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MODELLING AND CHARACTERISATION OF COLD ROLLING FRICTION

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1 Abstract

In the process of cold rolling, friction is essential. Low enough to ensure strip flatness, limit tool wear, and roll load as torque increases, while high enough to prevent sliding and poor surface quality caused by the roughening phenomenon. Practically all industrial rolling mills run on a mixed lubrication regime, which is about to fulfill all of these criteria.

A friction model based on external variables such as the total interface pressure, but also internal variables such as the local lubricant film thickness or the real area of contact was introduced in a two-dimensional elastoplastic code for cold strip rolling. The model named LAM2DTRIBO was developed by Nicolas MARSAULT as his Doctoral thesis in 1998.

The work presented in this thesis provides an understanding of the LAM2DTRIBO model and its code. The results obtained by Marsault in his thesis are reproduced with the help of an automatization code and the results obtained are criticized. The LAM2DTRIBO model is also validated by experimental results obtained from a production mill and the sensitivity of certain parameters is studied.

Keywords : Friction,Cold rolling,Mixed Lubrication,Reynolds equation,Parametrisation, Validation,Sensitivity

2 Acknowledgements

I am delighted to present my thesis report on **"Modelling and Characterisation of Cold friction rolling"**. I would like to express my gratitude to my mentors Alexandre Barthelemy and Ariane Viat for providing me an opportunity to work on this project in a prestigious organization such as C-TEC. It was a great pleasure to work with both of them and I am much obliged for all the expert knowledge, I could learn from them. I would also like to thank them for their consistent guidance and support throughout my internship.

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3 Definition of Terms in the friction model

x - Rolling Direction
y - Perpendicular Rolling Direction
z - Transverse Rolling Direction
p - Total Pressure at the Interface
p_b - Lubricant Pressure
p_a - Asperities Pressure
τ - Total Shear Stress at the Interface
R_q - RMS Roughness of Surfaces
η - Lubricant Viscosity
γ_s - Peklenik Number
A - Real Area of Contact
E_p - Plastic Deformation Rate
E_r - Young's Modulus of the Cylinder
υ_r - Poisson's Coefficient of the Cylinder
E_s - Young's Modulus of the Strip
υ_s - Poisson's Coefficient of the Strip
R_0 - Cylinder Radius
u_r - Cylinder Rolling Speed
r - Reduction Ratio
t_1 - Inlet Strip Thickness of the Strip
t_2 - Outlet Strip Thickness of the Strip
σ_1 - Back tension
σ_2 - Front tension
c_{geom} - Distance between cylinder axes
v_x - Speed of the strip in x-direction
v_1 - Entry speed of the strip
v_2 - Exit speed of the strip

4 Introduction

Production of harder, thinner sheet products at smaller costs is in huge demand nowadays. Also, Weight reduction has become more and more important in recent years. Increased hardness of the strip usually leads to the reduced thickness of the strip. This implies less material usage and less weight as well. Due to these consequences, New challenges arise in the production of strips and more specifically in Cold rolling.

Cold rolling takes place in tandem mills that consist of successive mill stands. The strip is pushed by the friction created by the work rolls in each stand, which gradually reduces its thickness. The cold rolling process is strongly dependent on friction. If the friction forces are greater, they unnecessarily increase the rolling force. Also, the consumption of energy and the wear of the work rolls is increased. But, the rolling force is limited by the mill stand. So, controlling friction in the roll bite is of crucial importance today.

LAM2DTRIBO is a friction model developed by Marsault during his doctoral thesis in 1998. The model was written in Fortran77.This model has not been industrially implemented due to the lack of physical phenomena considered in the code especially the thermal and chemical effects.This rather old model needs to be computed again,described,checked,which consists in the objectives of this study.This will enable further developments based on this initial code. The outline of the thesis is as follows. A brief introduction of the C-TEC is provided. Then, the introduction of Aluminium and its making process is described.

Then, The LAM2DTRIBO model is described. In particular rolling process, the mechanics of the strip, Spatial integration of the roll bite, and its algorithm are explained. The correlation between the theory of the model and its code is elaborated.

Next, The reference case from the Marsault thesis was considered and the influence of key parameters in rolling : Rolling speed, Young modulus of the strip, Roll radius of the cylinder, the composite roughness on friction coefficient, forward slip, film thickness, the real contact area . A parametrization code was developed in python to automate the process. The working of this code is elaborated.Flowcharts of the algorithm are presented.

Next, The model is computed with data from a production mill. The model was validated with respect to the experimental results. Then, the effect of parameters such as lubricant viscosity, Asperity half pitch, Composite Roughness, and surface peklenik number and its sensitivity on friction coefficient is studied.

5 About Constellium Technology Center (C-TEC)

5.1 Presentation of C-TEC

C-TEC is Constellium's Technology Center, a leader in research and technology for aluminum products and related solutions. It is Constellium's engine of innovation and the catalyst for profitable growth. C-TEC has a global reach, being operated by professionals from over 22 countries and connected to all constellium businesses and sites worldwide, as well as to a network of renowned academics. They have over 190 patent families and trademarks. C-TEC,Voreppe has 21 patents filed in 2017.

Constellium provides half-finished products(coils,plates,billets) made of both proprietary and standard aluminium alloys.Constellium's customers further transform the metal into pieces of aerospace,automotive,and packaging applications.C-TEC is at the heart of Constellium's innovation process, a global sector leader for a broad scope of markets and applications, focusing in particular on automotive, aerospace, and packaging. The R&D application field of C-TEC are :

- Traditional core competences (Alloys development,Casting process development,Rolling and extrusion process improvements)
- Emerging new competences (Digital industry development, Aluminium powders and recycling technologies)
- Maintaining technology networks, shared processes (recycling, casting, fabricating), to ensure best-practice sharing and excellent knowledge and talent management.

Figure 1: C-TEC Voreppe

5.2 Constellium Markets

- Constellium are a global leader in **Aerospace** plates,Aluminum flat rolled products,extrusion and fueslage sheets.
- Constellium's plates, sheets, extrusion, and precision sand casting aerospace products are used for a wide range of applications such as bulkheads, fuselage shells, wing skins, stringers, door frames, or engine gearboxes.
- Constellium is the global leader in **Automotive** field in Crash Management Systems (CMS) and they hold a leading position in Europe for Auto Body Sheet.
- Automakers turn to Constellium for a wide range of applications, including car body closures, Crash Management Systems, Body-in-White structural components, battery enclosures, chassis and mechanical parts, heat exchangers, and functional surfaces for interior and exterior design
- Constellium are a global leader in **Packaging** field in closure stock and they hold a leading position in Europe and North America for can body stock.
- Research activities include: the development of thinner sheets to lightweight can body/end stocks, Drawn and Wall Ironed (DWI) aerosols adaptation of an existing alloy to the specific needs of the new aluminum bottle.
- Reducing global carbon footprint remains a key target in this market as in others. They are developing sorting and recycling technologies to expand our end-of-life scrap sourcing.
- Constellium is exploring opportunities for tomorrow's production using Digital Manufacturing ("Industry 4.0").
- The key concept behind Industry 4.0 is the combined impact of multiple digital technologies to help further progress in aluminum production.The used technologies can be smartphone/tablet technology, the Industrial Internet of Things, cloud computing, Big Data and analytics, manufacturing simulation (with Digital Twin systems for example), augmented reality, and autonomous/collaborative robots.

(a) Aerospace

(b) Automotive

Figure 2: Constellium Markets

6 Aluminium

- **Aluminium (Al)**, a lightweight silvery white metal of main Group 13 (IIIa, or boron group) of the periodic table.
- Aluminum is the most abundant metallic element in Earth's crust and the most widely used nonferrous metal.
- Aluminum never occurs in the metallic form in nature because of its chemical activity, but its compounds are present to a greater or lesser extent in almost all rocks, vegetation, and animals.
- Aluminium is the second most used metal,both in tonnage and value.
- Aluminium is the second most malleable metal and sixth most ductile, it can be easily machined or cast.
- Aluminium is one of the lightest metals in the world: it's almost three times lighter than iron but it's also very strong, extremely flexible and corrosion resistant because its surface is passivated through an extremely thin and yet very strong layer of oxide film.
- The density of aluminum is three times lower than that of steel or copper. It doesn't magnetise, it's a great electricity conductor and forms alloys with practically all other metals.
- Aluminium can be easily processed using pressure both when it's hot and when it's cold. It can be rolled, pulled and stamped.
- Aluminium doesn't catch fire, it doesn't need special paint and unlike plastics it's not toxic. It's also very pliable so sheets just 4 microns thick can be made from it, as well as extra thin wire. The extra-thin foil that can be made from aluminium is three times thinner than a human hair.
- Aluminium is more cost effective than other metals and materials.The modern construction, automotive, aviation, energy, food and other industries would be impossible without aluminium.
- Aluminium has become a symbol of progress: all cutting edge devices and vehicles are made from it.

7 Aluminium making process

Constellium does not process Aluminium from its ore but purchases pure Aluminium and alloying elements which are already processed. The process from aluminium-containing ores to pure metallic aluminium is summed up in this section.

7.1 Aluminium Extraction

Bauxite is a sedimentary rock with a relatively high aluminium content. It is the world's main source of aluminium and gallium. It is used today as the primary raw material in aluminium production. It consists of Titanium oxide, Silicium, Water Iron oxide, and Alumina. The ore is crushed and then attacked with hot caustic soda, it is a bayer process allowing to generate alumina.Pure alumina is solved in a liquid cryolite bath (Na3AlFe6) at 950C (1740F) and then electrolyzed in reduced plants. The liquid aluminium is extracted at bottom of the tanks.

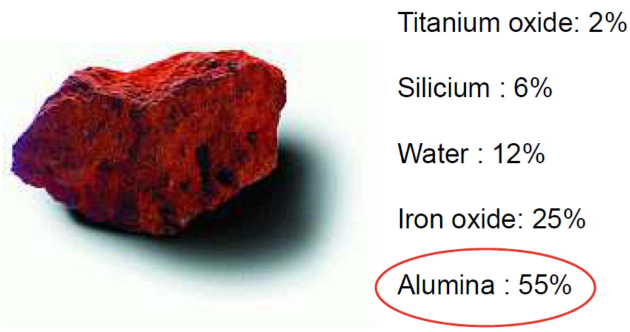


Figure 3: Bauxite ore and its composition

Pure aluminium is so soft that it cannot be used in hard industrial applications. So, Additional elements are added to it to obtain the required industrial aluminium properties, leading to several aluminium alloys. The properties are Mechanical resistance, corrosion resistance, welding ability, machining ability, forming ability, surface aspect, and lightness. The below table represents the effect of different elements on aluminium properties.

	Mechanical characteristics	Corrosion resistance	Electrical conductivity	Weldability	Machinability	Formability	Surface treatment ability
Cu (Copper)	↗↗	↘		↘5%↗	↗	↘	↘
Mn (Manganese)	↗	↗	↘↘	↗		↗	↘
Si (Silicon)	↗	↔	↘	↔	↘	↘	↘
Mg (Magnésium)	↗	↗		3%↗		↘	↗
Zn (Zinc)	↗↗	↔	↔			↘	↔

Figure 4: Aluminium alloys and their key features

7.2 Aluminium Sheets

The liquid aluminium is solidified as slabs. The slab which is several centimeters thick is transformed into millimeter-thick strips, by the rolling process.

7.3 Hot Rolling

Hot rolling is a process in which the metal is passed between the rollers above the re-crystallization temperature to plastically deform it. They are hot rolled at 300-550C, the high temperature reduces the material resistance. The process is occurred through reversing mills, and then tandem mills. The stages of the process are described as follows,

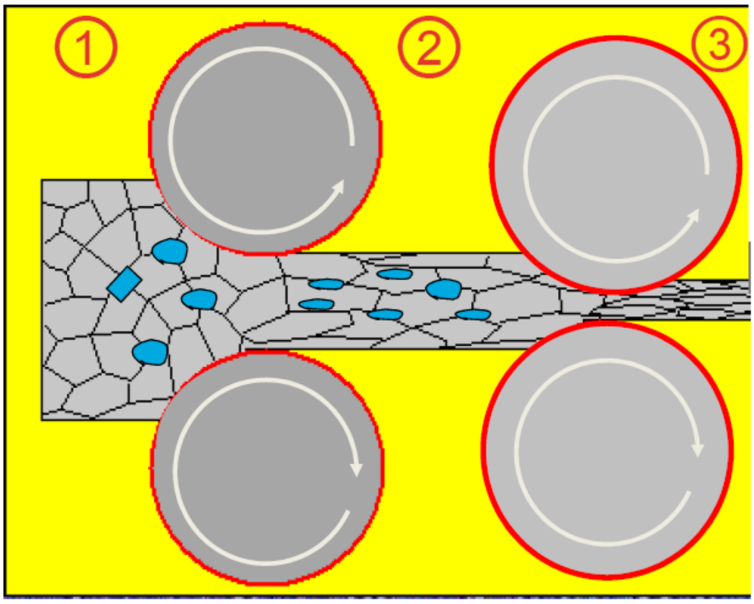


Figure 5: Stages in Hot Rolling

- At 1,The big grains structure which is coming from casting
- At 2,After the material is passed through the first set of rolls,the grains become longer.
- At 3,After the second pass,the grains become longer and longer leading to a fibered structure.

The strips are transported easily from one operation to the next by rolling them to coils.

8 Cold Rolling

Cold rolling is defined as the process in which the metal is passed between the rollers below the re-crystallization temperature to enhance its mechanical properties. Cold rolling as the name defines occurs at a relatively low temperature of about 100 C compared to hot rolling. The main advantages of rolling at low temperatures are:

- The possibility to satisfy stricter geometrical tolerances due to less significant thermal expansion of the work piece and the rolls.
- Better surface quality due to less oxidation.
- Lower temperatures prevent re-crystallisation.

8.1 Concept of Rolling

Rolling is the reduction of the strip thickness from an initial thickness t_{in} to a final thickness t_{out} when the strip moves in between the work rolls. By conservation of mass,the inlet strip v_{in} is

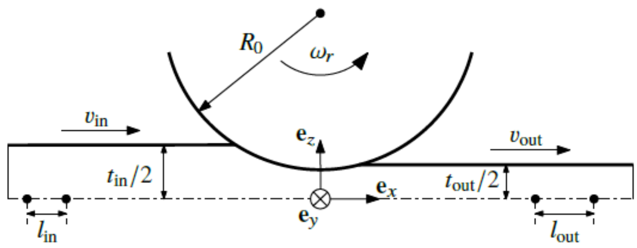


Figure 6: Schematic diagram of Rolling [2]

related to the outlet strip speed v_{out} as follows,

$$v_{in}t_{in} = v_{out}t_{out} \tag{1}$$

Due to the reduction,the velocity of the strip at outlet is greater than the velocity of the strip at inlet $v_{out} > v_{in}$.

8.1.1 Roll Bite

The zone of contact between the strip and the roll is called roll bite.The contact length of the roll bite is approximated as,

$$l_{rb} \approx \sqrt{R_0(t_{in} - t_{out})} \tag{2}$$

8.1.2 Forward Slip

The forward slip is defined as the relative speed of the strip at the exit of the roll bite with respect to the rolling speed.The forward slip is defined as:

$$s_f = \frac{v_{out} - v_r}{v_r} \tag{3}$$

8.1.3 Reduction Ratio

The reduction ratio r is defined as:

$$r = \frac{t_{in} - t_{out}}{t_{in}} \tag{4}$$

8.1.4 Elongation

As seen from the above figure...,The length of the strip is increased from l_{in} to l_{out}.The elongation e_x is defined as:

$$e_x = \frac{l_{out} - l_{in}}{l_{in}}$$

8.2 Need for friction control

Friction is essential in the cold rolling operation. It should be high enough to avoid skidding and poor surface finish due to roughing phenomena and also low enough to ensure strip flatness and limit tool wear.

There is a huge demand for harder and thinner sheet products by manufacturers. This implies a greater rolling force. But, there is a technological constraint which is that the rolling force is limited by the mill stand.

If friction was minimized while preventing skidding for the given mill stand,

- Harder and thinner products could be rolled.
- Energy consumption of rolling could be decreased.
- Roll wear could be reduced.

8.3 Lubrication Regimes

Friction is controlled through the presence of the lubricating film in the roll bite. The lubricant is made of base oil plus additives. Depending on the oil film thickness between the roll and the strip, the lubrication can be of 3 different types.

8.3.1 Hydrodynamic Lubrication Regime

In the hydrodynamic lubrication regime, there is no contact between the solid interfaces, the roll, and the strip. In this regime, the lubricant film thickness is significantly greater than the amplitude of roughness. So, the load is entirely supported by the lubricant film.From the figure below it can be observed that the friction coefficient is increasing as the the speed is increasing this is due to the increasing viscous friction forces.

