APPLICATION OF AUSTENITE MICROSTRUCTURAL EVOLUTION TOOLS TO HOT ROLLING CONDITIONS OF STRUCTURAL REINFORCING BARS *

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Abstract

The modeling of austenite evolution during the hot rolling of steels is covered in the literature for a wide range of chemical compositions, although mainly for carbon contents below 0.20%. In addition, most research on this topic is oriented for processes that are characteristic of flat products. Compared to those processes, the hot rolling of bars for structural applications presents considerable particularities concerning mainly deformation, rolling speed and rolling temperature profile. Those particularities result in considerable changes on process parameters that affect the austenite microstructure evolution, both in the softening and hardening mechanisms if microalloying elements such as Nb is present. The aim of this work was to develop a model to predict the evolution of austenite microstructure that is suitable for the hot rolling of structural reinforcing bars. Different torsion tests simulating industrial schedules particular from those type of processes were performed. The tests showed the need to investigate Nb strain-induced precipitation interaction with softening mechanisms that can occur during the deformation schedule. At the end, the new proposed kinetics and routines were introduced to a program, MicroSim-Bars®, that is able to model austenite evolution under structural bar hot rolling conditions.

Keywords: Bar rolling; Austenite modeling; Nb microalloyed steel.

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1 INTRODUCTION

The modeling of austenite evolution during the hot rolling of steels is covered in the literature for a wide range of chemical compositions, although mainly for carbon contents below 0.20% [1,2,3]. In addition, most investigation on this subject is oriented for processes that are characteristic of flat products. In these cases, hot rolling is well-defined in two zones: a roughing stage, where deformation temperatures are usually above 950 ºC, and a finishing stage, that is usually performed at temperatures below this range. If microalloying with elements such as Nb, that affect the austenite evolution during rolling, is applied, the process can be designed in order to take advantage of its contribution to enhance microstructure refinement. This is the aim of a conventional thermomechanical controlled rolling/processing, or TMCP [3].

When it goes to the hot rolling of reinforcing bars, or rebars, for structural applications, however, the process presents considerable particularities. First, in the hot rolling of bars, together with the dimensional changes, cross sectional shape is modified through each pass. This results in dimensional changes through width that cannot be neglected as in the rolling of flat products, and that leads to a more complex state of deformation. Second, as structural bar rolling is strongly driven by high production output, the process is performed at high speeds.

Considering the deformation parameters, those particularities result in: (1) strain values that are considerably higher than those applied in flat rolling (calculations according to a method proposed in the literature [4] shows that strain values are usually above 0.45); (2) short interpass times during the last stages of the rolling, usually in the order of fractions of seconds; (3) high strain rates, above 100 s^{-1} depending of the final diameter. Regarding the thermal profile, final rolling temperatures are usually above 1000 °C and in most cases the temperature does not reach values below 950 °C during the whole process. Also, due to mill and process design, there is less room for modifications of thermomechanical parameters during the rolling window: deformation is defined by the groove pre-machined in the roll, thus cannot be modified during rolling, and temperature throughout the whole process is a direct function of the reheating temperature.

All these characteristics affect the austenite evolution during the rolling. On the one hand, it is well-known that the application of high strains at high temperatures can activate dynamic recrystallization [5]. Therefore, post-dynamic softening mechanisms can play an important role in microstructure evolution. On the other hand, if the steel is microalloyed with Nb, strain-induced precipitation can take place during rolling and can interact with the dynamic and post-dynamic softening mechanisms.

This work will describe the steps adopted to develop a program that predicts the austenite microstructure evolution, Microsim-Bars®, taking into account the singularities mentioned above. The program is, thus, suitable for the hot rolling of structural bars. The input information is the composition and data from industrial schedule, that is converted to nominal deformation conditions following the approach proposed by Lee et al. [1]. Different types of torsion tests were performed in laboratory to develop austenite microstructure equations applicable for the steel compositions and deformation conditions usually employed in those processes, as well as to understand the interaction between the different mechanisms governing the microstructure evolution at these conditions. The kinetics observed have been implemented in the program and torsion tests have been used to validate the model.

