Modelling the Microstructural Evolution During Hot Strip Rolling of Niobium Microalloyed Steels

Antonio Gorni[1], Marcelo Rebellato[2], Vishwanathan Nagarajan[3] and Ronaldo Barbosa[4]
[1]Aranda Editora, Alameda Olga 315, São Paulo SP 01155-900, Brazil
[2]CBMM, Av. das Nações Unidas 12901, São Paulo SP 04578-910, Brazil
[3]Ferro Tech India, N.M. Joshi Road, Lower Parel (E), Mumbai Mararashtra 400013, India
[4]UFMG, Av. Antônio Carlos 6627, Belo Horizonte MG 31270-901, Brazil
E-mail: antonio.gorni@gmail.com

ABSTRACT

The occurrence of dynamic recrystallization in the intermediate stands of the finishing mill of a hot strip mill promotes substantial softening of the rolling stock, a situation that can cause operational problems and even scrapping of the strip. The aim of this work was to identify specific process conditions that can promote this situation, which was carried out through the application of a microstructural evolution model. It was verified, for the specific conditions of a Brazilian hot strip mill, that this problem generally occurs during the processing of thin hot strips, with a relatively low Nb content and under rolling temperatures slightly lower than the normal range.

KEYWORDS: *Hot Strip Rolling, Microalloyed Steels, Microstructural Evolution, Dynamic Recrystallization*

INTRODUCTION

The knowledge about the microstructural evolution of hot rolled steels, which allows not only the metallurgical characterization of the rolling stock during hot forming, but also its influence over final product properties, promotes important benefits regarding a better process control. This approach allows to optimize the chemical composition of steels, decrease the dispersion of mechanical properties and dimensional features, increase process reliability, as well minimize scrap and quality downgrading rates of the final product.

These improvement opportunities justify the several studies developed about this subject during the last decades, as well the intense activity still seen today. There is much to be understood, particularly in the industrial hot rolling processes, carried out under much more complex and far-from-perfect conditions than laboratorial tests. Under industrial conditions there is the presence of temperature, strain degree and strain rate gradients, as well chemical segregation across the rolling stock thickness; the nature of the interface work roll-rolling stock still is largely unknown and reliable data acquisition is very difficult. All these problems make the fitting and application of microstructural evolution models difficult in industrial hot rolling.

Several unexpected cobble occurrences during the rolling of Nb microalloyed steel in a Brazilian hot strip mill prompted a detailed analysis about their metallurgical state during processing. It is widely known from the literature[1,2] that certain conditions of microstructural evolution can promote dynamic recrystallization (DRX) in the intermediate stands of the finishing mill. This restoration process is much quicker than the static recrystallization (SRX) which normally occurs between the rolling stands of such mills. DRX totally eliminates residual strain hardening that accumulated in the rolling stock as it was being rolled in the former stands. So, the rolling stand following DRX will process a softened material, a situation that is not predicted in the finishing mill automation algorithms, which normally assumes that the rolling stock will become increasingly harder as it is being rolled. This unexpected behaviour can cause control problems in the finishing mill and, eventually, to cobble occurrences.

This work describes the application of a microstructural evolution model to the hot rolling process of Nb microalloyed steels in a finishing mill, in order to identify the specific process conditions that promote DRX in the intermediate stands, so they can be suppressed in order to avoid control disturbances in the rolling line and the potential occurrence of cobbles.

EXPERIMENTAL PROCEDURE

The model adopted in this work for microstructural evolution calculation during hot strip rolling was originally proposed by Siciliano et al.[1,2]. It is a relatively simple algorithm that was already described in detail and which can be easily applied. It was programmed for this work using Visual Basic for Applications language inside an Excel spreadsheet. So one can compute grain size evolution along the finishing mill according to the kinetics of relevant restoration mechanisms during austenite hot forming, like DRX or SRX, as well grain growth. The model also computes residual strain in austenite immediately before the application of a rolling pass, a very important parameter as it controls the occurrence of DRX and influences mean flow stress (MFS). Another point to be highlighted is the prediction of NbCN precipitation start during hot rolling, which halts completely austenite recrystallization.

