BASIC METALLURGY/PROCESSING DESIGN CONCEPTS FOR OPTIMIZED HOT STRIP STRUCTURAL STEEL IN YIELD STRENGTHS FROM 300–700 MPA*

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Abstract

Hot strip structural steel coil used in construction, engineering, transport, structural applications and other applications are widely used in yield strengths from 300 – 700 MPa. However, structural design engineers are now not only requiring various strength levels but also other mechanical properties, primarily good formability, toughness and weldability. To produce a balanced approach to a cost effective structural steel, hot strip coil requires an understanding of utilization of an optimized alloy composition designed for the layout/equipment capabilities of a given hot strip mill to produce the desired metallurgy for optimum mechanical property performance. The term "cost effective" does not just focus on alloy design, but also ease of overall processing from steelmaking, casting, rolling and cooling, stable mechanical properties with a statistically normal distribution, no downgrades/rejections and a product that the end user recognizes as being superior to others. The desired metallurgy is simply understanding what will be the optimum microstructure and cross sectional grain size/distribution needed to meet the mechanical property requirements. This paper is a follow up paper that previously described optimum base alloy designs along with steelmaking/casting processing considerations and will focus on proper reheating, rolling and cooling metallurgy/processing strategies to produce quality cost effective hot strip structural steel coil.

Keywords: Grain size; Niobium; Rolling; Cooling.

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1 INTRODUCTION

Proper design of the alloy/process to fit the layout/equipment capabilities of the hot strip mill to optimize the desired metallurgy through reheating, rolling and cooling is critical to cost effective production of hot rolled structural steel coils. The desired metallurgy for structural steels consists of designing the proper microstructure and cross sectional grain size/distribution [1]. When the proper alloy/process is designed to achieve the desired metallurgy to fit within the layout/equipment capabilities of the hot strip mill, then achievement of the desired strength/ductility properties will be realized. Reheating, rolling and cooling all contribute to the final microstructure and cross sectional grain size/distribution. This paper, utilizing the alloy designs presented in the accompanying paper [1], will give general strategy and guidelines for reheating, rolling and cooling on a hot strip mill producing structural steel coil. A current typical layout configuration for a hot strip mill of a single stand reversing roughing 4-high rolling mill followed by six or seven 4-high finishing stands with a typical laminar run-out table (ROT) and downcoilers will be used in the discussion. In addition, two different thicknesses representing lighter, 6 mm, and heavier, 12 mm, product will be considered. The ultimate goal of the two papers is to give guidance in the production of hot strip structural steel coil that can be technically marketed as an optimum cost effective solution in the market place.

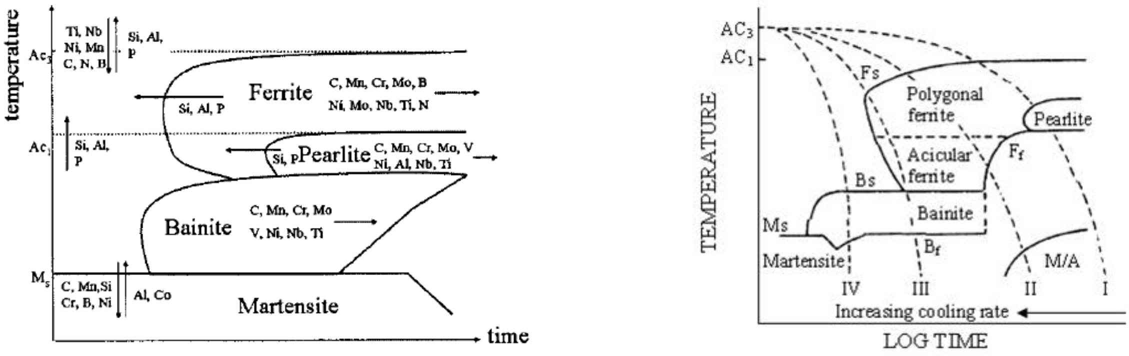
2 MICROSTRUCTURE/GRAIN SIZE DESIGN

2.1 Microstructure

Development of the proper microstructure for hot rolled structural steel coils of the primary volume fraction microstructural phases of polygonal ferrite along with lesser secondary volume phases of pearlite/upper bainite/acicular ferrite will be developed through proper alloying, rolling and cooling. Typical volume fractions of microstructural phases in hot strip structural coils were presented in the accompanying paper [1]. Carbon plus solute alloy additions of manganese and some cases molybdenum or silicon followed by microalloy additions of niobium and titanium used in the base hot strip structural coil alloy design will determine the microstructure phase kinetics during post rolling cooling. A continuous cooling transformation (CCT) diagram is very helpful in understanding for a given cooling rate which microstructural phases will be created. Figure 1 shows examples of the alloying elements effect on the CCT kinetics along with a visual of where acicular ferrite will form in relationship to the CCT diagram [2,3].

