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Modelling of metal forming lubrication by O/W emulsions

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Summary: *Oil lubrication of cold steel strip tandem rolling mills generally leads to decreasing friction when rolling speed increases; these transients impact on the pre-setting of the mill. Most mills however are lubricated with emulsions. In this case, various behaviors may be found: friction may either increase, decrease or remain stable as speed increases. This is due to a combination of factors (oil output through the nozzles, plate-out film formed ahead of the bite entry, and oil emulsion concentration in the bite inlet zone), connected both with fluid mechanics and with the physics and chemistry of emulsions. Models of film formation from emulsion and of mixed lubrication regime in strip rolling are used and connected to investigate these phenomena on pilot-mill experimental data. Parallels are drawn with measurements in EHD cylinder-on-disk experiments [1-3]. The results point to the importance of oil starvation mechanisms.*

Key words: Lubrication, emulsion, modeling, cold strip rolling

1. INTRODUCTION

Neat oil lubricated cold strip rolling mills generally show a decreasing rolling load as rolling speed increases, mainly due to the growth of the oil film thickness by hydrodynamic lubrication effects [1-2]. The opposite trend is rarely encountered, on some multi-stand mills where temperature may increase with speed to such an extent at some stands, that oil degrades and friction increases at higher speeds.

With emulsions, any possible speed-dependency may be found: friction (and load) may decrease, be rather stable, or increase, progressively or suddenly at a critical speed [3]. A full understanding of the origin of such behaviors would require observation of the oil droplets in a rolling mill bite entry, which is extremely difficult. But one may refer to observations under laboratory conditions, in EHD sphere / plane or cylinder / plane conjunctions [4-7]. The following conclusions can be drawn from these studies (figure 1, after [5]):

- At very low speed (i.e. below 0.01 – 0.1 m.s^{-1} depending on the emulsion), an oil pool is formed ahead of the conjunction by coalescence of oil droplets [4]; this is an emulsion inversion phenomenon. The measured film thickness is exactly what is expected from EHD theory for the pure oil. Only oil goes into the bite, water is rejected; oil lubrication conditions prevail.
- At intermediate speeds (0.01 – 1 m.s^{-1} in figure 2), the oil pool disappears (or becomes too small to be detected), and the film thickness – speed curve levels off. In some cases, it even drops in a very similar way to starvation phenomena in oil lubrication. This is particularly the case in figure 1 for unstable (pH=5), high concentration emulsions; emulsifier concentration is quite important in this respect [6], as is the "displacement energy" concept [8].

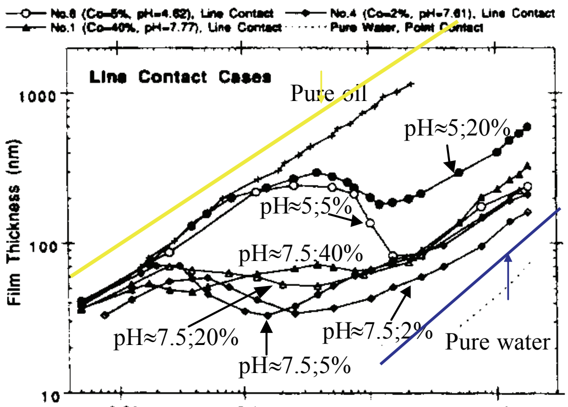

***Figure 1**. Interferometric measurement of film thickness as a function of entrainment speed in a cylinder / plane EHD line contact in pure rolling (after [5]).*

- Above 1 m.s^{-1}, the film thickness increases again, and it seems that a water + oil mixture goes through the bite (its concentration is not

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known). The film thickness – speed curve becomes parallel to the pure water EHD theoretical curve, which means that the system again behaves according to EHD theory, with a fluid which is more viscous than water.

These mechanisms are deeply influenced by the complex flow of the water and oil phases on both leading and trailing sides of the contact, and in particular by the lubrication system used.

