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A thermomicrostructural model for simulation disturbances in a hot strip mill and its effect in steel properties, roll force and exit strip thickness

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Abstract

Using Hot Strip Mill industrial data and a thermomicrostructural model was development to taking into account the effect of the strip tension and the work roll gap and the static, dynamic and metadynamic recrystallization to calculate the austenite grain size, mean flow stress that occurs in the steel and also the roll force, exit strip thickness and steel entry temperatures in each stand. Operational disturbances in the thermomicrostructural model were introduced in the strip tension and in the work roll gap. The sensitivity curves were plotted and showed the changes of these disturbances affect on the steel properties. The model showed that by increasing the gap of the previous stand increases the mean flow stress, and consequently the roll force. These disturbances increase the exit strip thickness, the strip temperature in all the stands and can cause dynamic and metadynamic recrystallization in the following passes. In addition, by increasing the gap within the stand itself reduces the mean flow stress and the strip temperature, and thereby results in an increase in the exit strip thickness. A group of qualitative rules were elaborated to show which actions should be taken if the disturbances occur, aiming to recover the strip thickness and improve steel properties.

Keywords: hot strip mill, thermomicrostructural model, microstructural model, thermic model.

1 Introduction

The automatic control of the mechanical properties in the hot strip mill contributes to cost savings by reducing the necessity of adding alloyed elements to the steel refining and in later reduction thermal treatments with the objective of improving the mechanical properties. Therefore, a computational microstructural model reduces the number of samplings and consequently it will increase the hot strip mill productivity. It is the first time that joins microstructural model and thermal model in the same model call thermomicrostructural model.

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Simbology

$\tau 1, \tau 2$	entry and exit strip tension
h1, h2	entry and exit steel thickness in the stand, respectively
r	reduction grade, r = (h1-h2)/h1
R'	flattned work roll radius
ε, εr, εt	efetive, redundant and total strain, respectively
ε_a	retained strain
$\dot{\varepsilon}, \dot{\varepsilon}_a$	strain rate and retained strain rate, respectively
Vr	work roll tangencial speed
Ve	exit strip speed
tip	interpass time
α	contact angle with material and work roll
U	work roll speed in RPM
ε_c	critical strain
ε_p	peak strain
$\varepsilon_{0.5}$	strain for 50% recrystallization
t_{ps}	time for 5% precipitation of the Nb(C,N)
$\sum$tip/tps	accumulated sum of tip and tps relation
Nb_{ef}	effective niobium concentration
$t_{0,5}$	time for 50% recrystallization
d_{rex}	recrystallized austenite grain size
d	final austenite grain size
d_{Fer}	final ferrite grain size
X	fractional softening
Xdyn	dynamic Fractional softening
MFS_{MK}	Misaka's mean flow stress
MFS_{mod}	Thermomicroestructural mean flow stress

In this model, the retained strains between passes were considered in order to incorporate the effect of the static, dynamic and metadynamics recrystallizations [1–5, 7, 8]. The model also predict the autenite grain size in every stands and ferrite grain size after it pass for the run out table and it calculate the thermal exchanges due to the effect of plastic strain of the steel, the heat conduction by work roll, the heat losses from: radiation, convection for the atmospheric air and for the water in the rolling mill [3,4,6]. Therefore the steel exit and entry temperature can be calculated for each stand. The mean flow stress (MFS) calculated from thermomicrostructural model is used in the Sims equation to determine the roll force [3, 4, 7].

A group of qualitative rules using the simulations, were elaborated to make it possible to determine which actions should be taken if the disturbances occur in the material thickness and/or entry temperature and/or mean flow stress and the corrections to be done in the manipulated variables, which are the roll gap, the strip tension between stand and the work roll speed, aiming to recover the strip thickness, improve mechanical properties and reduce roll force

2 Thermomicrostructural model flowchart

The actual roll force with the industrial data is not necessary in the Thermomicrostructural model where the flowchart model can see in figure 1; therefore in this case the model makes interactions to find itself at the stabilized final value of the flattened work roll radius and the other variables necessary to the hot rolling process. The thermomicrostructural model only needs the entry strip temperature in the first stand and the model calculates all the temperatures in every stands until the final temperature after the last stand.

To calculate the final ferrite grain size it is necessary to know the cooling rate in the run out table, or the strip temperatures measured before and after the run out table. The Thermomicrostructural model flowchart is shown in fig. 1.

3 Results analysis

With the thermomicrostructural model, it was possible to make simulations by means of changing the gap, the strip tensions between pass for each stands. This work was made with the hot strip mill industrials data, whose steel chemical composition used is shown in table 1.

Disturbances of ten percent for more and less in the gap and of one hundred percent for more and less for strip tension between passes were made in relation to the model nominal result data for second stand (F2). The effect of these changes in the steel properties were analyzed, such as; roll force, strip temperature, steel exit thickness and austenite grain size.

Table 1: Chemical composition of the C-Mn steel used in the Termomicroestrutural model

Chemical composition of the C-Mn steel used								
%C	**%Mn**	**%Si**	**%Nb**	**%Ti**	**%Cr**	**%Mo**	**%N**	**%V**
0.1311	0.52	0.0066	0.0	0.002	0.011	0.0	0.004	0.001

3.1 Effect of the gap's disturbances in F1 and its influence in F2

Note in fig. 2 that the MFS in F2 increases with the increasing of the gap the in F1 stand, this is because the gap's effect increases the strain and the strain rate, which is in accordance with the equation (1) [1,3–5] that shows the direct relationship with the strain and the strain rate of