The microstructural evolution of about 5,000 Nb microalloyed steel hot strips during their processing in the finishing mill of a Brazilian steelworks was computed using the model described above[3]. The process data required by this model was got from the supervisory system of the hot strip mill. Unfortunately some metallurgical parameters were not available, so some assumptions have to be assumed. It was considered that all Nb was solubilized in austenite after slab heating. Data from the roughing mills was also not available, so austenite grain size of the rolling stock immediately before its entry in the finishing mill was estimated as being equal to 100 microns[2]. It was assumed that there was no restoration between consecutive rolling passes. And, finally, it was assumed that rolling stock cooling after rolling was initially cooled in air and transformed to ferrite after it has reached the first water cooling bank of the run-out table.

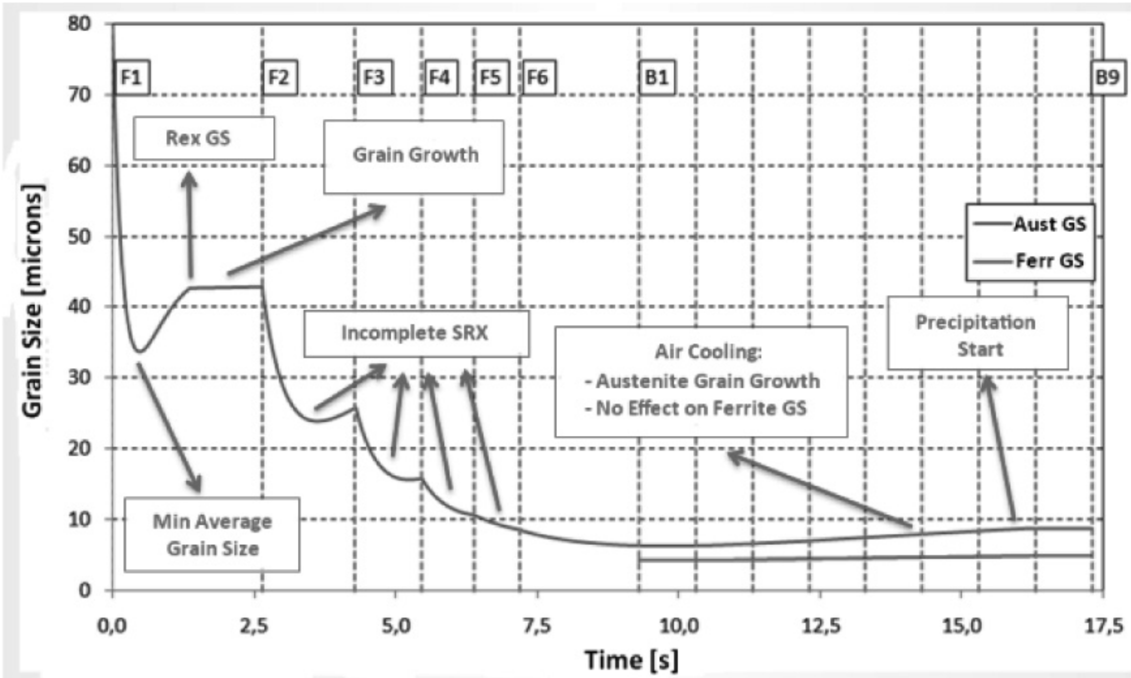
The calculation of the grain size of ferrite after austenite transformation was carried out in function of the final austenite grain size and residual strain, using the equations adopted by Siciliano and Jonas[2], considering an average cooling rate of 10°C/s. The effects of coiling temperature and slow cooling rate after coiling were not considered.

Unfortunately it is not possible yet to measure austenite grain size when the rolling stock is being rolled in order to validate model results. Alternatively a comparison was made between the values of MFS calculated by the Sims inverse model from the measured hot rolling loads and those determined using a theoretical model which considers the residual strain calculated by the microstructural evolution model[1,2].