Referring now to cold strip rolling, the hypothetical evolution of fluid films is quite complex (figure 2) as well. Sprays ahead of the bite bring in both water and oil. Depending on the wetting properties of the oil, a rather thick oil film may be deposited ahead of the bite (in particular in the Direct Application [DA] systems) and this "plate-out" phenomenon plays a prominent role in bite lubrication. Such an incoming film may also be the remnant of the lubrication of the previous stands. Then, oil droplets from the sprays of the current stand will undergo concentration / inversion phenomena as explained above.

If we assume conditions such that a pure oil film goes through the bite, we still have to examine what occurs at bite exit: the film will split in two parts (cavitation), one goes with the strip and the other with the roll. The film on the roll may be washed more or less by a coolant spray (emulsion or water), be thinned by wipers, and squeezed by the work-roll – back up roll contact; only a small part of it will then reach bite entry again and reinforce lubrication. The film on the strip will also be impacted by the coolant cascading from the spray and roll, and may be partly or completely washed away or re-emulsified before the next stand.

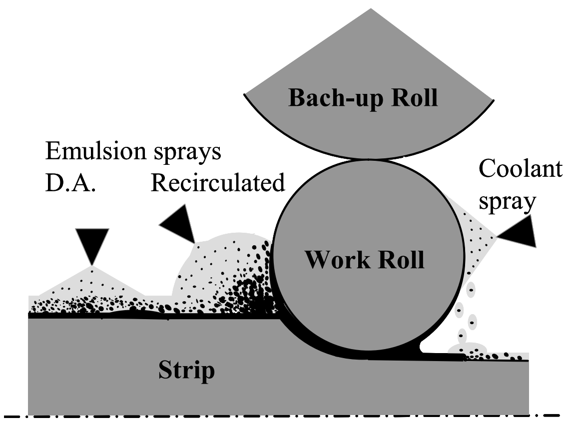

Figure 2 *Schematic description of oil film formation and destruction. Oil is in black, water in light grey.*

The fundamental hypothesis of the present paper is that oil concentration and emulsion inversion phenomena occur on the inlet side in strip rolling, similar to what has been measured in EHD devices, albeit in a different speed range due to significantly different conditions, and that this provides the explanation of the rolling speed effects on friction. Based on this idea, a model of film formation from an emulsion in the inlet zone is presented first, then a fully coupled (roll elastic deformation / strip plastic deformation / mixed lubrication interfacial model). Both are used sequentially to determine the lubrication regime, the rolling load, forward slip and final oil / emulsion film thickness and concentration in the bite. Comparison with experimental results will be described and analyzed; it must be emphasized however that the post-bite behavior was poorly controlled in these experiments, so that the interpretations given in the following are qualitative only.

2. MODELS

2.1. Emulsion film formation model

Two types of biphasic fluid flow models have been proposed to explain the experimental observations and predict the behavior of the system. Szeri's combination of a two-field biphasic model with Hydrodynamic Lubrication Hypotheses (HLH) results in a biphasic extended Reynolds equation [9] which shows the concentration of the oil ahead of the bite, as the less-viscous water is preferentially repelled in the high-shear rate backflow. Wilson and Schmid [10,11] argued that a continuum model can apply only where the gap is much larger than the droplet size, which is clearly not the case in EHD experiments or in strip rolling, where droplet size is a few µm, whereas the measured film thickness is a few hundred nanometers. They built a model privileging the droplet / solid surfaces interaction, illustrated in figure 3. Oil concentration starts when droplets, after first contacting the surfaces, have been flattened by a certain factor C (end of supply region, gap thickness h_s). They are then drawn into the convergent by the moving surfaces (entrainment velocity $U = (V_{roll} + V_{strip})/2$). As the gap reduces, they are more and more flattened, grow in diameter and eventually coalesce (inversion point, gap thickness h_i), which ends the concentration region. The pressure growth may then start, due to the higher viscosity of the continuous oil as compared to water. When the pressure has reached the strip yield stress, the roll bite begins (thickness h_c).

