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Thermomechanical simulation of roll forming process based on the coupling of two independent solvers

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Key words: cold rolling, mixed lubrication, thermomechanical coupling

Abstract. This paper deals with an industrial application of a coupling procedure involving two different computer programs : MetaLub and ThermRoll. The first one models the mechanical phenomena occurring in the roll-bite during cold rolling such as elasto-plastic strip strains, elastic-roll deformations, asperity flattening and lubricant flow. The second one uses the previous results to compute the steady-state temperature field of the work-roll and the strip. These two codes are briefly described and a model of an industrial stand demonstrates the importance of the thermomechanical coupling in order to get a better understanding of the process.

1 INTRODUCTION

The general framework of this paper is in the field of numerical simulation of lubrication in cold strip rolling. This process implies many complex mechanisms at different scale levels that prevail in the roll bite which is working in mixed lubrication regime. As this mixed type of contact condition is not yet fully understood from the physics point of view, numerical models are as essential as ever to get a better understanding of this industrial process. In this paper, the coupling of two independent computer programs, MetaLub and ThermRoll, devoted to strip rolling simulations, is presented.

MetaLub [1-10] is based on the slab method. It iteratively solves the one-dimensional equations resulting from the longitudinal discretisation of the strip and from a coupled model of mixed lubrication at the interface. This lubrication model takes into account the evolution of the oil film thickness as well as the asperity crushing along the roll bite. An adiabatic model can be used to compute the temperature rise in the strip due to its deformation. However, the thermal conduction as well as heat transfer between the roll and the strip cannot be taken into account. Nevertheless, is some cases, these heat transfers may have a huge impact on the rolling conditions. To model heat transfer during strip rolling, a software named ThermRoll, has been developed at CEMEF [11]. It predicts steady-state temperature field in the work-rolls and in the strip for several cooling configurations. ThermRoll uses the results of MetaLub to compute plastic and frictional heat generations and then solves the heat transfer equations for a given mechanical state. ThermRoll provides two temperatures profiles : one for the strip and one for the rolls. These profiles are then used by MetaLub for further iterations. An automatic external iterative procedure has been implemented to fully automate this coupling between the two codes. This method implies an exchange of result files between MetaLub and ThermRoll during the iterations. These operations are greatly simplified by thanks to the Python language [12].

The coupling between these two computer programs was used to model the behaviour of the last stand of an ArcelorMittal rolling mill. The following sections briefly describe the features of the mechanical and thermal models and the assumptions made to in order to be as close as possible of the real rolling conditions encountered in the stand. Then, the results obtained with these two codes are discussed and compared to measurements.

2 METALUB MODEL

In MetaLub, the strip equilibrium is solved by the classical slab method [13-14] which computes a mean value, through the thickness of the strip, of stresses, strains and velocity at each point along the roll bite. For the purpose of this application, the mechanical behaviour of the steel strip is described by an elastic perfectly-plastic law with a yield limit σ_0 of 778 MPa. Tension and strip thickness at the entry and the exit of the roll-bite are shown in Table 1.

Table 1: Tension and thickness in the strip at the entry and the exit

	Tension [MPa]	Thickness [mm]
Entry	155	0.349
Exit	110	0.210

The lubricant viscosity η is modelled using the Williams-Landel-Ferry law [15]. The numerical values corresponding to the various parameters of the WLF law are listed in Table 2. $T_g(p_l)$ is the glass transition temperature at the fluid pressure p_l.

$$\log\eta(T,p_l) = \log\eta_g - \frac{C_1\left[T - T_g(p_l)\right]\,F(p_l)}{C_2 + \left[T - T_g(p_l)\right]\,F(p_l)} \tag{1}$$

$$\begin{cases} T_g(p_l) = T_g(0) + A_1 \ln(1 + A_2 p_l) \\ F(p_l) = 1 - B_1 \ln(1 + B_2 p_l) \\ \eta_g = 10^{12}\, Pa.s \end{cases} \tag{2}$$

Table 2: Parameters of the WLF law used to model the viscosity of the lubricant η

A_1 [°C]	A_2 [Pa^{-1}]	B_1 [-]	B_2 [Pa^{-1}]	C_1 [-]	C_2 [°C]	$T_g(0)$ [°C]
3,65	$4{,}64.10^{-9}$	0,24381	$1{,}55.10^{-8}$	15,91	27,868	-108,18