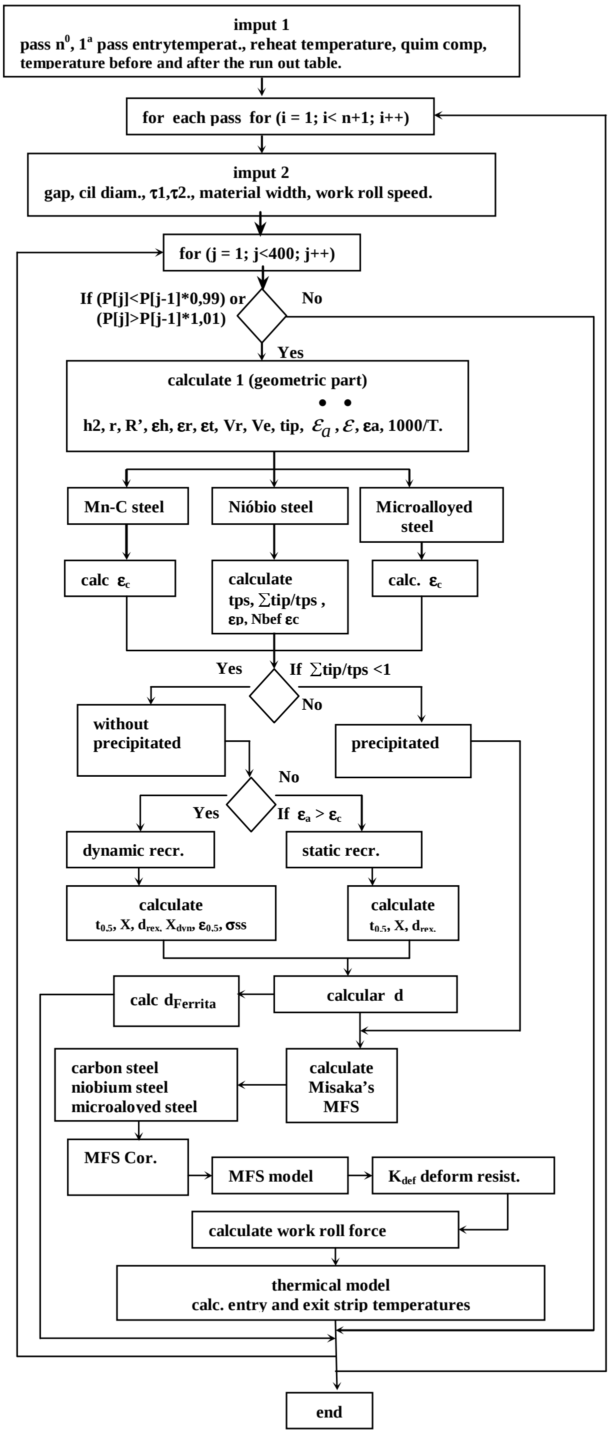

Figure 1: Thermomicrostructural flowchart model

the material.

$$MFS_{MK} = 1.15 \exp \left[0.126 - 1.75 [C] + 0.594 [C]^2 + \frac{2851 + 2968 [C] - 1120 [C]^2}{T} \right] .\varepsilon^{0.21} \dot{\varepsilon}^{0.13} \tag{1}$$

The increases in entry strip thickness in the F2 stand due to the gap increase in F1 resulting the same increase in the exit strip thickness in the F1 stand. This causes a decrease in the MFS in F1 as shown in fig. 3, thereby it reduces the strain and the strain rate and increases the MFS in the F2 stand due to the increase of these same variables.

These increases in thickness causes an increase in the dynamic and metadynamic recrystallization between the F2 and F3 stands causing a reduction in MFS in the following passes, as can be seen in table 1.

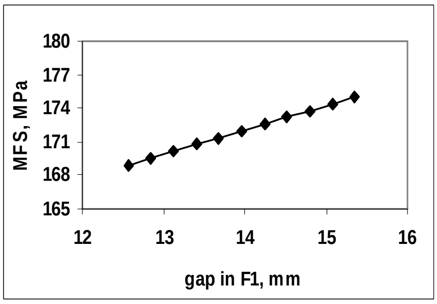

Figure 2: Effect of the changes in the gap in F1 in the MFS of the material in F2.

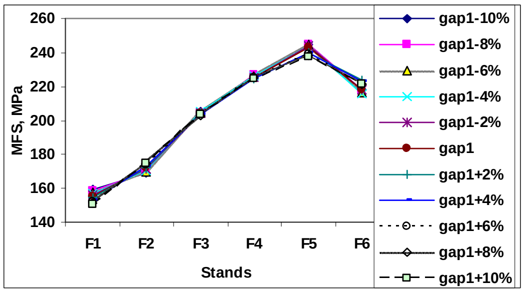

Figure 3: Effect of the changes in the gap in F1 in the MFS of the material in every stands.

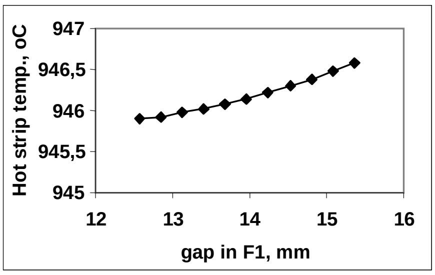

Figure 4: Effect of the changes in the gap in F1 in the strip temperature in F2.

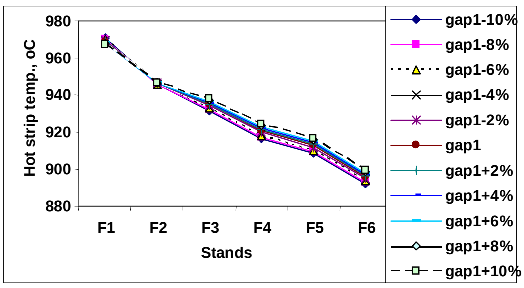

Figure 5: Effect of the changes in the gap in F1 in the Strip temperature in every stands.