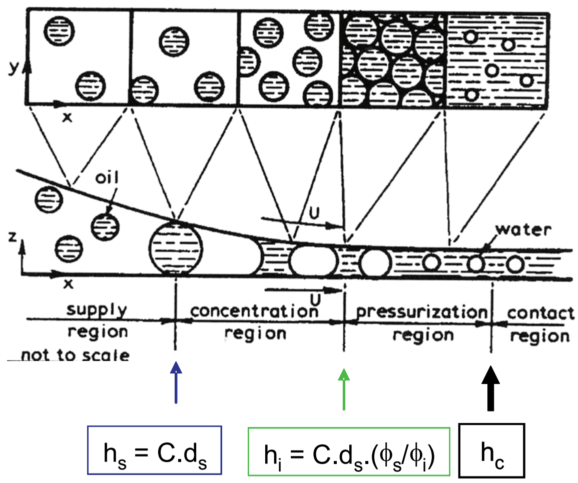

Figure 3. *Schematic description of Wilson and Schmid's model [10,11] ; d_s is the droplet diameter.*

This model is attractive since it is based quite directly on the observation and represents quite well the measured phenomena, as shown below. In this respect, it has been found superior to Szeri's model, this is why it is used in the following. It puts emphasis on the surface / droplet interaction forces rather than on the droplet / water interaction forces. Its disadvantage is the very strong impact of the unknown and arbitrary C factor, which is however moreover in line with Kimura and Okada's "trapping efficiency" concept [8]. In a previous paper, we have proposed to mix the two models, Szeri's model upstream, where the gap is larger than the droplet size, changing for Wilson and Schmid's model closer to the bite, when the droplet size equals the gap [12]. The former starts the concentration and brings a more concentrated emulsion at h_s, where the latter starts, resulting in slightly thicker films and higher oil concentration. However, the essence of the phenomena are unchanged and only Wilson and Schmid's model will be used in the following, for the sake of simplicity. The reader is referred to [12] for the details of the equations and the iterative solution method.

2.2. Strip rolling model

The 2D strip rolling model has been described first in [13]; in the following, an enhanced version [14] is used. It combines:

- The slab method to solve the elastic-plastic strip deformation equations and equilibrium equations (stresses and strains depend on abscissa x only);
- A 2D influence function method to compute the roll deformation;
- An interfacial model based on [15], solving Reynolds equation with flow factors to represent the effect of rough surfaces, and a roughness peak flattening equation.

From the numerical point of view, the core of the algorithm is based on a double shooting technique:

- on the lubricant throughput, as appears in Reynolds equation; the criterion is that the fluid pressure should come back to zero at the exit of the bite (where the strip normal stress comes to zero as well);
- on the strip speed (or forward slip), based on the strip longitudinal stress reaching the imposed tension stress at bite exit.

A third, external loop computes iteratively the roll elastic deformation and adjusts the roll centre position so as to maintain the exit film thickness constant.

Apart from the usual strip rolling data, the input of the model comprise strip / roll cumulated roughness (RMS, Peklenik's number, autocorrelation distance) and lubricant rheology $\eta(T,p)$: $\eta_0(T)$ and γ as in Barus' equation, or the coefficients of Roeland's equation [13]. One of the most important data is the boundary friction factor on the real area of contact, noted m_a.

The results of the model are microscopic characteristics of the surface (local fractional area of contact A(x), local lubricant film thickness h(x), local friction $\mu(x)$), together with usual output of a strip rolling model (rolling load and torque, forward slip, strip stresses, roll deformed profile…).

2.3. Connection between the two models

One of the new features of the rolling model is that it can model starvation effects, i.e. the input of a limited amount of oil on the strip / roll surface which decreases the lubricant film thickness in the bite. For emulsions, use has been made of this capability, by introducing as an input film the thickness of the gap at the inversion point (h_i) or at the inlet into the oil pool when it exists. Note that a more complete coupling of the mixed lubrication and emulsion equations has been proposed recently by Kosasih and Tieu [16]; a similar work is planned in the future.

