Influence of the Normalizing Rolling Parameters on the Toughness of a Nb, V and Ti Microalloyed Steel Processed in the Gerdau Plate Mill

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Keywords: Microalloyed Steel, Normalizing Rolling, Microstructural Evolution, Mean Flow Stress, Toughness

INTRODUCTION

Normalizing rolling (NR) is a thermomechanical treatment that has been widely applied in recent decades which allows the production of normalized steel heavy plates directly from hot rolling, without the need to perform an additional heat treatment of normalization in the furnace [1]. So, it contributes to speeding up manufacturing and reducing costs.

In general, one of the main metallurgical requirements of any Thermomechanical Controlled Processing (TMCP) to be executed in a plate mill is to create an adequate balance between the roughing and finishing stages. Thus, it is of paramount importance to know the critical temperatures of the steel to be processed, as well as the amount of Nb in solid solution, in order to develop an appropriate pass schedule for conditioning the grain size of austenite during the roughing stage and promote the strain-induced precipitation of Nb carbonitrides in the finishing passes that will suppress austenite recrystallization, resulting in the high refinement of the final microstructure [2,3].

The mean size and distribution of the transformed ferrite grains are defined by the austenite recrystallization types that result from the alloy design used and TMCP parameters. They are: Type I - Full Recrystallization, Type II - No Recrystallization and Type III - Partial Recrystallization. In order to achieve optimization of microstructure and mechanical properties, during the TMCP a minimum of 50-60% strain must be applied under rolling conditions that promote Type I recrystallization and a minimum of 30% strain must be applied where Type II recrystallization occurs. Ideally, there should be no occurrence of Type III recrystallization between rolling passes, or at least it should be kept to a minimum [3].

Plate performance in terms of toughness, as measured by the Drop Weight Tear Test (DWTT), is directly related to the temperature at which the finishing stage starts, as shown in figure 1 [4]. As can be seen, the values of shear fracture seen in the broken specimens of the DWTT show maximum dispersion when the finishing starts above the Recrystallization Limit Temperature (RLT). This dispersion progressively decreases when the finishing start temperature is below RLT and approaches the Recrystallization Stop Temperature (RST). Toughness measured by the DWTT assumes maximum values with low dispersion when finishing starts below RST.

EXPERIMENTAL PROCEDURE

The alloy design adopted was a CMn steel microalloyed with Nb, Ti and V, a composition traditionally used in the production of heavy plates via normalizing rolling according to the literature [5-7], with titanium acting in order to refine the grain size during slab reheating and niobium exercising the same effect, but during NR, besides contributing to some precipitation hardening, which is the main role of vanadium. Table I shows the chemical composition of the steel studied in this paper.

Four slabs were reheated, all 250 mm thick, at a temperature high enough to fully dissolve niobium precipitates according to the Irvine equation [8], but considering a decrease in the dissolved N content due to its reaction under stoichiometric ratio with Ti.

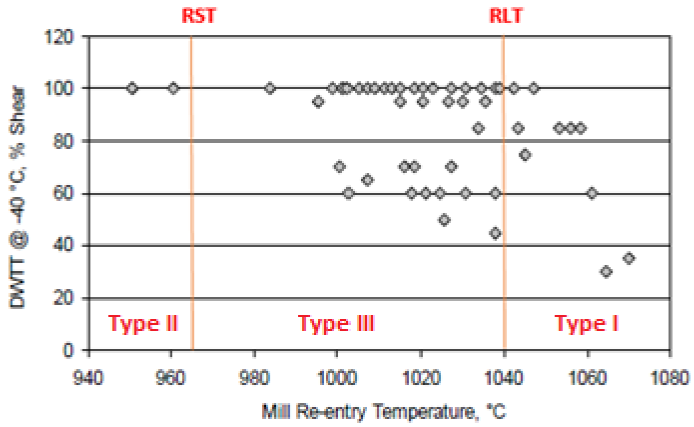

Figure 1: Effect of the temperature start of the finishing stage of TMCP over the fraction of shear fracture observed at DWTT [4].

Table I. Nominal chemical composition of the steel studied in this paper.

