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A Comparison between Full-Film and Mixed-Film Lubrication of Cold Strip Rolling

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Abstract

Nearly most of industries use a product of metal forming processes. The cold rolling is a major metal forming procedures used to make sheets of steel, aluminum and other ductile metals. The rolling is always lubricated with a kind of lubricant and the product quality, energy consumption and production speed is largely affected by the type of lubricant and most importantly the regime of lubrication. Since mass production is always important for cold rolling, speed of rolls and strips has to be high enough and the roll forces are considerably large values, therefore, the regime of lubrication might change between full-film and mixed-film type. In the present study, a comparison between these two kind of lubrication is presented for rolling of strips.

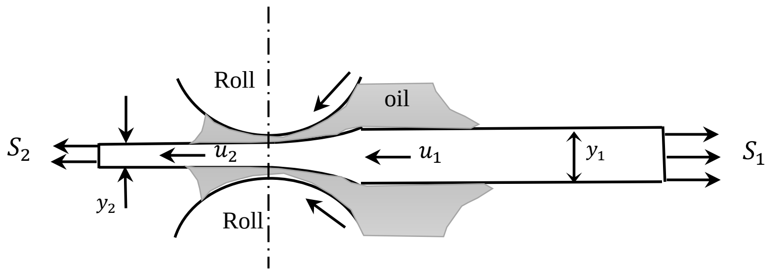
1. INTRODUCTION

Efficiency of the production is one of main concerns in almost all the industries. This means that knowing the real energy consumption is important to design and build the production facilities. One of the major industrial productions used are the strips and sheets of metals. The manufacturing processes of sheets and strip production lines involves the cold rolling. Cold rolling is the last part of the metal forming procedure of the sheets and a considerable amount of energy is consumed for this mechanical process. For many reasons, cold rolling is lubricated with oil. Lubrication of cold rolling helps the product to have better surface quality and reduce the energy consumption of production line sine friction is reduced. In general, there are different lubrication regimes which makes the mechanism of friction vary between these regimes[1-10] .When the speed of sliding surfaces is relatively high, a thick layer of lubricant is formed between the surfaces and the work piece and they get separated from the rolls. This regime is named full-film lubrication [3, 4]. As the speed of sliding surfaces decrease, the thickness of lubricant between the surfaces diminishes and friction become larger [5-8]. If the speed become less than a particular amount, the lubricant film is not consistently separating the two sliding surfaces which means that the asperities of metals get into contact. This regime of lubrication is called mixed-film lubrication [9-12]. For the full-film regime, all the shear stress on the strips is applied through the lubricant but in mixed-film regime, a part of the shear stress is applied by the asperities of the two surfaces. This means that friction is more in the mixed-film regime and consequently the energy consumption is larger in this regard.

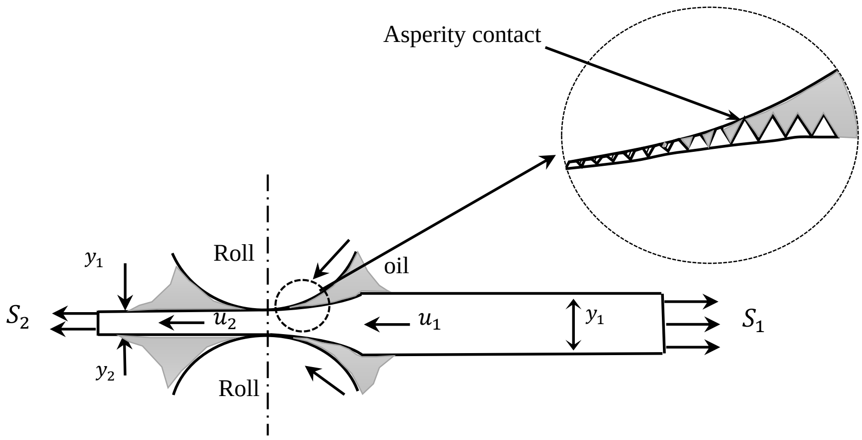
The difference of the two type of lubrication is a decisive factor in many applications and studying the differences helps to better understand the problem of cold rolling.