3. EXPERIMENTS

3.1. Tools and procedures

Annealed, ultra-low carbon steel strips (0.06% C, 0.4% Mn, 0.05% Al), 0.2 mm in thickness and 100 mm in width, have been rolled on the experimental rolling mill of Arcelor Research. The strip yield stress was:

$$\bar{\sigma}\ (MPa) = 60 + (377 + 177\bar{\varepsilon}).(1 + 0.01\exp[-1.21\bar{\varepsilon}]) \quad (1)$$

The reduction was constant (30.7%), the speed ranged between 1.67 m.s^{-1} (100 m/min) and 28.33 m.s^{-1} (1700 m/min). The steel roll diameter was 400 mm, its grinding roughness was Ra = 0.30 µm. The strip roughness was longitudinal, with Ra = 0.30 µm and a distance between ridges evaluated as 30 µm. Strip tensions were 113 MPa at entry, 270 MPa at exit.

A commercial steel strip rolling oil A was studied. It is used in industry as a Recirculated Application (RA) O/W emulsion; its viscosity is 37 mPa.s at 20°C, 7 mPa.s at 80°C. Its pressure - viscosity coefficient is unknown. It was used here as a neat oil on the one hand, as a 4% emulsion on the other hand; the emulsion was very stable (ESI = 90,5% after 30 minutes).

- As an emulsion, A was sprayed under 5 bars with an output of 250 cm^3/s (15 l/min). The droplet diameter at the inlet side spray (measured by Laser granulometry) was mainly comprised between 0.3 and 10 µm, with a maximum at 6 µm. The same emulsion was used as the coolant and sprayed on the exit side; nothing prevented the coolant to flow down on the strip.
- For neat oil A, the nozzles output was 33 cm^3/s (2 l/min) under 3 bars. No post-bite cooling was applied, so that the roll temperature increased, resulting in rather high exit strip temperatures, measured using a pyrometer.

Along with the rolling force, the forward slip was measured by the rotational speed of the tension block.

The residual oil quantity on the strip was also measured. Rolled strip coupons were lixiviated and analyzed by Gas Phase Chromatography.

3.2. Experimental results

Results are reported versus rolling speed in figure 4. The amount of oil measured on the rolled strip has been translated into an "equivalent oil film thickness", but it must be kept in mind that for the emulsion, nothing forbids that water penetrates into the bite, and the real film thickness might have been larger.

It is important to note that whenever an evolution of the rolling load is observed, it is confirmed by the same evolution of the forward slip: as furthermore all rolling parameters except speed are kept constant, the variations of the load are uniquely due to friction variations.

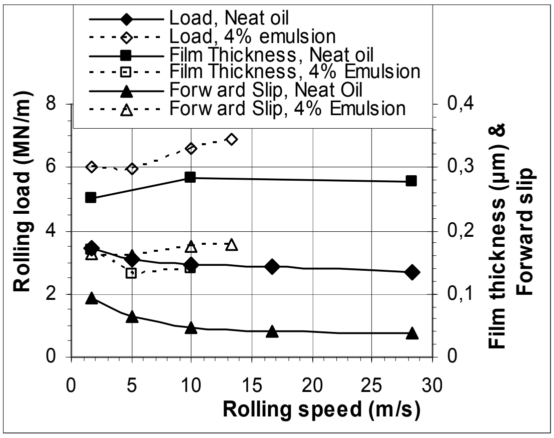

***Figure 4.** Experimental strip rolling results. Comparison of a neat oil (A) and its 4% O/W emulsion A.*

Neat oil A shows a "negative speed effect", i.e. the rolling load decreases when rolling speed increases; the measured oil quantity increases slightly, which means that hydrodynamic effects are the most probable candidate to explain this behavior.

On the contrary, oil A used as a 4% emulsion shows a "positive speed effect", with a slowly growing load, while the oil quantity drops between 1.67 and 5 m.s^{-1}.