2.2 Grain Size/Distribution

Optimization of strength comes from creating as fine as possible average cross sectional grain size. Optimization of ductility (toughness, elongation, formability) comes from creating a uniform distribution of the cross sectional grain size. By optimizing both size and distribution of the austenite grains through the cross section, utilizing proper control of the three recrystallization behaviors through a proper understanding of niobium microalloying technology and processing through rolling and cooling, a cost effective structural steel hot strip coil can be produced with excellent mechanical properties [4,5].



Alloy effects on microstructural phase kinetics of the CCT diagram

CCT showing where acicular ferrite forms relative to the other phases

Figure 1. Example of CCT diagrams showing alloy effects and acicular ferrite formation

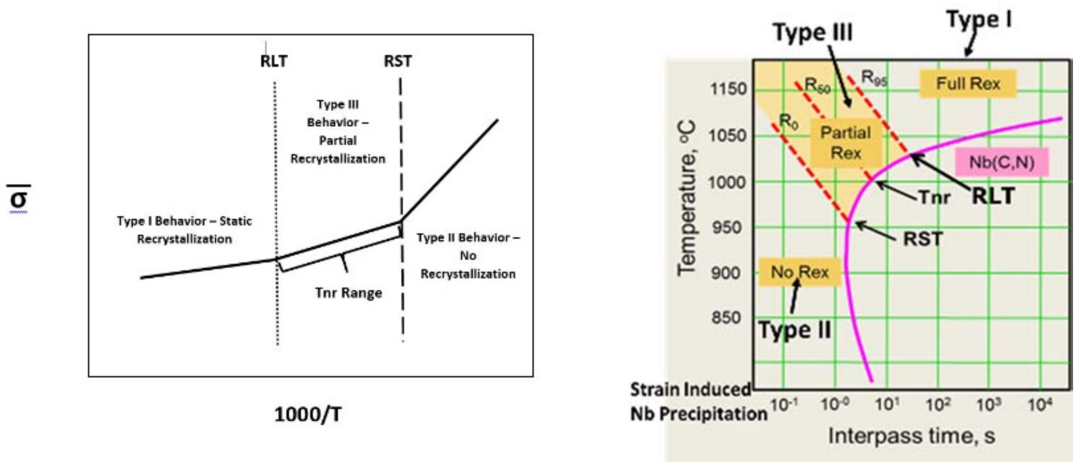
The three recrystallization behaviors of the austenitic grains are Type I static recrystallization, Type II no-recrystallization (pancaking), Type III partial recrystallization (a mix of Type I and Type II) and Type IV dynamic recrystallization. Type IV dynamic recrystallization is something that occurs predominately in hot strip rolling only and in typically in combinations of situations of light finish gauges, less than 6 mm, high strain accumulation and insufficient volume fraction of fine Nb precipitates to restrain the recrystallization. Mean flow stress from the actual mill production can be used to help determine what type of recrystallization behavior is occurring. Schematic illustrations of mean flow stress vs. recrystallization behaviors and niobium along with some actual hot strip mill mean flow stress (MFS) data showing the recrystallization behaviors are shown in Figure 2 [6,7].

To achieve the maximum strength for any given microstructure, an approximate cross sectional average final ferrite grain size target would be less than or equal to 8 μm. For optimum ductility (elongation, formability, toughness) of any given microstructure a target cross sectional distribution/standard deviation less than 4 μm is the goal. To achieve these optimum conditions a minimum of 50-60% Type I static recrystallization deformation is required followed by a minimum of 30% Type II no-recrystallization deformation. As long as the minimum requirement of Type I static recrystallization deformation is maintained, as the Type II no-recrystallization behavior increases beyond 30%, the cross sectional average grain size will decrease along with the distribution/standard deviation. For guidance purposes the recommended amount of Type I and Type II recrystallization behaviors for a given strength and toughness temperature can be seen in Table 1.

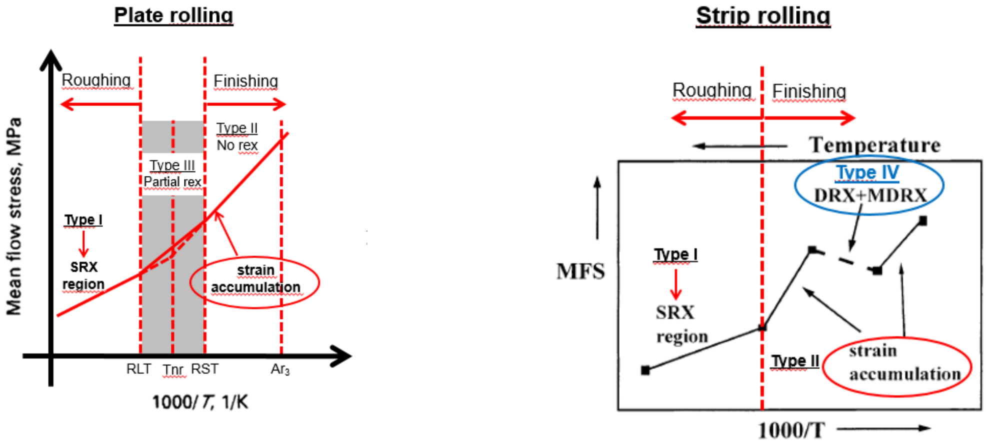
3 ALLOY, LAYOUT, PROCESSING CONSIDERATIONS