C	Mn	S + P	Nb +V+Ti	N
0.15	1.45	< 0.035	0.090	< 0.0070

The NR included a holding stage between the roughing and finishing stages in order to adequately synchronize the end of rolling with the specified finishing temperature range, which was within the fully austenitic field of the alloy, according to the value of Ar_3 temperature calculated by the Ouchi equation [9]. The plates were rolled in thicknesses of 15 and 30 mm, and the objective was to meet the mechanical properties specified by EN 10025-2 S355 J2, namely: yield strength equal or higher than 355 MPa; tensile strength between 470 and 630 MPa; total elongation ($5.65 \sqrt{A_0}$) equal or higher than 20% and mean energy absorbed in the Charpy test equal or higher than 27 J at -20°C.

Tensile tests were performed using specimens machined in the transverse direction of the processed plates, as well as Charpy tests at -20°C using specimens measuring 10 mm x 10 mm, machined in the longitudinal direction of the plate and with a V-shaped notch. Metallographic tests were also performed in order to determine the mean grain size of the plate microstructures according to the ASTM E112 standard.

The normalizing rolling process performance was evaluated through the calculation of mean flow stress (that is, austenite hot strength) for each rolling pass using the inverse Sims model [10], as well through the identification of the recrystallization types occurring during NR [2,11] and, finally, through the microstructural evolution occurred during the NR, which was calculated using the MicroSim computer program, developed by Centro de Estudios e Investigaciones Técnicas de Gipuzkoa – CEIT, in Donostia-San Sebastian, Spain, under the sponsorship of the Companhia Brasileira de Metalurgia e Mineração - CBMM [11].

RESULTS AND DISCUSSION

Mechanical Properties and Microstructures

Table II shows the results of the tensile and Charpy tests determined from selected plates. One can observe that they fulfilled the requirements specified by the EN 10025-2 S355 J2 standard. Despite compliance with the aimed specification, the values obtained in the Charpy test were very different among pairs of plates with same thickness. So, it was necessary to determine the reasons for these differences.

Figures from 2 to 9 show the typical microstructures of the normalizing rolled NbTiV steel plates studied here, in positions close to plate surface and at ¼ of the thickness. It can be observed that there are no significant visual differences between the microstructures presented here.

Table III shows the results of the mean grain size at ¼ thickness measured according to ASTM E112. Grain sizes of 6.0 and 8.2 µm were obtained for the 15 mm thick plates, respectively showing good and moderate toughness, which justifies, in a certain way, the different toughness values found for this material, as the finer grain was associated with the plate with good toughness. However, such difference was not observed for the pair of plates with 30 mm thickness.

Table II. Tensile and Charpy tests results got from the plates with thicknesses of 15 mm and 30 mm.

Plate	**Thickness [mm]**	**YS [MPa]**	**TS [MPa]**	**El 5,65 $\sqrt{A_0}$ [%]**	**CVN @-20°C [J]**
Moderate toughness	15	399	546	30	47
Good toughness	15	421	537	28	186
Moderate toughness	30	400	568	22	58
Good toughness	30	387	528	28	141

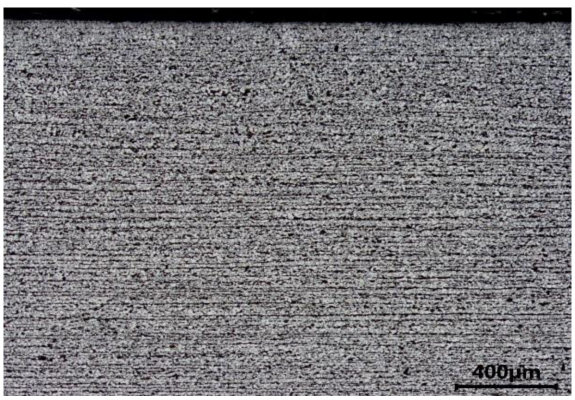

Figure 2: Microstructure near surface of the 15 mm plate with good toughness. Nital 4% etch, 50 x magnification.

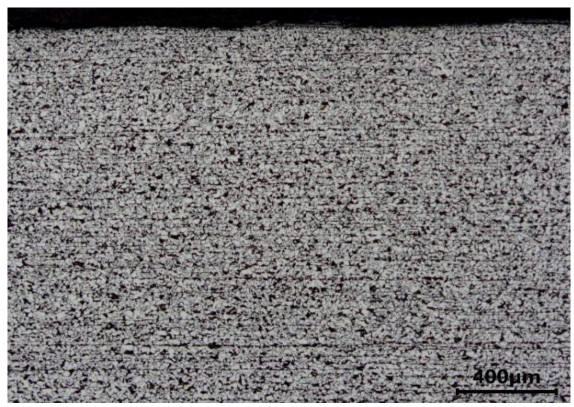

Figure 3: Microstructure near surface of the 15 mm plate with moderate toughness. Nital 4% etch, 50 x magnification.