The local average friction stress is computed using the following sharing law

$$\tau(x) = A\tau_a + (1 - A)\tau_b \tag{3}$$

where A is the relative contact area between the strip and the work-roll, τ_a is the shear stress due to solid-to-solid contact, and τ_b is due to friction between the lubricant trapped between the strip asperities and the work-roll surface. The value of τ_a is computed using a Coulomb law with a limiting stress :

$$\tau_a = \min\left(\mu_{Coulomb} . \sigma_n , \mu_{Tresca} \frac{\sigma_0}{\sqrt{3}} \right) \tag{4}$$

The parameter $\mu_{Coulomb}$ is set to match the experimental results (forward-slip i.e. the relative velocity difference between the strip and the work-roll at the exit of the roll-bite) and it is assumed that $\mu_{Tresca} = 2.6\ \mu_{Coulomb}$. τ_b depends on the lubricant viscosity, the lubricant film thickness, the relative contact area and the relative velocity between the roll and the strip.

The relative contact area A is computed using Wilson and Sheu's analytical crushing law [16]. A Christensen's profile [17] is used to model the distribution of the asperities heights . This is an approximation of a Gaussian profile, more realistic since it eliminates points at infinite distance from the centreline. The arithmetic roughness of the work-rolls at stand 4 and 5 are $R_{a,rolls,4} = 0.65$ µm and $R_{a,rolls,5} = 0.5$ µm respectively. The roughness of the strip between stand 4 and 5 is assumed equal to the roll roughness of stand 4.The corresponding composite roughness R_q, which is a quadratic mean of the work-roll and strip quadratic roughness, is 1.03 µm.

The rolls diameter is 515 mm and the rolling velocity is 1000 meters per minute. Work-rolls deformations are taken into account since, during the simulations, they appeared to be of primary importance in the heat generation. Indeed, rolls' deformations modify, among others, $Q_{Plastic}$ and $Q_{Friction}$ profiles. Jortner's [18,19] formulation is chosen to model this deformation.

3 THERMROLL MODEL

ThermRoll is a 2D thermal numerical model based on the Finite Volume method, which computes the temperature fields in the roll and the strip in the steady-state rolling regime.

The plastic heat generated in the strip $Q_{Plastic}$ as well as the frictional heat at strip/roll contact $Q_{Friction}$ are computed from the results of the mechanical simulation performed with MetaLub. Frictional heat at strip/roll contact is equally divided between the roll and the strip.

All boundary conditions are linear, with the heat flux ϕ given by:

$$\phi = H.(T - T_{ref}) \tag{5}$$

T_{ref} is the temperature of the local counterpart, solid or fluid. The heat transfer coefficients H are defined separately for the roll/air contact, roll cooling water contact, strip/roll contact, work-roll/back-up roll contact, strip/strip coolant jet contact... In each zone, a constant value, or a position-dependent function for a maximal flexibility, can be given. The solid contact $H_{contact}$ can be made pressure- and temperature-dependent, using for instance Tseng's correlation [20]:

$$H_{contact} = 3800 \cdot \frac{2\lambda_{Roll}\lambda_{Strip}}{\lambda_{Roll} + \lambda_{Strip}} \cdot R_q^{-0.257} \left[\frac{P}{P + 3.\sigma_0}\right]^{0.94} + \left(\frac{\lambda_{Lub}}{h}\right)(1 - A) \tag{6}$$

λ's are the conductivities of the roll and strip metals and of the lubricant, R_q is the RMS roughness, σ_0 the strip yield stress. The Hs values and the reference temperatures modelling the thermal behaviour of stand 5 are schematically represented in Figure 1 and listed in Table 3.