An increase in the gap in the F1 stand increases the strip temperature in F2 can be observed in fig. 4. This is due to a hot delivery in the material because of the higher plastic strain. It can be seen in fig. 5 that these increases in the strip temperature are maintained for the next stands.

The calculated final austenite grain size is the initial grain size that enters in the next stand. Therefore it is influenced by the temperature between the passes such as shown in equations (2) and (3) given for the dynamic recrystallization as is this case. Therefore, due to the temperature increases from the increases in the entry strip thickness there is a tendency for growth in austenite grain.

On the other hand, increasing the exit strip thickness in F1 will certainly increase the strain rate in the F2 which in turn will decrease the material grain size as can be seen in equation (2). Due to these concurrent effects, fig. 6 shows there is a small increase in the austenite grain size.

$$d_{rex} = 2.6 * 10^4 . \left[\overset{\bullet}{\varepsilon} . \exp\left(300000/_{R.T}\right)\right]^{-0.23} \tag{2}$$

$$d^7 = d_{rex}^7 + 8.2 * 10^{25} . \left(tip - 2.65 . t_{0.5}\right) . \exp\left(-400000/_{R.T}\right) \tag{3}$$

Where, R is a gas universal constant, T is a absolute temperature, d_{rex} and d are recrystallized and final austenite grain size, respectively.

It is observed in fig. 7 that there is a small effect in the grain size, which affects the next stands. It also shows that in the F3 stand there was a sudden growth in the grain size followed by a decrease in grain size to the next stands for gap less than gap1+2%. For gaps greater than gap1+2% the grain growth appears in the F4 stand. This grain growth is because there isn't more dynamic recrystallization in the considered pass [3, 4]. It can be seen in table 1.

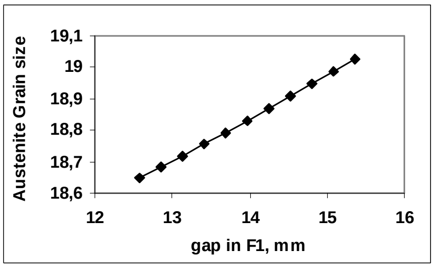

Figure 6: Effect of the changes in gap (mm) in F1 in austenite grain size after F2 stand, μm

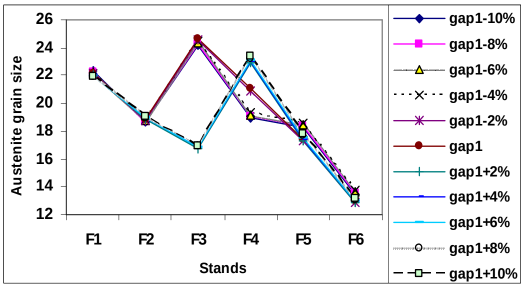

Figure 7: Effect of the changes in the gap in F1 in austenite grain size in every stands, μm

In the case of the changes of the grain size behavior in gap1-10%, gap1-8%, and gap1-6%, there was a decrease in the grain size, this was because there wasn't complete recrystallization (X<0,95). Thereby, there wasn't grain growth, thus resulting in a decreasing austenite grain size. The equation (4) used in the model shows this effect.

$$d = d_{rec} . X^{4/3} + d_{i-1} . \left(1 - X\right)^2 \tag{4}$$

It can be seen in fig. 8 that a greater gap in F1, produces a greater entry strip thickness in the F2, consequently the exit strip thickness in the hot rolling mill is greater. This is due to the increase of the work roll force because of the increase in the steel entry thickness makes the roll gap increase, resulting in the increase in the steel exit thickness. This is in accordance with the equation (7).

$$h2 = \frac{P_{Mod}}{Elm} + g \tag{5}$$

Where, P_{Mod} is the work roll force model, [ton.], Elm is the rolling mill rigidity modulus, [ton./mm] and g is the work roll, [mm].

It can be observed in fig. 10 that after the F2 stand, the increase in the exit strip thickness due to the increase in the F1 gap was insignificant.

Table 2: Results of the dynamic fractional recrystallization in every stands due to the changes in the gap in the F1 stand.

	Dynamic recrystallization - Xdyn						
	gap1-10%	gap1-8%	gap1-6%	gap1-4%	gap1-2%	gap1	gap1+2%
F1	0.236	0.222	0.208	0.195	0.182	0.17	0.158
F2	0.095	0.103	0.11	0.118	0.126	0.135	0.143
F3	0	0	0	0	0	0	0.012
F4	0	0	0	0	0	0	0
F5	0	0	0	0	0	0	0
F6	0	0	0	0	0	0	0

	Dynamic recrystallization - Xdyn			
	gap1+4%	gap1+6%	gap1+8%	gap1+10%
F1	0.146	0.135	0.124	0.114
F2	0.152	0.16	0.169	0.178
F3	0.012	0.014	0.015	0.018
F4	0	0	0	0
F5	0	0	0	0
F6	0	0	0	0

As can be seen in figure 10, the greater the gap in F1, the greater the entry strip thickness in the F2 and greater is the roll force in the F2, due to the greater opposite force from the strip during the plastic strain in the rolling mill. At the same time, the work roll force in the F1 decreases sees fig. 11. Equation (8) based in the Sims's model shows these relationships.

$$P_{Mod} = MFS_{Mod}.W.\sqrt{R'.(h1 - h2)}.Q \tag{6}$$

Where, Q is the geometric factor that is given by the Sims's equation.

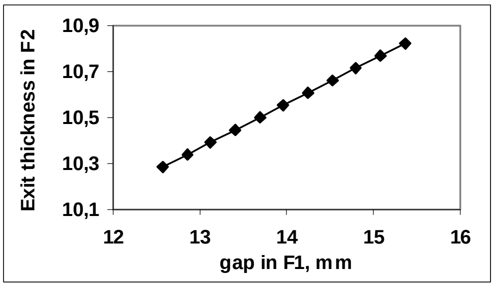

Figure 8: Effect of the gap's changes in F1 in the exit strip thickness in F2, mm.