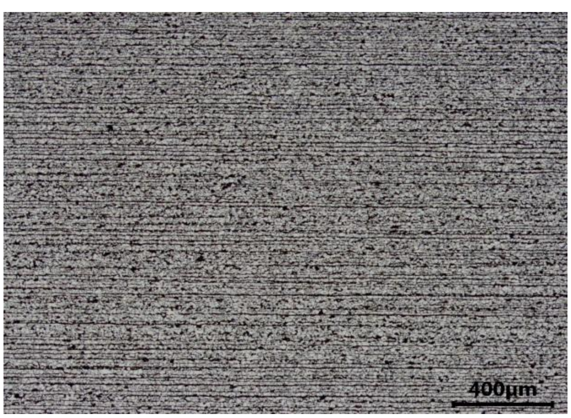

Figure 4: Microstructure at ¼ thickness of the 15 mm plate with good toughness. Nital 4% etch, 50 x magnification.

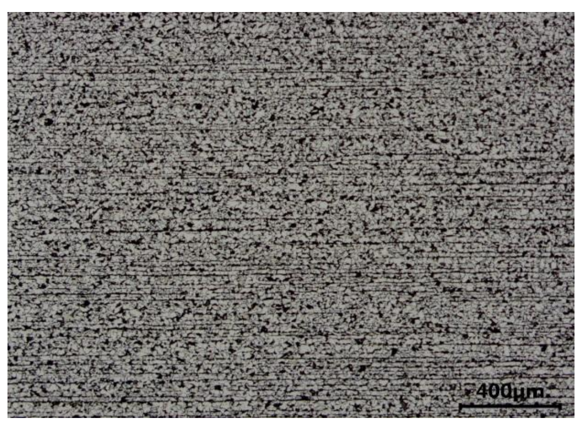

Figure 5: Microstructure at ¼ thickness of the 15 mm plate with moderate toughness. Nital 4% etch, 50 x magnification.

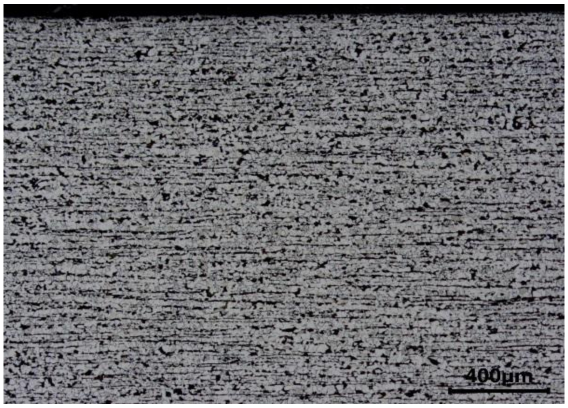

Figure 6: Microstructure near surface of the 30 mm plate with good toughness. Nital 4% etch, 50 x magnification.

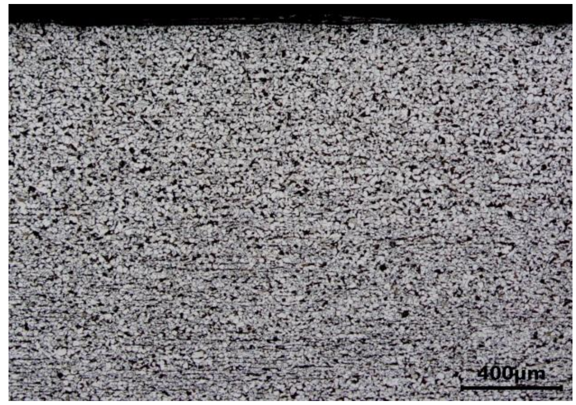

Figure 7: Microstructure near surface of the 30 mm plate with moderate toughness. Nital 4% etch, 50 x magnification.

