Flexible lubrication for controlling friction in cold rolling, crucial to be successful for the AHSS challenge.

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Summary

Since years, the cold rolling production evolves toward harder and thinner strip materials for both the sheet and tinplate rolled products, with in same time an increasing of the product diversity. In the current period this evolution trend is becoming impressive in particular for the automotive sheet products with the development of the **A**dvanced **H**igh **S**trength **S**teels justifying the questioning about the capability limits for sheet tandem mill. The present study shows that for strip yield stress over 750Mpa, the sensitivity increase of rolling force takes almost a form of exponential variation when the strip thicknesses become lower than 2mm. The typical friction variation easily occurring with conventional lubrications during cold rolling operations induces an important loss of capacity due to rolling force saturation. For instance it has been shown that a friction level established at 0.050 instead of 0.040 is clearly detrimental on tandem mill capability for AHSS production. For friction level at 0.080, as it could be established in transients or in low reductions domain, the induced loss of capacity is dramatically detrimental for the rolling process performances and becomes properly unacceptable. Control precisely the friction is then crucial, the AHSS products must be rolled at much lower friction level controlled inside a very narrower window. This can be done only by adjusting continuously the lubrication setups to the process events using a flexible lubrication system. The **F**lexible **L**ubrication is currently in roll out phase for sheet tandem mills of ARCELORMITTAL and industrial results had shown the current **FL** efficiency while highest performances are expected with new rolling oils in the low speed domain. Sheet tandem mills still staying with conventional lubrication will have a significant restricted capability for AHSS production due to uncontrollable friction variations. The **Flexible Lubrication is crucial to be successful for the AHSS challenge.**

Key Words

Cold rolling, friction control, Flexible Lubrication, AHSS, stands capacity, Tandem mills capability.

Introduction

Cold rolling production evolution: Since years, the cold rolling production evolves toward harder and thinner strip materials with an increasing of product diversity. Sheet and tinplate productions are both concerned. In first period from the years 2000 up to 2005, the rhythm of this evolution was quite a slow one. Since this evolution trend is becoming impressive in particular for the automotive sheet product with the development of the **A**dvanced **H**igh **S**trength **S**teel (**AHSS**). The **AHSS** ratio is strongly growing, mainly in substitution to previous automotive steels. This growth is strongly stimulated by the CO2 regulation through reducing the weight of steel product in a competitive way. It can be assessed that the trend is sustainable at least up to 2030. The tandem mills are the major cold rolling production tool for important production volumes for which high performances of productivity and cost are required. The most part of existing European tandem mills, were invested at least thirty years ago and sometimes more when production was mainly devoted to soft strip materials. Therefore the sustainable evolution of production makes the questioning about the capability limits, relevant for the tandem mills. For AHSS, the first challenge is to use as well as possible the full available capacity without loss related to uncontrolled parameters such as friction which plays a crucial role in thin strip cold rolling.

Lubrication evolution toward FL-REC: Even if the controlling of friction was quite early pointed out as a key issue for cold rolling process performances, the real friction control will remain inaccessible for so long as the **C**onventional **L**ubrications (**CL**) will be still used. This is the case as well for **CL** with recirculation (**REC**) as for **CL** with direct application (**DA**). In fact, the conventional lubrications mainly have succeeded to prevent from seizure-scuffing or skidding, avoiding the related strip defects and rolling incidents. Even progresses toward highest rolling performances were made, large friction variations still are occurring during rolling operations with **CL**. For the friction level control the major lubrication evolution occurred with the **F**lexible **L**ubrication concept which takes roots in the years 1998-2000. **F**lexible **L**ubrication **[1, 2]** aims at adjusting continuously the friction level at the three process time scales: the rolling campaign; the local scale, coil to coil; and the transients between two coils. The industrial interests are multiple: stands capacity, rolls campaign length, energy consumption, flexibility of production programming, avoidance of detrimental behaviors due to uncontrolled friction variations such as rolling force shoot-up and chattering **[3]**. In sheet tandem mills domain, the Flexible Lubrication is currently operating in addition to the recirculation system, the entire lubrication system is so called **FL-REC**. Due to progressive work for moving toward **FL-REC** on existing mills, the first industrial rollouts have had to compromise between new conceptions while using "secured" knowledge to overcome some constrains**.** It results that the **FL** still has an important field of progress. When the highest performances potential will be reached, **FL-REC** will be probably the most advanced lubrication system on technical-economical-environment point of view. Then it could be deployed for all cold rolling systems regardless the rolling production type: sheet, tinplate, and the others. If **FL** concept was developed with a global vision**,** the present paper focuses on the importance of the friction control for the AHSS.