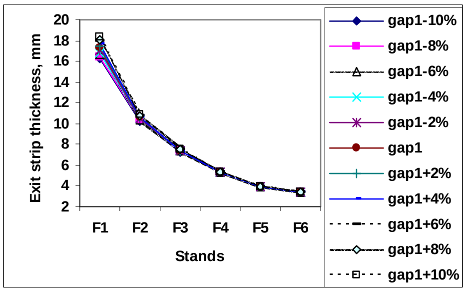

Figure 9: Effect of the gap's changes in F1 in the exit strip thickness in every stands, mm.

3.2 Effect of the changes in the work roll gap in F2 stand

Observe in fig. 12 the MFS decreases with the increasing of the gap in F2, which produces an increase in the exit strip thickness, thus reducing the strain and the strain rate. This is accordance with the (1) Misaka's equation. It also observes in fig. 13 that increasing the gap in the F2 causes a decrease in the MFS in this pass, and also causes a decrease in the dynamic and metadynamic recrystallization between the F2 and F3 stands, thus providing an increase in MFS in the next pass, as can be seen in table 3.

Figure 14 shows how a greater gap, greater is the exit strip thickness in the rolling mill and smaller is the work roll force, which is due to the smaller opposite force from the strip during the plastic strain in the rolling mill, see fig. 16. An Increase in F2 roll gap causes an increase in the entry strip thickness in F3 and consequently decreases the work roll force in F2 and also increases in F3, as observed in fig. 17.

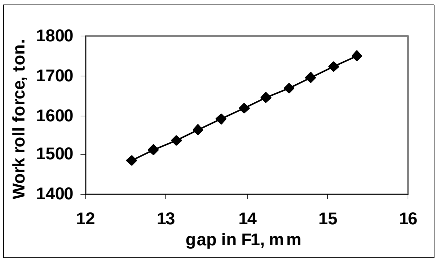

Figure 10: Effect of the gap's changes in F1 in the work roll force in F2, ton.

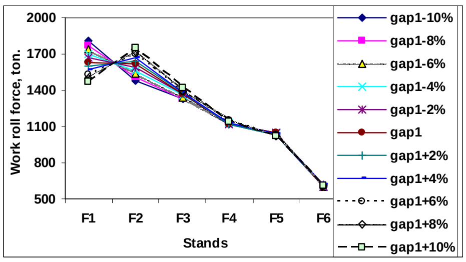

Figure 11: Effect of the gap's changes in F1 in the work roll force in every stands.

Figure 15 shows that after the F3 stand, the increase in the exit strip thickness due to the increase in the F2 gap was insignificant.

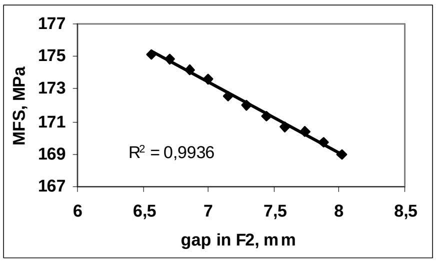

Figure 12: Effect of the gap's changes in F2 in MFS Fig. 11.

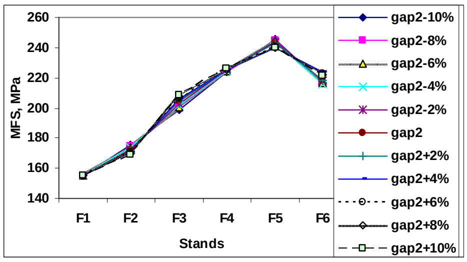

Figure 13: Effect of the gap's changes in F2 in the MFS in every stands.

Table 3: Results of the dynamic fractional recrystallization in every stands due to the work roll gap's changes in F2 stand.

	Dynamic Recrystallization - Xdyn						
	gap2-10%	gap2-8%	gap2-6%	gap2-4%	gap2-2%	gap2	gap2+2%
F1	0.17	0.17	0.17	0.17	0.17	0.17	0.17
F2	0.192	0.183	0.171	0.159	0.145	0.135	0.125
F3	0	0	0	0	0	0	0
F4	0	0	0	0	0	0	0
F5	0	0	0	0	0	0	0
F6	0	0	0	0	0	0	0

	Dynamic Recrystallization - Xdyn			
	gap2+4%	gap2+6%	gap2+8%	gap2+10%
F1	0.17	0.17	0.17	0.17
F2	0.115	0.108	0.098	0.089
F3	0.013	0.012	0.015	0.015
F4	0	0	0	0
F5	0	0	0	0
F6	0	0	0	0

It can be seen in fig. 18 that increasing the gap in F2 decreases the strip temperature, because of the smaller reduction grade. At the same time, the temperature increases in the next stands due to the increase in the exit strip thickness in F2 stand. This can be seen in fig. 19.

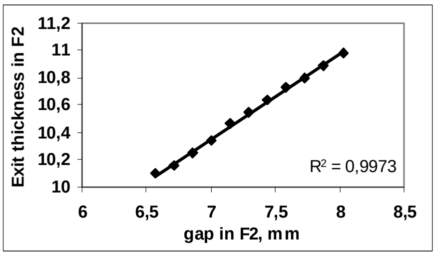

Figure 14: Effect of the gap's changes in F2 in the exit strip thickness.

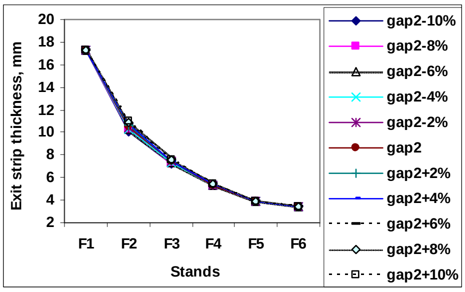

Figure 15: Effect of the gap's changes in F2 in the exit strip thickness in every stands.