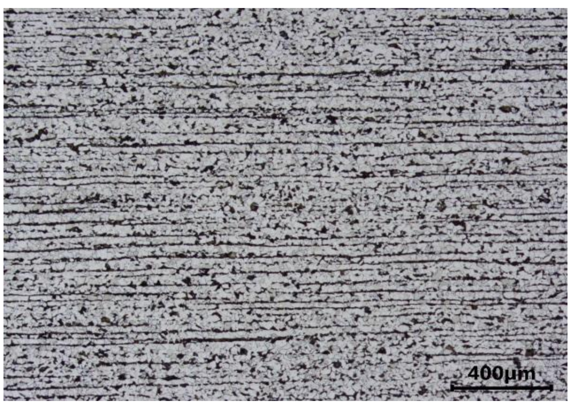

Figure 8: Microstructure at ¼ thickness of the 30 mm plate with good toughness. Nital 4% etch, 50 x magnification.

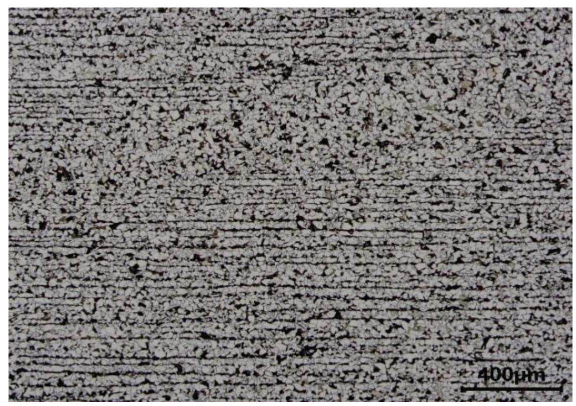

Figure 9: Microstructure at ¼ thickness of the 30 mm plate with moderate toughness. Nital 4% etch, 50 x magnification.

Table III. Measured values of ferritic grain size at ¼ thickness in the normalizing rolled plates with 15 and 30 mm thickness.

Plate	Thickness [mm]	Mean Grain Size [μm]	Standard Deviation [μm]	Amplitude [μm]
Moderate Toughness	15	8.2	1.27	0.64
Good Toughness	15	6.0	1.16	0.59
Moderate Toughness	30	8.4	1.44	0.73
Good Toughness	30	8.9	1.34	0.68

Mean Flow Stress

Figures 10 to 13 show graphs of mean flow stress (MFS) determined from the pass schedule process parameters corresponding to the four plates studied here. It was not possible to observe here any differences in the evolution of mean flow stress along pass schedule that would justify the differences observed in the toughness values. However, it should be noted that the extreme scarcity of data makes difficult a more comprehensive analysis.

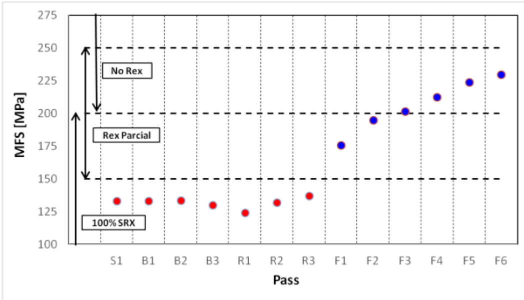

Figure 10: Mean flow stress along the pass schedule during NR of the 15 mm plate with good toughness.

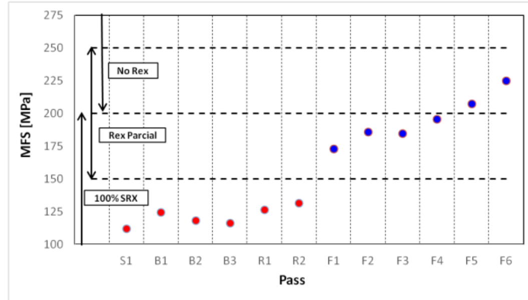

Figure 11: Mean flow stress along the pass schedule during NR of the 15 mm plate with moderated toughness.

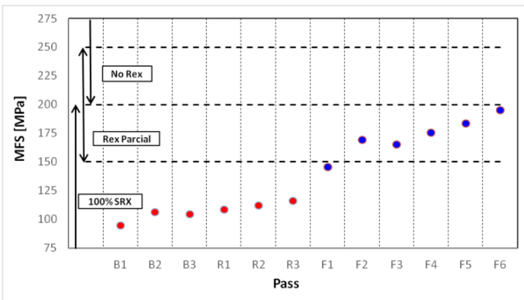

Figure 12: Mean flow stress along pass schedule during NR of the 30 mm plate with good toughness.