8.3.2 Boundary Lubrication Regime

In the boundary lubrication regime, there is contact between the solid surfaces, that is the roll and the strip without the lubricant acting as a pressure cushion. In this regime, the load is carried by the contacting asperities.The film thickness of the lubricant in regime is close to zero $(h_t \approx 0)$.

8.3.3 Mixed Lubrication Regime

This regime is a trade-off between the hydrodynamic and the boundary regimes. The forces between the surfaces are transmitted partially by the contact between their asperities and partially by the lubricant.The film thickness of the lubricant in the regime is approximately close to composite roughness $(h_t \approx R_q)$.

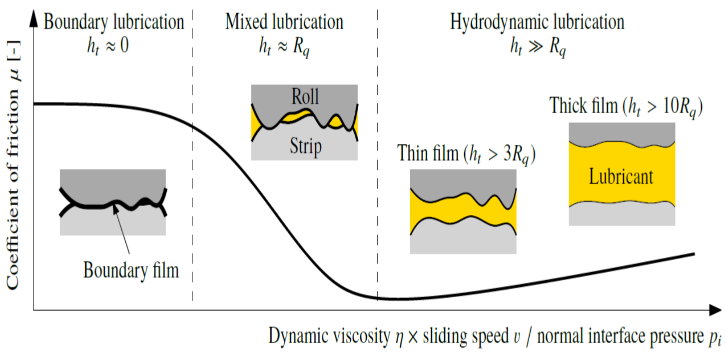


Figure 7: Stribeck Curve with different lubrication regimes,in which the coefficient of friction changes due to different dominant lubrication mechanisms [2]

9 LAM2DTRIBO

LAM2DTRIBO is a second-generation cold rolling model, which includes elastoplastic strip deformations, elastic roll deformations by the finite element, lubricant flow, and asperity flattening. In second-generation rolling models, mixed lubrication is introduced by combining the Reynolds equation with asperity flattening equations. It is a model developed by Nicolas Marsault during his Ph.D. thesis. It is written in Fortran77. The equations quoted or referred to in this section are from the Nicolas Marsault Thesis [1].

9.1 Rolling Process description

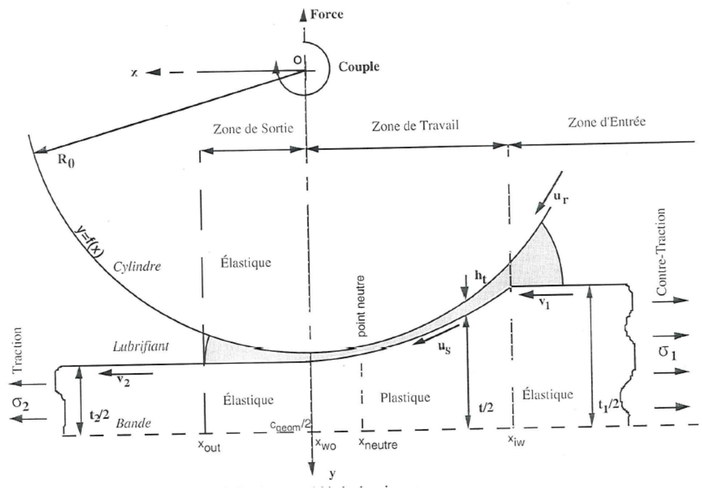


Figure 8: Roll Geometry [1]

In this section, a brief description of the rolling process is discussed. The system is modeled by considering only half as shown in the below figure. The strip enters the roll bite with an inlet strip thickness t_1 and an inlet velocity of v_1.The cylinder roll of radius R_0 is rotating with a velocity u_r.The strip exits the roll bite with an outlet strip thickness t_2 with a velocity v_2.The x_{neutre} is the neutral point, the point at which the rolling speed is equal to the strip speed $(u_s = u_r)$. The tension birdles apply the back tension σ_1 and front tension σ_2, which are assumed to be constant through the cross-section. The h_t represents the lubricant film thickness. The e_x is the rolling direction and e_y is the vertical axis. In the mixed lubrication regime, the forces from the rolls are carried to the strip partially by the direct contact between the solid asperities and partially by the lubricant.

$$F_i = F_a + F_l \tag{5}$$

where F_i is the total interface force,F_a is the force carried by the asperities and the F_l is the force carried by the lubricant.The relative contact area A is the ratio of the real contact area and the apparent contact area. The above equation in the pressure form which is known as the load sharing equation is written as follows,

$$p = Ap_a + (1 - A)p_b \tag{6}$$

where,p is the total interface pressure,p_a is the asperity pressure and the p_b is the lubricant pressure.

Similarly,in terms of shear stress is,

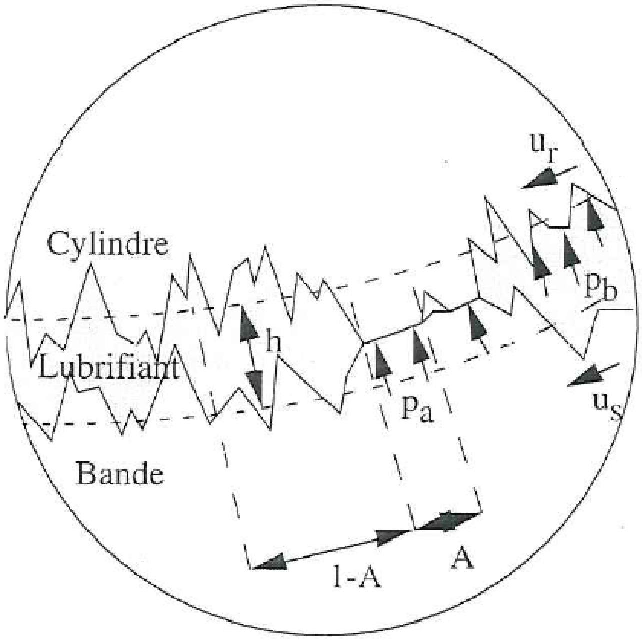


Figure 9: Strip and Roll interface in mixed regime [1]

$$\tau = A\tau_a + (1-A)\tau_b \tag{7}$$

where, τ is the total shear stress, τ_a is the asperity shear stress and the τ_b is the shear stress created by the viscosity of the lubricant.

9.2 Mechanics of the strip

In this section,the mechanics of the strip are discussed.

- First,the strains of the strip are derived as functions of kinematic variables.
- The strain obtained is used to compute the stresses in the strip by constitutive equations of the strip material.
- Then the stresses should satisfy the equilibrium equations derived by the slab method.

9.2.1 Strain Computation

The local deformations of the strip are quantified by its strain tensor ε.By plane-strain hypothesis, $\varepsilon_z = 0$.The evolution of these variables can be deduced from the evolution of the strip speed.The strain matrix is given by,

$$E^N = \begin{pmatrix} \varepsilon_x & 0 & 0 \\ 0 & \varepsilon_y & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

The stretch matrix U can be written as,

$$U = expE^N = \begin{pmatrix} e^{\varepsilon_x} & 0 & 0 \\ 0 & e^{\varepsilon_y} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

The deformation gradient is defined as $F = RU$.Then,$R = I$ because,no rotation of the strip material occurs in the model.Then,the velocity gradient can be computed as follows,

$$L = \dot{F}F^{-1} = \begin{pmatrix} \dot{\varepsilon}_x & 0 & 0 \\ 0 & \dot{\varepsilon}_y & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Thus,by definition of the velocity gradient,

$$\dot{\varepsilon}_x = \frac{\partial v_s}{\partial x}$$

The spatial evolution of the axial strain in the steady state is given by,

$$\frac{\partial \varepsilon_x}{\partial x} = \frac{1}{v_s}\frac{\partial v_s}{\partial x}$$

The evolution of the vertical strain is obtained as,

$$\frac{\partial \varepsilon_y}{\partial x} = \frac{1}{t}\frac{\partial t}{\partial x}$$

The generalised deformation is defined as,

$$\bar{\varepsilon} = \int \frac{\dot{\bar{\varepsilon}}}{v_x} dx \tag{8}$$

where,

$$\dot{\bar{\varepsilon}} = \sqrt{\frac{2}{3}(\dot{\varepsilon}_x^2 + \dot{\varepsilon}_y^2)} = \frac{2}{\sqrt{3}}|\dot{\varepsilon}_y = \frac{2}{\sqrt{3}} ln(\frac{t_{in}}{t})$$

9.2.2 Constitutive equations of the strip

The stress state depends only on the position of x in the roll bite along the rolling direction as symmetry is assumed along e_z and the small thickness of the strip. The stress state does not change along the vertical direction e_y and the transverse direction e_z.The internal stresses are neglected,i.e, all the elements of the Cauchy stress tensor are zero except for the diagonal terms which depend on x.

When the strip is passed through the rolls, it undergoes elastoplastic deformation at the entry and exit of the roll bite. Elastoplastic deformation occurs in between the entry and exit. The elastic and elastoplastic models are described below

Elastic Model

The elastic model at the entry and exit of the strip is described by Hooke's law. The strain and stress tensors are assumed to be diagonal due to symmetry and the small thickness of the strip with respect to the other dimensions.

The diagonal terms of the elastic deformation tensor ε^e are,

$$\varepsilon_i^e = \frac{1}{E_s}[\sigma_i - v_s(\sigma_j + \sigma_k)] \tag{9}$$

Due to the plane strain condition in the $e_x e_y-$plane,the above equation is simplified for $i = z$.Therefore,the elastic material equation of the strip can be written as follows:

$$\varepsilon_x = \frac{1}{E_s}[\sigma_x - v_s(\sigma_y + v_s(\sigma_x + \sigma_y))] \tag{10}$$

$$\varepsilon_y = \frac{1}{E_s}[\sigma_y - v_s(\sigma_x + v_s(\sigma_x + \sigma_y))] \tag{11}$$

Elastoplastic Model

The strip is assumed to be deformed elastoplastically in between the entry and exit elastic zones.This is described by the Prandtl-Reuss equations,

$$\dot{p}_{hydro} = -X trace(\dot{\varepsilon}) \tag{12}$$

$$\begin{bmatrix} \dot{s}_x \\ \dot{s}_y \\ \dot{s}_z \end{bmatrix} = 2\mu \left[1 - \frac{s \otimes s}{\frac{2}{3}\sigma_0^2(1 + \frac{H_s}{3\mu})} \right] : \begin{bmatrix} \dot{e}_x \\ \dot{e}_y \\ \dot{e}_z \end{bmatrix} \tag{13}$$

9.2.3 Equilibrium Equations

The stresses of the strip are determined by the strain computation and the constitutive equations. The equilibrium equation between these stresses and the applied surface tractions is computed by the slab method.

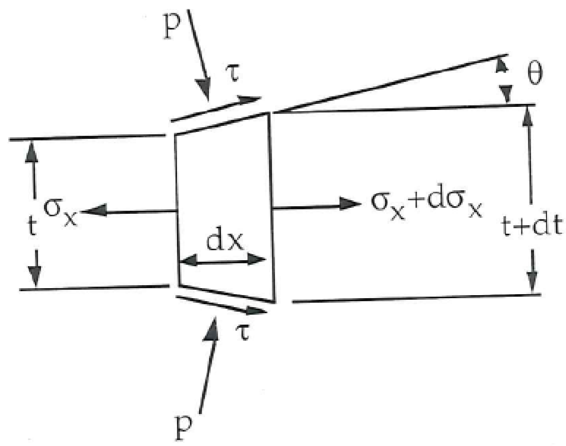


Figure 10: Forces applied for the equilibrium of a slice [1]

The equilibrium of the slice along the direction x is,

$$\frac{d(\sigma_x t)}{dx} = -p\frac{dt}{dx} - 2\tau \tag{14}$$

and along the direction y is,

$$\sigma_y = -p + \frac{1}{2}\tau\frac{dt}{dx} \tag{15}$$

where,τ is the total shear stress at the interface and p is the total pressure at the interface.

10 Spatial Integration of the roll bite

The roll bite is divided into the following zones based on the contact status between the roll and the strip,and the deformation mode of the strip as suggested by Marsault.The equations quoted or referred in this section is from the Nicloas Marsault Thesis [1].

- Zone 1 : Hydrodynamic Inlet Zone
- Zone 2 : Mixed Inlet Zone
- Zone 3 : Low-speed mixed work Zone
- Zone 3' : High-speed mixed work Zone
- Zone 4 : Low-speed mixed outlet Zone
- Zone 4' : High-speed mixed outlet Zone

10.1 Entry Zone

The entry zone is divided into two sub-zones,Hydrodynamic Inlet and Mixed Inlet zone.The strip is elastic in this zone.

10.1.1 Zone 1 : Hydrodynamic Inlet Zone

The hydrodynamic inlet zone starts at $x = -R_0$. the interface pressure is equal to the pressure of the lubricant, i.e.

$$p = p_b = -\sigma_y$$

Hooke's isotropic linear elastic law in plane strains is written as

$$\varepsilon_x = \frac{1}{E_s}\left((1-\nu_s^2)\sigma_x - \nu_x(1+\nu_s)\sigma_y\right)$$

$$\varepsilon_y = \frac{1}{E_s}\left(-\nu_s(1+\nu_s)\sigma_x + (1-\nu_s^2)\sigma_y\right)$$

We deduce from the above equations ,that

$$\frac{1}{t}\frac{dt}{dx} = -\frac{1}{E_s}\left[(1-\nu_s^2)\frac{dp_b}{dx} + \nu_s(1+\nu_s)\frac{d\sigma_x}{dx}\right]$$

The equilibrium equation in the slice according to the direction x is written

$$t\frac{d\sigma_x}{dx} + \sigma_x\frac{dt}{dx} = -p_b\frac{dt}{dx} - 2\tau$$

from the above equations,we get

$$\frac{d\sigma_x}{dx} = \frac{(1-\nu_s^2)(p_b+\sigma_x)\frac{dp_b}{dx}t - 2E_s\tau}{t[E_s - \nu_s(1+\nu_s)(p_b+\sigma_x)]}$$

$$\frac{dt}{dx} = \frac{(1-\nu_s^2)\frac{dp_b}{dx}t - 2\nu_s(1+\nu_s)\tau}{\nu_s(1+\nu_s)(p_b+\sigma_x) - E_s}$$

Strain rate $\dot{\varepsilon}_x$ is by definition,

$$\dot{\varepsilon}_x = \frac{dv_x}{dx}$$

substituting in the above equation,

$$\frac{dv_x}{dx} = \frac{v_x}{E_s}\left[(1-v_s^2)\frac{d\sigma_x}{dx} + v_s(1+v_s)\frac{dp_b}{dx}\right]$$

The Reynolds equation for the calculation of p_b is given by

$$\frac{dp_b}{dx} = \frac{12\eta}{\phi_x h_t^3}\left(\frac{u_s+u_r}{2}h_t + \frac{u_s-u_r}{2}R_q\phi_s - c_{debit}\right) \tag{16}$$

The system of equations to solve in this zone are,

$$\frac{dp_b}{dx} = \frac{12\eta}{\phi_x h_t^3}\left(\frac{u_s+u_r}{2}h_t + \frac{u_s-u_r}{2}R_q\phi_s - c_{debit}\right) \tag{17}$$

$$\frac{d\sigma_x}{dx} = \frac{(1-v_s^2)(p_b+\sigma_x)\frac{dp_b}{dx}t - 2E_s\tau}{t[E_s - v_s(1+v_s)(p_b+\sigma_x)]} \tag{18}$$

$$\frac{dt}{dx} = \frac{(1-v_s^2)\frac{dp_b}{dx}t - 2v_s(1+v_s)\tau}{v_s(1+v_s)(p_b+\sigma_x) - E_s} \tag{19}$$

$$\frac{dv_x}{dx} = \frac{v_x}{E_s}\left[(1-v_s^2)\frac{d\sigma_x}{dx} + v_s(1+v_s)\frac{dp_b}{dx}\right] \tag{20}$$

The boundary conditions are,
At the Entry,

$$x = -R_0, p_b = 0, t = t_1, \sigma_x = \sigma_1, v_x = v_1 \tag{21}$$

At the transition between the hydrodynamic Inlet zone and the mixed Inlet zone,

$$x = x_{xifm}, h_t = h_{t_{contact}} \tag{22}$$

This zone ends where the asperities of the roll and the strip enter into contact.