3.1 Alloy

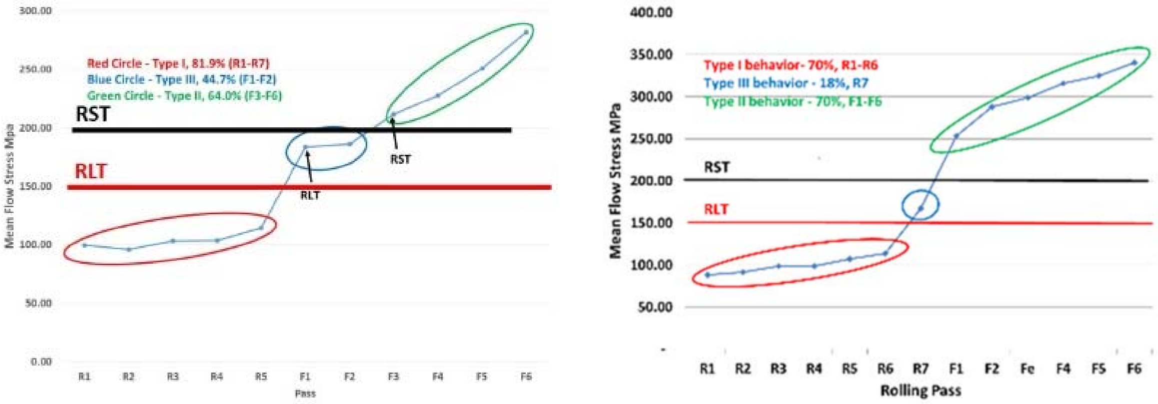
The optimum base alloy designs were presented in the table 1 of the accompanying paper [1].



Schematic of Type I, Type II and Type III recrystallization behaviors concept vs. MFS, left, and Nb strain induced precipitation curve, right.



Schematic of recrystallization behavior types in plate rolling vs. strip rolling introducing Type IV dynamic recrystallization behavior



Actual 700 MPa YS 6mm hot strip coil MFS showing three recrystallization behaviors

Actual 480 MPa YS 16 mm hot strip coil MFS showing three recrystallization behaviors

Figure 2. Schematic and actual examples of recrystallization behaviors

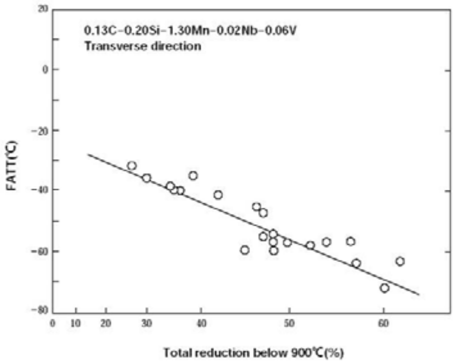
3.2 Layout

In designing the overall metallurgical strategy, considerations for the hot strip mill layout and equipment capability need to be factored. There are four basic hot strip mill layouts in the world as follows:

1. Completely continuous – consists of a series of four to six 2-high/4-high roughing stands with no reversing capabilities followed by either six or seven 4-high finishing stands – typically an older mill design, not common today.
2. One 2-high continuous roughing mill, one 4-high reversing roughing mill, two 4-high continuous roughing mill stands with an intermediate coil box followed by either six or seven 4-high finishing stands – popular in the 1960's/1970's.
3. One 2-high reversing roughing mill followed by one 4-high reversing roughing mill with an intermediate coil box followed by either six or seven 4-high finishing stands – one of today's standards.
4. One 4-high reversing roughing mill followed by either six or seven 4-high finishing stands – one of today's standards.

Table 1. Example of recommended percentage of recrystallization behaviors by strength and toughness temperature requirements.

Min 27J Charpy Toughness Required at [°C]	Recrystallization Behaviour [% of Reduction]		
	Type I	Type II	Type III
No Charpy	50~60	≥0	Minimum
0	50~60	10~20	Minimum
-20	50~60	20~40	Minimum
-40	50~60	40~60	Minimum
-60	50~60	60~80	Minimum



All hot strip mills use a laminar accelerated post rolling cooling system, the so called run-out table, and some of the newer mills now have high intensity pressurized cooling section in front of the traditional laminar cooling section.