RESULTS AND DISCUSSION

Most microstructural evolutions computed in this work showed that DRX occurrences during the rolling of Nb microalloyed steel strips have concentrated only in the first two stands of the finishing mill (F1 and F2). This tendency can be understood when one considers the formula used to calculate the critical strain which initiates DRX[1,2]. This parameter decreases for greater values of temperature and lower values of strain rate, conditions that are common in these rolling stands. Besides that, strain degree applied in these stands is relatively high and greater than those applied in the remainder stands. This is particularly true for thinner strips, where the slab:strip thickness reduction ratio is greater. In this case, strain applied in the F1 and F2 stands are even higher. This same situation was already predicted during the application of a microstructural evolution model for C-Mn steels in the same hot strip mill[4]. Under these conditions hot strength values increased steadily along the rolling stands of the finishing mill, the normal tendency assumed by the automatic control system of the mill. However, some strips can show a very different behaviour, as discussed below.

The first case to be analyzed is a pair of hot strips with same dimensions and Nb amounts, numbered as #1A and #1B, whose microstructural evolutions calculated along the finishing mill can be seen in Fig. 1. Although both strips have very similar processing conditions, one of them (#1A) has not shown DRX during its processing in the finishing mill, while the other one (#1B) showed DRX only in the F3 stand, which promoted a strong decrease in the MFS of the hot strip when it was rolled in the following stand, as can be seen in Fig. 2(b). It can be seen that a good fit was achieved between theoretical MFS values and those calculated from the measured rolling loads; the mean errors got for strips #1A and #1B were, respectively, 3.5% and 9.3%. In this figure, Tnr was calculated according to the Boratto formula[5].



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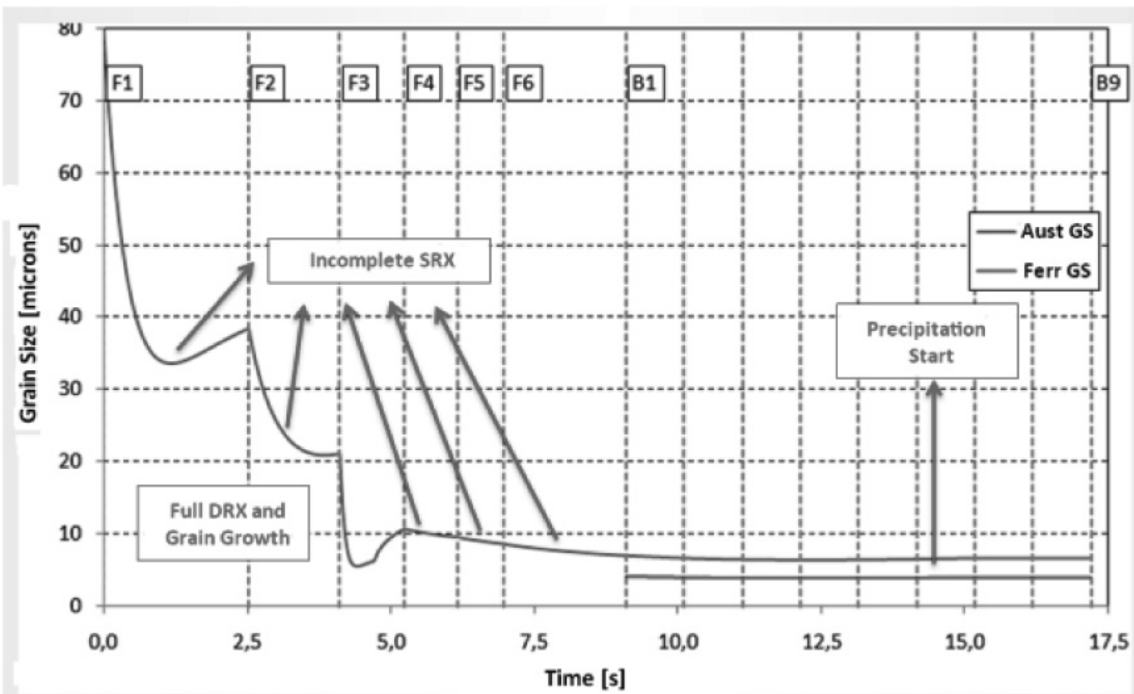
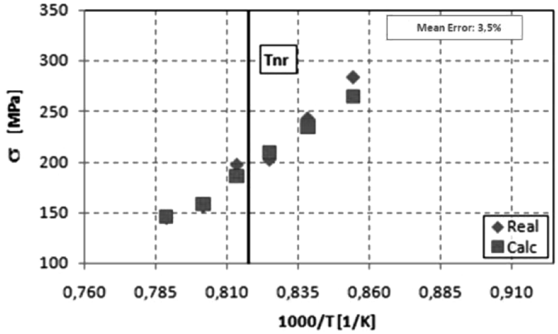