2 MATERIAL AND METHODS

Two steels were initially considered for the study of austenite microstructure evolution under bar rolling conditions, one plain C-Mn and one microalloyed with Nb. Table 1 shows the chemical composition of both steels.

Table 1. Chemical composition of steels considered for austenite evolution investigation under bar process conditions

Steel	C	Mn	Si	Nb	N	P	S
0.25C-Mn	0.25	0.55	0.23	0	0.010	0.018	0.017
0.24C-0.03Nb	0.24	1.25	0.5	0.03	0.006	0.03	0.027

A first batch of multipass hot torsion tests was performed simulating rolling conditions particular of rebars. The thermomechanical parameters were determined using data published in the literature [6,7,8] as well as industrial data that is not published and were previous known to the authors. A strain per pass of 0.45 was considered as an average value after data analysis. The strain rate per pass was 5 s^{-1}, this being a limitation of the study. Two bar diameters were simulated, ∅ 8 mm and ∅ 20 mm. Figure 1 shows the profiles of the anisothermal cycle applied, and Table 2 presents the number of passes, the deformation temperatures, T, the final rolling temperature FRT, and the interpass times, tip, considered for each diameter simulation.

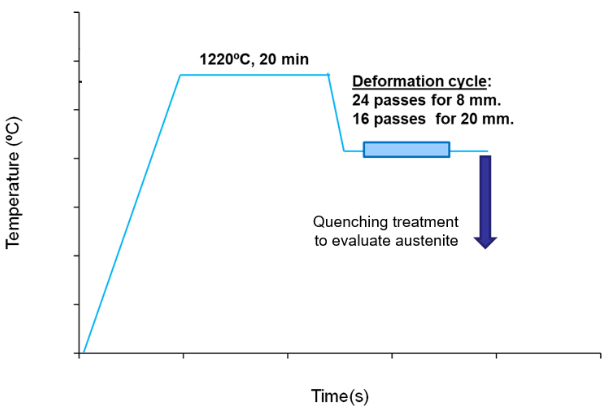


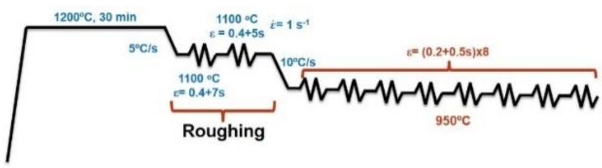
Figure 1. Thermomechanical cycle considered for first batch of multipass torsion simulations

Table 2. Number of pass, temperature, T, and interpass times, tip, considered for first batch of multipass torsion simulations

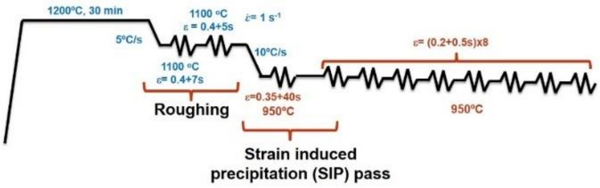
Pass	8 mm		20 mm	
	T(ºC)	tip(s)	T(ºC)	tip(s)
1	1130	5	1130	5
2	1105	5	1105	5
3	1080	5	1080	5
4	1055	5	1055	5
5	1030	5	1030	5
6	1005	5	1005	5
7	980	5	980	5
8	955	2	955	2
9	951	2	951	2
10	947	2	947	2
11	943	2	943	2
12	939	2	939	2
13	943	2	943	2
14	947	2	947	2
15	951	2	951	2
16	955	0.5	955	5.5
17	960	0.5		
18	965	0.5		
19	970	0.5		
20	975	0.5		
21	980	0.5		
22	985	0.5		
23	990	0.5		
24	995	3.5		
FRT	1030		1010	

The FRT was the temperature of quenching to evaluate the austenite microstructure resultant from the simulation.

In order to study the different mechanisms governing austenite microstructure and their interaction, two different tests were performed. First, multipass simulations were conducted to investigate dynamic recrystallization, DRX, kinetics and its interaction with Nb strain-induced precipitation. Figure 2 shows the cycles performed in this part.