Regardless of which layout/equipment capability is present, the basic metallurgical strategy remains the same and has to be properly implemented in each situation. For the purpose of this paper only hot strip mill layout #4 will be discussed.

3.3 Reheating of Slabs

Slabs are reheated for rolling from either ambient temperature, cold charging, or from a higher temperature up to 700 °C, warm/hot charging. Slabs should never be charged above a surface temperature of 700 C. Warm/hot charging at too high of temperature results in a very coarse as-cast grain structure being the starting point for rolling. For typical hot strip mill slab thicknesses of 150-250 mm, the absolute maximum surface temperature should be in the 550°C for 250 mm thickness and 650°C for 150 mm thickness. The reheating of slabs, whether from a cold charge or hot charge situation, has three main purposes:

1. Heat the slab hot enough to put the proper alloys into solution. In this case Nb solubility will typically govern the required temperature.

2. Heat the slab hot enough for good rollability so that proper per pass reductions can be taken within the rolling mill stands force/torque limitations.
3. Heat the slab not too hot to control austenite grain growth prior to rolling.
4. Heat the slab not too hot to control scale formation that can affect overall product yield losses and create poor surface quality issues.

The bottom line the slab needs to be hot enough to address the first two points above, but not too hot to address the last two points above. Typically, proper slab temperature for hot strip structural steel coil rolling is in the 1130-1200 °C range. Guidelines for total furnace residence time by slab thickness is as follows:

- 150-200 mm slab thickness – 3 hours
- 220-250 mm slab thickness – 4 hours

Table 2 shows the minimum solubilization temperatures for two representative alloy designs proposed in the table 1 of reference [1]: low Nb and NbTi. For each of these cases, five variants were considered, according to the corresponding specified composition range: maximum amounts of all elements; minimum amounts of all elements; average amounts of all elements; maximum amounts of Nb/Ti and minimum amounts of C/N (Pro Micr); and maximum amounts of C/N and minimum amounts of Nb/Ti (Pro Int).

The solubilization temperatures were calculated using the Irvine model [8] for the Nb steel, except when C/N ratio was lower than 10; in this case the model of Hudd [9] was used. In the case of NbTi steels it was assumed that Ti reacted preferentially with N, so the remainder amounts of soluble Ti or N after this reaction were calculated. If all Ti precipitated as TiN, then Nb will be the only microalloying element in solution, so solubilization temperatures were calculated as described above. However, if all N was precipitated as TiN, then there was some residual Ti in solution; in this case, solubilization temperatures were calculated according to a model proposed by CEIT [10], which was developed using equilibrium data calculated by Thermocalc for a C-N-Nb-Ti microalloyed steel.

Table 2. Minimum Nb solubilization temperatures for three recommended alloy designs. All of them have 0.05-0.09% C and 0.010% N maximum.

Alloy Variant	C [wt %]	N [wt %]	Nb [wt %]	Ti [wt %]	Solub. Model	$T_{Sol\ 0.015\%\ Nb}$ [°C]	T Sol Nb [°C]
Minimum	0,05	0,0005	0,015	-	Irvine	985	985
Maximum	0,09	0,0100	0,020	-	Hudd	1080	1109
Average	0,07	0,0053	0,018	-	Irvine	1025	1043
Pro Micr	0,05	0,0005	0,020	-	Irvine	985	1015
Pro Int	0,09	0,010	0,015	-	Hudd	1057	1057

(a) Low Nb steel: 0.015-0.020% Nb

Alloy Variant	C [wt %]	N [wt %]	Nb [wt %]	Ti [wt %]	Solub. Model	$T_{Sol\ 0.030\%\ Nb}$ [°C]	T Sol Nb [°C]
Minimum	0,05	0,0005	0,030	0,010	CEIT	1166	1166
Maximum	0,09	0,0100	0,040	0,025	Irvine	1130	1170
Average	0,07	0,0053	0,035	0,018	Irvine	1095	1117
Pro Micr	0,05	0,0005	0,040	0,025	CEIT	1130	1198
Pro Int	0,09	0,010	0,030	0,010	Irvine	1137	1137

(b) NbTi steel: 0.030-0.040% Nb, 0.010-0.025% Ti

Two solubilization temperatures were calculated in table 2: one considering the absolute minimum amount of Nb specified for the alloy design and another for the Nb amount of each variant of the alloy design. This last value is a better estimative, as it is generally associated to a higher soluble Nb amount, increasing the consistency of the mechanical properties of the strip. So, for the low Nb steel, the minimum solubilization temperatures range extends from 985 to 1080°C (corresponding to 0.015% soluble Nb), while the recommended range varies from 985 to 1109°C. For the NbTi steel, the minimum solubilization temperature range varies from 1095 to 1166°C (corresponding to 0.030% soluble Nb), and the recommended one extends from 1117 to 1198°C.