10.1.2 Zone 2 : Mixed Inlet Zone

The mixed inlet zone starts when the asperities of the roll and the strip enter into contact.The core of strip deforms elastically.The interface pressure is supported both by the lubricant and by the contacts between asperities.i.e.,

$$p = Ap_a + (1-A)p_b$$

The mechanics equations become,

$$\frac{d\sigma_x}{dx} = \frac{(1-v_s^2)(p_b+\sigma_x)p' t - 2E_s\tau}{t[E_s - v_s(1+v_s)(p+\sigma_x)]}$$

$$\frac{dt}{dx} = \frac{(1-v_s^2)(\frac{dp_b}{dx} - ay')t - 2v_s(1+v_s)\tau}{v_s(1+v_s)(p+\sigma_x) - E_s + \frac{1}{2}(1-v_s^2)td}$$

where,

$$d = \frac{dA}{dh}\left(H_a + A\frac{dH_a}{dA}\right)k_0$$

The average film thickness h_t is not equal to the average line distance h,but is given by the following geometric relation,

$$h_t = \frac{3R_q}{256}(35 + 128H + 140H^2 - 70H^4 + 28H^6 - 5H^8)$$

where,H,the dimensionless film thickness is given by

$$H = \frac{h}{3R_q}$$

A is given by,

$$A = \frac{1}{32}(16 - 35H + 35H^3 - 21H^5 + 5H^7)$$

The system of equations are,

$$\frac{dp_b}{dx} = \frac{12\eta}{\phi_x h_t^3}\left(\frac{u_s + u_r}{2}h_t + \frac{u_s - u_r}{2}R_q\phi_s - c_{debit}\right) \tag{23}$$

$$\frac{d\sigma_x}{dx} = \frac{(1 - v_s^2)(p_b + \sigma_x)p^{'}t - 2E_s\tau}{t[E_s - v_s(1 + v_s)(p + \sigma_x)]} \tag{24}$$

$$\frac{dt}{dx} = \frac{(1 - v_s^2)(\frac{dp_b}{dx} - ay^{'})t - 2v_s(1 + v_s)\tau}{v_s(1 + v_s)(p + \sigma_x) - E_s + \frac{1}{2}(1 - v_s^2)td} \tag{25}$$

$$\frac{dv_x}{dx} = \frac{v_x}{E_s}\left[(1 - v_s^2)\frac{d\sigma_x}{dx} + v_s(1 + v_s)p^{'}\right] \tag{26}$$

The zone ends when the strip starts to deform plastically,i.e.,

$$x = x_{iw}, \sigma_{eq} = \sigma_0 \tag{27}$$

10.2 Work Zone

In the work zone, the strip deforms plastically. It is integrated with the low-speed work zone and high-speed work zone. The high-speed work zone is introduced to counter the convergence problems, due to the hypersensitivity of the pressure distribution of the lubricant p_b.

10.2.1 Zone 3 : Low-speed mixed work Zone

In this zone,the core of the strip deforms plastically.For the modeling of the interface, the two tribologic equations, the Reynolds equation and the asperity equation are integrated. The generalized asperity crushing equation gives us the evolution of the distance between non-updated average lines h,

$$\frac{dh}{dx} = -\frac{y^{'}}{1 + \frac{E_p t}{2\bar{l}}}$$

The interface is modelled by,

$$\frac{dp_b}{dx} = \frac{12\eta}{\phi_x h_t^3}\left(\frac{u_s+u_r}{2}h_t + \frac{u_s-u_r}{2}R_q\phi_s - c_{debit}\right)$$

For the modeling of the mechanics in the band,From the elastoplastic formulation,we have,

$$\begin{bmatrix}\dot{s_x}\\ \dot{s_y}\\ \dot{s_z}\end{bmatrix} = 2\mu\begin{bmatrix}(1-as_x^2)\dot{e}_x & -as_xs_y\dot{e}_y & -as_xs_z\dot{e}_z\\ -ass_xs_y\dot{e}_x & (1-as_y^2)\dot{e}_y & -as_ys_z\dot{e}_z\\ -as_xs_z\dot{e}_x & -as_ys_z\dot{e}_y & (1-as_z^2)\dot{e}_z\end{bmatrix}$$

where,

$$a = \frac{1}{\frac{2}{3}\sigma_0^2(1+\frac{H_s}{3\mu})}$$

$$s_z = -(s_x+s_y)$$

$$\dot{e}_x = \frac{2}{3}\dot{\varepsilon}_x - \frac{1}{3}\dot{\varepsilon}_y$$

$$\dot{e}_y = -\frac{1}{3}\dot{\varepsilon}_x + \frac{2}{3}\dot{\varepsilon}_y$$

$$\dot{e}_z = -\frac{1}{3}\dot{\varepsilon}_x - \frac{1}{3}\dot{\varepsilon}_y$$

On substituting,

$$\frac{ds_x}{dx} = \frac{2\mu}{3v_x}\left[(2-3as_x^2)\dot{\varepsilon}_x - (1+3as_xs_y)\dot{\varepsilon}_y\right]$$

$$\frac{ds_y}{dx} = \frac{2\mu}{3v_x}\left[-(1+3as_xs_y)\dot{\varepsilon}_x + (2-3as_y^2)\dot{\varepsilon}_y\right]$$

where,

$$\dot{\varepsilon}_x = \frac{[2\mu(1+3as_xs_y)-3X]\dot{\varepsilon}_y + 3bv_x}{2\mu(2-3as_x^2)+3X}$$

$$b = \frac{1}{t}[(s_y-s_x)t^{'} - 2\tau]$$

The system of equations are,

$$\frac{dh}{dx} = -\frac{y^{'}}{1+\frac{E_pt}{2l}} \tag{28}$$

$$\frac{dp_b}{dx} = \frac{12\eta}{\phi_x h_t^3}\left(\frac{u_s+u_r}{2}h_t + \frac{u_s-u_r}{2}R_q\phi_s - c_{debit}\right) \tag{29}$$

$$\frac{ds_x}{dx} = \frac{2\mu}{3v_x}\left[(2-3as_x^2)\dot{\varepsilon}_x - (1+3as_xs_y)\dot{\varepsilon}_y\right] \tag{30}$$

$$\frac{ds_y}{dx} = \frac{2\mu}{3v_x}\left[(2-3as_xs_y)\dot{\varepsilon}_x - (1+3as_y^2)\dot{\varepsilon}_y\right] \tag{31}$$

$$\frac{dp_{hydro}}{dx} = -\frac{X}{v_x}(\dot{\varepsilon}_x + \dot{\varepsilon}_y) \tag{32}$$

$$\frac{dv_x}{dx} = \frac{[2\mu(1+3as_xs_y)-3X]\dot{\varepsilon}_y + 3bv_x}{2\mu(2-3as_x^2)+3X} \tag{33}$$

The model switches to low speed outlet zone under the condition,

$$x = x_{wols}, \sigma_{eq} = \sigma_0 \tag{34}$$

The pressure distribution becomes more and more sensitive to the value of the lubricant flow rate under mixed regime with a hydrodynamic condition.Due to this,the Poiseuille term $(\phi_x h_t^3/12\eta)dp_b/dx$ is negligible compared to the Couette term $(u_s+u_r)h_t/2$ in the Average Reynolds equation.This leads to the instabilities on the distribution of the pressure and hypersensitivity to the flow rate.And also when approaching the threshold of percolation,the Poiseuille term should disappear.The high speed regime is introduced to handle these situations in a stable way.
The model switches to the High-speed mixed work zone under the condition,

$$x = x_{xwlh}, p_b < p, \frac{p_b - p}{\sigma_0} < err_{p_b} \tag{35}$$

The zones ends when

- deformations become elastic again.
- lubricant pressure is about to become greater than the interface pressure at the end of the lubricant flow rate adjustment.

10.2.2 Zone 3' : High-speed mixed work Zone

The transition to the high speed work zone occurs when the rolling speed is relatively important,hence the name high speed work zone.The equations of mechanics thus remain unchanged. On the other hand, for the modeling of the interface, the equation of reynolds, after elimination of the term of poiseuille, is reduced to a simple conservation of the volume of the lubricant.

$$Q = \frac{u_s+u_r}{2}h_t + \frac{u_s-u_r}{2}R_q\phi_s \tag{36}$$

In both situations,when the lubricant pressure becomes close to the interface pressure due to the important rolling speed or the percolation threshold, the Reynolds equation is replaced by the previous volume conservation equation. Instead of computing the lubricant pressure by the Reynolds equation and the mean film thickness by the asperity flattening equation, the lubricant pressure is computed by the asperity flattening equation and the mean film thickness by the Reynolds equation without the Poiseuille term.

The derivation of the flow conservation equation,equation,with respect to x gives

$$\frac{dh_t}{dx} = \frac{u_s'(h_t + R_q\phi_s)}{[(u_s+u_r)+(u_s-u_r)R_q d\phi_s/dh_t]}$$

either in terms of distance between non-updated mean lines h,

$$\frac{dh}{dx} = \frac{(h_t + R_q\phi_s)}{[(u_s+u_r)+(u_s-u_r)R_q d\phi_s/dh_t]\frac{dh}{dh_t}\frac{dv_x}{dx}}$$

the term dh/dx appears in the expression of dv_x/dx through the intermediary of $\dot{\varepsilon}_y$, its extraction gives

$$\frac{dh}{dx} = \frac{[2\mu(1+3as_xs_y)+3(s_y-s_x-X)]y' + 3\tau}{[\mu(2-3as_x^2)+\frac{3}{2}X]ct - [2\mu(1+3as_xs_y)+3(s_y-s_x-X)]}$$

where,

$$c = \frac{dh_t}{dh} \frac{(u_s + u_r) + (u_s - u_r) R_q d\phi_s / dh_t}{(h_t + R_q \phi_s) v_x}$$

The pressure of the lubricant is then obtained by inverting the equation for crushing the asperities,

$$p_b = p - AH_a k_0$$

where,

$$H_a = f(A, E_p)$$

$$E_p = -\frac{2\bar{l}}{t} \left(\frac{y'}{\frac{dh}{dx}} + 1 \right)$$

Compared to the low-speed mixed work zone, the tribological equations have simply been reversed: the Reynolds equation which allowed us to calculate p now gives us the evolution of h, and conversely the equation for crushing the asperities gives us p instead of h. the integration of the model is stabilized. In the high-speed mixed working zone, the system to be solved is the following

The system of equations are,

$$\frac{dh}{dx} = \frac{[2\mu(1 + 3as_x s_y) + 3(s_y - s_x - X)]y' + 3\tau}{[\mu(2 - 3as_x^2) + \frac{3}{2}X]ct - [2\mu(1 + 3as_x s_y) + 3(s_y - s_x - X)]} \tag{37}$$

$$\frac{ds_x}{dx} = \frac{2\mu}{3v_x} \left[(2 - 3as_x^2)\dot{\varepsilon}_x - (1 + 3as_x s_y)\dot{\varepsilon}_y \right] \tag{38}$$

$$\frac{ds_y}{dx} = \frac{2\mu}{3v_x} \left[-(1 + 3as_x s_y)\dot{\varepsilon}_x + (2 - 3as_y^2)\dot{\varepsilon}_y \right] \tag{39}$$

$$\frac{dp_{hydro}}{dx} = -\frac{X}{v_x}(\dot{\varepsilon}_x + \dot{\varepsilon}_y) \tag{40}$$

$$\frac{dv_x}{dx} = \frac{[2\mu(1 + 3as_x s_y) - 3X]\dot{\varepsilon}_y + 3bv_x}{2\mu(2 - 3as_x^2) + 3X} \tag{41}$$

The transition from the high-speed mixed work zone to the exit zone takes place when the strip becomes elastic again,

$$x = x_{xwohs}, \sigma_{eq} = \sigma_0 \tag{42}$$

10.3 Exit Zone

In the Exit zone,the film thickness is assumed to be constant and is equal to the film thickness at the transition work-exit zone.that is,

$$h_t = h_{t_{wo}} \tag{43}$$

10.3.1 Zone 4 : Low-speed mixed outlet Zone

It is the zone following the low-speed work zone.The strip again deforms elastically in this zone.The geometry is imposed by that of the cylinder, since the average film thickness h_t is assumed to be constant.
The equilibrium equation in the slice along the x direction is given by,

$$\frac{d\sigma_x}{dx} = \frac{1}{t}\left[(\sigma_y - \sigma_x)t^{'} - 2\tau\right]$$

From the Hooke's law,in the direction z,

$$\frac{d\sigma_z}{dx} = v_s\left(\frac{d\sigma_x}{dx} + \frac{d\sigma_y}{dx}\right)$$

and from,

$$\dot{\varepsilon}_y = \frac{v_x}{t}\frac{dt}{dx}$$

$$\dot{\varepsilon}_y = \frac{1}{E_s}(\dot{\sigma}_y - v_s(\dot{\sigma}_x + \dot{\sigma}_z))$$

We get,

$$\frac{E_s t^{'}}{t} = (1 - v_s^2)\frac{d\sigma_y}{dx} - v_s(1 + v_s)\frac{d\sigma_x}{dx}$$

The system of equations in this zone are,

$$\frac{dp_b}{dx} = \frac{12\eta}{\phi_x h_t^3}\left(\frac{u_s + u_r}{2}h_t + \frac{u_s - u_r}{2}R_q\phi_s - c_{debit}\right) \tag{44}$$

$$\frac{d\sigma_x}{dx} = \frac{1}{t}\left[(\sigma_y - \sigma_x)t^{'} - 2\tau\right] \tag{45}$$

$$\frac{d\sigma_y}{dx} = \frac{E_s t^{'}}{(1 - v_s^2)t + \frac{v_s}{1 - v_s}\frac{d\sigma_x}{dx}} \tag{46}$$

$$\frac{d\sigma_z}{dx} = v_s\left(\frac{d\sigma_x}{dx} + \frac{d\sigma_y}{dx}\right) \tag{47}$$

$$\frac{dv_x}{dx} = \frac{v_x}{E_s(1 - v_s)\left[(1 - 2v_s)(1 + v_s)\frac{d\sigma_x}{dx} - \frac{v_s E_s t^{'}}{t}\right]} \tag{48}$$

The low speed outlet zone ends when σ_y becomes zero.By shooting method,the pressure at the outlet is made zero by adjusting the flow rate of the lubricant and the stress σ_x is made equal to σ_2 by adjusting the entry speed of the strip.

$$x = x_{out}, p_b = 0, \sigma_x = \sigma_2, \sigma_y = 0 \tag{49}$$

A high-speed transition zone was added when the lubricant pressure became greater than the interface pressure in low speed outlet zone for some rolling scenarios.

10.3.2 Zone 4' : High-speed mixed outlet Zone

It is the zone following the high-speed work zone.As the pressure p_b is equal to p, only the elastic equations are necessary. The system of equations in this zone are,

$$\frac{d\sigma_x}{dx} = \frac{1}{t}\left[(\sigma_y - \sigma_x)t^{'} - 2\tau\right] \tag{50}$$

$$\frac{d\sigma_y}{dx} = \frac{E_s t^{'}}{(1-v_s^2)t + \frac{v_s}{1-v_s}\frac{d\sigma_x}{dx}} \tag{51}$$

$$\frac{d\sigma_z}{dx} = v_s\left(\frac{d\sigma_x}{dx} + \frac{d\sigma_y}{dx}\right) \tag{52}$$

$$\frac{dv_x}{dx} = \frac{v_x}{E_s(1-v_s)\left[(1-2v_s)(1+v_s)\frac{d\sigma_x}{dx} - \frac{v_s E_s t^{'}}{t}\right]} \tag{53}$$

The end conditions for this zone are,

$$x = x_{out}, p_b = 0, \sigma_x = \sigma_2, \sigma_y = 0 \tag{54}$$

10.4 Numerical Methods

The LAM2DTRIBO model solves a number of first order differential equations.The system to be solved is,

$$y^{'} = f(x,y) \tag{55}$$

where, x is the position variable,y is the vector of variables, y' is derivative of the vector with respect to x and f is the system of differential equations with respect to zone by zone in LAM2DTRIBO.

10.4.1 Runge-Kutta 4 method and Adaptation of time step

Runge-Kutta methods is an explicit method used for the calculation of y_{n+1},which evaluates the second member of equation in the above equation in (x_n, y_n),starting from,

$$y_{n+1} = y_n + hf(y_n)$$

The subroutine related to the scheme is *rk4th*.Runge-Kutta methods are very simple to program,robust and are of good precision.The order of scheme utilised for LAM2DTRIBO is 4th order.So,the system is evaluated at 4 points

$$k_1 = hf(x_n, y_n)$$
$$k_2 = hf(x_n + \frac{h}{2}, y_n + \frac{k_1}{2})$$
$$k_3 = hf(x_n + \frac{h}{2}, y_n + \frac{k_2}{2})$$
$$k_4 = hf(x_n + h, y_n + k_3)$$

The final evaluation is defined as,

$$y_{n+1} = y_n + \frac{k_1}{6} + \frac{k_2}{3} + \frac{k_3}{3} + \frac{k_4}{6} + O(h^5) \tag{56}$$

The scheme is associated with the control of error on the step of time to be more effective and efficient.

