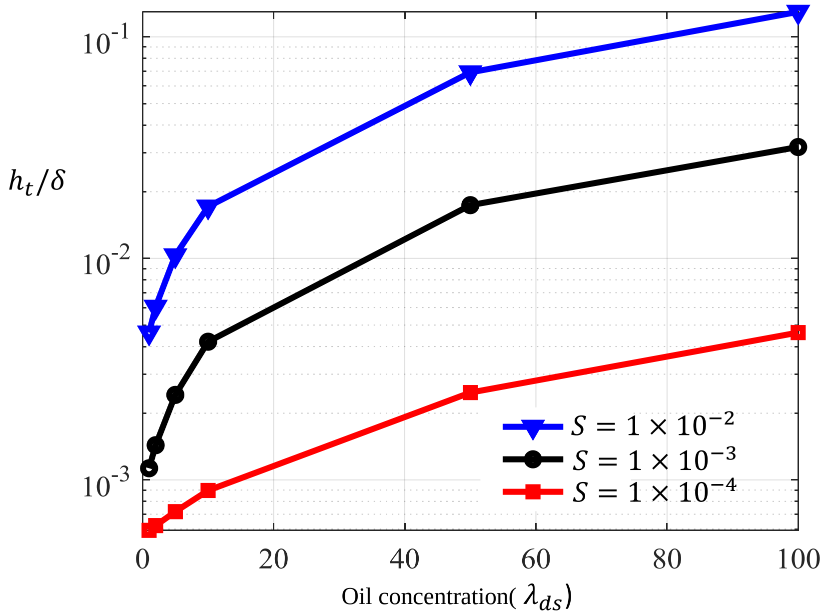

Fig. 8: Comparison between contact ratio of asperities in different oil concentrations (λ_{ds}) of emulsion for three non-dimensional rolling speed S.

In Fig.7, the value of contact ratio is plotted in different oil concentrations for three cases of rolling speed. The figure shows that oil concentration has more prominent role when the speed is higher. In low speed, concentration of emulation has lower effect on the contact ratio and film thickness compared to higher speed (Fig. 8).

5. CONCLUSION

A model is presented for cold strip rolling with O/W emulsion to find surface quality of product in terms of asperity contact ratio. The numerical procedure shows the importance of oil concentration in high-speed compared with low-speed rolling. The oil concentration increases the film thickness and reduces the contact ratio which leads to rougher surface because of the fact that asperities are affected less.

NOMENCLATURE

x	coordinate along the rolling direction
x_1	Roll contact length
x	coordinate of inlet zone entry plain.
x_b	coordinate of asperity contact
x_a	coordinate of inlet zone
ϕ_x	flow factor in x direction
h	surface separation
h_t	average film thickness
ξ	equivalent viscosity
p	interface pressure
p_f	(Non-dimensional) film pressure
y, y_1, y_2	inlet, Exit and local strip thickness
s_1	backward tension
s_2	forward tension
λ_{ds}	Supply Oil concentration
u_w	work-piece inlet speed
u_r	roll speed
S	non-dimensional roll speed
σ_y	yield stress
τ	Shear stress
q_a	friction force at contact area
q_f	friction force at film valley
c	adhesion coefficient
R	roll radius
E_s	non-dimensional strain rate
a	
L	asperity half-pitch
θ_a	asperity slope
η_d	(dynamic) viscosity of disperse phase
η_c	(dynamic) viscosity of continuous phase
A	Ratio of contact area
η_0	oil viscosity at ambient temperature.
δ	Equivalent RMS roughness of surface
λ_c	Water concentration
λ_d	Oil concentration
α	viscosity pressure coefficient

$$S = \frac{r\alpha\eta_0(u_r + u_{w1})}{\sigma_0 R_q x_1}$$

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