FLEXIBLE LUBRICATION CONCEPT.

THE FUTURE OF COLD ROLLING LUBRICATION.

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Abstract.

For cold rolling systems, in particular for tandem mill which is the major form of the process, the conventional lubrications have reached their limits. Thus, rolling process needs a more advanced lubrication concept. This concept called **F**lexible **L**ubrication aims at adjusting friction level at the three process time scales: the rolling campaign, the local scale (coil to coil), and the transient stages within two coils. The industrial interest and expected impacts will be on: roll campaign length increase, energy saving, mills capacity, flexibility of production programming, avoid the detrimental behaviours due to uncontrolled friction variations such as rolling force shoot-up and chattering. Previously Flexible Lubrication has been studied and developed in laboratory. Today, **F**lexible **L**ubrication is at industrial testing stage with the first successes.

Keywords**:** cold rolling, lubrication concept, friction control, process performances.

1 INTRODUCTION.

The rolling process heart, the roll bite, is a lubricated tribo-system. These mechanical systems generate the friction phenomenon which results of the combination of many complex mechanisms interacting at different scale level as it is symbolised in fig. n°1.

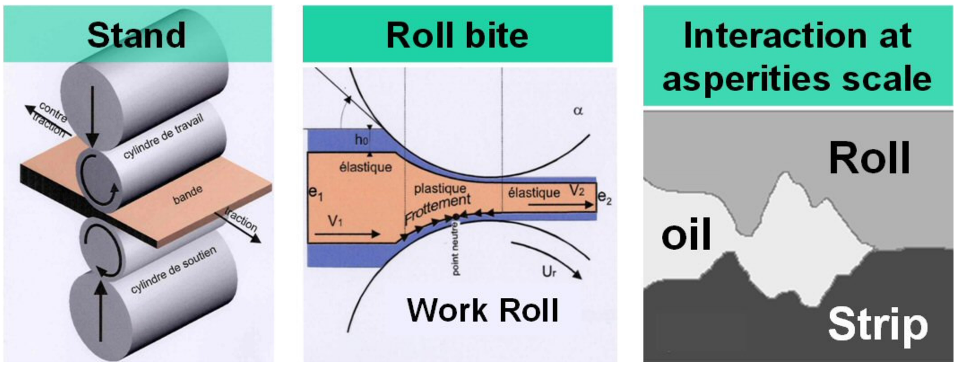


Figure 1: Rolling process heart is a tribo-system where many complex mechanisms interact at different scale level.

Friction phenomenon is an induced reaction at the interface between the bodies under relative motion. The friction level, quantified by friction coefficient, is sensitive to most of the system parameters; materials characteristics, contact configuration, surfaces topology, working conditions which include the specificity of metal forming with numerous space and time parameters dependence. **Therefore friction level can not be controlled directly in a simple way**. Lubrication which is the specifically dedicated function to act on friction has always a great global importance on the technical-economical process performance issues. Strategically lubrication is a core business competency for cold rolling industry justifying constant efforts to better process control thought the synergy of both experimental and theoretical ways.

Cold rolling systems work in the **mixed lubrication domain** [1, 2]. Only for didactic relevance, the figure 2a presents a drastic summary of mixed lubrication situation making the link between global (or average) friction $\boldsymbol{\mu}$ and the first's dominant parameters through the central notion of lubrication regime. Considering the working contact zone partly in boundary conditions and partly in hydrodynamic (or micro-hydrodynamic), mixed lubrication induces that $\boldsymbol{\mu}$ is resulting of the combination of the two components $\boldsymbol{\mu_L}$ and $\boldsymbol{\mu_h}$. The coefficient $\boldsymbol{\mu_L}$ is the friction level in boundary conditions due to the so called chemical lubrication. The coefficient $\boldsymbol{\mu_h}$ is an equivalent friction level due to the viscous lubrication. Consequently the global friction coefficient $\boldsymbol{\mu}$ can vary from boundary to full hydrodynamic conditions inducing a very wide range of possible friction level in cold rolling, [0.120 , 0.012] typically.

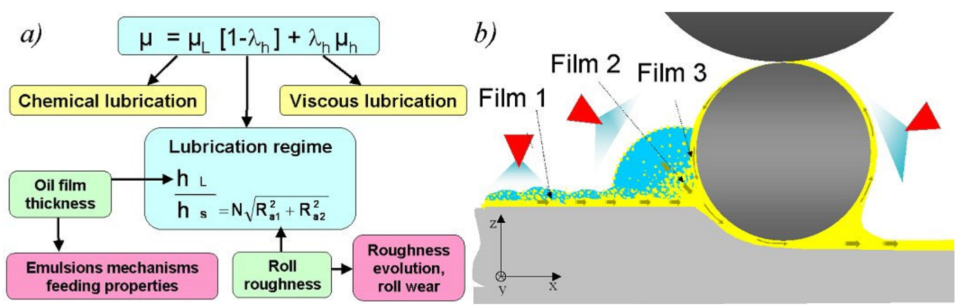


Figure 2: a) Drastic summary of mixed lubrication: b) Three oil films origins.