10.5 LAM2DTRIBO Algorithm

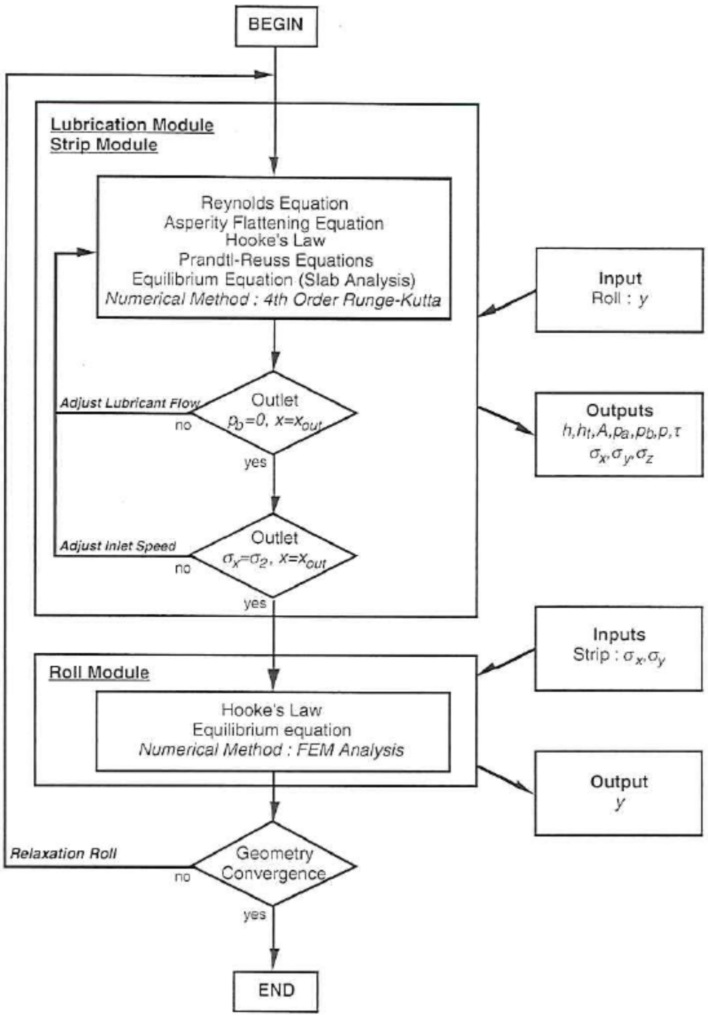


Figure 11: LAM2DTRIBO Algorithm [1]

The above diagram shows the algorithm of the LAM2DTRIBO.The Strip and lubrication model is coupled with the elastic deformation of the cylinder.The strip and lubrication modules are strongly coupled.The stresses calculated by this module are provided as a boundary conditions for the roll module.The elastic deformations of the cylinder are calculated by finite elements.The profile of the cylinder y_x is interpolated by the cubic splines which intervenes with equations of the Strip-lubrication module.The geometry of the cylinder is relaxed from an iteration to the other iteration of the program dealing with the geometric convergence of the deformation of the cylinder.

10.5.1 Input files

The input values to the model are provided by the following input files,

- **Bande.don** - Parameters related to description of Strip
- **Cylindre.don** - Parameters related to description of Roll
- **Lubricant.don** - Parameters related to description of Lubricant
- **Surface.don** - Parameters related to description of the strip surface
- **Profil.don** - Profile points of the cylinder
- **FEM-RK-Errors.don** - Parameters related to mesh and convergence criteria
- **ProgChoice.don** - Different options in the model
- **Tband.don** - Profile of surface temperature of the strip
- **Tcyl.don** - Profile of surface temperature of the roll

The input values are read and initial values for the model are assigned.The subroutine related to this operation is *Lecture*.

10.5.2 Strip and Lubrication Module

In this module,the subroutine *LBIntegration* controls the process of spatial integration of the roll bite.The equations related to the different zones are solved and the conditions related to the particular zone are satisfied.The equations are solved by the numerical method.The numerical method utilised in this model is Runge-Kutta 4th order.The Runge-Kutta method is chosen because of its simplicity and its robustness.

Adjustment of lubricant flow

After the spatial integration of roll bite,the adjustment of the lubricant flow is performed in the subroutine *AdjustFlow*.The volumetric lubricant flow rate (*cflow*) is adjusted such that the lubricant pressure is zero at the end of the roll bite.A double shooting method is utilised.

$$p_b = 0, x = x_{out} \tag{57}$$

Adjustment of inlet speed

After the adjustment of lubricant flow,the adjustment of the inlet speed is performed in the subroutine *Adjustvl*.The initial speed of the strip is adjusted so that the tension in the strip at the end of the roll bite is equal to the imposed front tension.

$$\sigma_x = \sigma_2, x = x_{out} \tag{58}$$

The Spatial integration of the roll bite,Adjustment of lubricant and inlet speed are nested with respect to one another.The spatial integration is the innermost loop and the adjustment of the inlet speed is the outer loop.

```
do while (action.ne.'DeformCyl ')

   call InitParametersFlow

   if ((itherm.eq.1).and.(itherband.eq.3)) then
      call ComputeTbandAdiabatic
   endif

   do while (action.ne.'Adjustvl  ')

      call LBIntegration
      call AdjustFlow

   enddo

   call Adjustvl

enddo
```

Figure 12: Strip and Lubrication Module

10.5.3 Roll Module

The stresses calculated in the strip and lubrication module are provided as the boundary conditions for the roll module.With the finite element analysis the elastic deformations are calculated.The subroutine related to this is *CylEntTra*.

Adjustment of vertical position of roll axis

If the roll is rigid,The vertical position of the roll is adjusted in order to obtain a final strip thickness after the lubricant flow rate and the entry speed of the strip have been calculated.The subroutine related is *ConvergenceLB*.

Adjustment of roll profile

If the roll is elastic,The profile of the roll is adjusted so that it corresponds to the resulting deformation by the stresses calculated in the strip-interface module.The criteria for stopping the program relates to the geometrical convergence of the deformed cylinder.The subroutine related is *ConvergenceLBandC*.

The geometry of the cylinder is relaxed from an iteration on the other of the program dealing with the geometric convergence of the deformation of the cylinder.The model is directed back to the strip and lubrication module and the process is repeated until convergence.The subroutine in relation to the relaxation of the roll is *CylRelaxation*.

```
do while (action.ne.'DeformCyl ')

   call InitParametersFlow

   if ((itherm.eq.1).and.(itherband.eq.3)) then
      call ComputeTbandAdiabatic
   endif

   do while (action.ne.'Adjustvl  ')

      call LBIntegration
      call AdjustFlow

   enddo

   call Adjustvl

enddo
```

Figure 13: Roll Module

10.5.4 Flow charts

The following flow charts describes the work flow of the LAM2DTRIBO model.It contains work flow of the major modules,its subroutines with respect to the code.The *Laminage2D* explains the work flow of the main algorithm of the program.The *LBIntegration* explains the work flow of the Lubricant and the strip module.The *Roll Part* explains the work flow of the roll module.

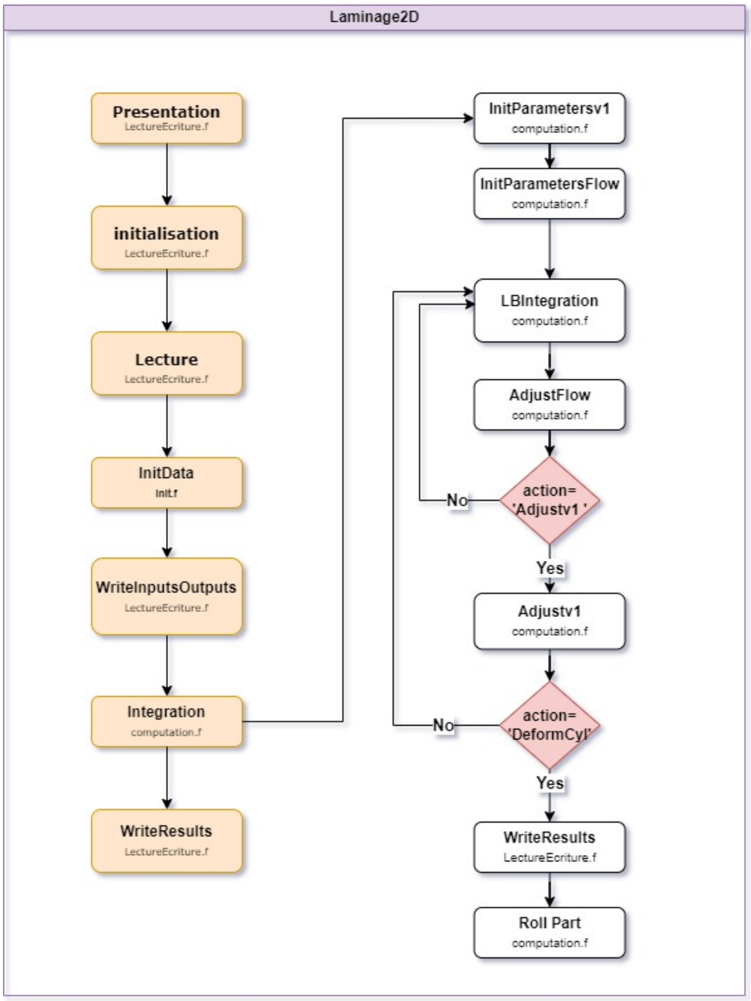


Figure 14: Flow Chart - Laminage2D

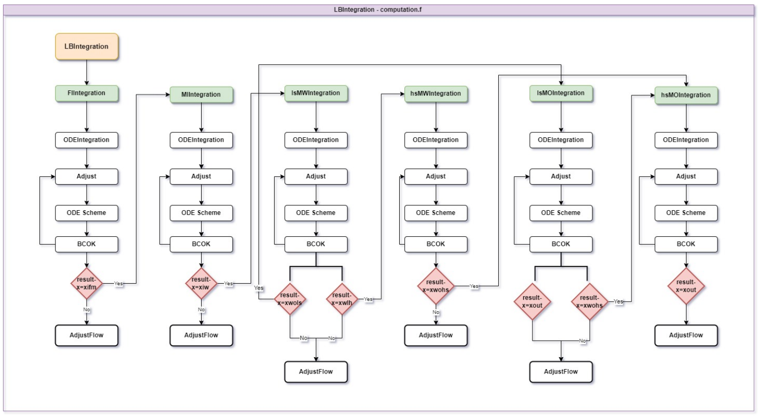


Figure 15: Flow Chart - LBIntegration

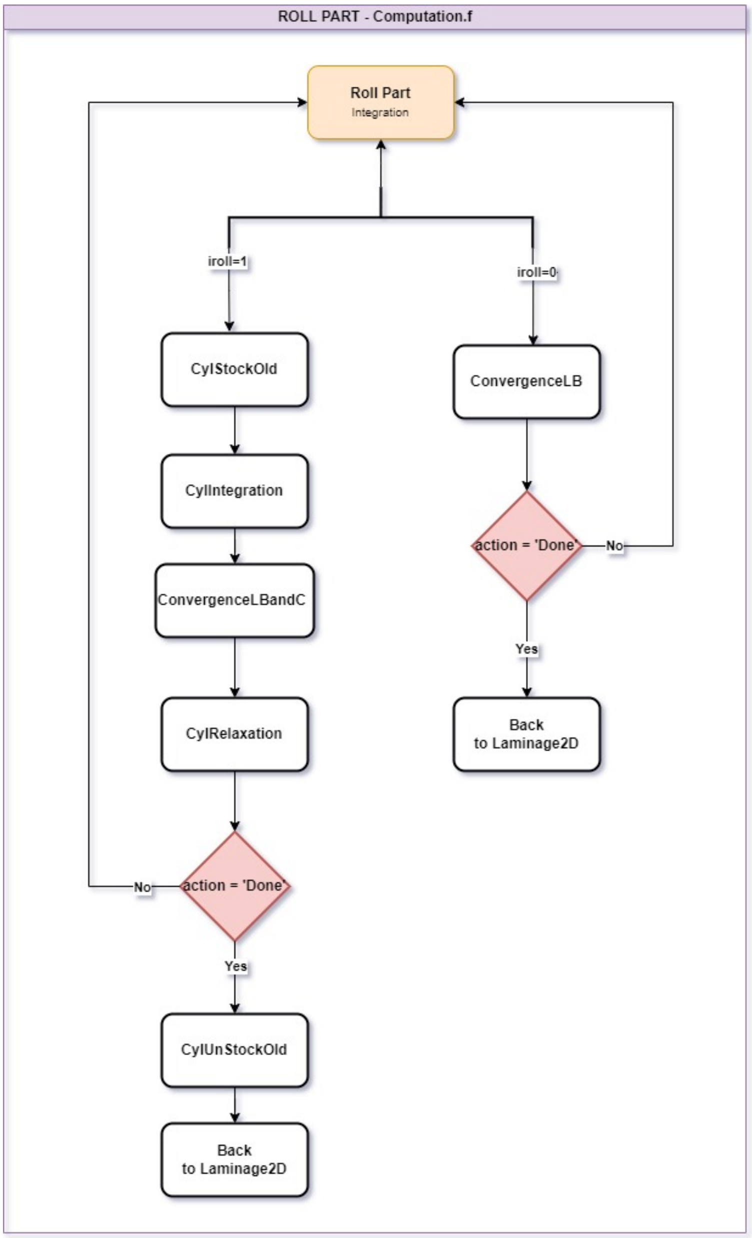


Figure 16: Flow Chart - Roll Part

10.5.5 Output files

The results are extracted and saved in the following output files,
If the roll is rigid

- **elastique.ban** - the local values of parameters related to strip
- **elastique.lub** - the local values of parameters related to lubricant
- **elastique.geo** - the values of parameters related to asperities
- **elastique.res** - the Input and Output values of computation

If the roll is elastic,additional files are generated,

- **elastique.cyl** - the profile points of the deformed cylinder if the roll is elastic
- **elastique.FEM** - the finite element meshing nodes of the roll if the roll is elastic

11 Parametrisation of the Model

The deep analysis of the existing code enabled to identify rooms of improvement.The idea was to first recreate the results presented in the Marsault thesis to check the robustness of the existing code and identify the areas for improvement.

11.1 Need for Parametrisation/Automatisation code

Main drawbacks :

- Having difficulties to input values to the model in a robust way.
- Not able to launch several computations of the model at a time.
- The input and output files of the model were not organised.
- Not able to post process the obtained results.

Goal :The Goal was to develop a code in python which could launch computations in parallel for a set of different parameter values and post process results once all the computations are completed.

11.2 Summary of Accomplished work

With the help of the developed code,we are now able to,

- Input the parameters values in an easy and robust way.
- Run and study the model for different values of a certain parameter.
- Launch multiple computations in parallel.
- Organise input and output files of each computation.
- Generate and Obtain the post-processing of each computations.
- Save the plots of each computation in their specific folder.
- Generate and obtain related comparison plots for all the input parameter values
- Obtain the status report of all the computations

The code was further developed to study the model for different values of two different parameter,i.e,

- Run the computations in parallel for two different parameters for a set of values
- Generate and obtain comparison plots of both the input parameters together.

11.3 Detailed accomplished work

The description of the procedure:

- Mention the parameter you want to study as shown below,

```
####################### Mention the parameter ################################

Parameter = "Ur = "
# Few Examples:"Ur = " for Rolling Speed
#              "R0 = " for Roll Radius
#              "Es = " for Young's Modulus of the strip
```

Figure 17: Parameter Studied

- Provide the range of values of the parameter

```
################# Values of the first parameter ##############################

Values=["10.0","34.0","34.1","34.2","34.3","34.4","34.5","34.6","34.7","34.8"]
```

Figure 18: Inputs of the Parameter

- Provide the name of the computation folder

```
##################### Mention the Folder name ################################

Folder="Rolling"
```

Figure 19: Name of the computation folder

- Next,Choosing the options with respect to Computations and post-processing.There are choices to launch multiple computations or single computation or not launch computations,this to start the post-processing if you already have the results of the computation.

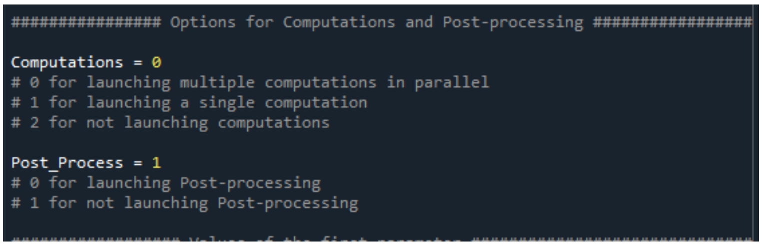


Figure 20: Options for Computations and Post-processing

- Once all this inputs are provided,the python program can be launched.
- Files are generated depending upon the range of input values.Each file represents a computation.