Cold rolling AHSS challenge.

Stand capacity problem: The rolling stands capacity problem, and consequently the tandem mill capability for the AHSS rolled products can be positioned at first in simple way. The considered sheet tandem mills are classical 4 high rolling mills technology with work rolls diameters closed to 560mm, excepted for Gent-TTS first stand, which has a six high technology. In all cases the nominal maximum available rolling force is 3000 t. With a 10% security margin, the real available rolling force is 2700t for the production programming. It can be easily deduced that each time the specific rolling force will exceeded 1600 t/m, the maximum width capacity of 1700mm for instance will be not achieved or the cumulated thickness reduction will have to be restricted. This drastically defines the limits of the strip rolling schema related to stand capacity ***on rolling force criterion.*** For traditional production of soft and middle strip materials defined by: a yield stress lower than 750MPa, a cumulated reduction up to 94%, exit strip thickness up to 0.8mm, the specific rolling force is usually between 700t/m up 1350t/m . This means that for traditional production an important capacity margin exists, the risk of rolling force saturation is negligible in normal working conditions. **Then rolling process can accept important friction variations without any detrimental impacts as strip out of gauge.** In comparison with traditional production, AHSS rolled products are much thinner and much harder strip materials. A currently yield stress reached value is up to YS=1000MPa and could be significantly more in the future, strip exit thicknesses lower than 0.5mm are targeted. The cumulated reduction is much lower, mostly fewer than 70% and could vary significantly with the rolled strip width.

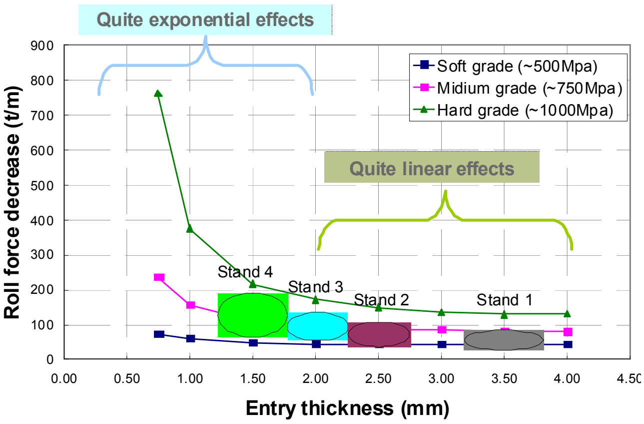


Figure 1: *Impact on rolling force decrease when friction decreases;* ***μ [0.050 -> 0.040]***

Figure 1 presents results obtained by calculation with numerical cold rolling model. All the calculations were made for 25% reduction and a fixed usual setup of back and front tensions. When Conventional Lubrication is used, a friction coefficient of 0.050 is a relevant reference value corresponding to a middle rolling campaign with a rolls initial roughness about 0.65µm. The three curves, respectively for soft, middle and hard strip material describe the rolling force decrease when the friction is decreased from 0.050 to 0.040 corresponding to a 20% variation. In practice when conventional lubrications are used, such 20% friction variations easily occurred in an uncontrolled way for a lot of reason partly recalled in the next sections. The colour spots are marking the position of the distribution of a traditional production in the first four stands. The last stand devoted to strip surface aspect, is out off the paper scope. In the domain of strip thicknesses over 2mm, the sensitivity of rolling force versus the yield stress is approximately quite a linear one. The impact of the 20% friction variation on rolling force variation can be considered as moderate. For a 2mm strip entry thickness and friction of 0.05, the specific rolling force reach 1350t/m for the YS=750MPa. That means that the full stand capacity could be use only for the soft and middle hard strip materials. For hard material the specific rolling force is already 2080t/m. In this situation the rolling stand capacity is then restricted to 1300mm width. The 20% friction decrease induces a 170t/mm decrease of the specific rolling force allowing recovering quite a 7% capacity. In the domain of strip thicknesses lower than 2mm; **the sensitivity of rolling force versus strip entry thickness takes almost a form of exponential variation.** For 1mm, the specific rolling force for hard material reaches 2240 t/m; the stand capacity is restricted to 1200mm in width. The 20% induces a 380t/mm decrease of the specific rolling force allowing recovering 20% of stand capacity in width. For strip entry thickness lower than 1mm, the sensitivity of rolling force to friction variation becomes **spectacular** and then the rolling process performances are dramatically impaired. For 0.75mm strip entry thickness, a loss of 60% stand capacity is reached when friction is 0.050 instead of 0.040. This underlines that controlling precisely the friction is crucial for AHSS production. Noticeable is that for thicknesses under 2mm, even at friction of 0.04, the forward-slips are highly positive. That induces the favourable point that the thinner strips could be rolled with a friction level much smaller than 0.040 for further reduce the loss of capacity. A 20% friction variation from 0.040 to 0.050 is nevertheless a small variation, easily occurring in steady state rolling, stronger variations could occurred during rolling operations when conventional lubrication are used.