The parameter $\boldsymbol{\lambda_h}$ giving the proportion between the two components $\boldsymbol{\mu_L}$ and $\boldsymbol{\mu_h}$ characterises the lubrication regime. The lubrication regime depends at first order on the ratio of the oil film thickness to the surfaces roughness where the tool roughness has a dominant effect. Reminding that in cold rolling, roll wear means roll roughness loss; this key parameter performs important evolution during rolling operations. The second key parameter is the lubricant film feeding the roll bite. Up today, lubrication with O/W (oil in water) emulsions is prevalent to neat oil. Emulsions lubricate quite well and have both technical and economical advantages in particular for tandem mills for which efficient cooling is needed. When emulsions are used, three oil films formations are related to emulsion specific mechanisms which promote the roll bite to be lubricated by the oil with a more or less important starvation effect [10, 12]. The figure 2b shows that the oil film feeding the roll bite could have three origins. The film n°1 formed by the strip **Plate-out** mechanisms, the film n°2 formed in the convergent zone by **Dynamic Concentration** mechanism [3], and a possible film n°3 formed by platting-out on roll surface and/or, recycled film passing through the Back-up roll – work roll contact. The figure n°3 symbolizes the two mains specific mechanisms of oil film formation.

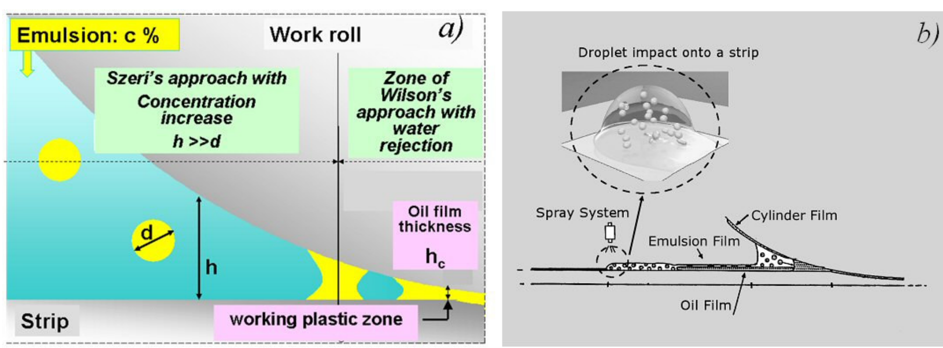


Figure 3: a) Dynamic concentration mechanism. b) Strip plate-out mechanism.

Fig 3a, relates Cassarini Dynamic Concentration model developed on the basis of Wilson's [3, 4] and. Szeri's [5] works. Theses results were several time published [7, 8, 9] and are also in quite good correlation to the numerous researchers observation work such as Zhu, Nakahara [7, 8] and Spikes [10, 11]. Globally it can be said that, today there is certain accordance on a draft description of emulsion behaviour in the inlet zone of the roll bite. For instance it is recognised that O/W emulsion efficiency is due to the phase separation with oil only passing through the bite considering the current speed rolling domain that means excluding the speed stage where water could create itself a significant hydrodynamic component. At low speed the behaviour of emulsion is quasi identical to neat oil. Up to a first critical speed the roll bite is always oil lubricated but in the starvation situation. The differences of two phase's viscosity play a key role in the water rejection mechanisms. More difficulties are remaining for a clear identification of the role of emulsion physico-chemistry in particular for emulsion stability and oil droplet size which are strongly coupled parameters in practice. The figure 3b relates recent work for strip plat-out numerical modelling [13]. Most of the plate-out studies emphasized emulsion chemistry effects on the oil film formation on the strip surface. This computational approach, dealing with dysphasic fluids mechanics when emulsion droplets impact a surface has shown that previously the right ballistic phase set up is a prerequisite off great importance for the oil film formation. If not, even with the good wetting properties, the plate-out mechanisms is not operating so well. That's underlines the great importance of spraying parameters.

In the last two decades, major steps were done in lubrication understanding and since 1995 great deals of effort were spent for lubrication modelling which is practically at the stage to link the lubricant film thickness at the roll bite inlet zone to the lubrication operational parameters that are the emulsion characteristics and the spraying parameters. Therefore reasoning in lubrication have been progressively modify integrating tribological behaviour in the investigation tools and consequently in industrial production analysis. One of the consequences is that the conventional lubrications, which main way of progress is traditionally focussed on the oil formulation improving, have showed theirs limits. In the same time the evolution of lubrication scene has opened the field for a lubrication conception change for future advanced process performances, [14].