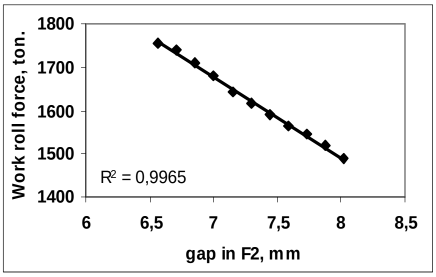

Figure 16: Effect of the gap's changes in F2 in the work roll force in F2.

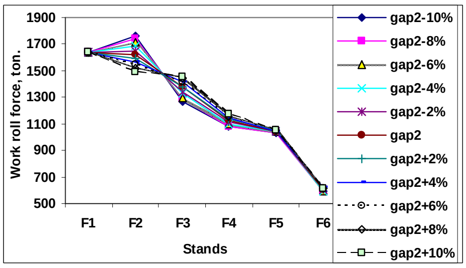

Figure 17: Effect of the gap's changes in F2 in the work roll force in every stands.

The austenite grain size is influenced by the temperature between passes as shown in equations (2) and (3). Therefore, due to the temperature decrease because of the decrease in the roll gap there is a tendency to reduce in austenite grain size.

On the other hand, increasing the roll gap in F2 will certainly decrease the strain rate in the F2 that in turn will increase the material grain size as can be seen in equation (2). Due to these concurrent effects figure 20 shows that there is a small decrease in the austenite grain size.

It is observed in fig. 21 that there is a small effect in the grain size, but it affects the following stands. It also shows that the F3 stand had a high growth in the grain size followed by a reduced grain size in the next stands, for gap a less than gap2+4%. For a gap greater than gap2+2% the grain growth appears in the F4 stand. This grain growth is because there isn't more dynamic recrystallization in the specific pass [3, 4], as can be seen in table 3.

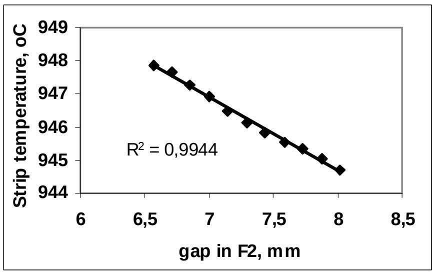

Figure 18: Effect of the gap's changes in F2 in the strip temperature.

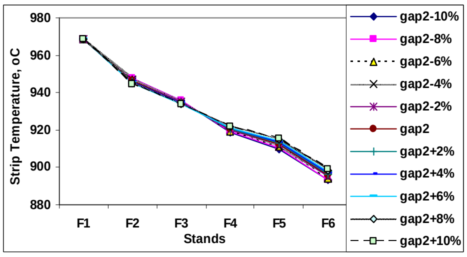

Figure 19: Effect of the gap's changes in F2 in the Strip temperature in every stands.

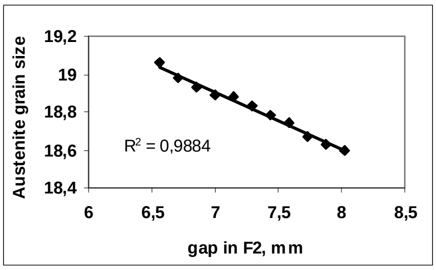

Figure 20: Effect of the gap's changes in F2 in the austenite grain size.

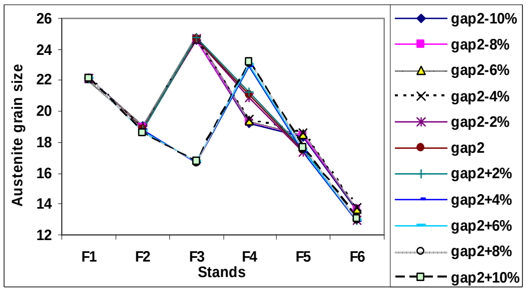

Figure 21: Effect of the gap's changes in F2 in the austenite grain size in every stands.

3.3 Effect of the changes in the entry strip tension in F2 stand

As can be seen in fig. 22, the greater the entry strip tension the smaller is the work roll force, which is mainly due to the reduction in the opposite force from the strip during rolling mill process, as can be seen in the equations (7) and (8). Consequently, a reducing in the exit strip thickness will be due to the smaller opposite roll force from strip during the rolling mill process, fig. 24.

$$K_{def} = TEM_{Mod} - \left(\frac{\tau_1 + \tau_2}{\alpha}\right).\phi n \tag{7}$$

$$P = K_{def}.W.\sqrt{R'.(h1 - h2)}.Q \tag{8}$$

Where τ_1 and τ_2 are the entry and exit strip tension, respectively. α and ϕn are the contact angle and the neutral angle of the work roll with the strip during rolling mill process, respectively.

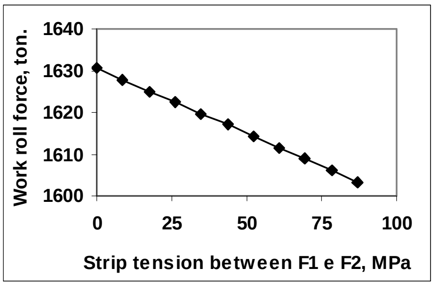

Figure 22: Effect of the changes in the entry strip tension at the F2 in the work roll force.

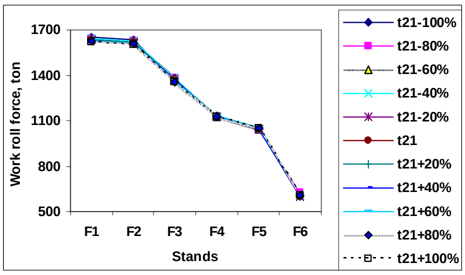

Figure 23: Effects of the changes in the entry strip tension at the F2 in the work roll force to every stands.