Main critical friction variations with CL-REC: Since the cold rolling process is operating in the mixed lubrication domain **[4, 5, 6]** then friction has physically the possibility to be established typically within a range, from 0.012 to 0.120, corresponding respectively from a quite full hydrodynamic lubrication regime to a boundary regime mainly governed by moderate ploughing mechanism. When **CL-REC** is used, which was the major situation for sheet tandem mills, the friction coefficient is mainly varying: with rolling speed; during rolling campaign due to rolls roughness loss; from coil to coil when different rolled products are mixed in the same rolling campaign; and with strip thickness reduction. The main critical friction variations are due to the speed effect in transients and to the reduction effect for which AHSS products are especially concerned.

Speed effect during transients: In normal situation for coupled and continuous tandem mills, the transients are necessary for rolling the weld between two coils. During transients (acceleration–deceleration) a friction variation mostly occurred with a friction increase when the rolling mill is slowing down. The more common explanation is that in mixed lubrication, friction is sensitive to speed, through the viscous (hydrodynamic) component. When mill decelerate the friction level tendency is to move back, in few seconds, to a situation with less hydrodynamic component and for some cases up to a boundary situation. Then the friction drop creates a rolling force shoot-up whose amplitude depends upon the considered rolling case.

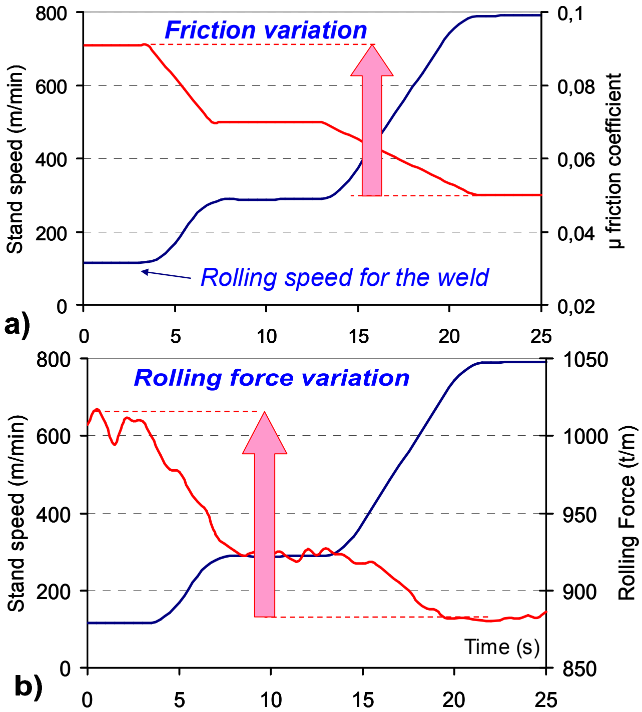


Figure 2: *Speed effect in transitory: a) Friction variation, b) induced rolling force variation.*