(a)



(b)

Figure 2. Thermomechanical cycle for DRX kinetics investigation and interaction with Nb strain-induced precipitation

The two first passes simulated a roughing stage and aimed to condition the austenite under static recrystallization regimen, SRX, prior to DRX. As in Figure 2(a), after the roughing passes, 8 passes were applied to induce DRX. In Figure 2(b), prior to those passes, a pass followed by a 40 s holding time was applied to promote Nb-strain induced precipitation and then the sequence to induce DRX was applied. The steel used in this part of the investigation was a 0.31% C - 0.029% Nb alloy.

In the second part of the study, double-hit torsion tests were performed with the same steels in Table 1 to investigate metadynamic recrystallization, MDRX, kinetics and grain sizes. Figure 3 shows the thermomechanical cycle considered for this study.

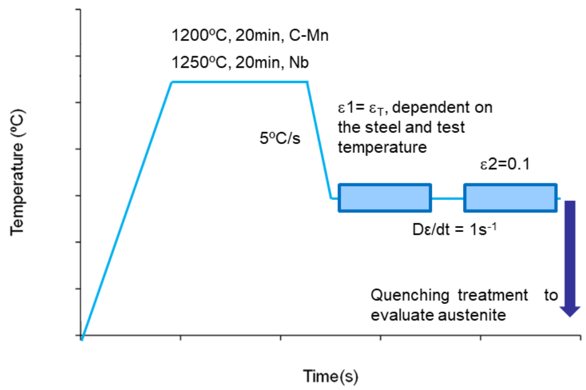


Figure 3. Thermomechanical cycle for MDRX kinetics study

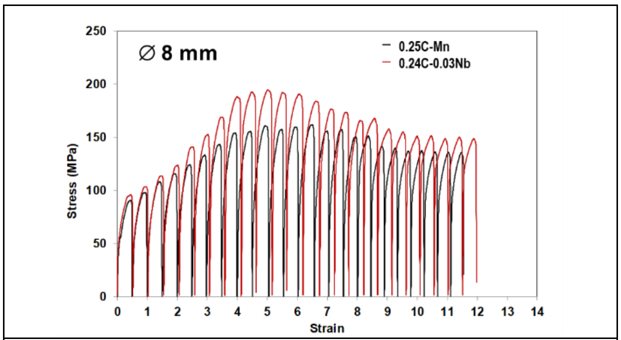
Reheating temperature used for 0.25C-Mn steel was 1200 °C and for 0.24C-0.030Nb steel was 1250 °C in order to put all Nb into solution. The thermomechanical cycle consisted on applying a first deformation pass above a critical strain, denominated as transition strain, ε_T, which represents the deformation above which the softening during the subsequent interpass time is only due to metadynamic recrystallization. Three deformation temperatures were considered: 900 °C, 950 °C and 1000 °C. A second pass with strain of 0.1 was then applied with varying interpass time between them.

Quenched samples were characterized using Bechet-Beaujard etching to reveal austenite microstructure. Precipitates were characterized by transmission electron microscopy (TEM) from carbon extraction replicas prepared from quenched samples.