2 FLEXIBLE LUBRICATION, INDUSTRIAL FOUNDATION AND INTEREST.

At idealised conception step **F**lexible **L**ubrication (**FL**) aims at continuously controlling the friction during process operations. At first glance this assumption could seem an easy one. Nevertheless it is useful way for investigating a vision of future lubrication from the cold rolling process needs analysis without any taboo at first. Thereafter to be realistic for achievement, it can be pragmatically derived three key questions:

- **What are the industrial foundation and interest of flexible lubrication?**
- **Are the physic and its understanding allowing FL to exist in the near future?**
- **Which technology has to be used for reaching the expected performances?**

The foundations of a renewal concept take root in an extended critical analysis of the **C**onventional **L**ubrication (**CL)** performances in production considering the roll bite behaviour at the three time scales of the rolling process; the rolling campaign, the local scale (coil to coil), and the transient stages within two coils. For each time scale the unsatisfying behaviours and their detrimental effects on the process performances promote the draft design of the **FL** project.

2.1 ANALYSIS AT ROLLING CAMPAIGN SCALE

The figure n° 4 illustrates what is typically happening in production through friction analysis with **CL**. For each coil, friction is back calculated from industrial data related to steady state speed. The long distance tendency with friction decrease is due to roll wear i.e. roll roughness loss with rolled mileage. Thank to mixed lubrication knowledge, this behaviour is quite well understood.

With a fixed lubrication setup as it is the case with **CL,** the roll roughness decrease induces the lubrication regime mowing toward more hydrodynamic component, which decreases consequently the friction level as it was explained before, confer to figure 2a.

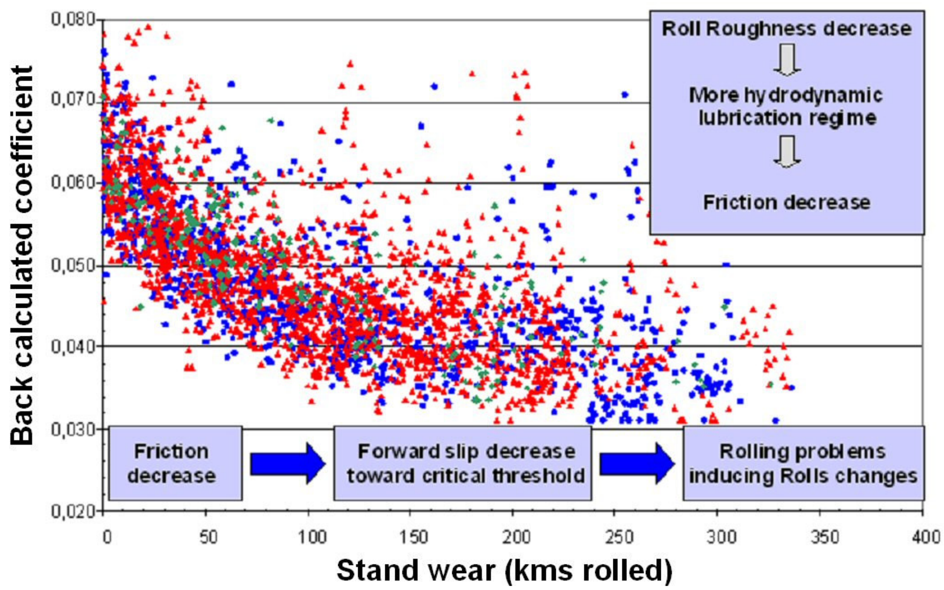


Figure 4: Typical friction evolution during rolling campaign with ***CL***

If friction decreases during rolling campaign, forward-slip decreases too. The forward-slip evolution induces the rolling process moving forward a critical domain when forward slip becomes near to zero with the brutal evolution forward negative values when neutral point will exit the roll bite. This domain is **called critical domain** because of the occurrence of the process regulation failure, of the risk of chattering in particular for high speed stands, and risk of rolling incident such as strip break. The second phenomenon observed on the figure n° 4 is an important friction scattering due to friction variations coil to coil when coil $_n$ and coil $_{n+1}$ are different rolled products.

Analysis of the detrimental consequences: During the first part of the rolling campaign the high friction level is responsible of energy loss, high rolling force and relatively poor strip cleanliness due to an important iron fine generation. Then, roll wear makes friction and forward-slip decreasing and progressively reaching a critical threshold when forward-slip value is near to zero or slightly negative. Therefore, work rolls have to be changed in order to avoid rolling problems such as; strip out of gage, chattering, and strip break rolling incident. With **CL,** as well for recirculation application (**Rec**) as for direct application (**DA**), roughness loss is one of the major causes of work roll changes. Effectively with conventional situation, practitioners are obliged to make a trade-off between roll campaigns length, and energy loss, strip cleanliness impaired by the relatively high needed initial roll roughness fixed to obtain the best possible balance between these antagonistic aspects.

From the production analysis at rolling campaign scale it can be conclude that the process needs a progressive lubrication adjustment during rolling campaign **following the roll roughness evolution.** In comparison with the current situation of the figure n° 4, the friction has to be decreased at the first part of the rolling campaign and after that, to be controlled by a **FL** to keep forward-slip outside the critical domain. If energy saving and rolling force decrease can be easily evaluated with the help of the current cold rolling models, a pending question with lubrication (friction) adjustment is: How far the threshold could be pushed away for increasing roll campaign length?