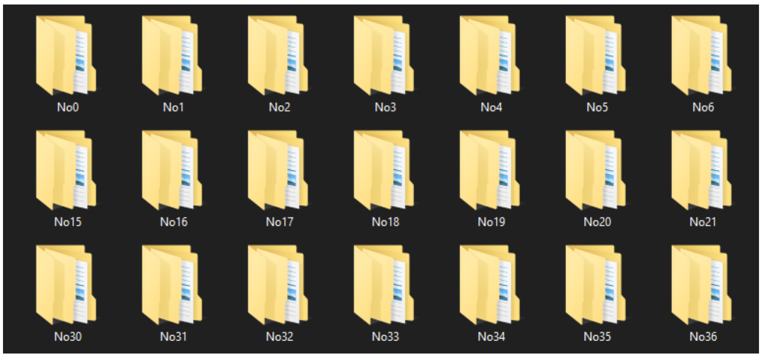


Figure 21: Generation of Input folders

- Inside the computation folder,Different files are organised as follows.The input files with all the input files required for that particular computation are placed in the "Input" folder.The executable "Rolling.exe" is placed in the bin folder. An output directory is created for the output files.

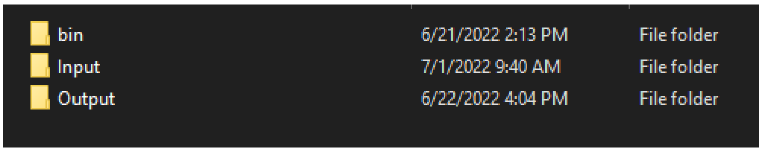


Figure 22: Files present inside each computation folder

- Once all the folder are ready with the required files.The computations are launched in parallel.
- When all the computations are completed.The output files generated are placed in that output folder of that specific computation.

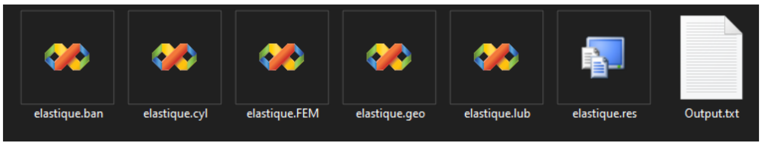


Figure 23: Output files of the computation

- Then,a status report is generated showing the success or failure of each computation. There are 3 statuses:
  Status = OK ; Computation has ran successfully
  Status = Stopped ; Computation has been stopped in between due to convergence issues or condition issues.
  Status = Error ; Computation has stopped at the beginning
  The below image shows the status report,it contains the path of the computation,the specific parameter values and the status of that computation.

KGFLsurf\Par0\No30	lsurf = 3.	Ur = 17.5	Status = OK
KGFLsurf\Par0\No31	lsurf = 3.	Ur = 20.0	Status = OK
KGFLsurf\Par0\No32	lsurf = 3.	Ur = 22.5	Status = OK
KGFLsurf\Par0\No33	lsurf = 3.	Ur = 25.0	Status = OK
KGFLsurf\Par0\No34	lsurf = 3.	Ur = 27.5	Status = OK
KGFLsurf\Par0\No35	lsurf = 3.	Ur = 30.0	Status = OK
KGFLsurf\Par0\No36	lsurf = 3.	Ur = 32.5	Status = OK
KGFLsurf\Par0\No37	lsurf = 3.	Ur = 35.0	Status = Stopped
KGFLsurf\Par0\No38	lsurf = 3.	Ur = 37.5	Status = Stopped
KGFLsurf\Par0\No39	lsurf = 3.	Ur = 40.0	Status = Error
KGFLsurf\Par0\No40	lsurf = 3.	Ur = 42.5	Status = Error

Figure 24: Status report

- The post processing is then launched.The post processing is performed only for the computations which has run successfully.
- The plots generated is placed in the output folder of that particular computation.

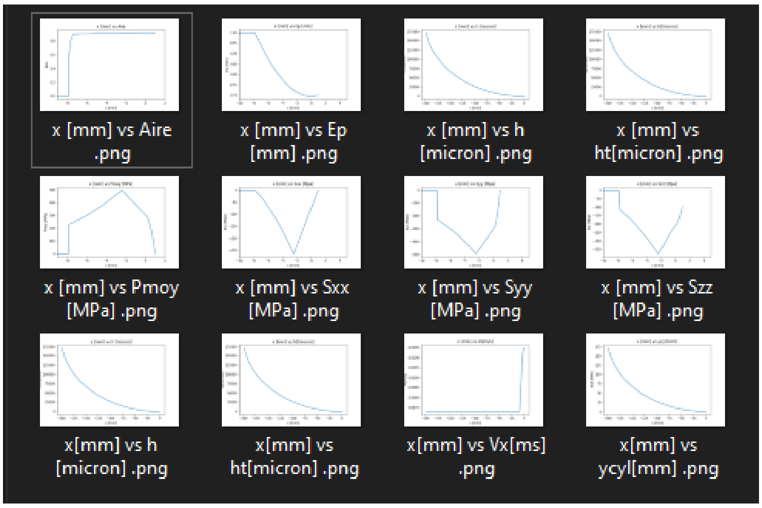


Figure 25: Post-processing plots

- Once the above process is performed for all the computations.The comparison plots are generated and placed in the main folder.A example of the plot is shown below.

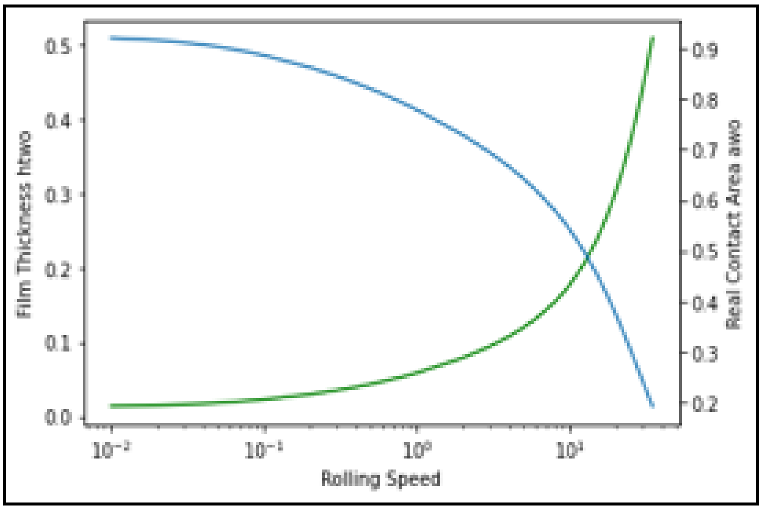


Figure 26: Typical Comparison output plot

If two different parameters are studied,the above process is performed but nested folders are created for the computation.In a way that one parameter value is set to a value and all the values of the other parameter are tested.And,also at the end of the post-processing the comparison plot between both parameter are generated.An example of the plot is shown below.

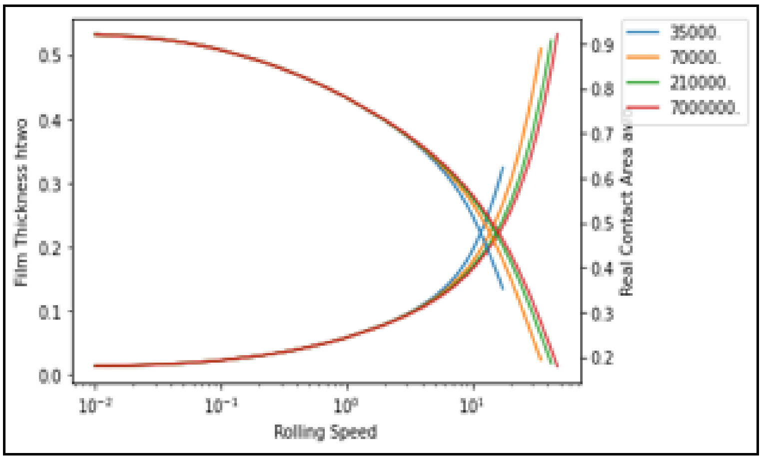


Figure 27: Typical Comparison plots of all parameters considered

12 Parameter Study

A reference case of Aluminium ($\sigma_0 = 200MPa$) was taken to study the effects of different parameters on friction.The case from Marsault thesis is presented below.With the same parameters as the reference case,the LAM2DTRIBO is ran.The results obtained were compared with the results from the Marsault thesis.The inlet strip thickness is $1.0mm$.The reduction of the strip is 30%.The cylinder is assumed to be rigid.The Value of the half distance between asperities is taken as $30\mu m$.The viscosity of the lubricant follows the Barus law.

Interface		
Barus		
Viscosité du Lubrifiant à p0	$\eta_0 =$	$0.01Pa.s$
Coefficient de Pression de la Viscosité	$\gamma_l =$	$1.10^{-8}Pa^{-1}$
Rugosité Composite RMS	$R_q =$	$0.5\mu m$
Demi Distance entre Aspérités	$l =$	$30\mu m$
Nombre de Peklenik	$\gamma_s =$	9
Coefficient de Tresca sur les Plateaux	$\overline{m}_a =$	0.25
Bande		
Épaisseur d'entrée	$t_1 =$	$1.0mm$
Épaisseur de sortie	$t_2 =$	$0.7mm$
Contre-Traction	$\sigma_1 =$	$0MPa$
Traction	$\sigma_2 =$	$0MPa$
Module d'Young	$E_s =$	$70GPa$
Coefficient de Poisson	$\upsilon_s =$	0.3
Contrainte d'Écoulement	$\sigma_0 =$	$200MPa$
Coefficient de Déformation	$K =$	0
Coefficient d'Écrouissage	$n =$	0
Cylindre		
Rayon	$R_0 =$	$200mm$
Vitesse de Laminage	$u_r =$	$0.01-100ms^{-1}$
Module d'Young	$E_r =$	$210GPa$
Coefficient de Poisson	$\upsilon_r =$	0.3

Figure 28: Parameters for the reference case [1]

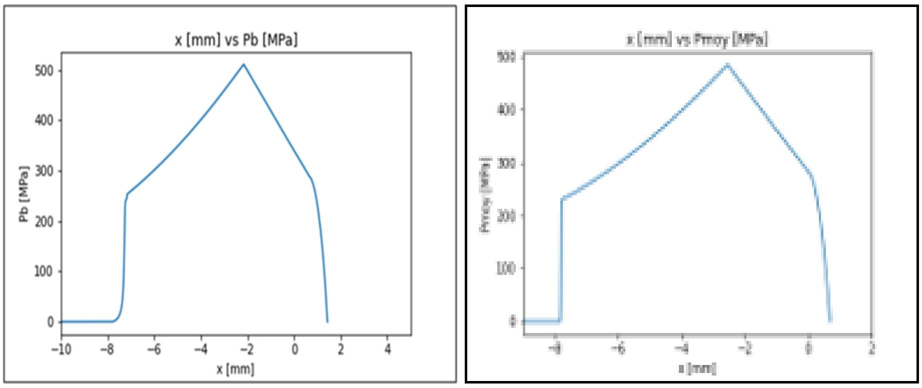
In the following sections,the parameter study of the influence of the rolling speed,Young's modulus of the strip,Roll radius of the cylinder and the composite roughness are discussed.The results obtained,mainly the friction coefficient,forward slip,film thickness and the area of contact at the work-outlet boundary are presented.Only the results for which the model ran successfully without any convergence issues or other problems are presented.The convergence of the model is evaluated.The physical consistency of the obtained results are discussed and they are compared with the results from the Marsault thesis.

12.1 Influence of Rolling Speed

In this section we are going to study the influence of the rolling speed.The LAM2DTRIBO model is ran for different values of rolling speeds in the range of $0.01 - 100m/s$.
Let's consider 3 different cases of rolling speed,

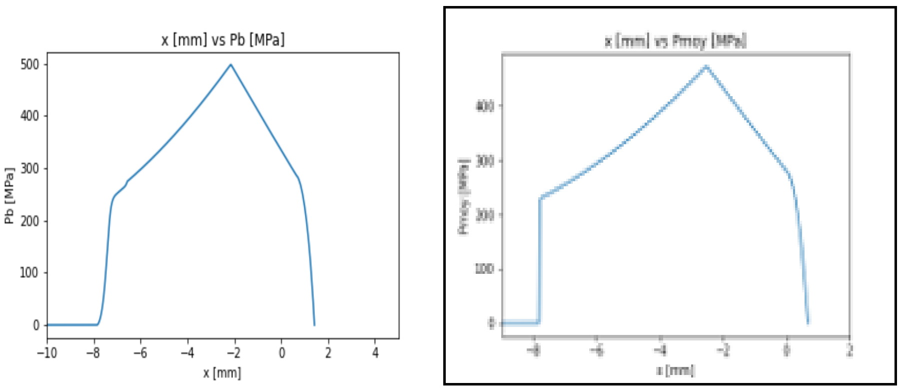
- $u_r = 0.01m/s$, Very Low speed case
- $u_r = 0.1m/s$, Low speed case
- $u_r = 10m/s$, High Speed case

The below plots shows the pressure distribution of the above mentioned cases,where P_b is the lubricant pressure and the P is the total pressure.



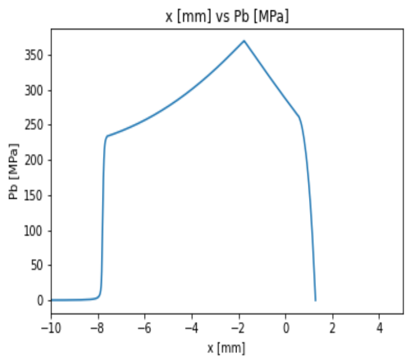
(a) P_b (b) P

Figure 29: Pressure distribution - $u_r = 0.01m/s$

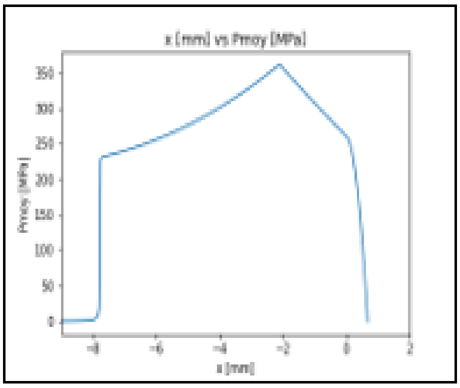


(a) P_b (b) P

Figure 30: Pressure distribution - $u_r = 0.1m/s$



(a) P_b



(b) P

Figure 31: Pressure distribution - $u_r = 10m/s$

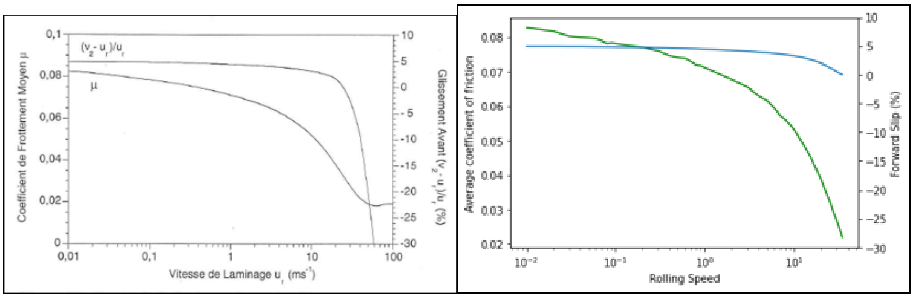
From the above plots, it can be observed, that the pressure distribution follows a classic friction hill shape[5]. As the rolling speed increases, the friction decreases, and the peak pressure at the neutral point also decreases. For the high-speed case, the pressure of the lubricant increases rapidly at the start of the working zone.

The results obtained were compared with the results from the Marsault thesis.The below table represents the comparison of coefficient of friction,Forward slip,Film thickness and the Real contact area.The results obtained were in good agreement.

Rolling Speed (m/s)	Co-efficient of Friction		Foward slip %		Film Thickness(mum)		Real contact area	
	Marsault	Obtained	Marsault	obtained	Marsault	obtained	Marsault	obtained
0.01	0.0825	0.08285	5	4.9197	0.01	0.014082	0.925	0.92045
0.1	0.078	0.07821	4.8	4.8148	0.025	0.023	0.875	0.088615
1	0.07	0.071242	4.4	4.4364	0.05	0.05866	0.78	0.77885
10	0.05	0.053105	3.2	3.2505	0.175	0.17662	0.5	0.54331

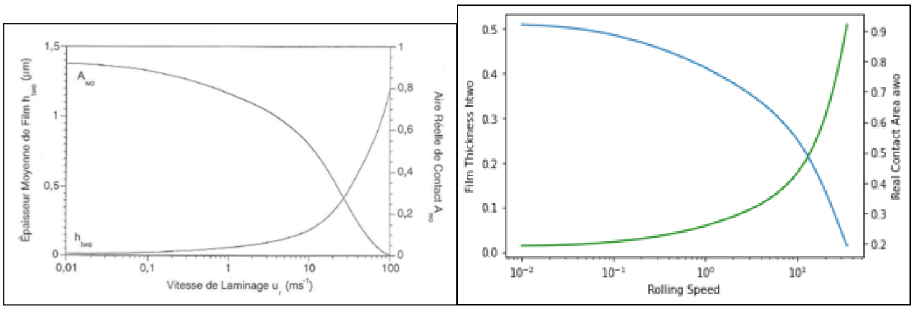
Figure 32: Comparison of values

The below plots shows the comparison of the rolling speed with coefficient of friction and forward slip.Also,the evolution of the film thickness and area of contact at work-outlet boundary.