In Fig.1. (a) the schematic of cold strip rolling is shown for the full-fil regime. As it is illustrated, there is a thick layer of oil between the surfaces. This layer is responsible for separation of rolls and strip. The strip is subjected to front and back tensions shown by S_2 and S_1 respectively. The strip goes under the rolls with speed u_1 and thickness y_1. After undergoing a plastic deformation, the strip becomes thinner and goes out of space between rolls with thickness y_2 and speed u_2. In all of this process, the strip is surrounded by a layer of oil. The oil is drawn into gap between strip and roll and experience a high pressure. This pressure is reason for deformation and thickness reduction.

The same plate of Fig.1.a is shown for mixed-film lubrication in Fig.1.b when asperities engage in contact. In order to show the contact clearer, just the saw-tooth asperity of strip is shown in this figure. This from the onset of contact between asperities, the lubrication regime changes and deformation of surface profile takes place. This deformation causes the change in roughness of strip surface because of asperity flattening. In this connection, the shear force on the strip is comprised of two components, the direct contact of asperities and the shear stress which is due to viscosity of the oil packets in the valleys of the surface geometry.



(a)



(b)

Figure .1. (a) strip rolling in full-film regime and (b) mixed-film lubrication

Mixed lubrication has been subject of study for many years. Many application including gears[12], metal forming involves mixed lubrication. Sargent and Tsao [13] were among the first who tried to model cold rolling in mixed film regime. Their model did not consider the effect of plasticity on the surface roughness. This deficiency was solved by Sheu *et al.* [14]and Sutcliffe and Johnson [15]. Recently Hajshirmohammadi *et al.* [16] studied effect of inter-stand tensions in rolling with O/W emulsion.

In recent years, new methods of heating of strips have emerged including heated microchannel and heated pores media [17] .

2. MODEL DESCRIPTION

2.1. Plasticity of the strip

The plastic deformation of the strip happens in the work zone between the rolls. To find the pressure needed to deform the strip, an element of the strip is considered which is shown in Fig.2

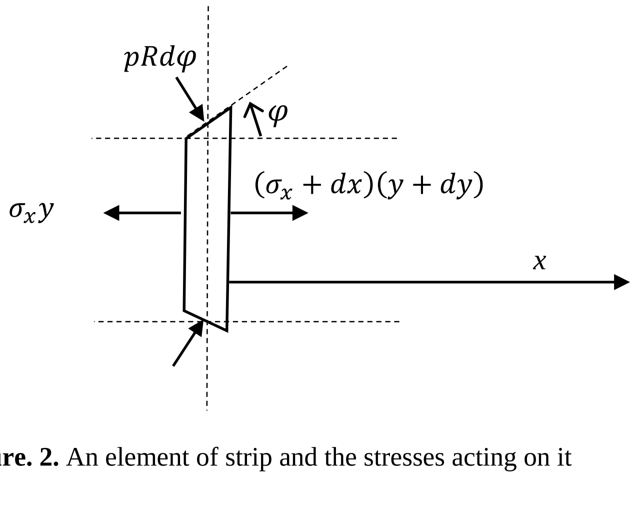


Figure. 2. An element of strip and the stresses acting on it

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The element of strip is subjected to forces in horizontal direction and the pressure which is applied from roll-strip interface. Since the width of strip is large compared to the thickness reduction, plane strain condition is dominant for this process. The equilibrium of forces in x direction is shown by Eq.1

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

in which p is pressure on the strip, τ is shear stress, σ_x is the stress in x direction and y is the strip thickness. Roll radius is shown by R. Eq.1 can be simplified to Eq.2

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

For the vertical direction, the force equilibrium is:

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

where σ_z is the vertical stress, since, $Rd\varphi\cos\varphi = dx$, Eq. 3 will be:

$$p + \tau\tan\varphi = -\sigma_z \quad (4)$$

Because the angle φ is small in rolling application, $\tan\varphi \cong 0$ and $p = -\sigma_z$

The von Mises criteria gives a condition for yield stress of strip

$$\sigma_x - \sigma_z = \sigma_k \quad (5)$$

in which σ_k is the plain strain yield stress of strip material. If σ_z is replaced with $-p$ in Eq. 5, plastic behavior of strip is found by Eq. 6

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

2.2. Shear stress

In the case of full-film regime, all the shear force between strip and rolls is transferred by lubricant. According to relation for Newtonian fluids, the shear stress in the oil is given by the following relation.