From these values one can see that, as expected, higher amounts of Nb, Ti, C and N increases solubilization temperature. The presence of soluble Ti also hinders Nb solubilization; this can be clearly seen in the high NbTi steel, where all alloy design variants showed soluble Ti – that is, all N was already precipitated as TiN before slab reheating.

3.4 Rolling

The main metallurgical purpose in rolling is to create the proper balance of Type I static recrystallization plus Type II no-recrystallization behaviors through the cross section of the strip for optimum cost effective mechanical properties. Some key process parameters to realize this is to understand where the Temperature of No-Recrystallization(T_{nr})/Recrystallization Stop Temperature (RST) will occur in the process based on the Nb in solution, develop a proper per pass reduction schedule to condition the cross sectional austenite grain in roughing (Type I behavior) and then create strain induced fine Nb precipitates in the appropriate finishing passes (Type II behavior), [11], and take a *critical reduction at a critical thickness* for proper cross sectional austenite grain homogenization [12]. Figure 3 shows an example of a proper per pass reduction strategy for hot strip structural steel coil rolling.

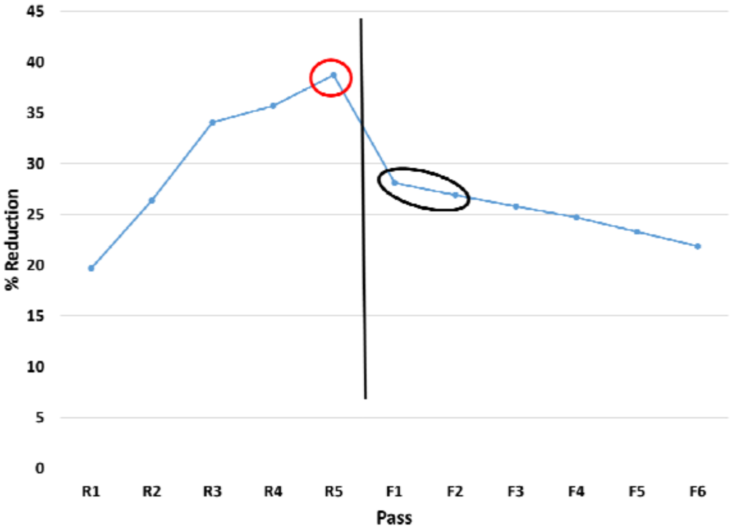
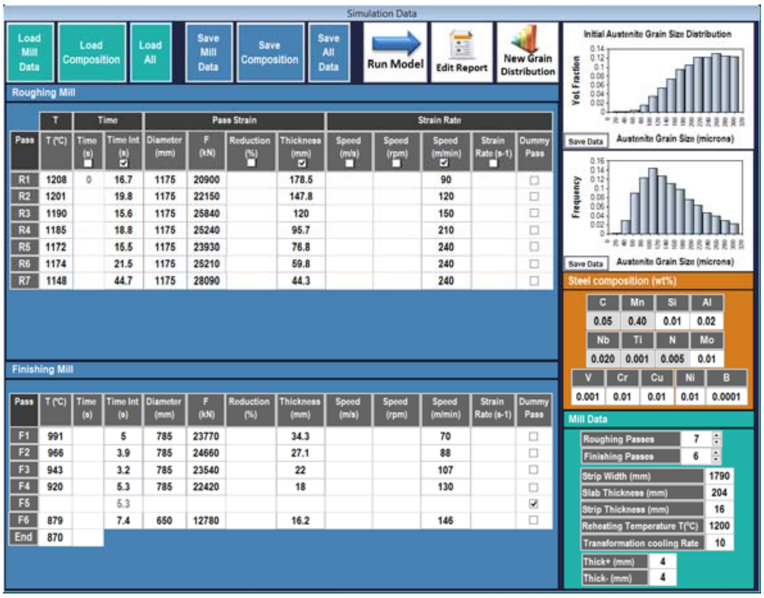


Figure 3. Example of proper per pass reduction schedule for hot strip coil structural coil of 6 mm final thickness on a single reversing roughing stand/six stand finishing mill layout. Red circle on R5 is the “critical reduction at a critical thickness” and the black circle on F1 and F2 is where strain induced Nb precipitation of solute Nb can start affecting the Type II no-recrystallization behavior.