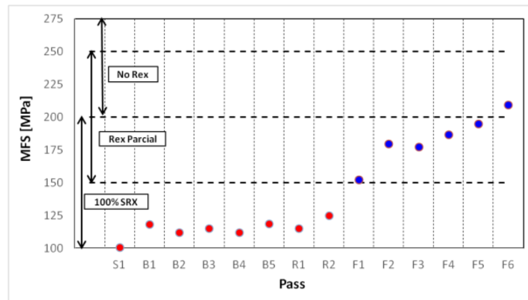

Figure 13: Mean flow stress along pass schedule during NR of the 30 mm plate with moderated toughness.

Microstructural Evolution

Figures 14 and 15 show austenite recrystallization fractions between hot rolling passes calculated by the MicroSim model from the actual hot rolling parameters for the 15 mm thick plates. Table IV shows the different recrystallization types predicted by the MicroSim model along the pass schedule for these plates. Table V shows the final mean grain size values predicted by the MicroSim model for the two 15 mm thick plates.

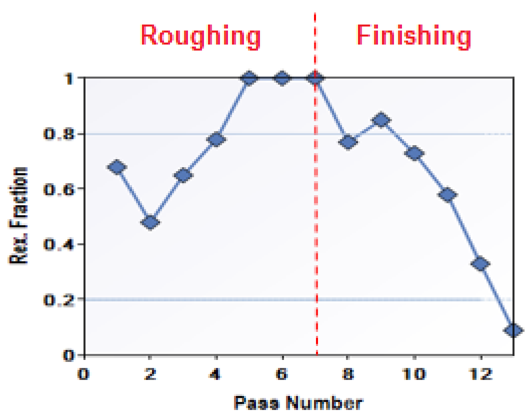

Figure 14: Recrystallization fraction after rolling passes for the 15 mm plate with good toughness.

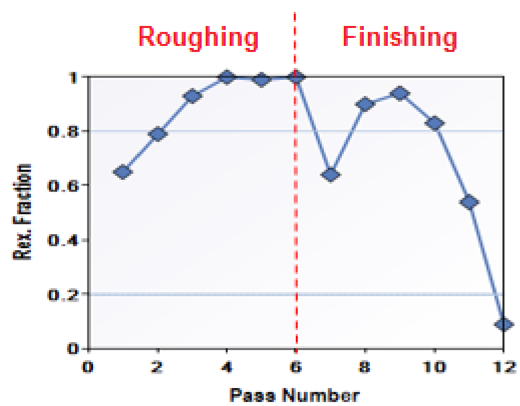

Figure 15: Recrystallization fraction after rolling passes for the 15 mm plate with moderate toughness.

Table IV: Recrystallization types predicted by the MicroSim model during the NR of the 15 mm plates.

15 mm Plates	Nominal Thickness Reduction [%]			
	Full (Type I)	Partial (Type III)	Null (Type II)	Residual Strain
Good Toughness	73.1	61.8	23.0	0.91
Moderate Toughness	81.5	26.0	21.5	0.55

Table V: Microstructural evolution for the 15 mm plates as predicted by the MicroSim model.

15 mm Plates	Mean Grain Size [µm]				
	Austenite (Final)				Ferrite
	Mean	Maximum	Z_d	Critical (*)	
Good Toughness	9.3	133	14.3	34	8.2
Moderate Toughness	14.5	132	9.1	48	9.9

* Critical: 10% of the grain population has size larger than this value.

Figure 15 shows that MicroSim predicted the occurrence of recrystallization fractions higher than 80% between the finishing passes from 2 to 4 in the case of the moderate toughness plate, making them virtually roughing passes. Therefore, it can be inferred that much of the microstructural refining effect that the finishing phase should exert on austenite was lost.

Table V shows that the plate with moderate toughness had a greater final austenitic grain size, which is directly related to the ferritic grain size obtained, which was less refined. In addition, this plate showed a lower degree of strain hardening of austenite (0.55) compared to the material with good toughness (0.91), which should have reduced the density of ferrite nucleation during austenite transformation, contributing to the higher value of its grain size. Interestingly, the material with moderate toughness presented a more homogeneous microstructure, i.e., a lower value of the ratio between the maximum and mean values of grain size (Z_d). This is certainly a consequence of the greater effect of microstructural homogenization resulting from the application of a greater number of passes where more than 80% of austenite recrystallization occurred in the time interval between passes.