2.2 ANALYSIS AT LOCAL SCALE, COIL TO COIL

Production analysis has also revealed an important friction scattering. In order to understand this local friction variation, an extended analyse of one year production was performed for different cold rolling situations. The extraction in figure n° 5a gives a statistical point of view concerning a sheet tandem mill using a six-high technology in first stand. The friction level is strongly sensitive to the strip product type with a clear ranking of the three different strip product families. It could be remarked that between family n°1 and family n°3, at any stages of the rolling campaign the friction level is quite twice for family n°1 than for family n°3 operating with strictly the same conventional lubrication setup. Then, when product of the different families are mixed in the same rolling important local friction variations occur as it is illustrated in the figure n° 5b.

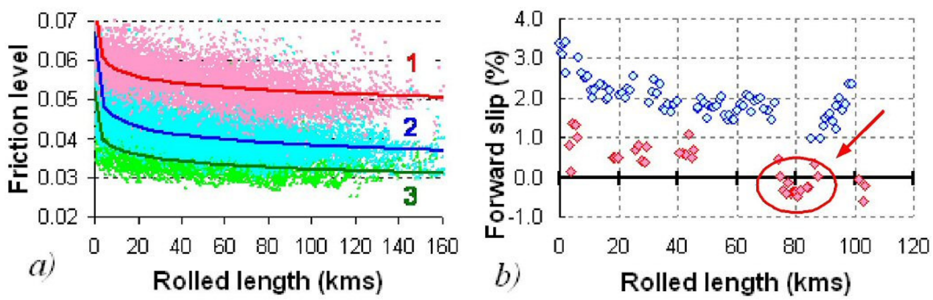


*Figure 5: **a**) ranking between different strip product families1, 2, 3; **b**) Local, coil to coil friction variation due to each coil specific characteristics: 1 point = 1coil.*

Analyse of the detrimental consequences: The figure 5b focuses on a specific rolling campaign where two strip product types are mixed. The same lubrication setup is clearly not adapted to both strip products types. The product in red reaches much earlier the critical domain of negative forward-sip. Moreover, the mixing of the different products creates brutal forward-slip local variations which increase the occurrence of strip out of gage, rolling incident and premature roll changes, as it is shown with red circle situation of the figure 5b.

It can be conclude that a coil to coil friction adjustment will reduce the production friction scattering. This is all the more important that related to economical strategy, the production programming tendency is to mix more and more the different strip products to be rolled. The evolution toward this **production flexibility** without detrimental effects argues for coil to coil lubrication adjustments, that means the need of a **FL** at local scale.

2.3 ANALYSIS AT TRANSIENT BETWEEN TWO COILS.

During transients (acceleration– deceleration) a speed effect occurs creating a rolling force shoot-up. The force shoot-up main cause is the mixed lubrication sensitivity to speed through the viscous (hydrodynamic) component. When the tandem is slowing down for rolling the welds or for other any reasons, the friction level tendency is to grow up toward the boundary friction level in few seconds. The example of figure 6a shows a rolling specific force variation of 150 t/m during transient. The figure 6b, confirms that the friction level doubling for a speed variation from 800 to 120 m/min is the rolling force shoot-up cause. The rolling force shoot-up effect depends also on the roll roughness stage and the rolling scheme. As example for a given friction variation, the thinner the strip is, the bigger the force shoot-up is.

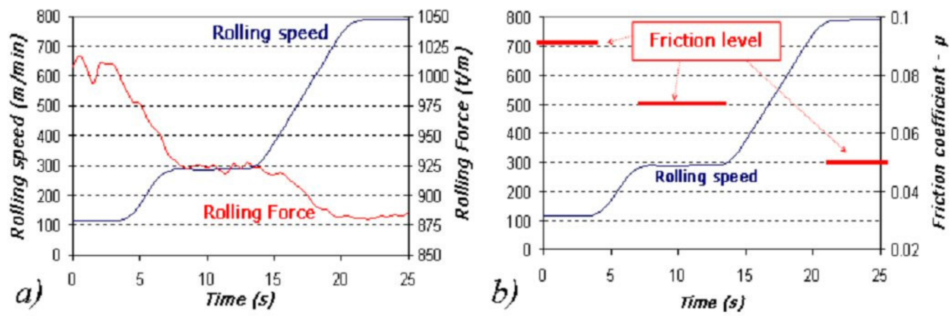


Figure 6: Typical rolling force shoot-up in stand4 of a 5 stands sheet tandem mill.

Analyse of the detrimental consequences: During the transient stage, the rolling force shoot-up corresponds currently to a 15-25 % stand capacity loss. Moreover for continuous and coupled tandem mills in case of abnormal rolling speed slow down in case of upstream problems, tandem mill capacity saturation can be reached with strong detrimental consequences such as strip out of gage length, coil reparation, productivity loss. In the near future the acuteness of this problem will dramatically increase because of the harder and thinner strips production evolution.