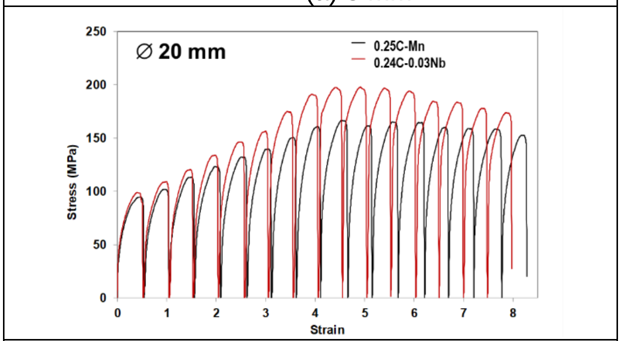
3 RESULTS AND DISCUSSION

3.1 – Preliminary torsion tests

Figure 4 shows stress-strain curves for 0.25C-Mn and 0.24C-0.03Nb steels under ∅ 8 mm and ∅ 20 mm rolling schedules. During the first seven deformation passes, the stress increases due to temperature decrease for both steels. However, for the Nb steel, after pass four, stress increases at a higher rate. This is in agreement with behavior of Nb microalloyed steels at schedules where temperature decreases: Nb retards softening kinetics due to solute drag and/or strain-induced precipitation effect [2]. As a result, strain accumulation leads to the higher stress levels observed for the Nb steel. However, it is interesting to note that when the interpass time decreases to 2 seconds, between passes 8 to 11, although the temperature continues to decrease, stabilization of stress and even some decrease is observed for both steels. This indicates that some interpass softening takes place during this period. After pass 11, that is the finishing rolling stage for the 20 mm simulation, the temperature increases and this makes difficult the interpretation of the stress-strain behavior. On the other hand, for both steels, during the last 9 passes of 8 mm simulation that comprehends interpass times of 0.5 s, the stress increases slightly from pass 9 to 10 but then decreases during the subsequent deformations. This indicates that strain accumulation takes place during the first deformation at this stage while some softening takes place during subsequent deformation passes. This shape is characteristic of dynamic recrystallization activation [5].



(a) 8 mm



(b) 20 mm

Figure 4. Stress-strain curves obtained in 8 mm and 20 mm simulations

Figure 5 shows the fractional softening, FS, obtained from the stress-strain curves by a method described somewhere else [9]. As already demonstrated by stress-strain curves, softening values are lower for the Nb steel denoting that Nb delays softening, that is, recrystallization.

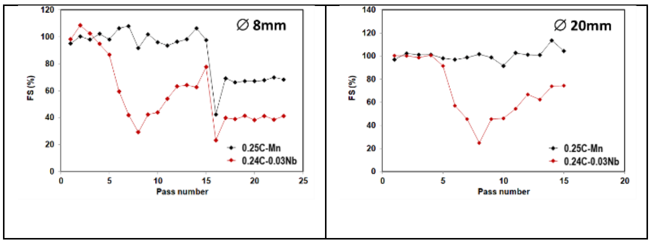


Figure 5. Fractional softening obtained in 8 mm and 20 mm simulations

Figure 6 shows the austenite microstructures characterized from specimens quenched after the deformation sequences. For both steels, fine and equiaxed microstructures were obtained at all conditions. The austenite microstructures obtained in these sequences indicate that the classical role of Nb, of avoiding recrystallization and thus promoting pancaking during hot deformation, is not applicable for the current rolling schedules. Regardless reheating rolling sequence, recrystallization took place during or after the last deformation passes of the torsion tests. This suggests that these routes do not necessarily need the application of classical TMCP. Nevertheless, effect of Nb microalloying was observed: CMnNb steel presented significant austenite grain refinement compared to the CMn one.