It is worth mentioning that the values of ferritic grain size measured and calculated by MicroSim for the 15 mm thick plates were not exactly the same, but showed the same trend: lower value for material with good toughness.

Figures 16 to 17 show the graphs of austenite recrystallization fraction between hot rolling passes obtained for the two 30 mm thick plates. Table VI shows the different recrystallization types predicted by MicroSim model along the pass schedule for the 30 mm thick plates from actual process parameters. Table VII shows the final mean grain size values predicted by the MicroSim model for the two 30 mm plates from actual process parameters.

The excessive number of light roughing passes applied in the NR of the 30 mm plate with moderate toughness (figure 17) prevented the occurrence of successive full recrystallization cycles along roughing, making its microstructure less homogeneous than that of the material that showed good toughness. Besides that, also according to the MicroSim model, partial recrystallization occurred after all final finishing passes, further refining austenite grain size and increasing residual strain, which was reflected in a slightly smaller mean ferritic grain size in the plate with moderate toughness, but with a higher dispersion, which must have compromised toughness. The Z_d parameter of the plate with moderate toughness was 13.8 µm, against 10.4 µm from the 30 mm plate with good toughness.

Also in this case the trend observed between the measured ferritic grain sizes for the 30 mm thick plates was the same as that found in the values calculated by MicroSim.

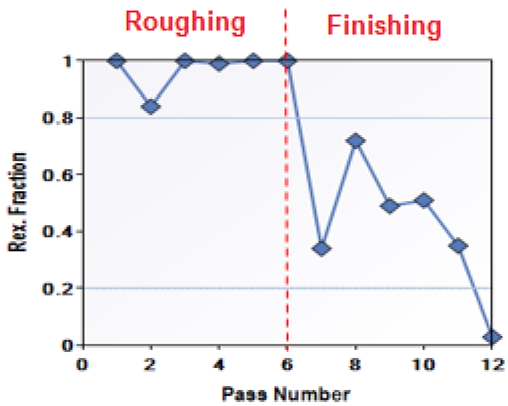

Figure 16: Recrystallization fraction after rolling passes for the 30 mm plate with good toughness.

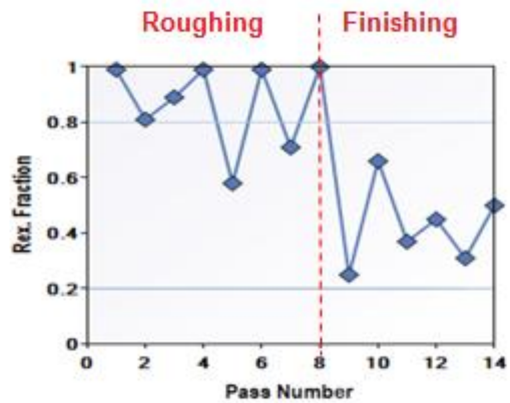

Figure 17: Recrystallization fraction after rolling passes for the 30 mm plate with moderate toughness.

Table VI: Recrystallization types predicted by the MicroSim model during the NR of the 30 mm plates.

30 mm Plates	Nominal Thickness Reduction [%]			
	Full (Type I)	Partial (Type III)	Null (Type II)	Residual Strain
Good Toughness	45.9	61.4	14.4	0.53
Moderate Toughness	23.1	77.0	0.0	0.70

Table VII: Microstructural evolution for the 30 mm plates as predicted by the MicroSim model.

30 mm Plates	Mean Grain Size [µm]				
	Austenite (Final)				Ferrite
	Mean	Maximum	Z_d	Critical (*)	
Good Toughness	19.2	199	10.4	51	14.5
Moderate Toughness	11.8	162	13.8	35	12.9

(*) Critical: 10% of the grain population has size larger than this value.

CONCLUSIONS

Fundamental aspects related to toughness, microstructure, mean grain size and normalizing rolling of heavy plates were presented in this paper. No differences could be observed in the evolution of mean flow stress along pass schedule between the different plates studied here that could justify the differences in the toughness values measured by Charpy tests. The analysis via the MicroSim model presented interesting results that helped to explain the different toughness values measured in the plates considered for this study. Although there was no full numerical agreement, the mean ferritic grain size calculated by MicroSim were consistent in terms of trend with the measured values. However, it is still necessary to analyze a much larger number of cases to reveal more accurately and reliably the relationships between the NR parameters and the final microstructure in order to obtain good toughness values in the rolled plates.

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