(b)

Fig. 1: Computed microstructural evolutions along finishing mill for strips (a) #1A and (b) #1B.

A comparison between the respective process parameters of the #1A and #1B strips, which can be seen in Table 1, shows a subtle difference in the rolling temperature evolutions, which was slightly lower in the last case. As one can see, temperature of the #1A coil in the F1 stand was equal to 995°C. According to the microstructural evolution model, this condition promoted 100% SRX plus grain growth after the pass applied in the F1 stand, with no residual strain in the austenite when the strip arrived at the F2 stand. From this point on, only partial SRX occurred in austenite after hot rolling in each of the remainder stands. However, its kinetics was quick enough to avoid a substantial build up of residual strain, so no DRX occurred during rolling. MFS evolution was monotonically increasing along finishing mill in the case of #1A strip, as can be seen in Fig. 2(a).

For its turn, the #1B strip was rolled under slightly lower temperatures, so temperature in the F1 stand was equal to 985°C. According to the microstructural evolution model, this was enough to significantly restrict SRX kinetics after rolling at F1 and F2 stands, progressively increasing austenite residual strain until its value was sufficient to promote DRX in the F3 stand. This restoration mechanism eliminated all strain hardening in the strip, which arrived to F4 stand showing not only complete recrystallization, but some grain growth as well. This situation was associated with a significant decrease in the MFS value in the F4 stand, as Fig. 2(b) shows.



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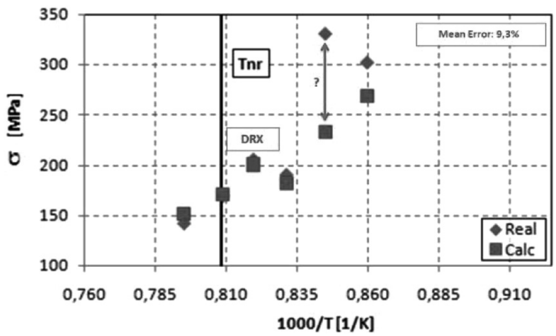


(b)

Fig. 2: MFS evolution along finishing mill for strips (a) #1A and (b) #1B.

Some comments still can be done about the microstructural evolution predicted for these two strips. Fig. 1(a) shows that, immediately after the rolling of the #1A strip in the F1 stand, its grain size decreased progressively down to a minimum value, followed then by a quick growth until austenite recrystallization end. At this point grain growth stage has started, at a slower rate, which ended when the strip was bite by F2 stand. This typical evolution of grain size during recrystallization and grain growth is the result of the adoption of the Beynon and Sellars equation[6], which calculates a weighted average between original and recrystallized grain sizes in function of the recrystallized fraction of austenite after the rolling pass.

Table 1: Comparison between chemical composition and hot strip rolling process parameters between strips #1A and #1B.