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

u_r in this equation is the roll linear speed and u stands for strip speed. This should be mentioned that roll speed is constant but strip speed changes during the stage of plastic deformation. This means that τ in Eq. 7 changes sign when it is considered in all the plastic zone in which strip become deformed. There is always a point in which roll circumferential speed u_r and strip speed u are equal which is called neutral point. The location of this point depends on lubricant and rolling parameters including the normal forces applied on the strip from back and front. The flow rule for plastic deformation is used to find speed of work piece in the work zone.

$$u_w y = u_{w1} y_1 = u_{w2} y_2 \quad (8)$$

y_1 and y_2 are the thickness of strip in the inlet and outlet of work zone. u_1 and u_2 denote the strip speed in inlet and outlet of work zone respectively.

As it was mentioned in last part, the shear stress in mixed regime is combination of asperity contact and fluid shear stress. The lubricant part of shear is the same as the full-film case.

$$q_f = \frac{\eta(u_w - u_r)}{h_t} \quad (9)$$

where h_t represents the average film thickness. The asperity contact part of the shear force is:

$$q_a = \frac{c}{2}\sigma_y sign(u_w - u_r) \quad (10)$$

in which c is the adhesion coefficient between roll and work piece and $sign$ is the sign function.

The total shear stress is found by:

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

A in Eq. 11 is the contact ratio of asperities (Fig. 3).

$$A = \frac{a}{L} \quad (12)$$

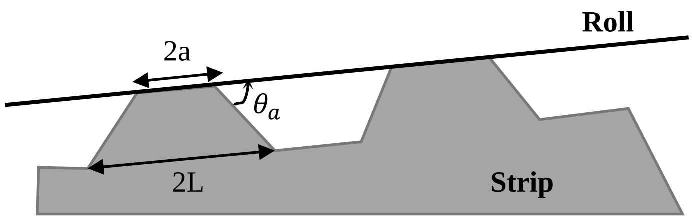


Figure 3. Schematic of asperity in contact with roll

2.3. Reynolds equation

In mixed film regime, shear stress is found by solving the Reynold equation for mixed film lubrication. Eq. 13 shows this relation.

$$\frac{d}{dx}\left(\frac{\phi_x h_t^3}{\eta}\frac{dp_f}{dx}\right) = -\frac{d}{dx}\left((u_w + u_r)h_t\right) \quad (13)$$

In which ϕ_x is the flow factor in x direction.

2.4. Asperity flattening

Due to plastic deformation of the asperities, the contact ratio, A, changes during rolling. This effect has crucial role in the shear stress applied on the strip since the direct contact part of shear force increases. Asperity flattening relation proposed by Chang and Wilson [17]. Defines this change.

$$\frac{dA}{dx} = \frac{x}{La\theta_a\left(1 - A + \frac{yE_s}{2L}\right)} \tag{14}$$

in which,

$$E_s = \frac{2A - (p - p_f)}{(p - p_f)f_1} \tag{15}$$

$$f_1 = -0.86A^2 + 0.345A + 0.515 \tag{16}$$

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

p_f is the oil pressure.

2.5. Boundary condition

If the elastic deformation of the strip is neglected in the inlet and outlet, the stress condition has to satisfy the von Mises criteria there. In the inlet $x = x_1$, (x_1 is the length of work zone) the total stress applied on the strip is combination of pressure from the roll and the backward tension and in the outlet, $x = 0$, the same situation happens except for the tension which is forward tension. These two boundary conditions are shown in Eq.17 and Eq.18.

$$x = x_1 \qquad p = \sigma_y - s_1 \tag{17}$$

$$x = 0 \qquad p = \sigma_y - s_2 \tag{18}$$

The oil pressure increases rapidly once it enters the work zone. This abrupt change starts from zero value of oil pressure.