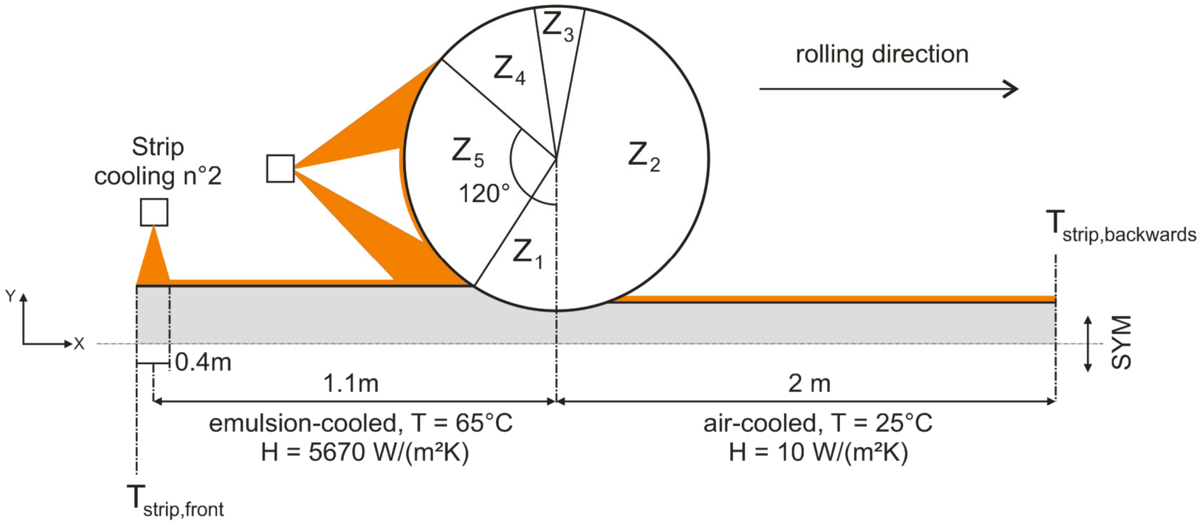

Figure 1: Schematic illustration of the thermal model of the fifth stand

Table 3: Inputs of the work-roll thermal model of the fifth stand

	Z_1	Z_2	Z_3	Z_4	Z_5
H ($Wm^{-2}K^{-1}$)	2.10^6	10	2.10^5	10	18000
T_{ref} (°C)	-	25	40	25	65
	Roll-bite	Air-cooled	Contact with back-up roll	Air-cooled	Emulsion cooled

4 COUPLING PROCEDURE BETWEEN MECHANICAL AND THERMAL COMPUTATIONS

The iterative scheme involving MetaLub and ThermRoll can be seen in Figure 2. A first simulation is launched with MetaLub. Once MetaLub simulation is completed, ThermRoll comes into play using $Q_{Plastic}$ and $Q_{Friction}$ obtained with the mechanical model. ThermRoll computes a two-dimensional temperature field in the strip and the work-roll as well as the corresponding mean profiles; $T_{strip}(x)$ and $T_{roll}(\theta)$ along the roll-bite and the work-roll circumference respectively. These profiles are then employed in the next mechanical iteration. This procedure stops once the maximum difference between two successive strip temperature profiles $T_{strip}(x)$ is less than a tolerance specified by the user (0.5°C).

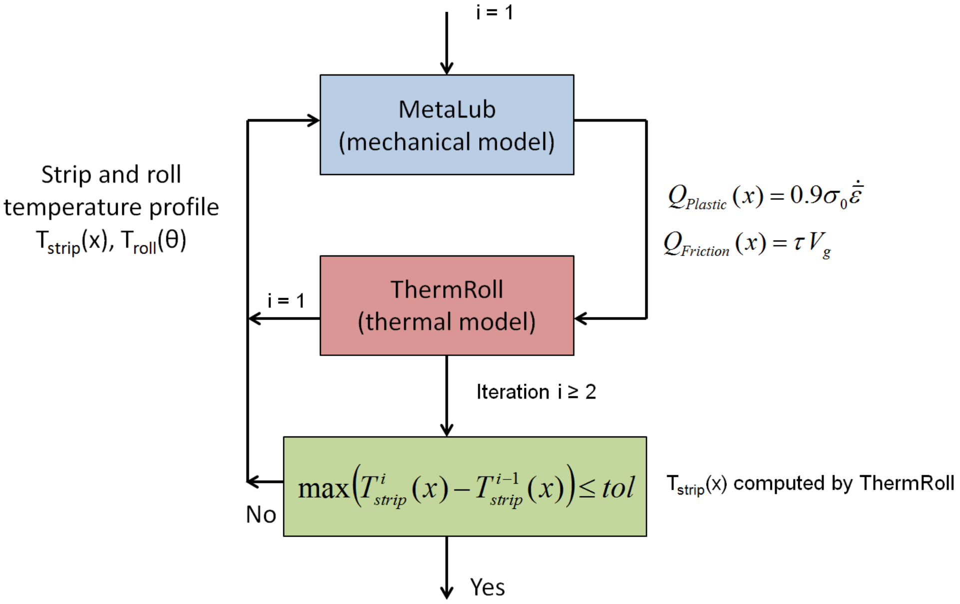

Figure 2: Staggered thermomechanical scheme

MetaLub and ThermRoll are two independent software. Moreover, the first one is written in C++ while the second one is coded in Fortran90. They essentially communicate by exchanging files; once a mechanical or thermal simulation is completed, the following is started using the results of the previous one.