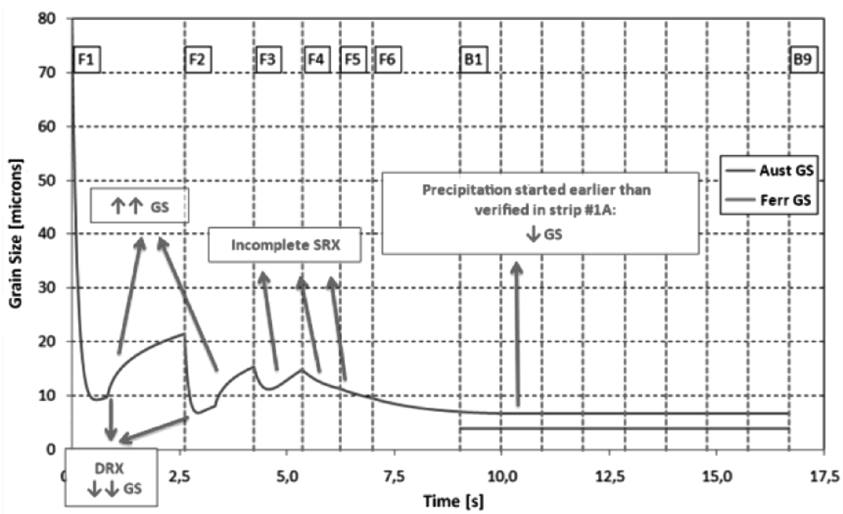
Strip	Chemical Composition [%]			
	C	Mn	Si	Nb
#1A	0.08	0.41	0.06	0.020
#1B	0.07	0.54	0.07	0.023

Strip	True Strain					
	F1	F2	F3	F4	F5	F6
#1A	0.77	0.58	0.48	0.37	0.23	0.14
#1B	0.78	0.59	0.47	0.36	0.19	0.13

Strip	Temperatures [°C]					
	F1	F2	F3	F4	F5	F6
#1A	995	974	956	939	930	897
#1B	985	963	947	930	911	890

The lower rolling temperatures promoted a slight greater grain size refining in #1B strip in comparison with #1A strip. However, according to this model, the influence of this smaller grain size over the final ferrite grain size has little significance. Besides that, in both cases, the model has predicted the NbCN precipitation start only during air cooling after hot rolling. Apparently this condition is default for all strips processed in the hot strip mill analyzed in this work.

Some interesting considerations can be done during the analysis of results relative to other two thin hot strips, #2A and #2B, similar to the previous ones, but whose Nb amounts (0.014% and 0.015%, respectively) were slightly lower. The microstructural evolutions relative to this second pair of hot strips can be seen in Fig. 3. In the same way like the previous case, both strips showed almost identical final thicknesses, chemical compositions and processing conditions. However, one of them, #2A, showed DRX in the F1 and F2 stands. The other one, #2B, showed DRX only in the F4 stand, so MFS value decreased significantly at F5, as Fig. 4 shows. One more time the fit between predicted and calculated MFS values was good, showing mean errors of 4.3% and 7.0% for the #2A and #2B strip, respectively.