Proper metallurgical strategy for rolling starts with calculating key processing parameters such as T_{nr}/RST, ferrite start of transformation (Ar_3) and bainite (B_s)/martensite (M_s) transformation temperatures. Once that is done, practical hot strip mill models and actual mill mean flow stress analysis can be utilized to evaluate the alloy/process design’s effect on the recrystallization behaviors, cross sectional grain size and the overall microstructural evolution pass by pass.

The thermomechanical processing in the hot strip mill can be previously simulated using a microstructural evolution model, like MicroSim-HSM, developed at CEIT, in the Basque Country. This program calculates austenite grain size distributions from the slab down to the finished product, allowing the prediction of the degree of microstructural homogeneity [13]. Figure 4 shows a screenshot of the input data layout of MicroSim-HSM for the specific case of a 16 mm gauge coil of low C-Nb microalloyed structural steel processed in a hot strip mill, while figure 5 shows the corresponding screenshot of the simulation results for each rolling pass. These results, in tabular and graphical form, include recrystallized fraction, non-recrystallized fraction (due to solute drag or strain induced precipitation), mean and maximum austenite grain sizes, critical grain size $D_{c(0.1)}$ (a measure of microstructural heterogeneity degree: grain size relative to the 10% of the coarsest grains in the tail of the distribution), ZD (D_{max}/D_{mean} ratio) and retained strain. The program also determines Recrystallization Limit Temperature (RLT, temperature above which there is at least 80% of austenite recrystallization between passes) and RST (temperature under which there is a maximum of 20% of austenite recrystallization between passes). If user inputs the rolling loads for each pass, the program also permits the graphical determination of T_{nr} as proposed in [4], as shown in figure 6.

As RLT and RST are known, the program can calculate the corresponding deformation shares applied under each recrystallization type. As stated above, toughness maximization in the final product requires minimization of rolling in the temperature range between RLT and RST, where Type 3 recrystallization - that is, partial recrystallization - is active. Figure 7 shows recrystallization evolutions along rolling for a 16 mm strip of microalloyed low C structural steels with 0.020% and 0.040% Nb. One can see that, for the first case, the five last rolling passes where applied under temperatures between RLT and RST – that is, in the partial recrystallization zone (Type III recrystallization). For its turn, only two passes where applied in this zone for the 0.040% Nb steel; the last three passes where applied in the no-recrystallization zone (Type II recrystallization). This last condition is more favorable to microstructural homogeneity and, consequently, to product toughness.



Roughing Mill

	T	Time		Pass Strain				Strain Rate				
Pass	T (°C)	Time (s) ☐	Time Int (s) ☑	Diameter (mm)	F (kN)	Reduction (%) ☐	Thickness (mm) ☑	Speed (m/s) ☐	Speed (rpm) ☐	Speed (m/min) ☑	Strain Rate (s-1) ☐	Dummy Pass
R1	1208	0	16.7	1175	20900		178.5			90		☐
R2	1201		19.8	1175	22150		147.8			120		☐
R3	1190		15.6	1175	25840		120			150		☐
R4	1185		18.8	1175	25240		95.7			210		☐
R5	1172		15.5	1175	23930		76.8			240		☐
R6	1174		21.5	1175	25210		59.8			240		☐
R7	1148		44.7	1175	28090		44.3			240		☐

Finishing Mill

Pass	T (°C)	Time (s)	Time Int (s)	Diameter (mm)	F (kN)	Reduction (%)	Thickness (mm)	Speed (m/s)	Speed (rpm)	Speed (m/min)	Strain Rate (s-1)	Dummy Pass
F1	991		5	785	23770		34.3			70		☐
F2	966		3.9	785	24660		27.1			88		☐
F3	943		3.2	785	23540		22			107		☐
F4	920		5.3	785	22420		18			130		☐
F5			5.3									☑
F6	879		7.4	650	12780		16.2			146		☐
End	870											

Steel composition (wt%)