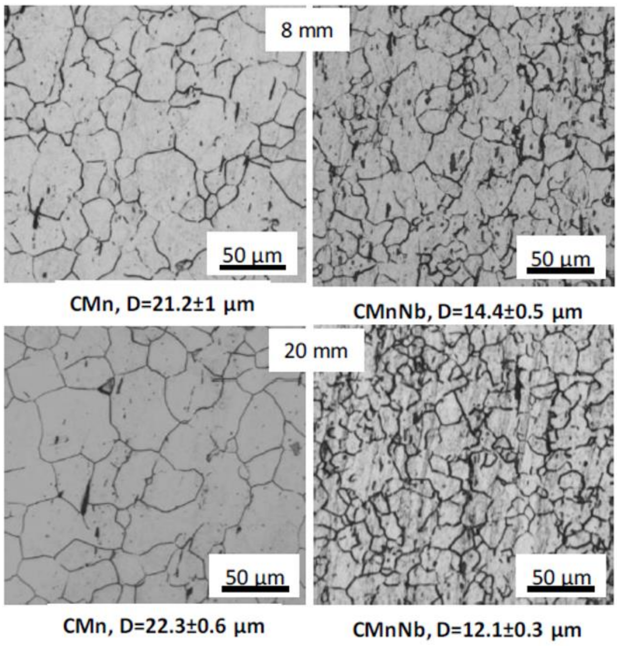


Figure 6. Austenite microstructures obtained from quenched specimens

Carbon extraction replicas were prepared from 8 mm CMnNb quenched samples to investigate the precipitation state. Figure 7 shows an example of precipitates observed. Particles smaller than 15 nm were detected indicating that some strain-induced precipitation has taken place during the sequence. It is well known that

Nb-strain induced precipitation can stop of retard static recrystallization considerably [2,3]. This is in good agreement with the detection of the stage in stress-strain curve on Figure 4 where and interpass time of 5 s was applied and the stress increases abruptly. However, when the interpass time decreases to 2 s or 0.5 s, the stress-strain behavior and the microstructures obtained after the cycles indicate that during these stages precipitates are not able to stop recrystallization, and equiaxed microstructures are obtained even for Nb steel.

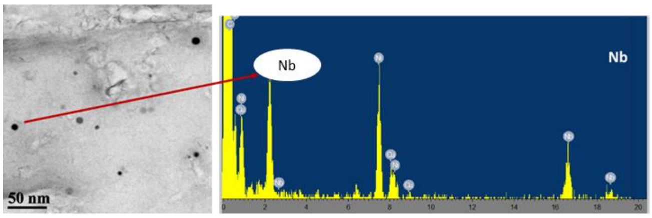
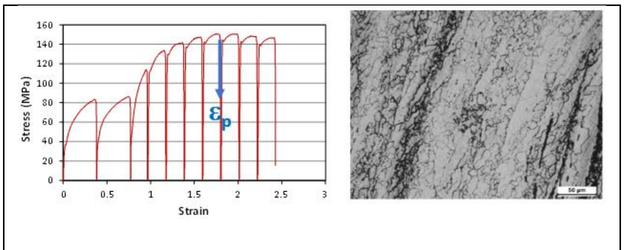


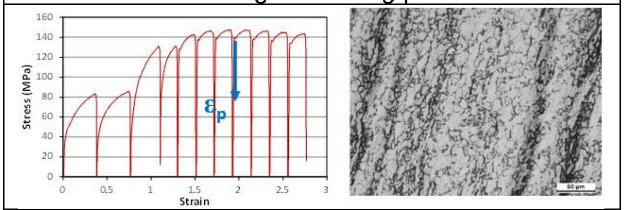
Figure 7. Precipitates detected from carbon replicas extracted from 8 mm quenched specimen

3.2 – Dynamic recrystallization

Nb-strain induced precipitates were found after the torsion schedules. Nevertheless, they seemed not to be able to stop recrystallization. Mainly, studies found on literature regarding Nb strain-induced interaction with softening mechanisms rely on static recrystallization conditions [3]. However, as noted from the stress-strain curves above, DRX took place during the last passes of the multipass torsion simulations, at short interpass time conditions, as well as strain induced precipitation. To study this interaction in more detail, torsion tests were performed following the thermomechanical cycles indicated above. Figure 8 shows the stress-strain curves and austenite microstructures obtained after these multipass torsion tests. On the condition represented by Figure 8(a) two passes simulating a roughing stage were applied followed by 8 passes with interpass times of 0.5 s, simulating a finishing schedule. It can be noted that during the first passes of the finishing stage strain accumulation takes place and results in an increase of stress. At the last passes, however, the stress-strain curve indicates that DRX took place and as a result a peak in the stress is observed. The austenite microstructure is fine and also denotes dynamically recrystallized grains. In the case of Figure 8(b) an intermediate pass between the roughing and the finishing stages was applied to promote Nb(C,N) precipitation. It can be seen that after this pass, during the first passes of the finishing stage the stress increases slightly but then decreases, denoting that dynamic softening also takes place at this stage.