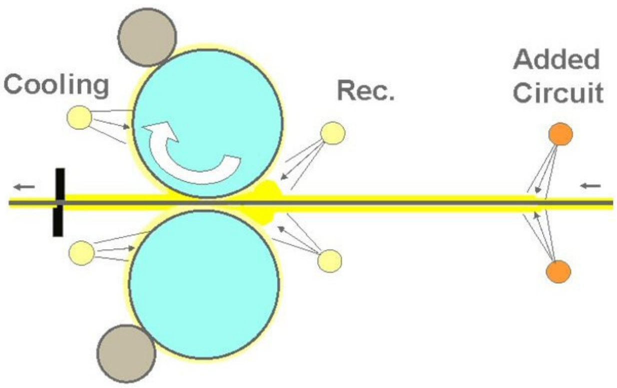
2.4 CONCLUSION ON **FL** INDUSTRIAL FOUDATION.

Since one decade, the conclusion coming up is that **conventional lubrications are reaching there limits** because they oblige compromising with incompatible thing due the impossible friction adjustment (control) at the three natural scales of the process. This situation is judged less and less acceptable because off detrimental to the process technical-economical performances. Whatever the production is and will be, the rolling process challenge is to have; less energy loss, less mill capacity loss, less cleanliness variation, and no more roll changes, due to uncontrolled friction. **Consequently, rolling**

process needs a Flexible Lubrication. For the expected **FL** performances friction adjustment in the transients is the more demanding and difficult challenge. Taking **CL** performances as reference, **FL** requires a wide **accessible friction adjustment range** about a 40% - 50% possible variation. Reasonably 25 % would be a success at first step. **FL** needs to act in this range reliably and progressively. In practice, this will depends on the smaller accessible friction increment under control. To be efficient in transients **FL** needs a **response time** as short as possible, in few seconds order. These defined criteria and performance targets have orientated the choice of the lubrication parameters and technology to be used for **FL** development.

3 FLEXIBLE LUBRICATION AT LABORATORY SCALE.

The first trials program performed on pilot mill was devoted to screen different possible lubrication configurations, emulsion parameters, and spraying conditions effects. The present section focuses on the configuration for sheet tandem mills which currently have a conventional lubrication with recirculation (**Rec)** as it represented in figure n°7.



Pilot mill working point	
Rolling speed	875 m/mn
Reduction	23.1%
Strip grade	IF
Entry thickness	0.8 mm
Exit thickness	0.62 mm
Work roll diameter	390 mm

Figure 7: Double circuit configuration used on pilot mill; Conventional lubrication with recirculation + flexible lubrication additional circuit.

As **ArcelorMittal Sagunto** is the pilot plant. The stand 4's working conditions of the 5 stands tandem mill of Sagunto are simulated. For **FL** trials, the additional circuit used was an available circuit previously used for hot rolling lubrication studies which allows an emulsion concentration variation up to 18% in few seconds thank to a static mixer technology. The same oil is used for the two emulsions; exception of a lower emulsion stability of the additional circuit in order to favour strip plate-out mechanism efficiency. Finally the actuator of flexibility is the emulsion concentration of the additional circuit, the setup of conventional lubrication **Rec** remain fixed during all the trials

3.1 FLEXIBLE LUBRICATION RESULTS.

Accessible friction adjustment range: The accessible friction range is defined by the relative performances between Rec friction level and Rec + Add-circuit with the upper concentration setup of 18 %. The figure 8a shows the obtained results for different roll roughness stages corresponding to a typical rolling campaign at Sagunto. In all the cases the accessible friction adjustment range is in order of 40%. As example, with an initial roll roughness of 0.55 µm Ra, friction decreases from 0.080 with **CL** alone to 0.046 when activated additional circuit performs with 16 % concentration.

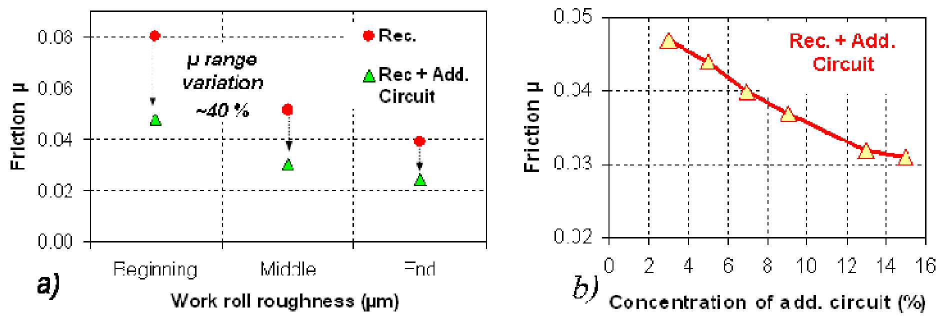


Figure 8: a) accessible friction adjustment range; b) Emulsion concentration effect on friction.