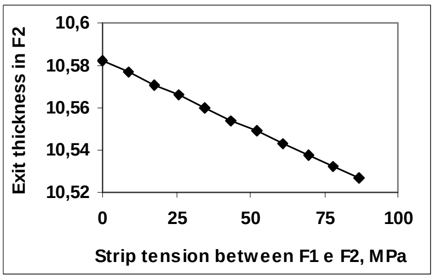

Figure 24: Effect of the changes in the exit entry strip tension at the F2 in the exit strip thickness.

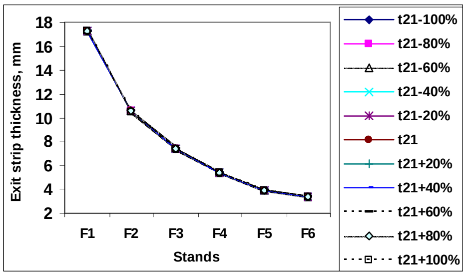

Figure 25: Effect of the changes in the exit entry strip tension at the F2 in the exit strip thickness of every stand.

The effect in work roll force and exit strip thickness by changes in entry strip tension was insignificant for the next stands. It can be seen in figures 23 and 25.

Observe in fig. 26 the MFS increase slightly with the increase of the entry strip tension. It is due to this increase in entry strip tension that reduces the work roll force and consequently decreases the exit strip thickness, thereby increasing the strain and strain rate. The strip temperature will reduce slightly and can cause a slightly increase in the MFS too.

The austenite grain size is influenced by the strip temperature between passes. So, if strip temperature decreases, the grain size decreases slightly too. Sees fig. 27.

3.4 Effect of the changes in the exit strip tension in F2 stand

In the same way as shown in the entry strip tension, the fig. 28 and 29 shown that the greater the exit strip tension, the smaller the work roll force, the exit strip thickness and austenite grain size and greater the MFS. In addition, the effect in the work roll force and exit strip thickness due to changes in exit strip tension was insignificant to the next stands.

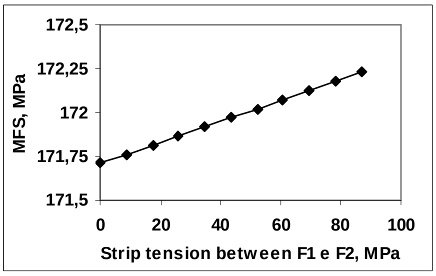

Figure 26: Effect of the changes in the entry strip tension at F2 in the MFS.

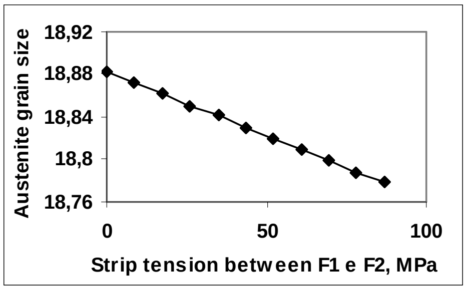

Figure 27: Effect of the changes in the entry strip tension at F2 in the austenite grain size.

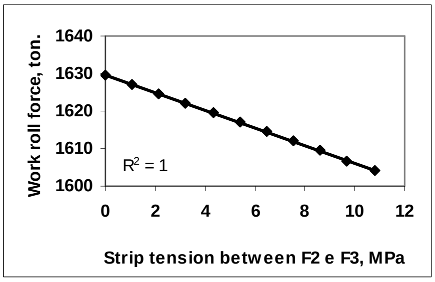

Figure 28: Effect of the changes in the exit strip tension at F2 in the work roll force.

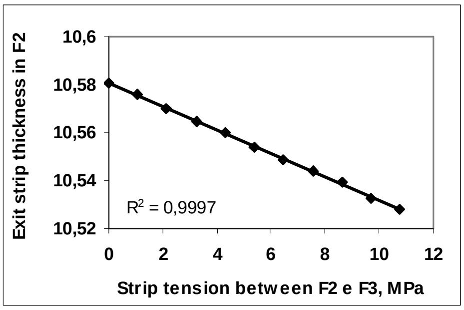

Figure 29: Effect of the changes in the exit strip tension at F2 in the exit strip thickness.

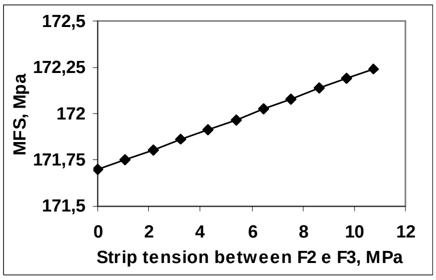

Figure 30: Effect of the changes in the exit strip tension at F2 in the MFS.

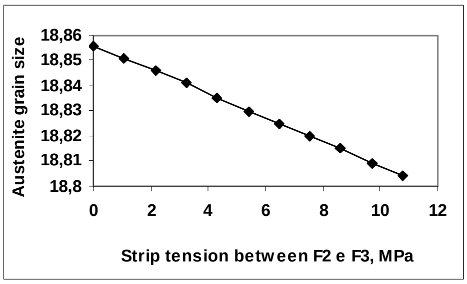

Figure 31: Effect of the changes in the exit strip tension at F2 in the austenite grain size.

4 Qualitative rules aiming at process control

Using the simulations, a group of qualitative rules were elaborated which make it possible to determine what actions should be taken if there are changes in the exit strip thickness, the mean flow stress and the austenite grain size take place, as well as the work roll force. These actions aim to recover the exit strip thickness, improve steel properties and reduce the work roll force. It can therefore determine the priorities and measures that are needed for the steel properties, microstructure and exit strip thickness and also the work roll force as an operational parameter. These qualitative rules provide a base to develop some type of programming aimed at hot strip mill control, such as a soft computing program.