Figure 2 shows a typical speed effect in transitory phase in stand 4 of the sheet tandem mill of Sagunto. Data was recorded for a middle hard strip case for instance. In figure 2a, when the rolling speed is decreased from 800m/min to 120m/min the friction coefficient increased from 0.055 up to 0.090, inducing a significant specific rolling force increase about 180t/m for instance figure 2b. For AHSS products, the rolling force shoot-up could be much greater and could lead to stand capacity saturation, in particular for the wider products as it was shown in the previous section. The risk of generating strip out of gauge during transients becomes high. Moreover, for continuous and coupled tandem mills, abnormal situations can occur in case of upstream problems. In these situations some practice consists in going on rolling at very low speed much lower than 120m/min in order to avoid the strip accumulator to be emptied and consequently the tandem mill to be obliged to stop. If the mill is obliged to stop, the rolled coil has to be repaired because it produces indentation marks at the strip core. The figure 3 shows a picture of the strip defect type. For the AHSS strip rolled closely to the rolling force capacity limit, such abnormal transients at very low speed will be mostly impossible without generating strip out of gauge, and then the risk of increasing mills stop frequency becomes high. So, an efficient lubrication would have to minimize the friction variations in transients that means in low rolling speed domain and ideally in very low speed domain.

Figure 3: *Picture of indentation mark on strip when tandem mill stops at the core of the rolled coil.*

Reduction effect related to MPH mechanism: The figure 4 shows friction evolution due to reduction effect, when high strength steels with yield stress up to 800MPa are rolled on Mardyck sheet tandem in stand 3. Friction values are back-calculated from industrial data using cold rolling numerical model. The variation of strip reduction produces significant friction variations, as the reduction decreases, the friction increases.

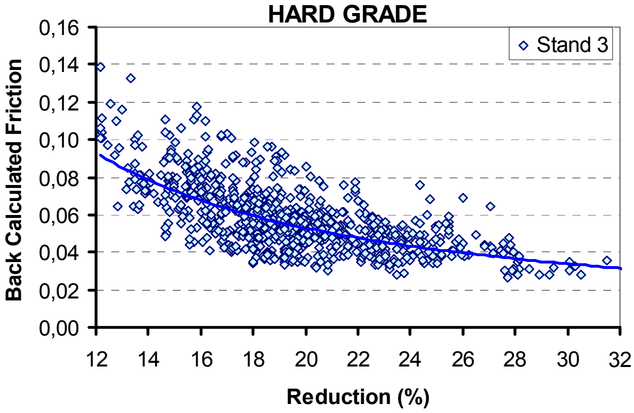


Figure 4: *Friction variation due reduction effects, when reduction decrease, friction increase.*

Table A summaries the friction variation tendency due to reduction effect referring to figure 4. It can be noticed that for a reduction decrease from 25% to 16% the friction increased from 0.040 to 0.080. Friction value is doubling, therefore AHSS rolled products are obviously strongly concerned by this drastic increase of friction when decreasing the stand reduction.

Table A: *schematic reduction effect on friction level with conventional lubrication oil viscosity.*

12 % reduction	→	friction μ = 0.120
16 % reduction	→	friction μ = 0.080
25 % reduction	→	friction μ = 0.040

Reduction effect understanding: The reduction effect is attributed to the local (micro-scale) lubrication regime evolution inside the roll bite related to the physical phenomenon of **M**icro-**P**lasto-**H**ydrodynamic (**MPH**) **[10].** Specific work was devoted to **MPH** understanding and implementation in numerical cold rolling model **[7, 8, 9].** In summarised way, at the roll bite entry a certain quantity of lubricant is entrapped in the free volumes created by the contacting of the two surfaces topography. Then plastic deformation promotes the reduction of the free volumes, progressively the lubricant is pressurized and can escape, changing the local lubrication regime toward more (micro) hydrodynamic component which is decreasing drastically local friction value from an initial boundary situation. It induces that the average friction will decrease with the cumulated reduction. It is assessed that the ratio between the initial free volumes and entrapped oil quantity is a dominant factor on the MPH threshold activation. Then it could be expected that increasing oil viscosity will promote the possibility of lowering friction in the low reduction domain.

Friction variation impact at low reduction of 16%: Due to reduction effect presented in table A, calculations were made for; 16% thickness reduction, two strip yield stress of 500 and 1000Mpa and two friction values of 0.080 and 0.040. The results are presented in figure 5 for the low strip entry thicknesses < 1mm.