The dosing system of the additional circuit makes easy to perform a well controlled 2% emulsion concentration increments. A 2% concentration increment gives **a 0.003 friction** coefficient increment corresponding for the studied case to a **0.3%** forward-slip variation. The performing of different concentration increments, successively up and down, gives very reproducible results. These results are excellent for a progressive friction adjustment management. It can be also remarked in the figure 8b, that the curve friction versus concentration has a regular feature (quite linear). At a stage corresponding to a roll roughness about Ra = 0.35, if flexible circuit is switch off from a 16% concentration setup, the forward-slip re-increases of + 1.7 %. Whatever the performed concentration increment, the response time was closed to 7 seconds. Considering that the available additional-circuit used was not optimised for this purpose, this result is not so bad. But for friction adjustment in transients, it would be necessary to obtain shorter response time.

3.2 POTENTIAL INDUSTRIAL IMPACT OF FLEXIBLE LUBRICATION.

Laboratory pilot mill, in comparison with industrial mill, is a simplified rolling system and allows only partly estimating the industrial potential impact of the flexible lubrication performances. The figure n° 9 is showing how to manage a Flexible Lubrication during a rolling campaign from the classical feature of a rolling campaign with **CL.** At the beginning of the rolling campaign the **FL** will be used to decreasing friction level, the impact is on rolling force decreasing and energy saving. As illustration considering Sagunto production for the mean mixed product, an adjustment of 30% friction decrease at the beginning of the rolling campaign corresponds, for the stand 4 both, to a 26 % rolling force decrease and a 14 % reduction of the roll bite energy consumption. Then **FL** is used to follow the effect of roll roughness loss avoiding critical domain. The possible impact on roll campaign length is a more difficult subject dealing with wear [15, 16]. There are two main ways for increasing the roll campaign length. The first one is if the new working conditions (lower friction during the rolling campaign) induces a slow down of the roll roughness loss kinetic.

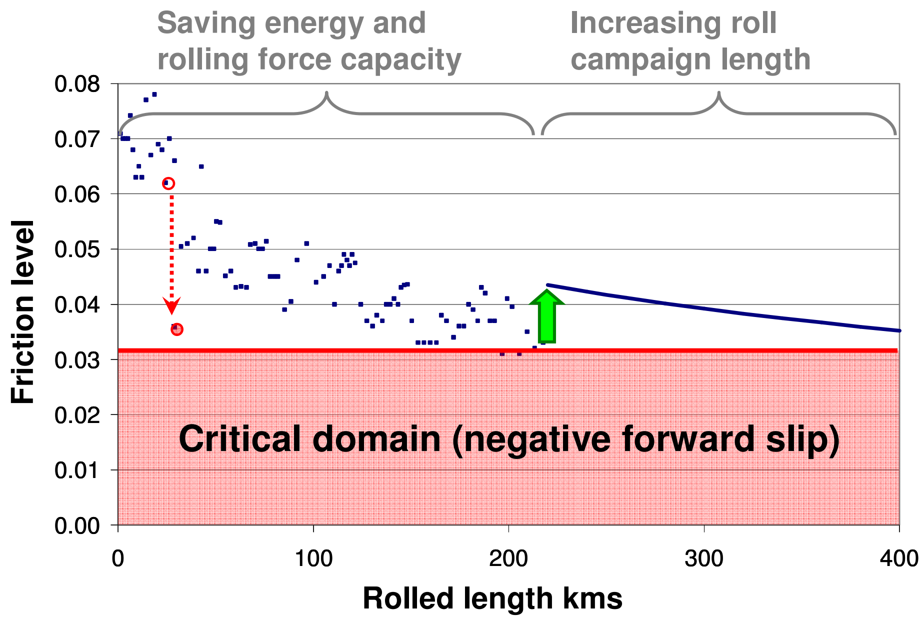


Figure 9: Principle of Flexible Lubrication management during a rolling campaign.

The second one is to avoid the consequence of the roughness loss by adjusting friction to avoid the forward-slip reaching the critical domain. Obviously the best possible performances are obtained when the two ways are combined. The effect of lubrication (friction level) on roughness loss kinetic remains a controversial subject. It was assess that if abrasive wear type mechanism is the dominant one, increasing the hydrodynamic component as it is the case with **FL** the roll wear kinetic could be slow down. But in counter part the shape of relative reciprocating motion inside the roll bite will change. To secure this assessment, wear trial were performed on pilot mill with the two possible extreme lubrication setups. Even the trials correspond to a third of industrial campaign length; the roughness kinetic is significantly slowed down with boosted lubrication. Then taking into account the difference between the two wear kinetics, estimation from laboratory results of the possible roll campaign length increase is between 30% and 100%.