(a) From Marsault thesis (b) Obtained results

Figure 33: Evolution of friction coefficient and forward slip over the rolling speed



(a) From Marsault thesis (b) Obtained results

Figure 34: Evolution of Film Thickness and Area of Contact at Work-Outlet Boundary

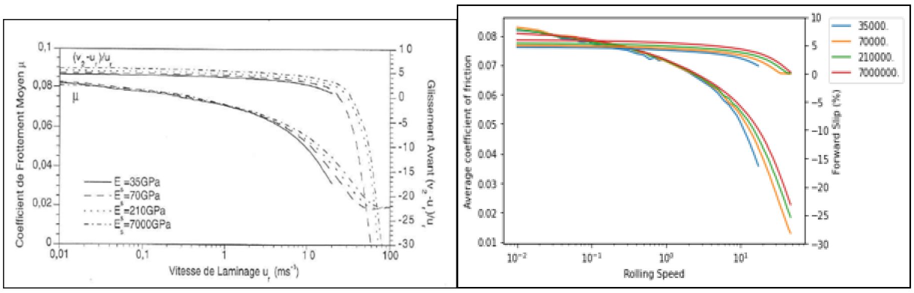
It was observed that for the rolling speed greater than 35m/s,The model wasn't able to predict the output or it wasn't able to handle high speeds.Because for high rolling speed cases,when the model enters the low-speed work zone.The lubrication regime becomes hydrodynamic that is $h_t > R_q$ and the real area of contact drops to zero.Due to this,certain parameters in this zone are tended to infinity or NaN(Not a Number).This leads to an infinity loop situation in the model for some cases and it isn't handled well.By construction, LAM2DTRIBO, model does not allow entering the work area with zero real contact area. The results in Marsault thesis was obtained by modifying and trying different parameter values until the results was obtained.The plot above shows the results for which successful results were obtained(upto rolling speed of 35m/s for this reference case). In the next sections, some parameters have been changed over a certain range to evaluate the convergence of the model. The physical consistency of the obtained results can then be discussed.

12.2 Young Modulus of the strip

To study the influence of Young's Modulus of the strip,The model was tested for different rolling speed in the range of [0.01-100m/s] and for the following values of Young's modulus of the strip,

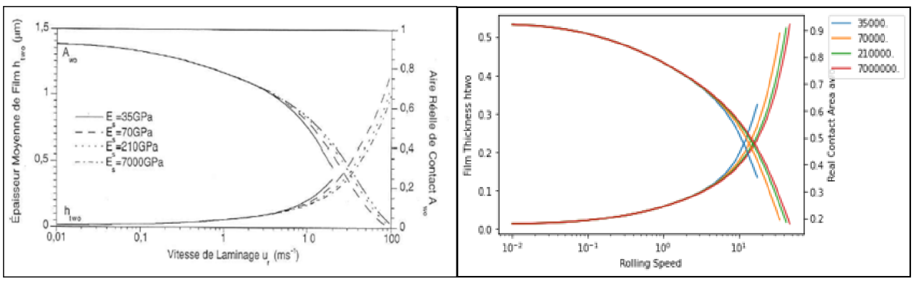
- $E_s = 35$ GPa
- $E_s = 70$ GPa
- $E_s = 210$ GPa
- $E_s = 7000$ GPa (Rigid case)

The below plots show the comparison of different Young's Modulus in respect to rolling speeds with coefficient of friction and forward slip.Also,the evolution of the film thickness and area of contact at work-outlet boundary.The results shown in the obtained results are the results up to the rolling speed for which the computation was completed successfully.In the work by Lugt[1992],the author shows that by taking into account the elastic deformations of the strip and the cylinder,the film thickness inside the roll bite can be multiplied by a factor of 1.5 in case of hydrodynamic regime.But in mixed regime with limited tendency,it can be seen from the plots that there is no influence of elastic deformations on the film thickness and real contact area.



(a) From Marsault thesis (b) Obtained results

Figure 35: Evolution of friction coefficient and forward slip over the rolling speed



(a) From Marsault thesis (b) Obtained results

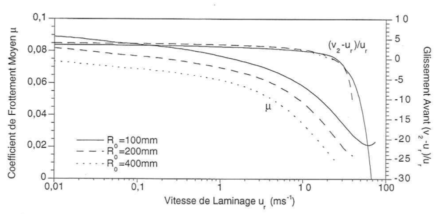
Figure 36: Evolution of Film Thickness and Area of Contact at Work-Outlet Boundary

12.3 Roll radius of the cylinder

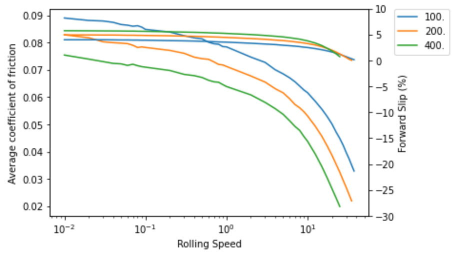
In this section,the cylinder parameter roll radius is studied.The values of Roll Radius considered are,

- $R_0 = 100$ mm
- $R_0 = 200$ mm
- $R_0 = 400$ mm

The below plots shows the comparison of different roll radii in respect to rolling speeds with coefficient of friction and forward slip.Also,the evolution of the film thickness and area of contact at work-outlet boundary is presented. The results shown in the obtained results are the results up to the rolling speed for which the computation was completed successfully.The radius has little influence on the real contact area and film thickness at low speeds.This is because,the Asperity equation which controls the interface at these lubrication is relatively insensitive to the value of the radius.But when the speed increases,the Reynolds equation controls the interface.So,The reduction in radius leads to a reduction in the thickness of the film at the exit of the roll bite.The evolution of the average friction with the radius at low speeds is depended on the choice of tresca friction and the increase in the friction hill with the radius.

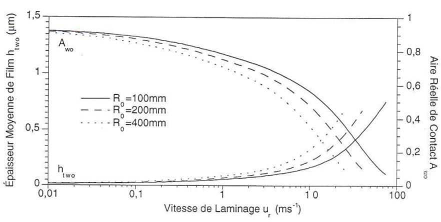


(a) From Marsault thesis

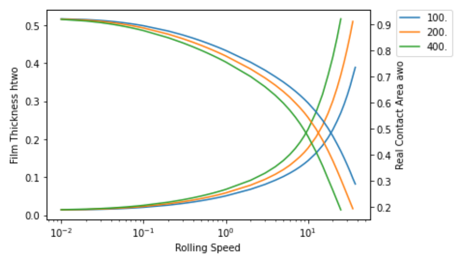


(b) Obtained results

Figure 37: Evolution of friction coefficient and forward slip over the rolling speed



(a) From Marsault thesis



(b) Obtained results

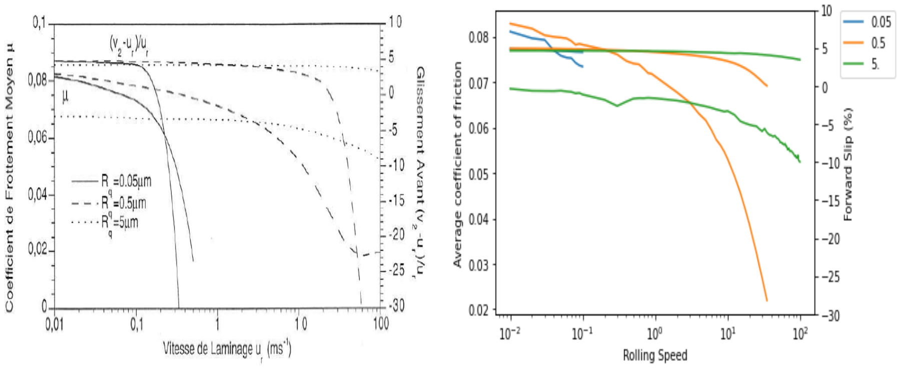
Figure 38: Evolution of Film Thickness and Area of Contact at Work-Outlet Boundary

12.4 Composite Roughness

In this section,the surface parameter composite roughness is studied.The values of composite roughness considered are,

- $R_q = 0.05\mu m$
- $R_q = 0.5\mu m$
- $R_q = 5\mu m$

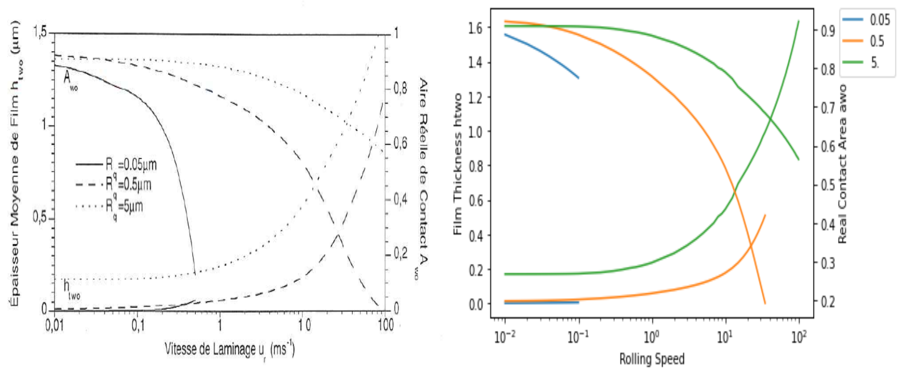
The below plots shows the comparison of different roll radii in respect to rolling speeds with coefficient of friction and forward slip.Also,the evolution of the film thickness and area of contact at work-outlet boundary is presented. It was observed that the roughness has a first order effect on the lubrication,because at constant rolling speed,the thickness of the film entrained in the grip is constant.Also,When the roughness is decreased,the film thickness decreases and the forward slip drops at lower speeds.0



(a) From Marsault thesis

(b) Obtained results

Figure 39: Evolution of friction coefficient and forward slip over the rolling speed



(a) From Marsault thesis

(b) Obtained results

Figure 40: Evolution of Film Thickness and Area of Contact at Work-Outlet Boundary

13 Sensitivity Analysis

Rolling data from a real production mill is used as input parameters of the model.The mill is a 3-stands cold rolling mill,which means,3 pairs of rolls operate successively for the same coil in 1 machine.The stands are named L8,L9, and L10.The results from the L-8 mill are considered for this study.

GOAL :*The goal was to run the LAM2DTRIBO model with the input values extracted from production rolling operation and compare the results obtained to validate the model.Also,to study the effects of various parameters on the friction coefficient.*

The input parameters which are taken from the experimental case are :

- Inlet thickness
- Outlet thickness
- Front tension
- Back tension
- Roll radius
- Rolling speed

The other parameters are set based on the observations made from the Marsault thesis.The influence of lubricant viscosity,Asperity half pitch,Composite roughness and Surface Peklenik number on the friction coefficient is studied.

13.1 Python Script for cluster network

As several computations were needed to be launched for the study,The cluster network of C-TEC known as Vorace was utilised to launch the computations.The parameter values obtained from the mill are stored in a excel sheet.

The goal was to create python scripts to create input files and folders from the Input.csv file,launch the computations in the Vorace cluster network and extract the results to store them in an Output.xlsx file

Two python scripts were developed for this matter.

13.1.1 Python Script 1

The script works in the following manner,

- The Input.csv file-path ,folder name,Input directory of the Source input files and path of the rolling.exe is provided as the input for the script.

```
csvname=r"Input.csv"
Foldername="Rocky"
InputDirectory = r"C:\Users\shettys\Desktop\Code\Tst1\modelling_lam2dtribo\tests\Input"
Rollexepath=r"C:\Users\shettys\Desktop\Code\Tst1\modelling_lam2dtribo\bin\rolling.exe "
```

Figure 41: Inputs for the script

- Based on the input in the Input.csv, the input files for the model are generated and are placed in their specific folder.

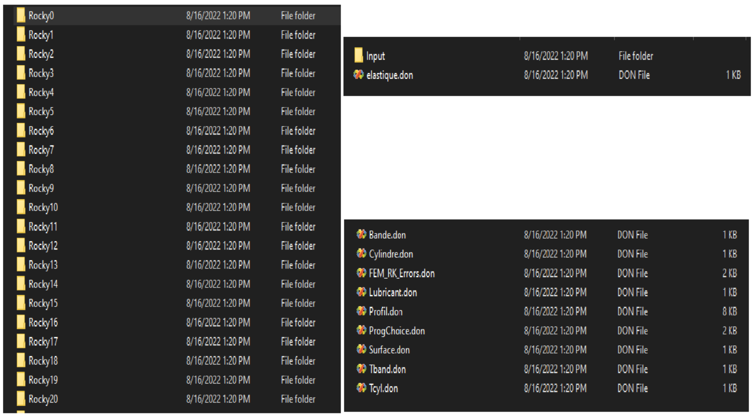


Figure 42: Generation of files

- Once the input files are generated ,the computations are launched in the cluster Vorace by partitions of twenty.

13.1.2 Python Script 2

Once all the computations launched are completed.The Python Script is launched.The script works in the following manner,

- The script extracts the output file (.res) from each computations.This process is performed only for the computations for which the model has generated output.

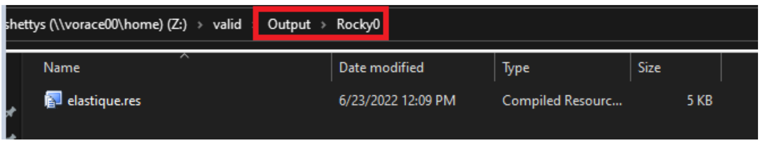


Figure 43: Extraction of the Output files

- Once the above process is completed.The Input and Output values from each computations are stored in an excel sheet

13.2 Parameter Study

13.2.1 Lubricant Viscosity

Lubricant Viscosity is the internal resistance of the lubricant fluid to the flow.It is one of the most important factors in lubrication modelling.

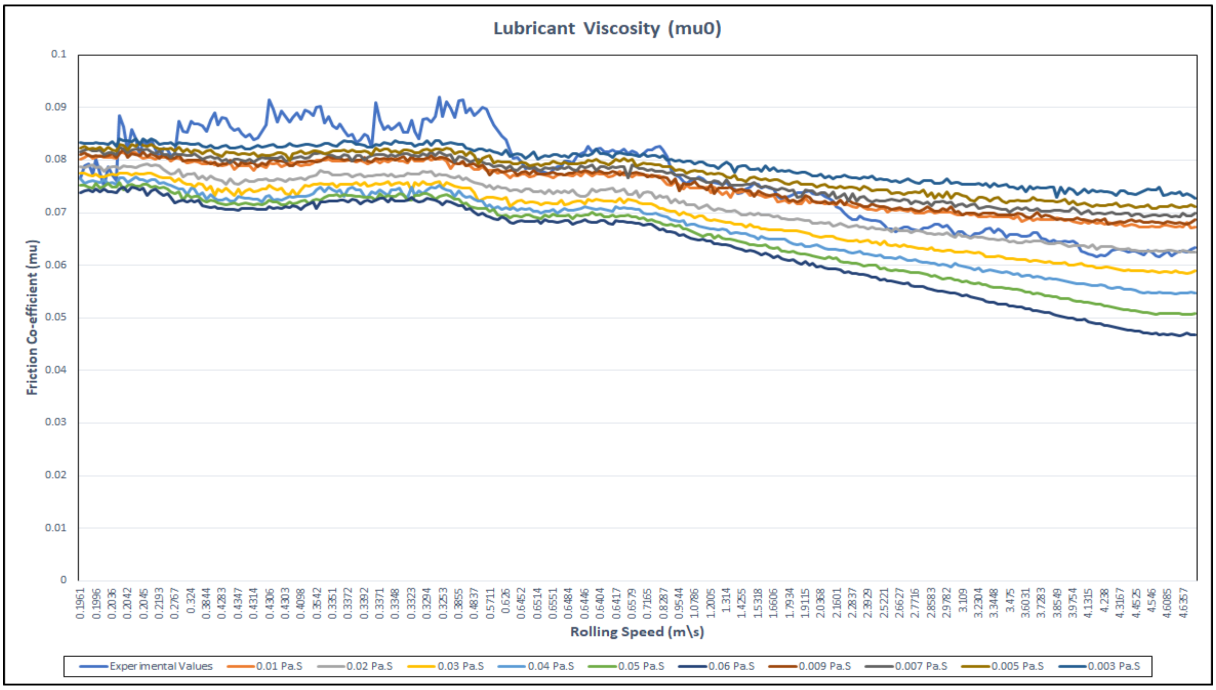


Figure 44: Lubricant Viscosity

Different values of lubricant viscosity were tested and the results obtained were compared with the experimental values.The friction coefficient of the experimental values are plotted directly from the production data.The values of lubricant viscosity tested are,[0.003 Pa.S,0.005 Pa.S,0.007 Pa.S,0.009 Pa.S,0.01 Pa.S,0.02 Pa.S,0.03 Pa.S,0.04 Pa.S,0.05 Pa.S,0.06 Pa.S].The inlet temperature of the lubricant was set to 293F.The fluctuations or the instabilities observed in the experimental values is because in the domain of low rolling speeds which is the running-in stage,the parameters are not stabilised and their evolution can be quick and erratic.The model is not performant to mimic the running-in stage.The fluctuations are stabilised as the rolling speed is increased.