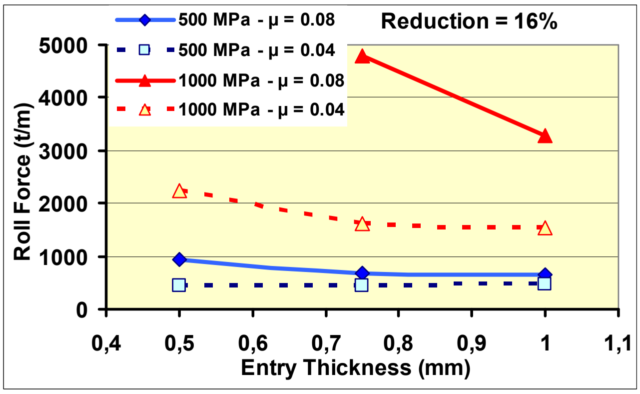


Figure 5: *Specific rolling force variation versus strip entry thickness for a 16% reduction rolling case.*

Even for a low reduction the sensitivity of the specific rolling force to friction variation is extreme for the harder strip material. For friction of 0.080, the loss of stand capacity is literally dramatic since the 1 mm thick, whereas with 0.040 values the 0.75mm thick is feasible in the full width capacity. The figure 6 shows that forward-slip still remains clearly positive at 0.5 and 0.75mm thick, this confirms that even for low reduction of 16% the thinner and harder AHSS product could be rolled at much lower friction than 0.040 without any risk of skidding.

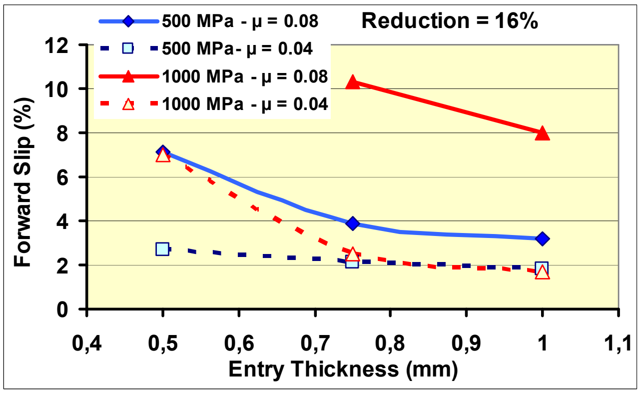


Figure 6: *Forward-slip versus strip entry thickness for a 16% reduction rolling case.*

For the thinner and harder AHSS the extreme sensitivity of the specific rolling force could not be only explained by the cumulative direct effects of plastic deformation of thin strip, the high level of yield stress, and friction effect. Other hypothesis is the induced phenomenon of the three previous effects on the roll bite contact length and the possible change of the deformation shape of the work roll. Figure 7a and b, shows for two thicknesses of 1 and 0.75mm that over a certain threshold of loading with the YS=1000MPa and friction of 0.080, the shape of roll deformation is drastically changed and a 50% increase of the roll bite contact length occurs. This is similar to what happens in severe working conditions of a skin pass process.

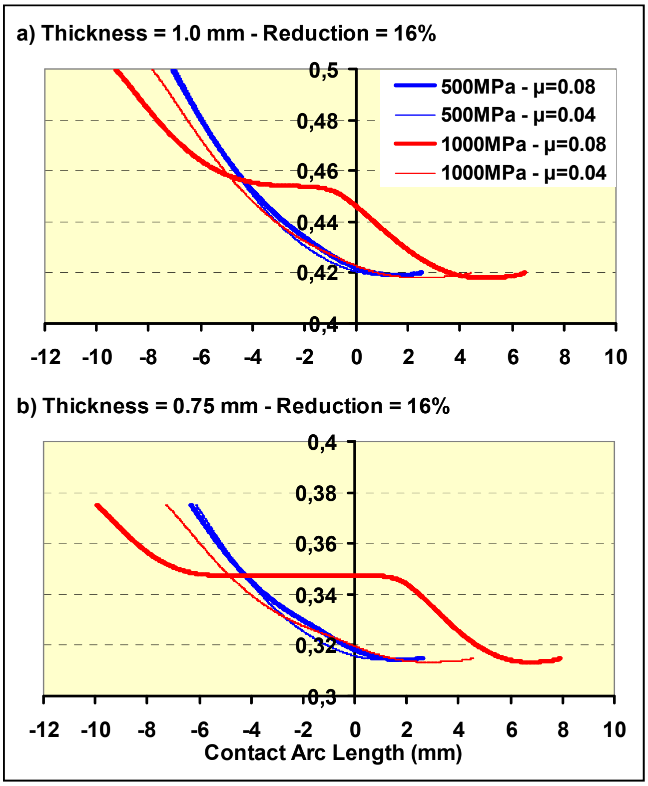


Figure 7: *Roll-strip contact length variation versus strip yield stress and friction.*

Noticeable is that when the friction is decreased to 0.040 the work roll is recovering a normal cylindrical shape and then even if the strip yield stress varies from 500MPa to 1000MPa, the consequence on the roll bite contact length will remains very moderate.