3.3 CONCLUSION ON FLEXIBLE LUBRICATION AT LABORATORY.

Even response time had to be improved; at laboratory scale, **FL** seems to have globally the potential for reaching the expected performances. At the current time, concentration of the instable emulsion is the easiest parameter in use with the existing static mixer technology. But whatever is the lubrication parameter used, the principle of **FL** is to control the starvation degree of the roll bite. The other interesting parameters tested have more complex behaviours and/or restricted efficient domain with some threshold effects like for the flow rate. Particular attention is paid to the emulsion particles size, for which investigations are progressing. Nevertheless, considering the satisfying results in laboratory, AcelorMittal Flat Carbon Steel Europe has decided that the next step of the project has to be the **F**lexible **L**ubrication testing in the industrial context.

4 FLEXIBLE LUBRICATION TESTING IN INDUSTRIAL CONTEXT.

Over few years **FL** industrial testing is on going for different cold rolling situations. **For sheet tandem mill** the **FL** testing phase starts with the conception and the achievement of a **F**lexible **L**ubrication **I**ndustrial **P**ilot (**FLIP**). FLIP is the additional circuit consisting of a dosing system part and a specific spraying device which was installed at Sagunto for testing in the 4th intermediate stand. The figure n°10 is showing the additional spraying installed in front of stand n° 4.

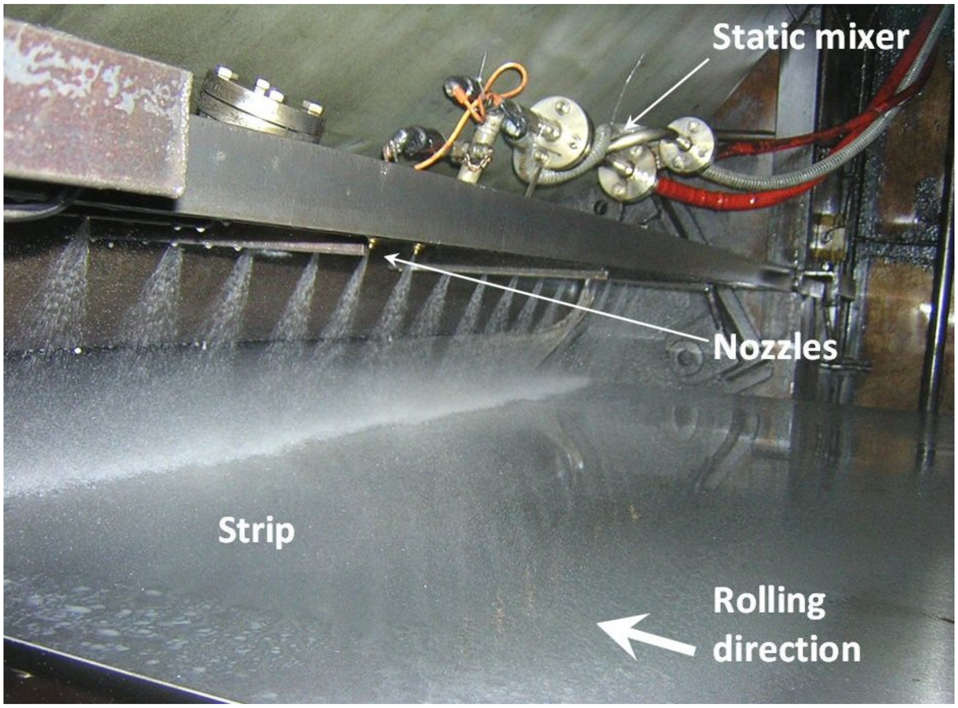


Figure 10: FLIP spraying device installation at Sagunto for FL in stand n° 4.

The first spraying condition setup is similar to the one used in **CL** direct application. Double circuit configuration has been used in the past on some tandem mills stands as a punctual help for difficult rolling cases. **FL** has now the objective to a quasi continuous friction adjustment and the technology used present some significant differences. Contrarily to **CL** direct application headers, the FLIP header is a non crossing flow conception. That means that for the same exit emulsion flow rate at the nozzles, the emulsion volume built up is ten times smaller. In this case the static mixer is small enough to be integrated to the header. Consequently the emulsion is built up few centimetres before the spraying nozzles. Whatever the concentration required drop, FLIP response time is closed to 2s. FLIP has also a possible spraying flow rate variation of four times order and a controlled spraying emulsion temperature between 40°C to 70°C. After a consequent verification and setting up phase, FLIP is in good work order and effective **FL** testing phase has started at mild 2010 and will going on up to mild 2011 to achieve the relevant FL testing program. The figure n° 11 presents as illustration one of the first trial results showing stand 4 reactions in terms of forward-slip variation when FLIP is activated with different emulsion concentration in the steady state phase of the rolled coil at rolling speed closed to 900 m/min.