4. INTERPRETATION USING MODELS

4.1. Neat oil A

In order to understand in depth the respective behavior of neat oil and emulsion lubrication, the case of neat oil A has been modeled in some details. The unknowns are:

- the pressure viscosity coefficient γ, which has not been measured in this case;
- the local, boundary friction factor m_a;
- the efficient amount of sprayed oil; the nozzles output was 33 cm^3/s (2 l/min) under 3 bars in the experiments, but part of it flowed sideways far ahead of the contact and did not take part in the lubrication process;
- the roll temperature: the strip temperature at entry was 20°C; the exit strip temperature was measured, showing a large speed effect, but roll temperature was not measured.

Figure 5 summarizes a short parametric study, aiming at fitting load, forward slip and oil film thickness with as far as possible speed - independent unknown parameters, to avoid multiple fitting coefficients. The following parameters are found to be important:

- The pressure-viscosity coefficient has finally been fixed as γ = 10 GPa^{-1}, after investigations in the realistic range 5 – 20 GPa^{-1}. Values above 10 GPa^{-1} gave much too high film thickness.
- The roll surface temperature has some impact through its effect on oil viscosity. Reasonable values have been chosen once and for all, from 30°C at 1.67 m.s^{-1} to 80°C at 28.33 m.s^{-1}.

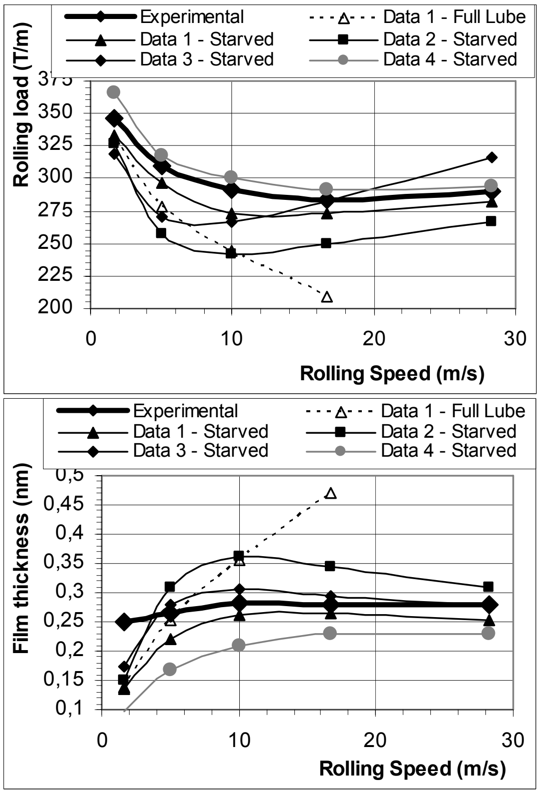

***Figure 5.** Computed rolling load and exit film thickness versus rolling speed, neat oil A.*
Data set 1 : γ = 10 GPa^{-1}, m_a=0.11, T_{roll} =f(V_{roll})
Data set 2 : γ = 10 GPa^{-1}, m_a=0.11, T_{roll} = 20°C
Data set 3 : γ = 15 GPa^{-1}, m_a=0.11, T_{roll} =f(V_{roll})
Data set4 : γ = 5 GPa^{-1}, m_a=0.11, T_{roll} =f(V_{roll})

- Even with the rather low value of γ, very high thickness was found at higher speeds (10 m.s^{-1} and above), if fully-flooded conditions were assumed. Accounting for the roll surface temperature somewhat reduced the film thickness, but it proved necessary to assume that only a part of the sprayed oil was in fact involved in the lubrication process. The amount of oil spread was 16,67 cm^3/ s / strip side. This corresponds to an ideal thickness of 167 µm at 1 m/s, inversely proportional to the strip inlet speed (i.e.16,7 µm at 10 m.s^{-1} e.g.). The best fit of film thickness was obtained with a spraying efficiency of 8% for all speeds, so that the efficient sprayed thickness at entry is e.g. 10 µm at 1.67 m.s^{-1} (100 m/min).
- γ and the spraying efficiency, and to a lesser extend roll temperature, are the most important parameters for film thickness, impacting on the real area of contact. Once these have been selected based on film thickness, it is easy to scan values of m_a to fit the load and forward slip, which are mainly sensitive to the average friction level, i.e. m_a.A. A constant value of

m_a=0.11 was found valid whatever the speed.