C	Mn	Si	Al
0.05	0.40	0.01	0.02

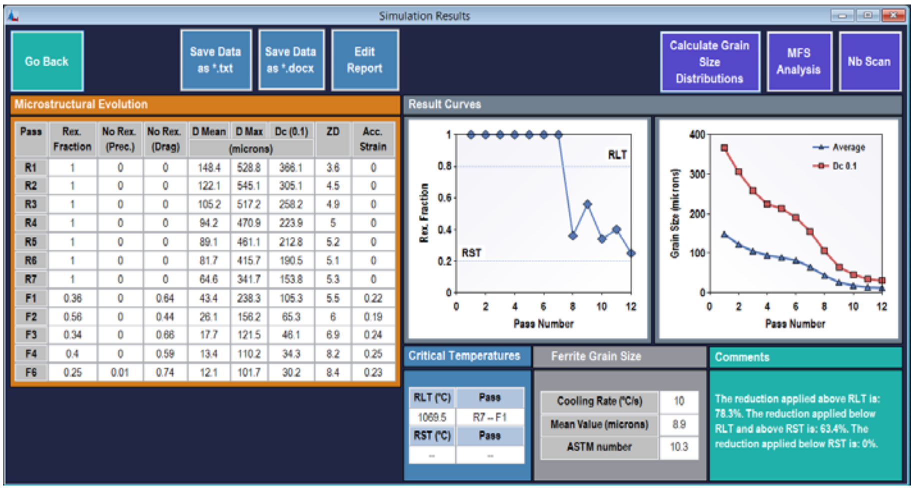
Nb	Ti	N	Mo
0.020	0.001	0.005	0.01

V	Cr	Cu	Ni	B
0.001	0.01	0.01	0.01	0.0001

Mill Data

Roughing Passes	7
Finishing Passes	6
Strip Width (mm)	1790
Slab Thickness (mm)	204
Strip Thickness (mm)	16
Reheating Temperature T(°C)	1200
Transformation cooling Rate	10
Thick+ (mm)	4
Thick- (mm)	4

Figure 4. Screenshot showing the input data layout for the MicroSim-HSM model for a low C-0.020%Nb microalloyed structural steel with thickness of 16 mm.



Microstructural Evolution

Pass	Rex. Fraction	No Rex. (Prec.)	No Rex. (Drag)	D Mean	D Max	Dc (0.1)	ZD	Acc. Strain
				(microns)				
R1	1	0	0	148.4	528.8	366.1	3.6	0
R2	1	0	0	122.1	545.1	305.1	4.5	0
R3	1	0	0	105.2	517.2	258.2	4.9	0
R4	1	0	0	94.2	470.9	223.9	5	0
R5	1	0	0	89.1	461.1	212.8	5.2	0
R6	1	0	0	81.7	415.7	190.5	5.1	0
R7	1	0	0	64.6	341.7	153.8	5.3	0
F1	0.36	0	0.64	43.4	238.3	105.3	5.5	0.22
F2	0.56	0	0.44	26.1	156.2	65.3	6	0.19
F3	0.34	0	0.66	17.7	121.5	46.1	6.9	0.24
F4	0.4	0	0.59	13.4	110.2	34.3	8.2	0.25
F6	0.25	0.01	0.74	12.1	101.7	30.2	8.4	0.23

Critical Temperatures

RLT (°C)	Pass
1069.5	R7 -- F1
RST (°C)	**Pass**
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Ferrite Grain Size

Cooling Rate (°C/s)	10
Mean Value (microns)	8.9
ASTM number	10.3

Comments

The reduction applied above RLT is: 78.3%. The reduction applied below RLT and above RST is: 63.4%. The reduction applied below RST is: 0%.

Figure 5. Screenshot showing the output data layout for the MicroSim-HSM model for a low C-0.020% Nb microalloyed structural steel with thickness of 16 mm.

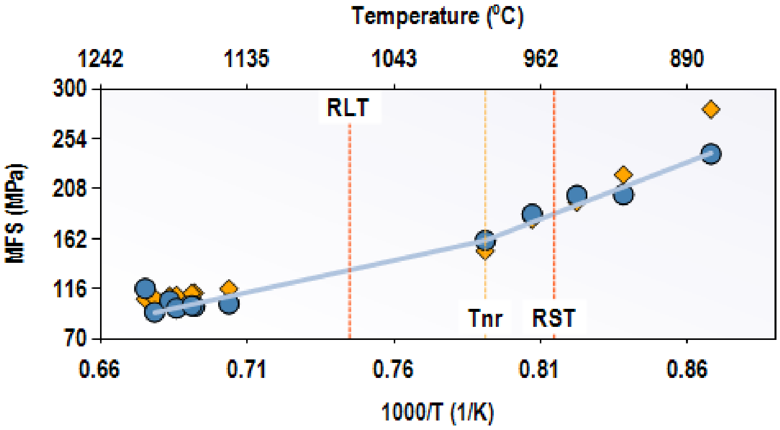
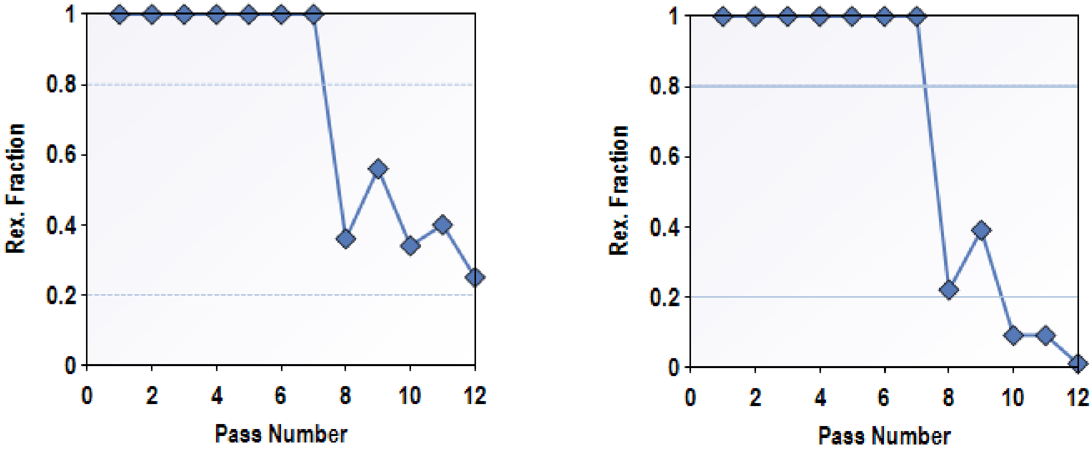