$$x = x_1 \qquad p_f = 0 \tag{19}$$

The strain rate has to be consistent in the *x=0*. Since before this point, there is not deformation, the strain rate is zero. That means:

$$x = 0 \qquad E_s = \frac{2A - (p - p_f)f_2}{(p - p_f)f_1} = 0 \quad p_f = p - \frac{A}{f_2} \tag{20}$$

2.6. Viscosity-pressure relation

The pressure of oil increases dramatically in the work zone because of the need for high force to deform the plates. This rapid increase changes the viscosity of oil in a sense that shear stress of oil is noticeably affected. There are several relations in this regard. One of the simplest models is given by Barus equation which considers an exponential function for oil viscosity in respect with pressure. This relation is given by Eq. 21.

$$\eta = \eta_0 e^{\alpha p} \tag{21}$$

α is the pressure coefficient and η_0 stands for oil viscosity in ambient condition.

Another relation which is more reliable in high pressures is the Roeland equation given by Eq. 22

$$\eta(p, T) = \eta_0 \exp\left((\ln(\eta_0) + 9.67)\left\{\left(1 + \frac{p}{p_r}\right)^z - 1\right\}\right) \tag{22}$$

where p_r is a constant of 1.963×10^8 value and z is viscosity-pressure power which is related to η_0 and α shown by Eq.23.

$$\alpha = z\left[\frac{1}{p_r}(\ln\eta_0 + 9.67)\right] \tag{23}$$

2.7. Roll flattening effect

As it was mentioned, the pressure in the plastic work zone gets high that the deformation of rolls is not negligible anymore. This effect has to be taken into account to accurately calculate force and torque the rolls stand. Hitchcock relation is widely used in this regard.

$$R' = R\left(1 + 2\sqrt{\frac{f}{Ery_1}} + 2\frac{f}{Ery_1}\right) \tag{24}$$

Where the rolling force per unite width is shown by f , r is reduction of thickness, and E is the modulus of elasticity of the work roll.

3. NUMERICAL PROCEDURE

Numerical solution for full-film and mixed-film regime is shown in Fig. 5. Solution starts with assuming the radius of un-deformed roll. Finding inlet speed of strip is carried out in an iterative approach. During which, lubricant pressure and total pressure (for mixed regime) is determined.

Eq. 6 is a one-dimensional differential equation that can be solved by Rung-Kutta method. In each iteration, the pressure is evaluated in the inlet by Eq. 17. For the mixed-film regime, the asperity flattening relation (Eq. 14) is solved simultaneously with the Reynolds equation in a system of differential equations. At the final step, deformed roll radius is calculated using Eq. 24. If the difference between the assumed radius and the deformed radius is smaller than error, *e*, the program is executed and other parameters (rolling torque, rolling force) are found by integrating the total pressure in the work zone.