It is clear that fitting could have been done with other combinations of the unknown parameters (γ, T_{roll}, spraying efficiency); however the main conclusion is considered strong, i.e. the stabilization (and even slight increase) of the rolling load and slip at the highest speeds cannot occur without lubricant starvation. Starvation should be understood here in the sense that the limited amount of oil delays the oil pressure growth, eventually decreasing the film thickness. Starvation must therefore be considered even with neat oil, if the supply is not very large, as is the case in the present experiments.

4.2. Recirculated emulsion A – 4%

The pressure-viscosity coefficient was kept constant, since the same oil A was used for this emulsion. The roll temperature was kept constant at 20°C, since cooling was on. The main parameter is then C [10], the droplet flattening factor which fixes the upstream extremity of the concentration region (figure 3). A single value of this parameter was chosen, identical for all speeds, to obtain the correct value of the average final oil thickness. Figure 6 pictures the film thickness and oil concentration at work-zone inlet (point x_c), assuming a droplet radius of 3 µm and C = 0.66. The predictions of the model are qualitatively good, showing the three successive speed ranges displayed in figure 1. In the low speed range, the film thickness is indeed identical to oil lubrication, because an oil pool is formed as shown by the large ratio h_i/h_c. Then a plateau is found, on which h_i/h_c decreases and tends to 1: the inversion point moves closer and closer to the work-zone, leaving less space for pressure growth. This reduces the inlet film thickness h_c compared with oil lubrication, indeed a starvation effect induced by the presence of water. In the third range, the inversion point has reached the work-zone entry: water is present there and may be entrained into the bite. For still higher speeds, the amount of oil entrained remains the same, but more and more water penetrates into the bite, which is reflected in the decreasing film concentration.

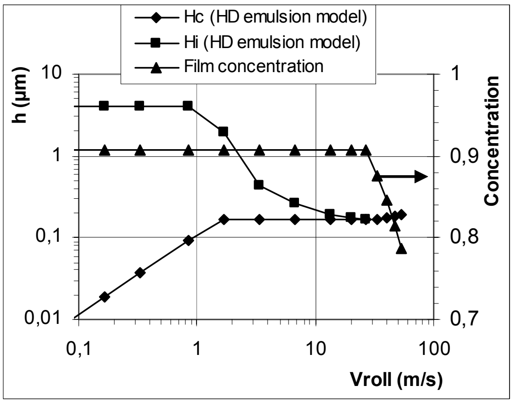

Figure 6. *Computed film thickness at inversion point (h_i),and at work-zone entry point(h_c). Emulsion of oil A, 4%, droplet diameter 6 µm, parameter C = 0.66.*

The corresponding $h_i(V)$ was entered into the rolling model as explained in paragraph 2.3. Note that in all the cases investigated, the oil concentration at work-zone inlet was 90%, the maximum value allowed by the model. It was therefore considered that pure oil lubrication prevailed, but with a much reduced amount of oil available, inducing severe starvation. As a result, the final film thickness shown in figure 7 was obtained. The order of magnitude of the film thickness is correct. This was in turn reflected in the rolling load versus speed curve of figure 7, which shows the right tendency: first a stable load, then an increase at the highest speeds, due to the decrease of h, the increase of A and of the local friction m_a.A. A constant value of m_a = 0.19 is sufficient to describe the whole curve in this case.