For the analyses the principle that was adopted is that the changes of a manipulated variable does not mean changes of the other variables, therefore it is considered that the local controllers keep them in theirs set-points. So, tables for each stand were made which considered as disturbances; the entry exit thickness (h1), entry strip temperature (Te) and MFS. As a result of these disturbances, changes take place in the exit strip thickness (h2), austenite grain size (d), MFS and work roll force (P), as can be seen in the tables 4 and 5 for the F2 stand. The work roll force is the measured variable and it can identify the disturbances.

The MFS is only considered as a disturbance when its changes occur separately, without changes in the exit strip thickness and/or entry strip temperature. On the other hand, the MFS will be considered as result of the exit strip thickness and the entry strip temperature changes.

The tables 4 and 5 also show the corrections to be made in the manipulated variables that are gap (g), entry strip tension ($\tau 1$) and exit strip tension ($\tau 2$). After that, the corrections will be made, these results in the exit strip thickness, work roll force, austenite grain size and MFS are shown in the same tables.

The information in the tables 4 and 5 are qualitative. Thus, when one variable increases its value appears as the symbol ($\uparrow$), when it decreases the symbol is ($\downarrow$). In the cases where there are no changes in the variable the symbol will be (=). After the corrections in the manipulated variable are made, the tables show the consequences in h2, P, MFS and d. When the result of these consequences has a concurrent effect, the variable that produced greater influence is the one that determines the final result and the symbol will appear underlined like ($\underline{\uparrow}$) or ($\underline{\downarrow}$), if the final result increases or decreases, respectively. The corrections in the manipulated variable are made aiming to recover the strip thickness and observing the behavior of the mechanical properties and microstructure of the material.

In the table 4 we can see a work roll force increase due to only the MFS increase, causes an increase in the exit strip thickness, disturbance condition 7 (DC 7). In cases where a decrease in the gap is required for recovery the exit the strip thickness, work roll force, MFS and austenite grain size will increase even more. Conversely, in cases where there is an increase in the exit strip tension, MFS will increase slightly, but the work roll force, exit strip thickness and the austenite grain size will decrease. Evidently, that gap correction produces a more significant effect in the exit strip thickness than the correction in the strip tension between stands.

Table 4: Qualitative analysis results of the consequences of changes in the entry strip thickness and MFS in exit strip thickness and work roll force, and the corrections made in the manipulated variable for correction of the exit strip thickness.

DC	Disturbances			Mea Var	Consequence after disturbance		Manipulated Variable Corrections in:			Consequences in h2 and P, after corrections in g, $\tau 1$ and $\tau 2$					
										h2			P		
	h1	Te	TEM	P	h2	d	g	$\tau 1$	$\tau 2$	g	$\tau 1$	$\tau 2$	g	$\tau 1$	$\tau 2$
1	↑	↓	↑	↑	↑	↓	↓	↑	↑	↓	↓	↓	$\underline{\uparrow}$	↓	↓
2	↓	↑	↓	↓	↓	↑	↑	↓	↓	↑	↑	↑	$\underline{\downarrow}$	↑	↑
3	↑	↑	↑	↑	↑	↑	↓	↑	↑	↓	↓	↓	$\underline{\uparrow}$	↓	↓
4	↑	↑	↓	↓	↓	↑	↑	↓	↓	↑	↑	↑	$\underline{\downarrow}$	↑	↑
5	↓	↓	↑	↑	↑	↓	↓	↑	↑	↓	↓	↓	$\underline{\uparrow}$	↓	↓
6	↓	↓	↓	↓	↓	↓	↑	↓	↓	↑	↑	↑	$\underline{\downarrow}$	↑	↑
7	=	=	↑	↑	↑	↓	↓	↑	↑	↓	↓	↓	$\underline{\uparrow}$	↓	↓
8	=	=	↓	↓	↓	↑	↑	↓	↓	↑	↑	↑	$\underline{\downarrow}$	↑	↑
9	↑	=	↑	↑	↑	↑	↓	↑	↑	↓	↓	↓	$\underline{\uparrow}$	↓	↓
10	↓	=	↓	↓	↓	↓	↑	↓	↓	↑	↑	↑	$\underline{\downarrow}$	↑	↑
11	=	↑	↓	↓	↓	↑	↑	↓	↓	↑	↑	↑	$\underline{\downarrow}$	↑	↑
12	=	↓	↑	↑	↑	↓	↓	↑	↑	↓	↓	↓	$\underline{\uparrow}$	↓	↓

Notice that when gap correction aims for the same exit strip thickness recovery, it produces a contrary effect in the work roll force and in the austenite grain size in relation to the corrections in the strip tension between stands. With this, the priorities and measures that it wants for the steel properties can be defined, such as MFS, microstructure and exit strip thickness and also the work roll force as operational parameter.

In many hot strip mills the only measure variable is the work roll force. So, tables for each stand had been made where an identifier of the disturbances the work roll force were considered and as a consequence of these disturbances, changes take place in the exit strip thickness, austenite grain size and the MFS as can be seen in the table 6 for the F2 stand.

Table 6 shows that by increasing the work roll force, the exit strip thickness, the MFS increases and the austenite grain size decrease. Therefore there will be an improvement in the steel properties, but it will to have dimensional loss. In cases where it's necessary to increase the MFS ever more, the austenite grain size decrease more, reduces the work roll force and, moreover, corrects the exit strip thickness, thus, it is necessary to increase the entry and/or exit strip tension.