Controlling friction targets for AHSS: When **CL-REC** is used; friction at 0.080 is frequently reached in transients and at low reduction. When it occurs, the loss in process performances **is properly unacceptable for the AHSS production.** For AHSS the friction had to be controlled continuously at much lower level and inside a much narrower window at any time of the process, in a typical range of [0.020, 0.035]. Therefore the lubrication setup has to be adjusted during rolling campaign, coil to coil, and during rolling speed transients. Such high performances can be achieved only by using a **Flexible Lubrication.** The **CL-REC** is no more effective as it is characterized by a fixed lubrication setup during cold rolling operations. For sheet tandem mills remaining with **CL-REC** the capability of the mill will be drastically impaired for the most difficult part of the AHSS production. Moreover the presented investigations suggests to take into account the shape of the roll deformation as a new criterion for AHSS rolling schemas optimization with the reductions distribution and tensions balance of the tandem. It is also assessed that non cylindrical work rolls shape with enlarge contact length is detrimental for strip cleanliness as it favours the iron fine generation.

Flexible Lubrication performances

FL concept and the used technology was already published in 2011 **[1]**, the figure 8 presents the main additional part allowing a **CL-REC** to move toward **FL-REC.**

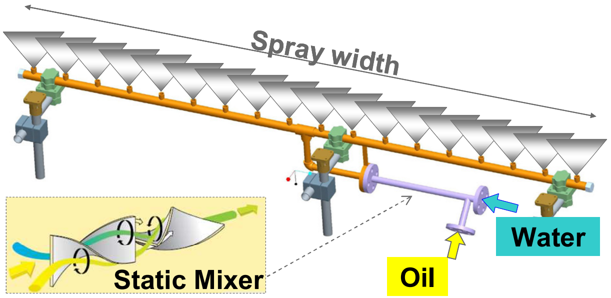


Figure 8: *Flexible Lubrication current technology with no crossing header associated to static mixer.*

Emulsion is built very close to the spray nozzles thanks to the static mixer technology which allows changing the oil concentration, in few seconds. A dosing unit provides precisely the needed flow rates of oil and water. The choice of the used static mixer allows adjusting emulsion particle size, regarding the chemistry of the emulsion used. The emulsion flow rate is adjusted with the rolling speed and the rolled strip width in order to minimise the added oil quantity. Top and bottom FL system can be used separately with different setup. The main parameter for flexibility is the oil concentration of the spayed emulsion on the strip. The concentration can vary up to 30% in 2-3 seconds. Oil film is formed on strip by the plate out lubrication mechanism. Figure 9 illustrates typical FL efficiency to decrease friction when lubrication setup is changed, increasing step by step the oil concentration for instance. The table B reports the mains process working conditions and the different oil concentration setups applied on the same coil rolled in steady speed of 500 m/min of the figure 9.

Table B: *Process conditions for the case of figure 9.*

Rolling conditions	
Yield stress entry tandem (Mpa)	466
Thickness entry stand 4 (mm)	0,69
Thickness exit stand 4 (mm)	0,5
Reduction Stand 4 (%)	27,5
Rolling Speed (m/min)	500
Width (mm)	1000