(a) Cycle (a), with two roughing passes and eight finishing passes



(b) Cycle (b), with an intermediate pass to induce Nb precipitation

Figure 8. Stress-strain curves and microstructures obtained after multipass torsion tests to investigate DRX interaction with Nb-strain induced precipitation for a 0.31%C-0.025%Nb steel

Figure 10 shows the results the analysis from carbon replica sample obtained from microstructure obtained at cycle (b). Abundance of Nb precipitates denotes Nb-strain induced precipitation was not able to stop DRX as occurs with SRX.

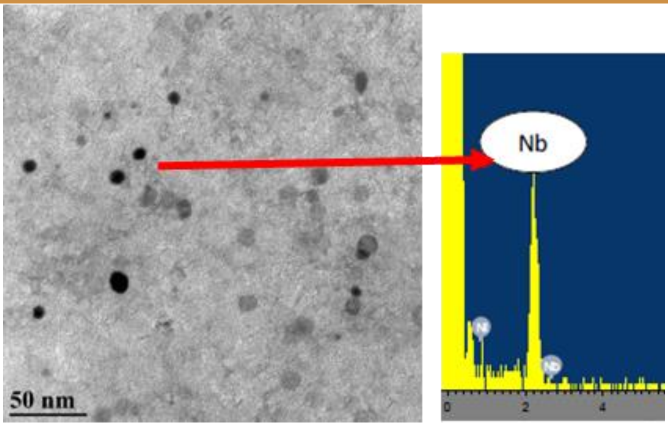


Figure 9. Precipitates detected from carbon replicas extracted from specimen quenched after cycle (b)

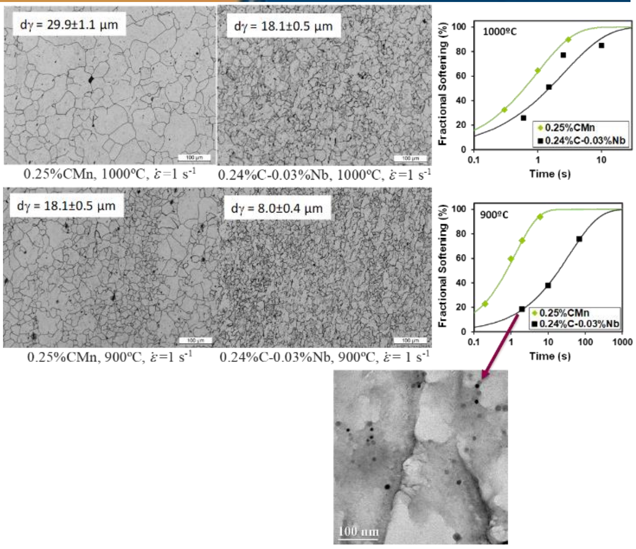


Figure 10. MDRX microstructures and softening determined at 1000 °C and 900 °C

3.3 - Metadynamic recrystallization

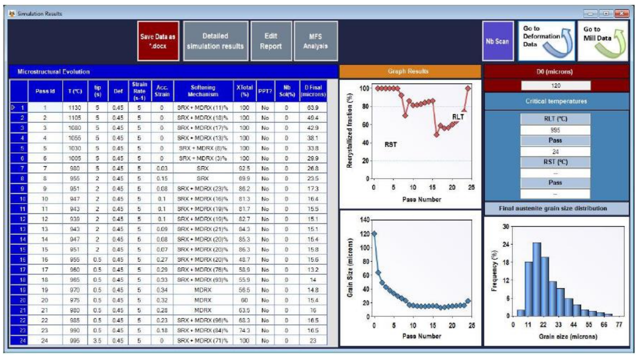
Figure 10 shows the results of cycles aimed to characterize MDRX kinetics and microstructures for the medium carbon steel range in question. The fractional softening was calculated from the stress-strain curves also following standard procedure [9]. In addition, specimens were quenched after times corresponding to 95% fractional softening to characterize MDRX microstructure. As can be observed, at 1000 °C, and more markedly at 900 °C, 0.03% Nb addition to a 0.25% C steel resulted in a significant softening delay, in good agreement with results of Figure 6. At 1000 °C contribution, delay of recrystallization is lower as is obtained mainly from solute drag effect. At 900°C, however, Nb precipitates were detected by replica analysis. The delay was more accentuated at this temperature, but still not able to fully stop recrystallization. Nb contribution on refining MDRX grain size can also be noted.