In cases where a more significant recoveries in the exit strip thickness aiming to decrease is wanted, a decrease in the work roll gap is necessary and as a result the work roll force and the MFS will increase and the austenite grain size will decrease.

Another important observed factor is that by increasing the entry strip tension there also

Table 5: Qualitative analysis result of the consequences of changes in the entry strip thickness and MFS in austenite grain size and MFS, and the corrections made in the manipulated variable for correction of the exit strip thickness.

DC	Disturbances			Mea Var	Consequence after disturbance		Manipulated Variable Corrections in:			Consequences in h2 and P, after corrections in g, $\tau1$ and $\tau2$					
										h2			P		
	h1	Te	TEM	P	h2	d	g	$\tau1$	$\tau2$	g	$\tau1$	$\tau2$	g	$\tau1$	$\tau2$
1	↑	↓	↑	↑	↑	↓	↓	↑	↑	↑	↑	↑	$\underline{\uparrow}$	↓	↓
2	↓	↑	↓	↓	↓	↑	↑	↓	↓	↓	↓	↓	$\underline{\downarrow}$	↑	↑
3	↑	↑	↑	↑	↑	↑	↓	↑	↑	↑	↑	↑	$\underline{\uparrow}$	↓	↓
4	↑	↑	↓	↓	↓	↑	↑	↓	↓	↓	↓	↓	$\underline{\downarrow}$	↑	↑
5	↓	↓	↑	↑	↑	↓	↓	↑	↑	↑	↑	↑	$\underline{\uparrow}$	↓	↓
6	↓	↓	↓	↓	↓	↓	↑	↓	↓	↓	↓	↓	$\underline{\downarrow}$	↑	↑
7	=	=	↑	↑	↑	↓	↓	↑	↑	↑	↑	↑	$\underline{\uparrow}$	↓	↓
8	=	=	↓	↓	↓	↑	↑	↓	↓	↓	↓	↓	$\underline{\downarrow}$	↑	↑
9	↑	=	↑	↑	↑	↑	↓	↑	↑	↑	↑	↑	$\underline{\uparrow}$	↓	↓
10	↓	=	↓	↓	↓	↓	↑	↓	↓	↑	↑	↑	$\underline{\uparrow}$	↓	↓
11	=	↑	↓	↓	↓	↑	↑	↓	↓	↓	↓	↓	$\underline{\downarrow}$	↑	↑
12	=	↓	↑	↑	↑	↓	↓	↑	↑	↑	↑	↑	$\underline{\uparrow}$	↓	↓

Table 6: Result of the qualitative analysis of the consequences of changes in the work roll force, and the corrections made in the manipulated variable for correction of the exit strip thickness.

Mea Var	Consequence			Manipulated Variable Corrections in:			Consequences in h2, P, TEM e d after corrections in g, $\tau1$ and $\tau2$											
							h2			P			TEM			d		
P	h2	TEM	d	g	$\tau1$	$\tau2$	g	$\tau1$	$\tau2$	g	$\tau1$	$\tau2$	g	$\tau1$	$\tau2$	g	$\tau1$	$\tau2$
↑	↑	↑	↓	↓	↑	↑	↓	↓	↓	$\underline{\uparrow}$	↓	↓	↑	↑	↑	$\underline{\uparrow}$	↓	↓
↓	↓	↓	↑	↑	↓	↓	↑	↑	↑	$\underline{\downarrow}$	↑	↑	↓	↓	↓	$\underline{\downarrow}$	↑	↑

is a reduction in the work roll force in the previous stand, which in turn will reduce its exit strip thickness and austenite grain size. Decreasing the exit strip thickness of the previous stand which will decrease the work roll force in the following stand, that in turn will decrease the exit strip thickness and austenite grain size (table 6). Thereby, the corrections in the manipulated variable can be made such a way as to have the best product with the best dimensions and with the best steel properties and microstructure too.

It was shown that with no dynamic recrystallization in one specific pass, a significant growth of the austenite grain size of the strip occurred until its entrance of the following pass. So, it can be considered that the end of the dynamic recrystallization causes a disturbance in the austenite grain size by increasing. However, the occurrence of the dynamic recrystallization can also cause a disturbance in the austenite grain size by decreasing it significantly. Therefore, in cases where the model detects the end of the dynamic recrystallization, the austenite grain size will grow sharply and if it wants to refine the austenite grain more to improve the steel properties and not to move the roll gap, the entry and/or exit strip tension must be increased in the following stand. Consequently, the MFS and the work roll force will be reduced.

With these rule bases some type of soft computing program can be developed, aiming to control the hot strip mill process using techniques of non conventional automatic control.

5 Conclusions

The increase in gap of the previous stand increases a MFS and consequently the work roll force in the pass increase.

The increase in gap in the previous stand increases the strip temperature in every stand and can cause an increase in the dynamic recrystallization between passes, providing a reduction in the MFS in the next passes.

The increase in gap in the specific stand decreases the MFS, the work roll force and the strip temperature and increases the exit strip thickness in the pass. This increase in the exit strip thickness causes an increase in the work roll force in the following stand.

The increase in the entry strip tension causes a reduction in work roll force and exit strip thickness.

The increase of the exit strip tension produces the same effect of those gotten from the entry strip tension, but in this case the change also will introduce changes in the material in the next stand.

Gap corrections aiming for the same recovery for exit strip thickness produces contrary effect in the work roll force and in the austenite grain size in relation to the corrections in the strip tension between stands.

It can therefore determine the priorities and measures that are needed for the steel properties, microstructure, exit strip thickness and the roll force.

These qualitative rules provide a base to develop some type of programming aimed at hot strip mill control, such as a soft computing program.

The Thermomicrostructural model can calculate many variables of the hot rolling process as well as the metallurgical variables too, that can help the engineer to better understand the rolling process to solve problems and to improve the quality of the final product.

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