The coupling procedure is greatly simplified by using the Python language [12]. Indeed, this language makes very simple the reading of the data set, the execution of the simulations, the creation of new directories, the copy of result and input files from one directory to another, etc.

5 APPLICATION TO AN INDUSTRIAL MILL

5.1 Roll mill cooling configuration

In this section the thermomechanical model of the Stand 5 of an ArcelorMittal rolling mill is fully described and discussed. The configuration is schematically represented in Figure 3. Prior to stand 5, the strip is cooled down by emulsion sprays. One of them is located between the stand 4 exit and a wiping roll while the other one is about 1.1 m ahead of the stand 5 roll bite entry.

Several experiments were conducted on this mill. For example the cooling of the strip prior to the Stand 5 and its influence on the rolling behaviour and on the strip exit temperature.

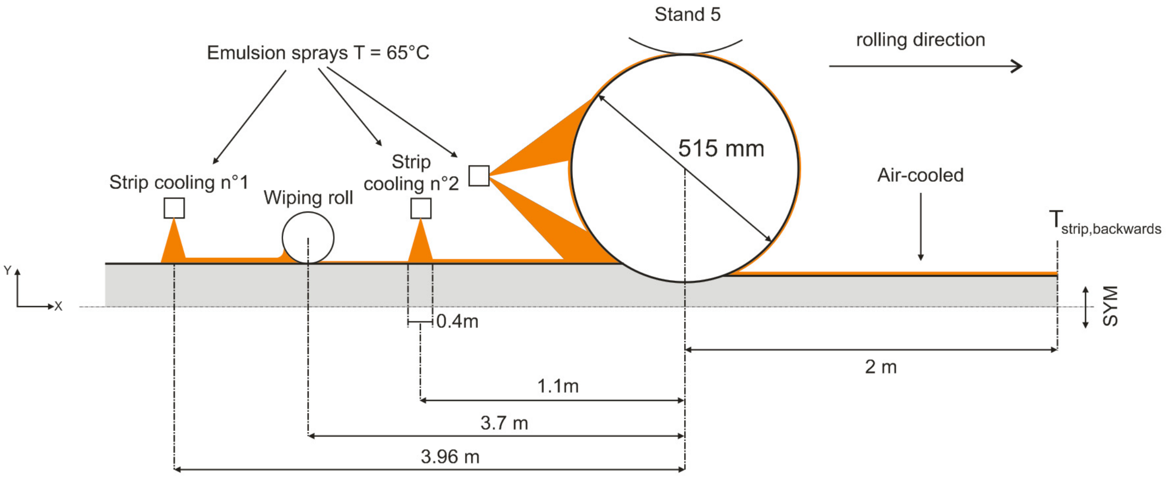

Figure 3: Interstand 4-5 cooling configuration

During the experiments, three lubrication conditions were investigated. First of all, the first spray was turned ON and the second one was turned OFF. Then, the second spray was turned ON. In this case, no significant impact on the stand 5 behaviour was observed; neither the forward slip nor the exit temperature changed. Finally, the first spray was turned OFF. This lead to an increase of the forward slip by 2.5% (showing an increase of friction) and an increase of the exit temperature by 7°C. Moreover, some vibrations occurred on the stand 5. The sections below discuss numerical results corresponding to these experiments.

5.2 Fully-lubricated configuration : spray 1 ON and spray 2 ON

In the first experiment, the strip cooling sprays 1 and 2 were enabled. In this case, fully lubricated (non-starved) conditions, which means the roll-bite absorbs as much oil as it can, were assumed in MetaLub. Two numerical parameters were set in order to match the experimental conditions. The first one is the friction coefficient $\mu_{Coulomb}$ of the mechanical model which allows us to get close to the forward slip experimental value. The second one, in the thermal model, concerns the temperature ($T_{strip,front}$) about 1.3 m prior to the roll-bite entry which is set to approach the exit temperature ($T_{strip,backwards}$) measured 2 m behind stand 5 exit. Numerical results obtained with $\mu_{Coulomb} = 0.04$, $T_{strip,front} = 118°C$ are shown in Table 4. As one can see, the fully-lubricated simulations match experimental values of the forward slip and the exit temperature for an initial temperature of 118°C.