	Oil conc.	***Rolling force (t/m)***	***Forward slip (%)***	***Friction***	***Delta friction (%)***
REC	2%	844	2,4	0,032	-
FL1	5%	825	1,8	0,028	13
FL2	10%	817	1,5	0,027	16
FL3	20%	800	1	0,024	25
FL4	30%	795	0,8	0,022	31

$$Delta\ \ friction = \frac{(\mu REC - \mu FLx)\times 100}{\mu REC}$$

REC: *Conventionnal recirculation lubrication*

FLx: *Flexible Lubrication with recirculation*

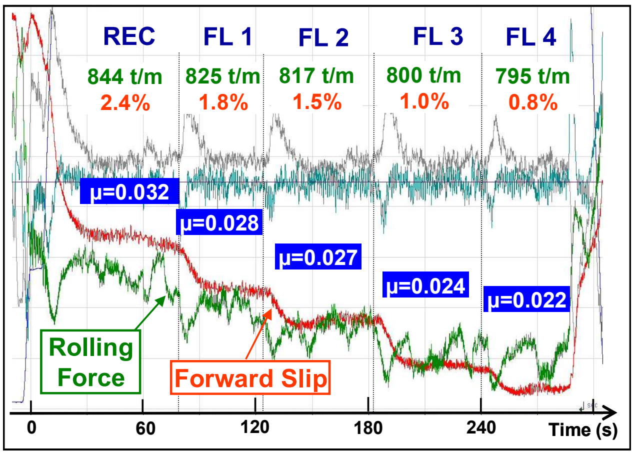


Figure 9: *Data records of rolling force and forward slip in stand 4 for a coil rolled in steady state.*

The forward slip and rolling force are recorded and then the average Coulomb friction coefficient is back-calculated. The friction variations are determined as shown in table B referring to friction level when the convention lubrication with recirculation is alone. It can be seen the progressive and regular effect of the FL. The friction can be adjusted progressively up to a cumulated decrease of 31%. Dosing unit easily allows controlling a 1% emulsion concentration variation when more high precision is needed. The forward slip is lowered up to remaining slightly positive at 0.8% instead the initial value of 2.4%. It can be seen that the thin strip of 0.69mm can be rolled in a well controlled way at **much lower friction of 0.022.** The figure n ° 10 gives a summarized overview of the FL efficiency domain screening the rolling production domain in terms of rolling speed and strip ***tandem mill entry thickness*** of Sagunto traditional production with a yield stress between 350 and 550MPa. The results are based on around 300 trials performed in stand 4. All the trials were performed with conventional oil viscosity. It appears clearly that FL efficiency is sensitive to rolling speed and rolled strip thickness. The thinnest are the strips and the highest are the rolling speeds, the more efficient the FL is. Reversely the current Flexible Lubrication efficiency is not fully satisfying in low speed domain and for strip thickness over 2.5mm, typically corresponding to the first stands working conditions and for tandem mill transient rolling speed. This is one of the main axes of progress for future improved FL systems.

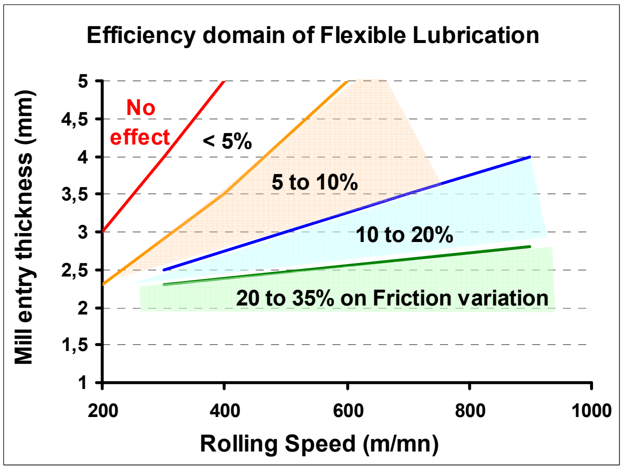


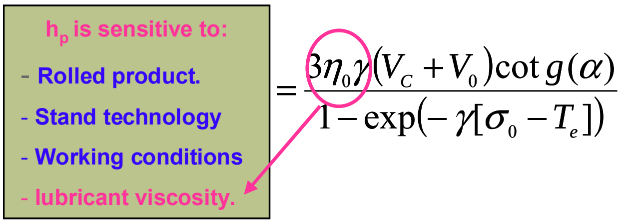
Figure 10: *Flexible Lubrication efficiency domain; results on stand 4 of sheet tandem of Sagunto*

Flexible Lubrication is acting at first by variation of the oil film thickness **h**$_L$ supplying the roll bite entry inducing variations of the hydrodynamic component inside the roll bite. The full hydrodynamic potential of the roll bite is defined by **h**p which is the maximum oil film thickness accepted by the roll bite in full flooded situation (saturation threshold). The domain between boundary lubrication and full flooded situation is the roll bite starvation domain. The first condition for FL is operating well is the roll bite to be inside the starvation domain which depends upon the rolling working conditions. The maximum oil film thickness **h**p is determinant, highest **h**p is, wider the **FL** operating domain is.This is summarized as below:

If $h_L < h_p$ then FL is operating well.
If $h_L \geq h_p$ then FL is no more operating.