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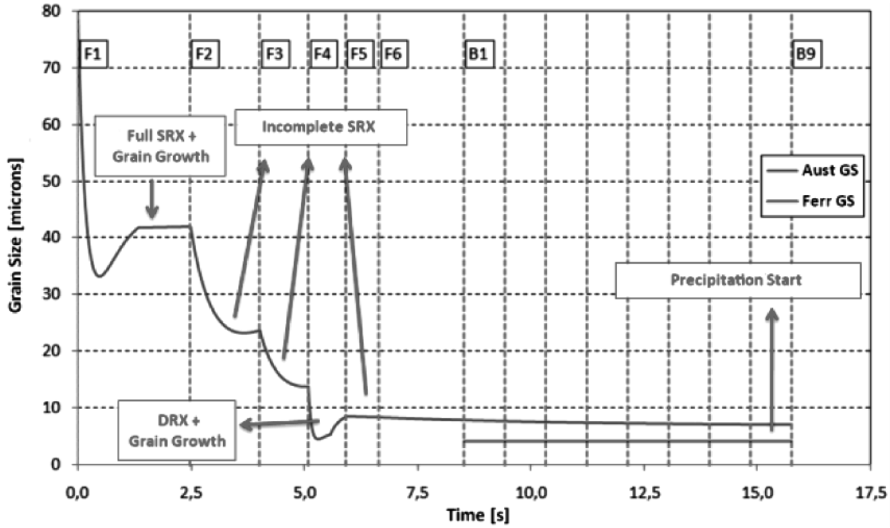
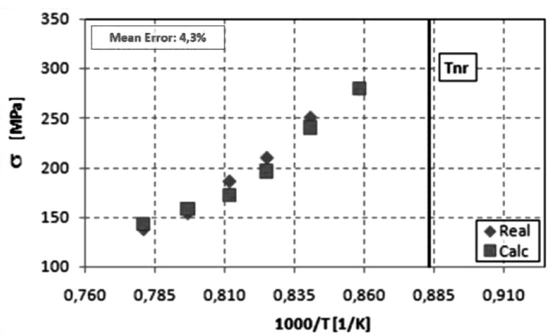


(b)

Fig. 3: Computed microstructural evolutions along finishing mill for strips (a) #2A and (b) #2B.

Once more these different microstructural evolutions can be attributed to a subtle difference in the temperature evolutions between these two strips. Rolling temperatures of strip #2A were slightly higher than those of strip #2B, as Table 2 shows. One can see, in Fig. 3(a), that grain growth calculated for strip #2A after DRX in stands F1 and F2 was much greater than that observed after SRX.

It is curious to note that strip #2A showed DRX in the F1 and F2 stands, while strip #1A only showed SRX along all its processing in the finishing mill. This can be due to the higher temperature evolution recorded for strip #2A in comparison with strip #1A, so the critical strain to start DRX was lower for the first strip, as chemical composition and processing parameters were almost the same for both strips. For their turn, strips #2B and #1B showed very similar strain degrees and temperature evolutions along the finishing mill. However, the lower Nb content in strip #2B favored the occurrence of SRX, especially in the F1 stand, where it not only was complete, but also included some grain growth, while SRX was incomplete for strip #1B. So the residual strain evolution in strip #2B was slower, delaying DRX occurrence, shifting it from F3 (strip #1B) to F4 stand (strip #2B).



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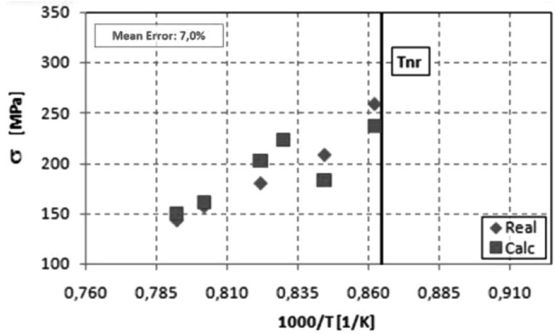


(b)

Fig. 4: MFS evolution along finishing mill for strips (a) #2A and (b) #2B.

So, the results got in this work show that, for the specific conditions of the hot strip mill being analyzed, DRX in the intermediate stands of the finishing mill only occurred in very specific cases, involving light strips, with thicknesses about 2,3 to 2,6 mm, relatively low amounts of Nb between 0.014% and 0.023%, and rolling temperatures slightly lower than the usual ones. However, it must be noted that new conditions for such kind of occurrence can arise if some modification is to be made in the product mix or rolling conditions.