Table 4: Comparison between experimental measurement and numerical results obtained with $\mu_{Coulomb} = 0.04$ and $T_{strip,front} = 118°C$ in fully lubricated conditions

	Experiment	Numerical results
Forward slip S_F	3 [%]	3.3 [%]
$T_{strip,backwards}$	153 [°C]	152.4 [°C]

5.3 Sub-lubricated configuration : spray 1 OFF and spray 2 ON

Turning OFF the spray 1 has two main consequences. The first is the decrease of the amount of lubricant available at the inlet of the roll-bite in stand 5. The second effect is an increase of the strip temperature before stand 5. These two effects have been separately studied in the numerical model by modifying $T_{strip,front}$ and h_0 .

In the first case, the initial temperature was kept constant ($T_{strip,front} = 118°C$) and the inlet lubricant film thickness (h_0) was progressively decreased. These results correspond to the green curve in Figures 4 and 5. One can see in Figure 4 that h_0 higher than 10 µm gives similar results as the ones obtained in a fully lubricated case. For lower initial lubricant film thickness starvation occurs. Indeed, reducing h_0 from 10 µm to 5 µm induces a slight rise of the forward slip of about 2.7%. Then a significant increase is observed until a film thickness of 0.1 µm is reached. Finally for a lubricant film thinner than 0.1 µm, the forward slip is more or less constant. In Figure 5, it is observed that the value of the inlet oil film thickness does not change the exit temperature much.

In Figure 4, numerical results, corresponding to an inlet film thickness of 3.48 µm, match the forward slip experimental value measured after having turned OFF the spray 1. Nevertheless the exit temperature obtained in this case is 5°C lower than the experimental measurement.

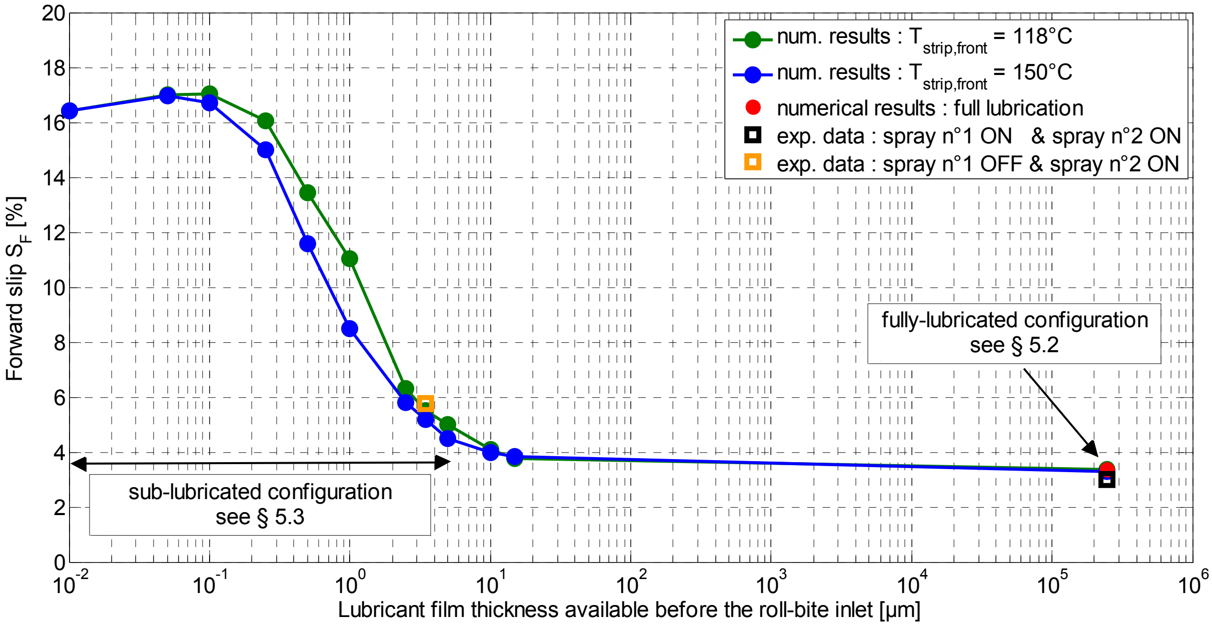

Figure 4: Forward slip corresponding to two entry temperatures ($T_{strip,front}$ ~1.3 m ahead of the roll-bite entry) for various lubricant film thicknesses available at the inlet of the roll-bite