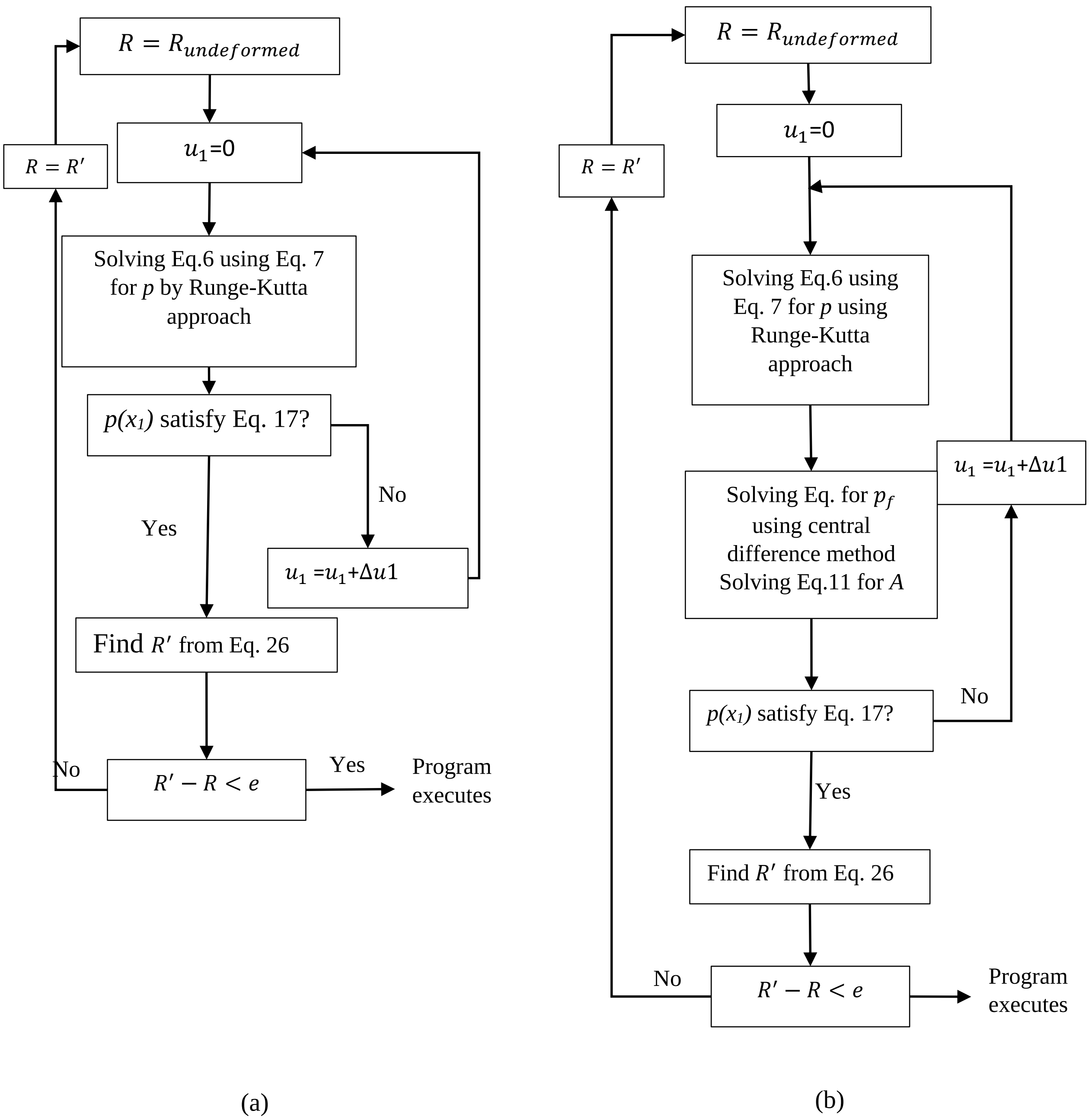


Figure 5. Numerical procedure flow chart for (a) full-film regime and (b) mixed-film regime.