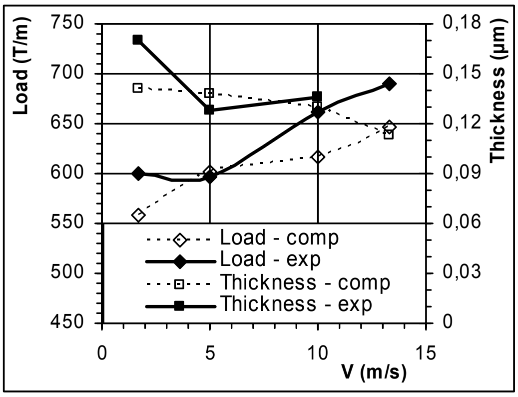

Figure 7. *Computed and experimental rolling load and film thickness vs speed. 4% O/W emulsion of oil A, droplet diameter 6 µm, parameter C = 0.66.*

4.3. Discussion

The weak coupling of an inlet zone, emulsion-oriented, HD film formation model, and a mixed lubrication, oil-oriented strip rolling model, although not fully satisfactory, proves able to shed some light on the lubrication mechanisms and the influence of the main parameters: oil properties ($\eta(T)$, γ), emulsion behavior (C, d_s), strip properties… Yet a number of unknown or even non-measurable parameters make the conclusion somewhat speculative. The discussion will be focused on the two most questionable parameters: the boundary friction factor m_a and the droplet flattening factor C.

For neat oil A, m_a = 0.11, independent of rolling speed, gives a good fit of the measured load. Boundary friction thus seems to be roughly speed-independent, in spite of increasing strip temperature. When A is used as a 4% O/W emulsion however, m_a = 0.19 must be used, again constant with speed. As the film is found to be quasi-pure oil, we would expect a similar value of boundary friction. Can the few water droplet going through the bite explain this difference? Alternatively, micro-hydrodynamic lubrication could occur with neat oil A but not with A-emulsion, because of the smaller amount of oil available in the valleys. But this is speculative.

Another critical choice for emulsions is C. It determines the range of speed $[U_1,U_2]$ of the film thickness « plateau », together with the corresponding thickness $h_{c,p}$. Approximate values have been derived (d_s is the droplet diameter, ϕ_0 the nominal emulsion concentration - here 4%, ϕ_{inv} the inversion concentration - 90,7% according to Wilson and Schmid's model, μ_{oil}

and μ_w the oil and water viscosity, σ_0 the strip yield stress at bite entry and α the bite angle):

$$U_1 \approx \frac{C.d_s.\phi_0}{3\mu_{oil}}.\frac{1-\exp(-\gamma.\sigma_0)}{\gamma}.\cot\alpha$$
$$U_2 \approx \frac{C.d_s.\phi_0}{3\mu_w}.\frac{1-\phi_{inv}}{\phi_{inv}}.\sigma_0.\cot\alpha \qquad (2)$$
$$h_{c,p} \approx \frac{C.d_s.\phi_0}{\phi_{inv}}$$

The choice of C is supposed to be related in particular to the wetting properties of the emulsion droplets on the solid surfaces.

Based on (2), it is easy to fit the film thickness range h_{cp} using C; at the same time, the constant film thickness range is fixed, and seems to fit our experiments too.

5. CONCLUSION AND PERSPECTIVES

A comparison has been performed between a complete rolling model in the mixed lubrication regime, including a simple emulsion lubrication approach, and experiments performed under realistic semi-industrial conditions. The rolling load, forward slip and residual oil on the strips have been compared. It shows that such complex models are able to analyze these experimental results, including the effects of velocity. They may guide reflections on important aspects of mixed lubrication, such as the real nature of phenomena occurring in the "real contact area": chemical boundary lubrication, micro-hydrodynamic lubrication; what is the impact of speed, is there any difference between oil- and emulsion-lubricated cases?

However, a number of phenomena and parameters can and must still be used to fit the results. This calls for more complete experimental characterization: thermal measurements on the mill are required, so that roll and strip temperature can be used or predicted, rather than assumed; the pressure-viscosity behaviour is also absolutely necessary. Furthermore, the residual oil quantity is quite difficult to measure, and the uncertainty is probably large; yet it is the essential item to validate the lubrication model; efforts must therefore be devoted to develop accurate methods, such as fluorescence measurements proposed by Azushima [17] and recently extended to fluid mixtures [18].

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