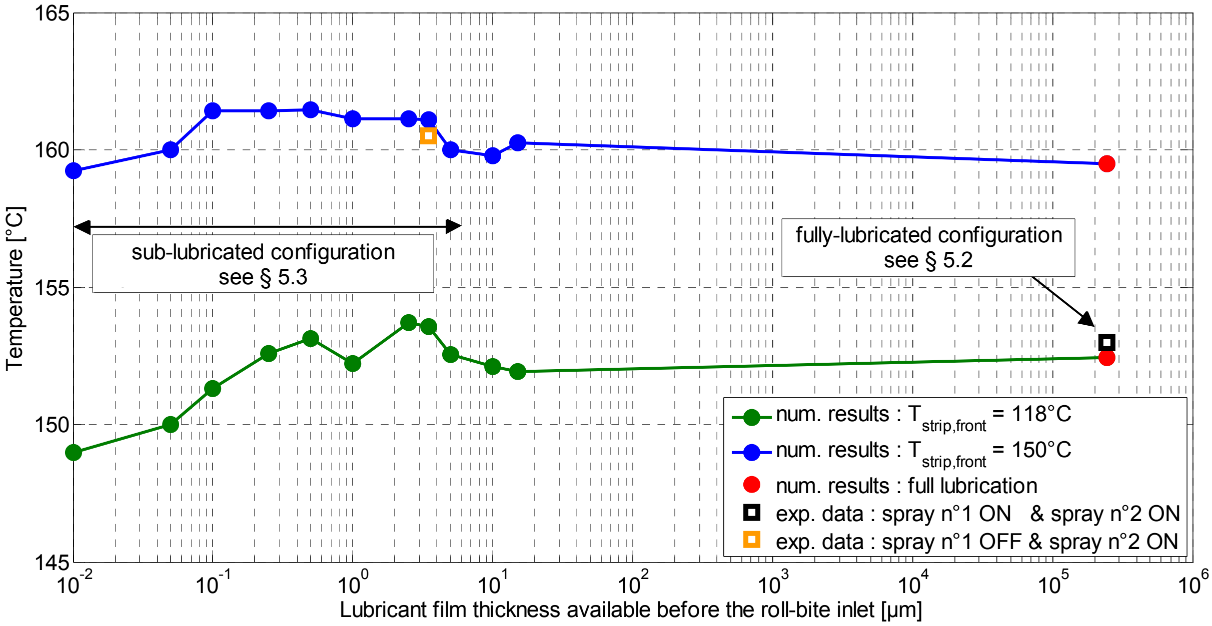

Figure 5: Exit temperature ($T_{strip,backwards}$, 2m after the roll-bite exit) corresponding to two entry temperatures ($T_{strip,front}$ ~1.3m ahead of the roll-bite entry) for various lubricant film thickness available at the entry of the roll-bite

In the second case, simulations were performed with $T_{strip,front}$ = 150°C. The forward slip values are close to the one obtained with $T_{strip,front}$ = 118°C. The maximum absolute difference between these two curves is less than 2%. The temperature difference at the entry of the roll-bite, after the emulsion cooling, is 10 °C. Figure 4 shows that this temperature difference, for a given inlet lubricant film thickness, does not have a huge impact on the forward slip. As one can see in Figures 4 and 5, $T_{strip,front}$ = 150°C and a 3.48 µm initial lubricant film thickness match the forward slip and the exit temperature measured when the spray 1 is OFF.

From the analysis of Figures 4 and 5, it can concluded that reducing the amount of lubricant at the roll-bite entry essentially affects the forward slip while the exit temperature does not vary much. On the contrary, moderate temperature change at the entry of the roll-bite does not affect much the forward slip while its has a more important impact on the exit temperature.

6 CONCLUSION

A coupled mechanical / thermal / tribological model has been created to examine the behaviour of the stand 5 of an industrial mill. A parametric study on lubrication and thermal conditions has been conducted. These numerical results have been compared to the experimental ones. This comparison gives a better understanding of the stand behaviour. Indeed, experimental results revealed that turning OFF a lubricant spray on the strip had two impacts: an increase of the forward slip, and a temperature rise at the exit of the roll-bite. The thermomechanical model highlights that these two effects are due to two different reasons: the exit temperature rise is due to an increase of the entry temperature while the increase of the forward slip is due to lower lubricant film thickness at the entry of the roll-bite.

In the two lubrication configurations investigated here, the obtained numerical results are close to experimental ones.

To sum it up, the coupling of MetaLub-ThermRoll has been proven to be a very helpful tool to better understand some complicated rolling mill configurations that can occur when the mixed lubrication regime as well as the strip temperature play a critical role on the behaviour of the process. This thermomechanical model can be a solid support for industrial cold rolling process optimisation.

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