As the lubricant viscosity was increased,the friction coefficient was decreased.For the value of **0.02 Pa.S**,At higher speeds,the result was in agreement with the experimental values.It can be observed that at low rolling speeds,the change of lubricant viscosity has a small effect on the friction coefficient.But as the rolling speed is increased the lubricant viscosity has a significant effect on the friction coefficient.

13.2.2 Asperity Half Pitch

The Strip and work roll have a geometrical surface with peaks, which are called asperities.The asperity half pitch is a surface parameter which is defined as the half of the distance between the two consecutive peaks.

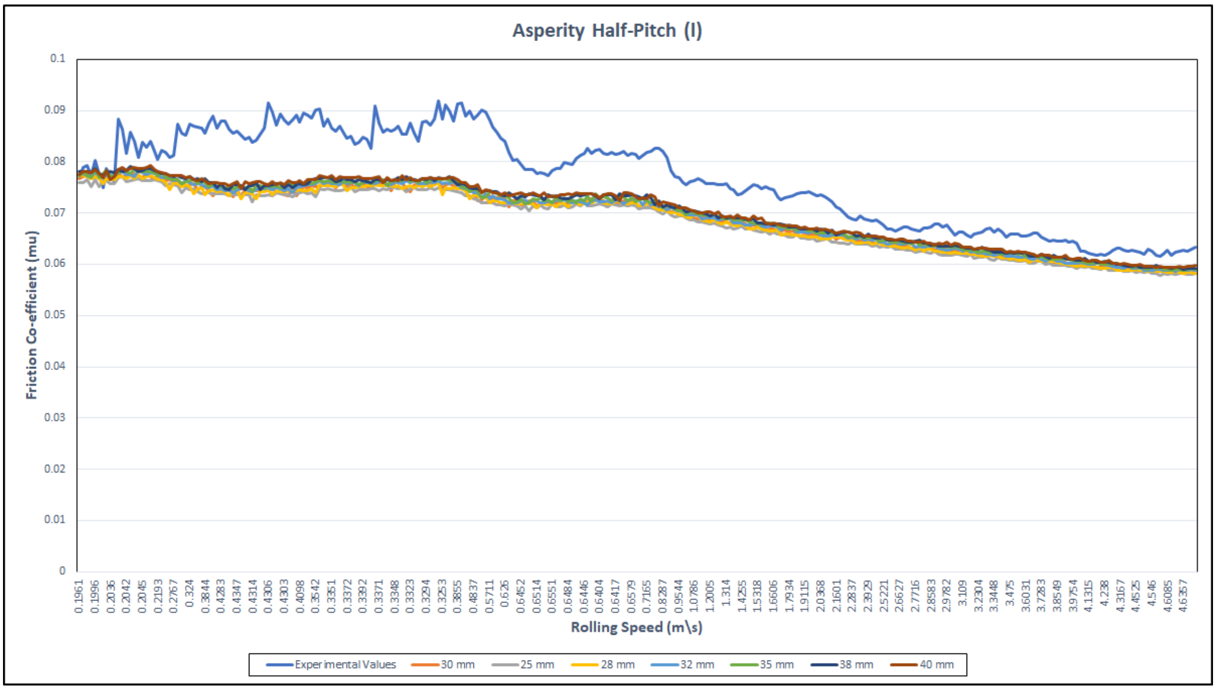


Figure 45: Asperity Half Pitch

Different values of Asperity half pitch was tested and the results obtained was compared with the experimental values.The friction coefficient of the experimental values are plotted directly from the production data.The values of Asperity half pitch tested are,[25 mm,28 mm,30 mm,32 mm,35 mm,38 mm,40 mm].It can be from the results and the comparison in the plots that for different values of asperity half pitch,has **no significant effect** on the friction coefficient.

When the rolling speed is less,the area of contact decreases when the half pitch decreases.Due to this the angle of asperities increases and the asperities are more difficult to crush. As the rolling speed is increased,the differences are reduced,because the Reynolds equation which controls the interface is independent of the values of Asperity half pitch.The friction coefficient follow the same evolution,the differences fade in a mixed regime with a hydrodynamic tendency irrespective of the rolling speed.

13.2.3 Composite Roughness

If $R_{q,r}$ and $R_{q,s}$ are the root mean-square roughness of the roll and the strip,their composite root-mean-square(RMS) is given by

$$R_q = \sqrt{R_{q,r}^2 + R_{q,s}^2} \tag{59}$$

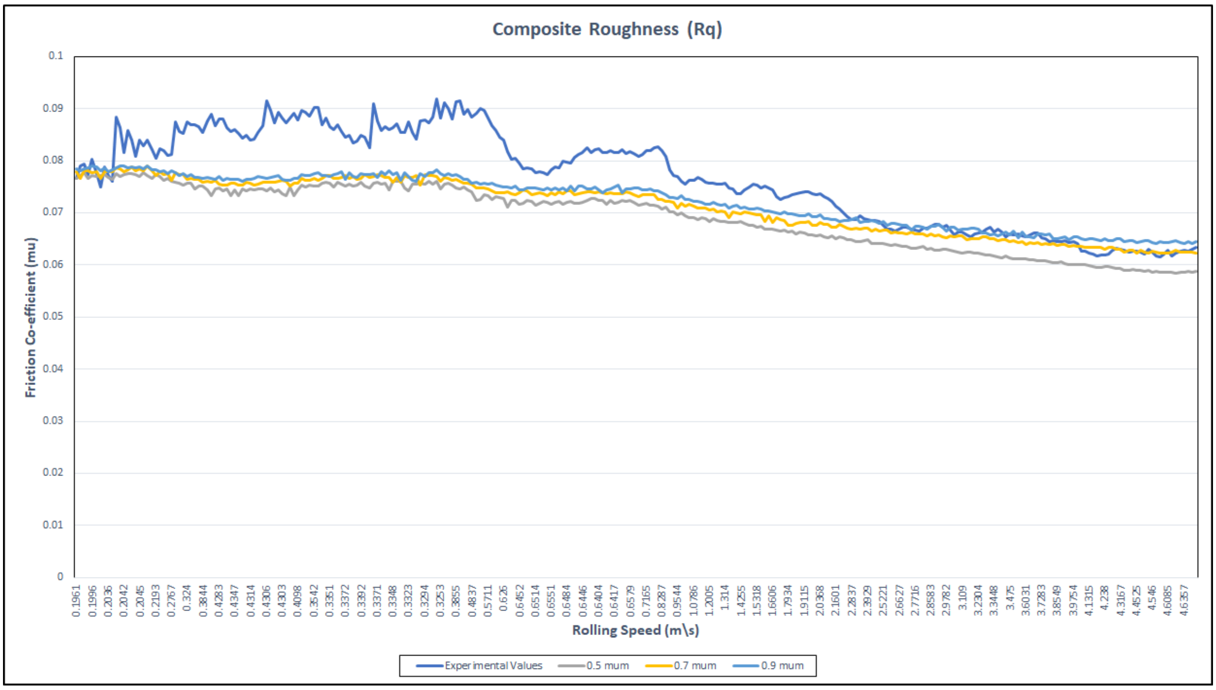


Figure 46: Composite Roughness

Different values of Composite Roughness was tested and the results obtained was compared with the experimental values.The friction coefficient of the experimental values are plotted directly from the production data.The values of Composite Roughness tested are,[0.5,0.7,0.9].As mentioned before,the model is not performant to mimic the running-in stage.Contrary to the other input parameters,the composite roughness has a rather strong influence on the obtained friction values.

From the observations made,As the rolling speed is increased the roughness has an effect on the friction coefficient.Increasing the roughness leads to an increase in the friction coefficient.At high rolling speeds,the optimal value of composite roughness for the experimental case considered is $0.7\mu m$.

13.2.4 Surface Peklenik Number

Peklenik number is a surface parameter which characterises the directional orientation of the roughness.It is defined by the ratio,

$$\gamma = \frac{\lambda_{0.5x}}{\lambda_{0.5y}} \tag{60}$$

The values $\lambda_{0.5x}$ and $\lambda_{0.5z}$ are the lengths at which the auto-correlation function of y,which is the composite roughness height of the roll and the strip,reduces to 50% of its initial value,respectively along x and along z according to Peklenik.

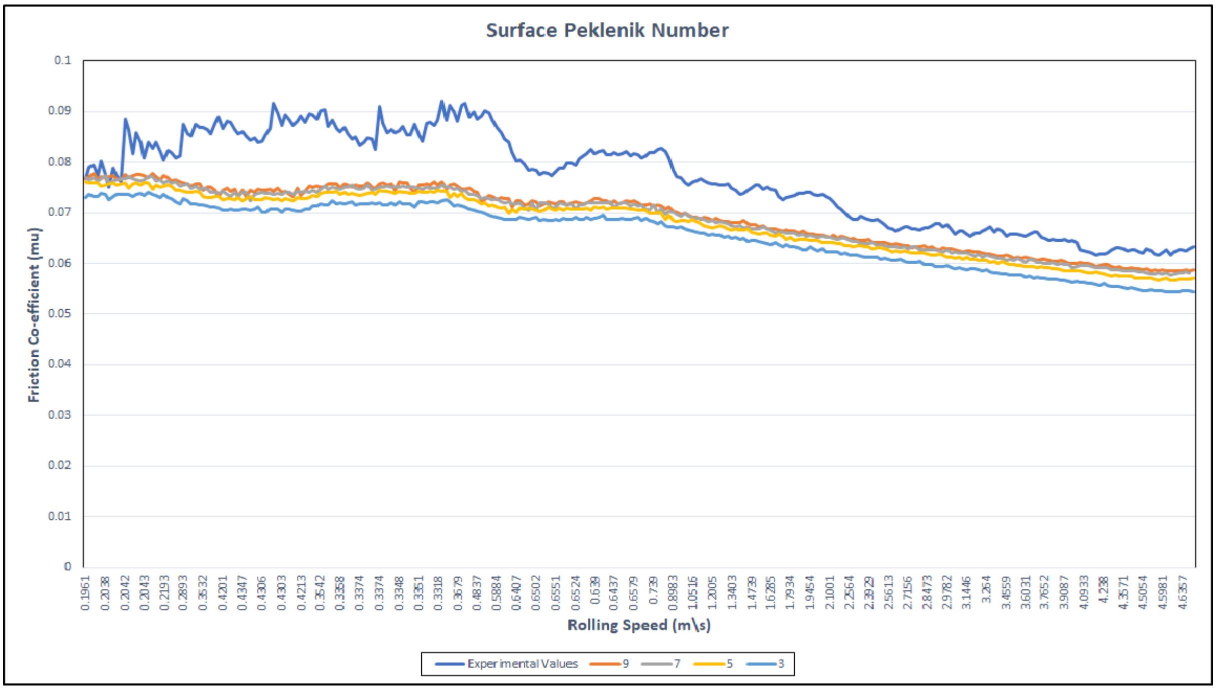


Figure 47: Surface Peklenik Number

Different values of Surface Peklenik number was tested and the results obtained was compared with the experimental values. The friction coefficient of the experimental values are plotted directly from the production data. The values of Surface Peklenik number tested are,[3,5,7,9]. The Peklenik number 9 refers to Longitudinal roughness and 3,5,7 refers to Isotropic roughness. As the Peklenik number is decreased,the friction coefficient is decreased. The Surface Peklenik number **9** is the optimal value for this case. It was also observed that longitudinal orientation generates a smaller film thickness than an isotropic orientation. The Peklenik number has a second order effect in high-speed lubrication condition.But,the orientation of the roughness has a first order effect in a mixed regime with limited tendency.

14 Conclusion

In Conclusion, The LAM2DTRIBO model was studied, described, and several computations were performed to check the computational capacity and robustness of the code. A deep understanding of the theory of the LAM2DTRIBO model and its code was developed. The documentation of the code was prepared.

Next, The Results obtained in the Marsault thesis were reproduced. For this cause, a parametrization code was developed. With the help of this code, the results from a reference case were reproduced.The influence of Rolling speed, Young's modulus of the strip, Roll radius of the cylinder, and the composite roughness were studied. It was observed that the model had convergence issues when it was at high speed and in the hydrodynamic regime. The model does not support the hydrodynamic regime (real area of contact drops to zero).Besides,on a production mill,hydrodynamic regime is almost non-existent in the work zone.So,when the code comes to hydrodynamic regime it diverges from reality.

Then, the sensitivity analysis of the code was performed. The rolling data from a real production mill was used to validate the model. A couple of python scripts were developed to launch the calculations in the cluster network and to extract the results. It was observed, that the model had trouble mimicking the results at low speed, this is because, in the running stage, certain parameters are not stabilized and are erratic. Also, Lubricant viscosity has a significant effect on the friction coefficient,as well as roughness.Different roughness parameters(Asperity half pitch,Composite roughness,Surface peklenik number) has been tuned to fit the experimental data.

15 Future Work

As a scope for future work, Improvements can be made to the convergence issues observed at high speeds by improving the physics related to the high speed and the hydrodynamic regime.To do so,deeper understanding of key parameters is required,as many of them are evolving along the roll bite.

Improvements can be carried out on the LAM2DTRIBO model. The code of LAM2DTRIBO is written in Fortran77, so converting the code to a more powerful programming language like C will improve the computational time and efficiency of the model. Also, the model has several nested loops and each nested loop has to satisfy certain convergence criteria to exit the loop and get to the outer loop. So, improving the convergence rate or the convergence criteria of these loops will certainly improve the model efficiency.