Figure 6. Mean flow stress versus inverse of temperature graphic, generated by MicroSim-HSM, showing RLT, T_{nr} [4] and RST. Blue points indicate real MFS values, calculated from rolling forces, while the yellow ones are predicted MFS values.



(a) (b)

Figure 7. Comparison between recrystallized fraction evolutions during the rolling of a 16 mm strip of microalloyed structural low C steel with (a) 0.020% Nb and (b) 0.040% Nb-0.010% Ti.

3.5 Post Rolling Cooling

The post rolling cooling serves four main purposes:

1. Controls the microstructural phase formations.
2. Controls the final cross sectional ferrite grain size/distribution.
3. Controls the interphase precipitation strengthening mechanisms, especially important in higher strength TiC precipitation strengthening grades.
4. Controls the final texture formations which affects toughness.

In regard to microstructural control, the Ar_3 temperature needs to be known and then an understanding of the CCT kinetics for the given alloy, as discussed prior, is helpful, so that the correct cooling rate/cooling stop temperature can be chosen. In addition, cooling rate affects final ferrite grain size/distribution, texture formation, and interphase precipitation formation. As with all processing within the steel plant water temperature/yearly seasonal conditions can play role in the cooling rate and hence the final metallurgy/mechanical properties that can be achieved, Figure 4 [14].

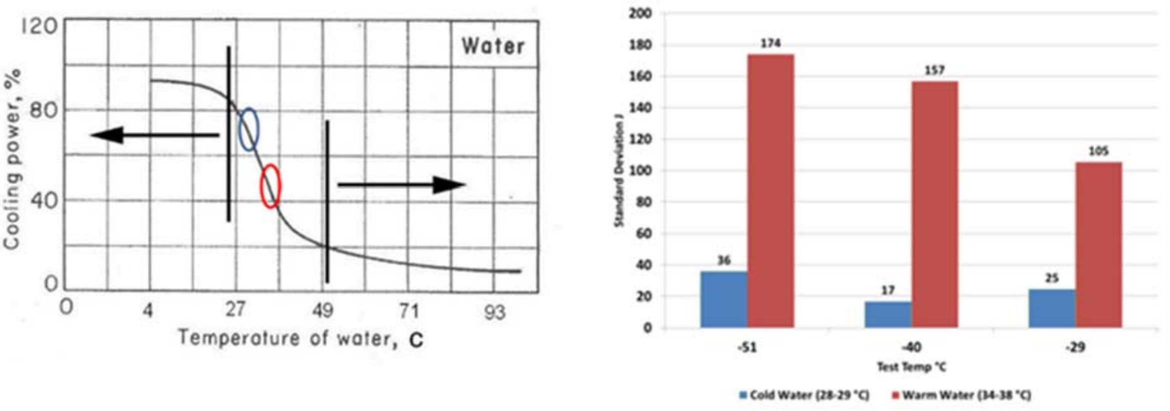


Figure 8. Example of post cooling water temperature on standard deviation between individual Charpy toughness tests at lower temperatures.

4 CONCLUSION

Fundamental aspects related to microstructure, grain size/distribution and thermomechanical processing (slab reheating, hot rolling and cooling) of hot strip structural steel coils from 300-700 MPa yield strength were discussed in this paper, complementing an accompanying paper about alloy design and steelmaking/casting considerations [1]. The optimized thermomechanical processing of a balanced alloy design, starting with proper Nb solubilization at the slab reheating furnace, full recrystallization between passes during roughing stage, minimization of partial recrystallization between passes during finishing stage, and an optimized coupling between steel chemical composition and run-out accelerated cooling are the key for the production of consistent and cost effective high quality structural coils. A predictive model which can simulate these processes, like MicroSim-HSM, is extremely useful to make a diagnosis of the proposed thermomechanical treatments, considering the specific hot strip mill configuration of a given steelworks, thus accelerating the conception of an optimized and reliable hot strip mill process.

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