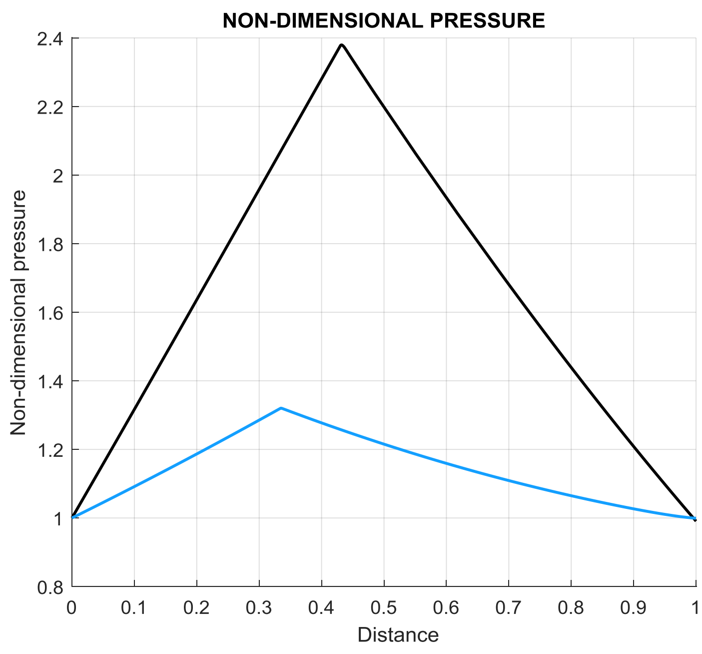
4. RESULTS AND DISCUSSION

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

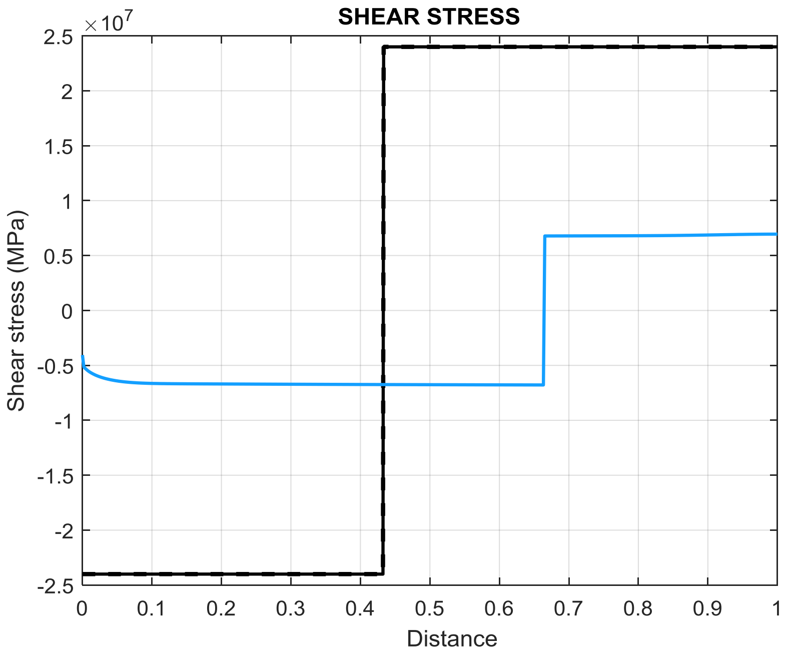
It is seen from Fig.6.a that pressure is considerably higher when the mixed-film case is investigated. This is understandable because the pressure needed when asperity tips are engaged is much higher compared to full-film case.

Table 1. Rolling parameters used for simulation of cold rolling

Parameter	η_0 **(mm)**	θ_a	**L(μm)**	α**(1/Pa)**	R**(mm)**	σ_y**(MPa)**	c	y_1**(mm)**	y_2**(mm)**
Value	0.02	0.2	35	6.2e-8	0.2	97.75	0.2	1	0.8



(a)



(b)

Figure 6. Comparison between the full-film and mixed-film lubrication for (a) pressure and (b) shear stress

Fig.6.b shows the shear stress on the strip-roll interface. This figure illustrates the lower shear stress for the full-film regime. In addition, the neutral point shifts toward the inlet for full-film lubrication.

Nomenclature

x	coordinate along the rolling direction
x_1	Roll contact length
u_{w1}	Strip speed in the inlet
u_w	work-piece inlet speed
u_r	roll speed
y_1	Strip thickness in the inlet
x	coordinate of inlet zone entry plain.
ϕ_x	flow factor in x direction
h	surface separation
h_t	average film thickness
α	viscosity pressure coefficient
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
S	non-dimensional roll speed $S = \frac{r\alpha\eta_0(u_r + u_{w1})}{\sigma_0 R_q x_1}$
σ_y	yield stress
τ	Shear stress
u_{w2}	Strip speed in the outlet
y_2	Strip thickness in the outlet
q_a	friction force at contact area
q_f	friction force at film valley
c	adhesion coefficient
R	roll radius
R'	Deformed roll radius
E_s	non-dimensional strain rate
a	
L	asperity half-pitch
θ_a	asperity slope
η	(dynamic) viscosity of oil
δ	Equivalent RMS roughness of surface
A	Ratio of contact area
η_0	oil viscosity at ambient temperature.
E	Elastic modulus

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