16 Bibliography

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17 Appendix

17.1 Snippets of the python script for the Parametrisation code

The snippets of the python script of the parametrisation code is presented in this section.

```
####################### Mention the parameter ################################

Parameter = "Ur = "
# Few Examples:"Ur = " for Rolling Speed
#              "R0 = " for Roll Radius
#              "Es = " for Young's Modulus of the strip

##################### Mention the second parameter #########################

Parameter1="Es ="
# Few Examples:"Rq = ",lsurf = "

################### Input File name of the Parameter ########################

Inputfilename = ["\Cylindre.don","\Bande.don"]

################## Path of the executable Rolling.exe #######################

Rollexepath=r"C:\Users\shettys\Desktop\Code\Tst1\modelling_lam2dtribo\bin\rolling.exe "

################## Name of the Input File to the Model ######################

donpath=r"elastique.don"

#################### Path of the Input Files ################################

InputDirectory = r"Tst1\modelling_lam2dtribo\tests\Input"
```

Figure 48: Inputs for the code

```
################ Options for Computations and Post-processing ################

Change = 0
# 0 for launching multiple computations in parallel
# 1 for launching a single computation
# 2 for not launching computations

Post_Process = 1
# 0 for launching Post-processing
# 1 for not launching Post-processing

################# Values of the first parameter #############################

Values=["35.0","35.1","35.2","35.3","35.4","35.5","35.6","35.7","35.8","35.9","36.0"]

################# Values of the second parameter ############################

Val=["35000.","70000.","210000.","7000000."]
```

Figure 49: Program choices and Parameter values

```
###################Creating a New directory and Input File####################

   Foldername=Foldern+r"\No"
   filename = Foldername+str(i)+r"\Input\Cylindre.don"
   os.makedirs(os.path.dirname(filename), exist_ok=True)

   outputname=r"Output"
   os.mkdir(Foldername+str(i)+r"\Output")

######### Opening the new file and replacing the desired Parameter ############

   with open(filename, "w") as f:

    for line in lines:

     index=line.find(Parameter)
     index1=line.find(Parameter1)

     if(index>=0):
      Var1=line.partition(Parameter)[2]
      #Var1_replace=r"0.0"+str(i)+r"D0"
      x = line.replace(Var1, Values[i])
      f.write(x)
      f.write("\n")
      continue

     f.write(line.strip())
     f.write("\n")
```

Figure 50: Creating a new directory and Input file

```
################## Copying the Remaining Input Files ###########################

    if(Inputfilename[0] != "\Bande.don"):
      Bandedon= Foldername+str(i)+r"\Input\Bande.don"
      Bandedon_original = InputDirectory+"\Bande.don"
      shutil.copyfile(Bandedon_original, Bandedon)

   if(Inputfilename[0] != "\Cylindre.don"):
     Cylindredon= Foldername+str(i)+r"\Input\Cylindre.don"
     Cylindredon_original = InputDirectory+"\Cylindre.don"
     shutil.copyfile(Cylindredon_original, Cylindredon)

   if(Inputfilename[0] != "\Lubricant.don"):
     Lubricantdon= Foldername+str(i)+r"\Input\Lubricant.don"
     Lubricantdon_original = InputDirectory+"\Lubricant.don"
     shutil.copyfile(Lubricantdon_original, Lubricantdon)

   if(Inputfilename[0] != "\Profil.don"):
     Profildon= Foldername+str(i)+r"\Input\Profil.don"
     Profildon_original = InputDirectory+"\Profil.don"
     shutil.copyfile(Profildon_original, Profildon)

   if(Inputfilename[0] != "\ProgChoice.don"):
     ProgChoicedon= Foldername+str(i)+r"\Input\ProgChoice.don"
     ProgChoicedon_original = InputDirectory+"\ProgChoice.don"
     shutil.copyfile(ProgChoicedon_original, ProgChoicedon)

   if(Inputfilename[0] != "\Surface.don"):
      Surfacedon= Foldername+str(i)+r"\Input\Surface.don"
      Surfacedon_original = InputDirectory+"\Surface.don"
      shutil.copyfile(Surfacedon_original, Surfacedon)
```

Figure 51: Copying the Input files

```
################## Running the Program with New Parameter ######################

   os.chdir(r"C:\Users\shettys\Desktop\Code\\"+Foldername+str(i)+r"\Input")

   #os.system(exedon)
   with open(r"C:\Users\shettys\Desktop\Code\\"+Foldername+str(i)+r"\Output\Output.txt", "w") as f:
    subprocess.Popen(exedon, shell=True,stdout=f)

   os.chdir(Progfilepath)
```

Figure 52: Running the Program with new parameters

```
################### Generation of Status Report ##############################

 time.sleep(180)
 status=[]
 for g in range(0,len(Values)):
  chek=r"C:\Users\shettys\Desktop\Code\\"+Foldername+str(g)+r"\Output\Output.txt"
  z=1;nooflines=0;fail=0;

  if os.path.exists(chek):
         with open(chek) as openfile:
             for line in openfile:
                 nooflines+=1;
                 if "Integrate                    61" in line:

                     while z==1:
                       with open(chek) as openfile:
                        for line in openfile:
                          if "Temps de calcul : " in line:
                             time.sleep(10)
                             z=2;
                             status.append("OK" )
                             print("Time ",g);

                          elif "Where Do We Stop" in line:
                              time.sleep(10)
                              z=2;
                              status.append("Stopped" )
                              print("Stop ",g);

                 else :
                     fail+=1;

  if  nooflines==fail:
   status.append("Error" )
   print("Fail",g)


 with open(r"C:\Users\shettys\Desktop\Code\\"+Folder+r"\status"+str(b)+r".txt", 'w') as f:
   for m in range(0,len(Values)):
    f.write(Foldername+str(m)+r"   "+Parameter1+Val[b]+r"   "+Parameter+Values[m]+r"    Status = "+status[m])
    f.write("\n")
```

Figure 53: Generation of Status report

```
########################## Functions ##########################################

def ban():

       global x,Sxx,Syy,Szz,Ep,Vx

       ban = pd.read_csv('elastique.ban',sep='\s+',header=None)
       ban = pd.DataFrame(ban)

       x       = ban[0][1:].astype(float)
       Sxx     = ban[1][1:].astype(float)
       Syy     = ban[2][1:].astype(float)
       Szz     = ban[3][1:].astype(float)
       Ep      = ban[4][1:].astype(float)
       Vx      = ban[5][1:].astype(float)

def lub():

    global x,h,ht,Aire,Pa,Pb,Pmoy,Tauf

    lub = pd.read_csv("elastique.lub",sep='\s+',header=None)
    lub = pd.DataFrame(lub)

    x     = lub[0][1:].astype(float)
    h     = lub[1][1:].astype(float)
    ht    = lub[2][1:].astype(float)
    Aire  = lub[3][1:].astype(float)
    Pa    = lub[4][1:].astype(float)
    Pb    = lub[5][1:].astype(float)
    Pmoy  = lub[6][1:].astype(float)
    Tauf  = lub[7][1:].astype(float)
```

Figure 54: Function definition

```
########################### Post-Processing ###################################

if(Post_Process==0):

 for b in range(0,len(Val)):
  Foldern=Folder+r"\Par"+str(b)
  Foldername=Foldern+r"\No"
  comp_time=np.zeros(len(Values))
  forward_slip=np.zeros(len(Values))
  inlet_strip_speed=np.zeros(len(Values))
  outlet_strip_speed=np.zeros(len(Values))
  flow_constant=np.zeros(len(Values))
  roll_sep_force=np.zeros(len(Values))
  roll_torque=np.zeros(len(Values))
  mu=np.zeros(len(Values))
  htwo=np.zeros(len(Values))
  awo=np.zeros(len(Values))

  for t in range(0,len(Values)):

    check=r"C:\Users\shettys\Desktop\Code\\"+Foldername+str(t)+r"\Output\Output.txt"

    if os.path.exists(check):
        with open(check) as openfile:
         for line in openfile:
            if "Temps de calcul : " in line:
                line = line.replace("Temps de calcul :", "")
                line = line.replace("s", "")
                comp_time[t]=(float(line))

    else:
        print("Error")
```

Figure 55: Post-processing

```
##################### Plots Related to elastique.lub ###########################
   if os.path.exists("elastique.lub"):
    lub()

    plt.plot(x, ht)
    plt.xlabel('x [mm]')
    plt.ylabel('ht[micron]')
    plt.title('x [mm] vs ht[micron]',loc='center')
    plt.savefig("x[mm] vs ht[micron] ")
    plt.savefig(r"x [mm] vs ht[micron] ")
    plt.show()

    plt.plot(x, h)
    plt.xlabel('x [mm]')
    plt.ylabel('h [micron]')
    plt.title('x [mm] vs h [micron]',loc='center')
    plt.savefig("x[mm] vs h [micron] ")
    plt.savefig(r"x [mm] vs h [micron] ")
    plt.show()
```

Figure 56: Plots related to the output files

```
#########################Comparison Plots ####################################

  for p in range(0,len(Values)):

     os.chdir(r"C:\Users\shettys\Desktop\Code\\"+Foldername+str(p)+r"\Output")
     if os.path.exists("elastique.lub"):
      lub()

      plt.plot(x, ht ,label=Values[p])
      plt.xlabel('x [mm]')
      plt.ylabel('ht[mm]')
      #plt.xlim([-10, 5])
      plt.legend(bbox_to_anchor=(1.05, 1), loc='upper left', borderaxespad=0)
  plt.savefig(r"C:\Users\shettys\Desktop\Code\\"+Foldern+r"\x [mm] vs ht[mm]")
  plt.show()

  for p in range(0,len(Values)):

     os.chdir(r"C:\Users\shettys\Desktop\Code\\"+Foldername+str(p)+r"\Output")
     if os.path.exists("elastique.lub"):
      lub()

      plt.plot(x, h ,label=Values[p])
      plt.xlabel('x [mm]')
      plt.ylabel('h[mm]')
      #plt.xlim([-10, 5])
      plt.legend(bbox_to_anchor=(1.05, 1), loc='upper left', borderaxespad=0)
  plt.savefig(r"C:\Users\shettys\Desktop\Code\\"+Foldern+r"\x [mm] vs h [mm]")
  plt.show()
```

Figure 57: Comparison plots

```
####################### Comparison plots of all parameters ####################################################
 for b in range(0,len(Val)):

  htwo=[]
  awo=[]
  comb=[]

  Foldern=Folder+r"\Par"+str(b)
  Foldername=Foldern+r"\No"
  print("b ",b)
  if b==0:
   for p in range(0,len(Values0)):

      residual= r"C:\Users\shettys\Desktop\Code\\"+Foldername+str(p)+r"\Output\elastique.res"
      #print("p ",p)
      if os.path.exists(residual):
          with open(residual) as openfile:
              for line in openfile:


                  if "Film Thickness at the Work-Outlet Boundary (mum)" in line:
                       line = line.replace("Film Thickness at the Work-Outlet Boundary (mum)    ht =", "")
                       htwo.append(float(line))
                       comb.append(float(Values0[p]))

                  if "Area of Contact at the Work-Outlet Boundary  " in line:
                       line = line.replace("Area of Contact at the Work-Outlet Boundary         A  =", "")
                       awo.append(float(line))
```

Figure 58: Comparison plots of all parameters

17.2 Snippets of the python script for the Cluster network

The snippets of the python script for the cluster network is presented in this section.

```
# reading CSV file
data = read_csv("Input.csv")
Foldername="Rocky"
InputDirectory = r"C:\Users\shettys\Desktop\Code\Tst1\modelling_lam2dtribo\tests\Input"
Rollexepath=r"C:\Users\shettys\Desktop\Code\Tst1\modelling_lam2dtribo\bin\rolling.exe "

# converting column data to list
Inlet_Thickness = data['Inlet_Thickness'].tolist()
Outlet_Thickness = data['Outlet_Thickness'].tolist()
Front_Tension  = data['Front Tension '].tolist()
Back_Tension = data['Back Tension'].tolist()
YoungModulusofstrip = data["Young\'s Modulus of strip"].tolist()
poissonsratio = data['poisson\'s ratio'].tolist()
Initial_yield_stress = data['Initial yield stress'].tolist()
Strain_coef = data['Strain coef'].tolist()
Strain_hardening_exponent = data['Strain hardening exponent'].tolist()
Initial_temperature = data['Initial temperature'].tolist()
Heat_capacity = data['Heat capacity'].tolist()
fplasticity = data['fplasticity'].tolist()

Roll_Radius = data['Roll Radius'].tolist()
Roll_Surface_speed = data['Roll Surface speed'].tolist()
YoungsModulus = data['Young\'s Modulus'].tolist()
poissons = data['poisson\'s'].tolist()
Initial_Temperature = data['Initial Temperature'].tolist()
```

Figure 59: Input parameters and reading the data

```
######################################### File creation Bande.don ##########################################################

rows=len(itherm)

for i in range(rows):
    filename=r"Z:\valid\\"+Foldername+str(i)+r"\Input\Bande.don"
    os.makedirs(os.path.dirname(filename), exist_ok=True)

    with open(r"Z:\valid\\"+Foldername+str(i)+r"\Input\Bande.don", "w") as f:
         f.write("Inlet Strip Thickness (mm)                                      t1 = "+str(Inlet_Thickness[i])+"\n")
         f.write("Outlet Strip Thickness (mm)                                     t4 = "+str(Outlet_Thickness[i])+"\n")
         f.write("Front Tension (MPa)                                         frontt = "+str(Front_Tension[i])+"\n")
         f.write("Back Tension (MPa)                                           backt = "+str(Back_Tension[i])+"\n")
         f.write("\n")
         f.write("Strip Elastic Behavior \n")
         f.write("Young's Modulus (MPa)                                          Es = "+str(YoungModulusofstrip[i])+"\n")
         f.write("Poisson's Ratio                                               nu = "+str(poissonsratio[i])+"\n")
         f.write("\n")
         f.write("Strip Plastic Behavior Sigma0=Y(1+K eps)^n \n")
         f.write("Initial Yield Stress (MPa)                                     Ys = "+str(Initial_yield_stress[i])+"\n")
         f.write("Strain Coefficient                                             Ks = "+str(Strain_coef[i])+"\n")
         f.write("Srain Hardening Exponent                                      xns = "+str(Strain_hardening_exponent[i])+"\n")
         f.write("\n")
         f.write("Strip Thermal Behavior \n")
         f.write("Initial Temperature (Kelvin)                              T0band = "+str(Initial_temperature[i])+"\n")
         f.write("Heat Capacity (J.K-1.m-3)                                   rauc = "+str(Heat_capacity[i])+"\n")
         f.write("Part of the Plastic Work Changed into Heat [0;1]       fplasticity = "+str(fplasticity[i])+"\n")
         f.close()
```

Figure 60: File creation of Bande.don

```
################################Launching the model in the cluster network #########################################

run_command='run -s rolling-D2_1_3 -f elastique.don -p twenty'

change_direct=r"/home/shettys/valid/"

name="elastique.res"


for i in range(rows):

   cd1=change_direct+filename+str(i)

   os.chdir(change_direct+filename+str(i))

   subprocess.call([run_command], shell=True)
```

Figure 61: Launching the model in the cluster network

```python
###################### Extraction of the elastique.res ##########################################

subprocess.call(["mkdir Output"],shell=True)
def find(name, path):
    for root, dirs, files in os.walk(path):
        if name in files:
            return os.path.join(root, name)


for i in range(rows):

    path=change_direct+filename+str(i)
    creat="mkdir Output/"+filename+str(i)
    subprocess.call([creat],shell=True)
    x=find(name, path)
    if x is not None :
     op="cp "+x+" Output/"+filename+str(i)
     subprocess.call([op], shell=True)
    else:
     continue
```

Figure 62: Extraction of the elastique.res

```python
################## Extraction of Output values ##################################

for r in range(rows-1):

    residual= r"Z:\valid\Output\\"+Foldername+str(r)+r"\elastique.res"

    if os.path.exists(residual):
        with open(residual) as openfile:
            for line in openfile:
               if "Forward Slip (%)" in line:
                   line = line.replace("Forward Slip (%)                              v4/ur =", "")
                   forward_slip[r]=(float(line))

               if "Inlet Strip Speed (m/s)" in line:
                   line = line.replace("Inlet Strip Speed (m/s)                          v1 =", "")
                   inlet_strip_speed[r]=(float(line))

               if "Outlet Strip Speed (m/s)" in line:
                   line = line.replace("Outlet Strip Speed (m/s)                         v4 =", "")
                   outlet_strip_speed[r]=(float(line))

               if "Flow Constant" in line:
                   line = line.replace("Flow Constant                                     c =", "")
                   flow_constant[r]=(float(line))

               if "Roll Separating Force (tons/m)" in line:
                   line = line.replace("Roll Separating Force (tons/m)               Force = ", "")
                   roll_sep_force[r]=(float(line))

               if "Roll Torque (kg.m/m)" in line:
                   line = line.replace("Roll Torque (kg.m/m)                          Torque =", "")
                   roll_torque[r]=(float(line))

               if "Average Value of tau/p in the Work Zone" in line:
                   line = line.replace("Average Value of tau/p in the Work Zone           mu =", "")
                   mu[r]=(float(line))

               if "Film Thickness at the Work-Outlet Boundary (mum)" in line:
                    line = line.replace("Film Thickness at the Work-Outlet Boundary (mum)    ht =", "")
                    htwo[r]=(float(line))

               if "Area of Contact at the Work-Outlet Boundary   " in line:
                    line = line.replace("Area of Contact at the Work-Outlet Boundary          A  =", "")
                    awo[r]=(float(line))
```

Figure 63: Extraction of Output values

```python
###################### Writing to the excel file ###########################################################
outWorkbook = xlsxwriter.Workbook("valid\output.xlsx")
outSheet = outWorkbook.add_worksheet()

outSheet.write("A1", "Status")

outSheet.write("B1", "Inlet_Thickness")
outSheet.write("C1", "Outlet_Thickness")
outSheet.write("D1", "Front_Tension")
outSheet.write("E1", "Back_Tension")
outSheet.write("F1", "Es")
outSheet.write("G1", "Nus")
outSheet.write("H1", "Ys")
outSheet.write("I1", "Ks")
outSheet.write("J1", "Xns")
outSheet.write("K1", "T0band")
outSheet.write("L1", "rauc")
outSheet.write("M1", "fplasticity")

outSheet.write("N1", "Roll_Radius")
outSheet.write("O1", "Roll_Surface_Speed")
outSheet.write("P1", "Ec")
outSheet.write("Q1", "xnuc")
outSheet.write("R1", "T0cyl")

outSheet.write("S1", "Lubricant_viscosity")
outSheet.write("T1", "Viscosity_p")
outSheet.write("U1", "Viscosity_t")
outSheet.write("V1", "Tlub0")
```

Figure 64: Writing to the excel file