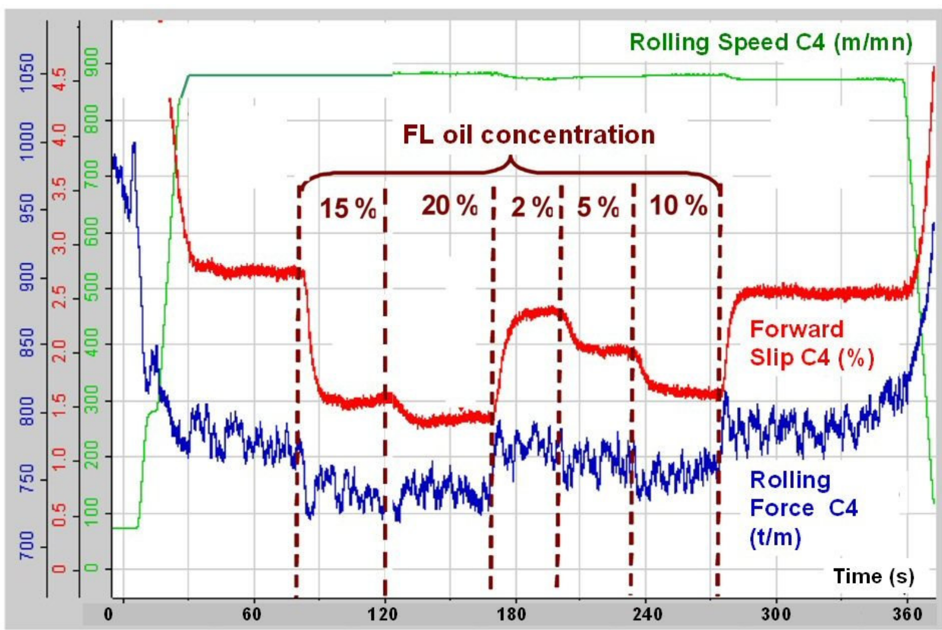


Figure 11: illustration of FLIP results at Sagunto in stand 4 through the recorded process parameters variation; forward-slip, rolling force and rolling speed.

At rolling working conditions steady state, forward-slip is the industrial recorded parameter directly sensitive to friction variation. It can be seen that from the reference value due the central lubrication **Rec** (without FL before time of 80s) the forward-slip is following well the emulsion concentration variation up and down and forward –slip go back to the reference value when **FL** is switch off at 270 s. On physical point of view this behaviour is the sign of successful perspectives for Flexible Lubrication at industrial scale even in the complex context of an intermediate stand of sheet tandem mill with central recirculation lubrication. Regarding the defined performance criteria the figure n°11 case shows a forward-slip variation range about 50% corresponding to a friction variation of 22% when FLIP is at 20 % emulsion concentration. The scheduled **FL** testing program had now to be performed before concluding on the effective **FL** performances and with longest trialling period in order to verify if the expected industrial impacts are reached.

FL using emulsion concentration variation was also tested on a 2-stand temper mill for packaging steels at ArcelorMittal Basse-Indre which was initially a typical **CL** direct application type. In this case the new lubrication device was used instead of the **CL** direct application. Previously with **CL** the double reduction process (say elongation from 20% to 55%) has strong speed effect in the transients. **FL** with emulsion concentration adjustment to rolling speed was very efficient to counteract speed effect and to keep rolling force constant in transients. Before with **CL**, the response time to adapt the emulsion concentration to strip elongation was in order of several minutes, not short enough to avoid the different production parts to be scheduled in specific rolling campaigns. With the coil to coil friction adjustment, **FL** has brought the right production flexibility, no more need of specific rolling campaign. Moreover the lubrication system and its maintenance are simplified, no need of premixed emulsion tank in the cellar. Consequently to this first industrial success [17] **FL** were deployed on two other 2-stand temper mills for packaging steels.

5 CONCLUSION

As well as the other domains cold rolling is challenging for increasing the process technical-economical performances all the more difficult because, over several years, production is also significantly mowing toward harder and thinner strip materials. For such a challenging scene, the conclusion has came up that the conventional lubrications were reaching there limits. The process requires friction adjustment at the three time scales; rolling campaign scale, coil to coil scale and transient phase between two coils. The **F**lexible **L**ubrication concept aims at adjusting the friction level and has relevant foundations which take roots in an extended production critical analysis. The basic knowledge and study at laboratory has demonstrated that the physic and its understanding allow **FL** to exist in the near future. The Flexible Lubrication potential covers the global domain which could be impaired by uncontrolled friction with the conventional lubrications, that is to say: energy consumption, mill capacity, roll changes frequency, strip cleanliness, production flexibility and catastrophic behaviours such as chattering. For **FL** industrial application, emulsion concentration is the easiest lubrication parameter in use at this moment, but Flexible Lubrication conception has opened a field of investigations and technological developments. First important industrial success occurred with the temper cold rolling application. But the tough challenge is the tandem mill domain, the major form of the cold rolling process where first important results were obtained in mild 2010. The next testing period will really answer if **Flexible Lubrication Concept** brings the expected advanced performances, and becomes **the future of cold rolling lubrication** in an extended way.

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