3.4 – Austenite microstructure evolution model, MicroSim-Bars®

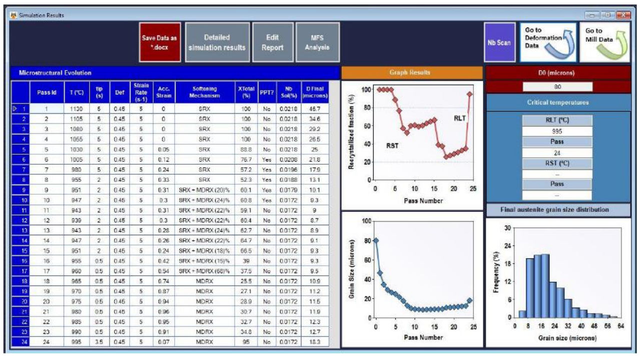
The results above show the need to develop a specific routine to predict austenite microstructural evolution that takes into account the effect of Nb microalloying in medium-carbon steels under bar rolling conditions. A suitable microstructure evolution model, MicroSim-Bar® was developed in this framework, based on the approaches described in references [2] and [3]. The interactions between different mechanisms that can take place during the rolling, such as DRX and MDRX with Nb strain-induced precipitation, were incorporated into the model. Also, coming from a perspective that the model need to accept industrial conditions as input data, methodology proposed on reference [4] was considered to convert industrial process data into thermomechanical parameters necessary to calculate austenite evolution during hot rolling.

Figure 11 shows predictions performed considering the data from multipass torsion tests presented on the first part of the results of this work. The austenite grain size predicted for the CMn steel agrees well with the measured values: 23 µm predicted versus 21.2 µm experimental.

For the CMnNb steel, the value is slightly overestimated, 18.3 µm predicted versus 14.4 µm experimental, although the austenite refining effect observed experimentally with Nb addition is well represented. In terms of the mechanisms governing the austenite evolution, for both steels, fully static recrystallization is predicted during the first passes. However, for the Nb steel, after pass 4, the recrystallized fraction starts to decrease, first due to solute drag effect, and next due to the occurrence of strain-induced precipitation. That is also in good agreement with TEM experimental results showed in Figure 8. During the last passes, when interpass times decreases, the model predicts activation of dynamic recrystallization during deformation for both steels, and metadynamic recrystallization is thus the main softening process taking place within the interpass times. The predictions agree well with the equiaxed microstructures observed at the end of the deformation sequences.



(a) CMn steel



(b) CMnNb steel

Figure 11. Predictions of Microsim-Bars® model for austenite evolution prediction

4 CONCLUSION

Results from hot torsion tests simulating rolling conditions of reinforcing bars showed that the final austenite microstructure obtained in these processes is equiaxed, resultant from recrystallization. This is due to the particularities of these processes, that contribute to high finishing rolling temperatures, usually above 1000 °C.

Also resultant from high temperatures observed and high strain values applied in reinforcing bar rolling, dynamic and metadynamic recrystallization are softening mechanisms that take place and govern the austenite evolution besides static recrystallization.

Multipass torsion tests showed that Nb strain-induced precipitation is not able to fully stop dynamic neither metadynamic recrystallization in this process. However, Nb strain-induced precipitation delays MDRX kinetics, and refines MDRX grain size.

At the end, a program to model the austenite microstructure evolution that is suitable for the hot rolling conditions of structural reinforcing bars was developed, considering the behaviors described above. Predictions of the model in terms of final austenite grain size were in good agreement with values measured from multipass hot torsion tests. The results showed that addition of Nb to 0.25% C steel refined the austenite grain sizes after simulations of ∅ 8 mm and ∅ 20 mm rebars.

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