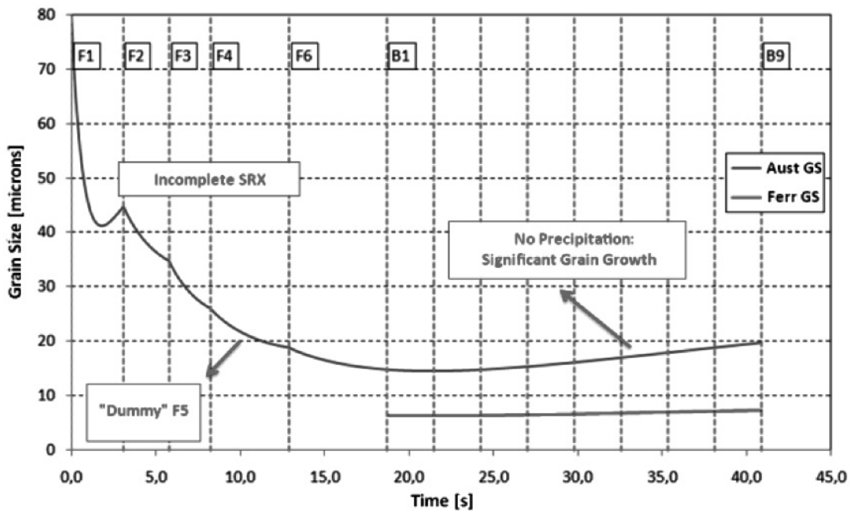
Table 2: Comparison between chemical composition and hot strip rolling process parameters between strips #2A and #2B.

Strip	Chemical Composition [%]			
	C	Mn	Si	Nb
#2A	0.05	0.34	0.19	0.014
#2B	0.05	0.33	0.16	0.015

Strip	True Strain					
	F1	F2	F3	F4	F5	F6
#2A	0,78	0,59	0,49	0,39	0,24	0,17
#2B	0,79	0,60	0,51	0,36	0,26	0,13

Strip	Temperature [°C]					
	F1	F2	F3	F4	F5	F6
#2A	1008	982	959	939	916	892
#2B	989	974	944	927	906	882

Finally, it is interesting to analyze a third case, #3, regarding a heavy hot strip of Nb microalloyed steel with thickness of 12.4 mm. Fig. 5(a) shows the microstructural evolution computed for the processing of such strip in the finishing mill, while Fig. 5(b) shows the good fit between forecast and calculated MFS values, with a mean prediction error of 8.4%. As rolling stock thickness at the entry of the finishing mill is relatively independent of product gauge, obviously in this case total thickness reduction ratio was significantly lower than the values corresponding to the former cases. As can be seen in Table 3, obviously this situation was reflected in the individual pass strains, which were much lower than those observed for the previous cases, although F5 stand was not used during the rolling of this heavy strip (that is, in this case it was a dummy stand). These lower strain degrees prompted the occurrence of DRX, which promoted a significant increase in the austenite grain size which, however, was not completely transferred to the ferrite grain size of the final product, according to the microstructural evolution model used here. This is an aspect that must be analyzed with more care in the future.



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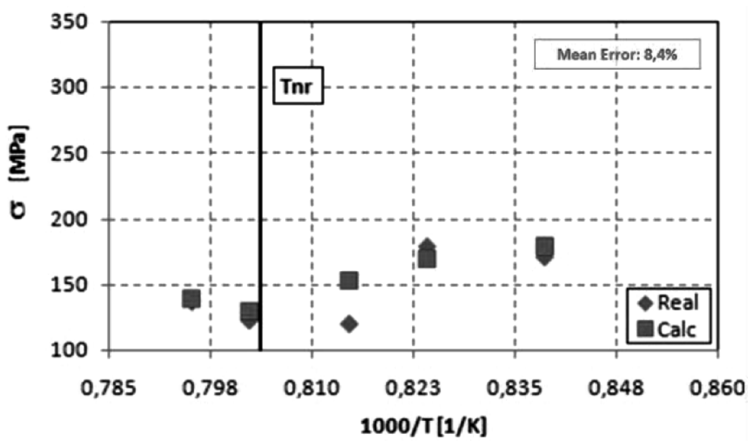

(b)

Fig. 5: Evolutions computed for #3 strip: (a) microstructural and (b) MFS.

Table 3: Chemical composition and hot strip rolling process parameters of strip #3.