Highest h_p will be, wider FL efficiency domain will be.

The figure 11 is recalling, the famous analytical model of WRD. Wilson and JA. Walowit **[11]** showing that the full hydrodynamic potential **h**p is depending upon the rolled product through entry thickness and reduction, stand technology through work roll diameter, rolling working conditions as speed and tensions, and explicitly the **oil viscosity parameters** of Barrus law for instance. For quantifying, the Wilson and Walowit model is no longer used as far as 3rd generation of numerical cold rolling model such as METALUB **[12,17]** is able to investigate and quantify the oils film thickness variation taking into account the roll bite entry geometry variations related the work roll and strip elastic deformations. Whereas for didactic the Wilson and Walowit is easily expressing the mains influent parameters suggest some explanation for the performances presented in figure 10. In particular it can be deduced that more viscous oils could enlarge **h**p at low rolling speed and consequently increase the FL performance potential at low speed.



$$= \frac{3\eta_0\gamma(V_C + V_0)\cot g(\alpha)}{1 - \exp(-\gamma[\sigma_0 - T_e])}$$

Figure 11: *Wilson & Walowit analytical model, oil film thickness in full flood situation.*

The second condition for FL operating well is that the plate-out efficiency will be sufficient to allow the oil film formed on the strip to cover the entire starvation domain, that mean that **h**$_L$ is able to reach **h**p value. Important work was devoted for understanding and developing a numerical plate-out model **[13, 14, 15, 16]**. The model allows parametric study to optimize the plate-out efficiency ratio considering both emulsion and spraying parameters.

Conclusion

For traditional production of soft and mild strip materials the rolling process of sheet tandem mills can accept the friction variations related to conventional lubrications while keeping rolling force far under the stands capacity limit, and therefore without any detrimental impacts on the dimensional capability of tandem mills . In comparison, the **AHSS** rolled products are much thinner and harder strip materials and, for strip thicknesses lower than 2mm; **the sensitivity of rolling force** versus strip entry thickness takes almost **a form of exponential variation.** For strip thickness lower than 1mm, the effect of a friction variation, even a small one becomes spectacular. For instance, at 0.75mm strip entry thickness, a loss of 60% stand capacity is reached when friction is 0.050 instead of 0.040. This underlines that controlling precisely the friction is crucial for AHSS production. It was also demonstrated that the extreme sensitivity of the rolling force was not only due to direct cumulated effects of strip thickness, strip yield stress, and friction. Over a certain loading threshold the shape of the work roll deformation plays a key role. The induced phenomena had to be taken into account as complementary new criterion for the strip rolling schemas optimization when balancing the reductions distribution and tensions setup. The second interest of minimizing the roll bite contact length will be **on strip cleanliness** because of such contact length favours the iron fine generation. Considering forward slip it has been deduced that AHSS had to be rolled at much lower and much narrower friction range, typically [0.020, 0.035]. Such high performances can be achieved only by adjusting continuously the lubrication setups to the process events using a **flexible lubrication system.** The **F**lexible **L**ubrication is currently in roll out phase for sheet tandem mills of ARCELORMITTAL and industrial results had shown the current satisfying **FL** efficiency while highest performances are expected with more viscous rolling oils in the low speed domain of tandem mills transients. Apart for chattering situations for which a specific friction window have to be indentified for each concerned rolling stands **[3, 18, 19]**, the real strategy of using Flexible Lubrication is to manage friction at critical friction level with a certain margin defined with forward-slip criterion. The critical friction is the lowest friction value before the neutral point exits the roll bite. It corresponds to the theoretical highest reachable performances, by controlling friction in terms of: rolling force capacity saving; saving energy, and productivity excepted when chattering. For such friction control objectives, the conventional lubrications are no more effective. Sheet tandem mills still staying with conventional lubrications will have a significant restricted capability for AHSS production due to uncontrollable friction variations. **Flexible Lubrication is crucial to be successful for the AHSS challenge.**

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