Chemical Composition [%]			
C	Mn	Si	Nb
0.14	0.76	0.02	0.013

True Strain					
F1	F2	F3	F4	F5	F6
0,51	0,17	0,15	0,13	–	0,07

Temperature [°C]					
F1	F2	F3	F4	F5	F6
985	974	955	940	–	920

The microstructural evolution analyses carried out during this work, including those not included in this paper, indicate that the final grain sizes of the hot strip – both austenitic and ferritic – were not greatly influenced by the specific kind of the restoration mechanism (DRX or SRX) that were apparently working. The total thickness reduction applied in the finishing mill has a much more significant influence over grain size refining. DRX promotes an intense microstructural refining, but this effect is virtually lost due to the subsequent pronounced grain growth, as can be seen in Fig. 3(a). As a matter of fact, during the production of hot strips with ultra fine grain, where DRX has a vital role in microstructural refining, the rolling process is conducted in order to promote its occurrence in the last stands of the finishing mill and to avoid subsequent grain growth through a quick decrease in temperature as forced cooling is applied to the rolling stock and time intervals between passes are reduced[7].

The cases analyzed in this work showed that little differences in the process parameters – like pass strain and temperature – can be enough to change the actuating restoration mechanisms and all microstructural evolution along the finishing mill, with important consequences to rolling load evolution. This situation stresses that industrial data precision and consistency are vital for a correct prediction of the microstructural evolution of the strip. This is particularly valid for temperature data, a vital parameter for the determination and kinetics calculation of microestrutural phenomena. Unfortunately, a precise measurement or calculation of this parameter is particularly difficult, either to the inherent lack of precision of the temperature sensors, which are intensely affected by the presence of scale, steam and water over the hot strip, or the unavoidable temperature gradient that is created across stock thickness as it is being rolled. The specific conditions of the work roll-strip interface also induce strain degree and strain rate gradients across the thickness of the rolling stock, which modify the locally active microstructural mechanisms.

Another vital parameter for the microstructural evolution computation is the effectively solubilized Nb amount in austenite, which could not be calculated in this work due to the lack of reheating furnace data. Data from the roughing mills was also not available, so the initial grain size immediately before the entry of the rolling stock in the finishing mill had to be estimated. So, the precision of a microstructural evolution model fundamentally depends on a precise tracking of the rolling line, from slab introduction in the reheating furnace to strip coiling, as well a precise calculation of process parameters which cannot be directly measured – like, for example, strip temperature evolution when it is being hot rolled in the finishing mill.

Finally, the own microstructural evolution model must be critically analyzed, as it includes many empirical equations, which must be validated or fitted when they are applied to specific rolling mill lines or steels.

CONCLUSIONS

A microstructural evolution model was applied in the analysis of about 5000 hot strips of Nb microalloyed steel in order to identify the conditions under which DRX occurs in the intermediate stands of the finishing mill. In this case, the stand immediately after the occurrence of DRX receives a strongly softened strip, as this restoration mechanism is very quick. This situation normally is not considered by the mill control system and eventually can cause serious operational disturbances, and even cobbles.

The metallurgical analysis described in this paper, considering the specific process and product mix conditions of a Brazilian hot strip mill, allowed to determine that that such situation is associated to the processing of light hot strips, with a relatively low Nb content, which were processed in a temperature range slightly lower than the normal.

The experience got during this massive application of a microstructural evolution model also showed the need to have precise and reliable process data, like the effective slab reheating conditions, roughing pass schedule and precise temperature evolution along the hot strip mill line. The microstructural model itself also need to be continuously reviewed and fitted according to the specific conditions of the hot strip mill and product mix which are being analyzed.

TABLE OF SYMBOLS

Aust: Austenite

DRX: Dynamic Recrystallization

Ferr: Ferrite

GS: Grain Size

Rex: Recrystallization

SRX: Static Recrystallization

T: Temperature

Tnr: No-Recrystallization Temperature

σ: Mean Flow Stress

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