PARTIAL REPLACEMENT OF MANGANESE BY NIOBIUM IN LOW CARBON STRUCTURAL STEELS*

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Abstract

Manganese is a ubiquitous alloy element in structural steels, where it suppresses the hot brittleness caused by sulfur, promotes solid solution hardening and increases the pearlite fraction in the microstructure, consequently increasing its mechanical strength. However, at levels above 1%, it presents some inconveniences, such as the rephosphorization of liquid steel and greater damage to refractories in oxygen steelworks without ladle furnaces. Another problem is its strong tendency to segregate at the center of the thickness of continuously cast slabs. Even so, the intensification of Asian demand for high-strength structural steels has been promoting an increase in their manganese contents, which is increasing the consumption and, obviously, the price of its ferroalloys. Therefore, this situation prompted the emergence of new alloy designs, having motivated the development of many studies, both on laboratory and industrial scale, to design alternative compositions for structural steels where manganese is partially replaced by niobium, without affecting product performance, reducing its price and carbon footprint, and without necessarily requiring the use of controlled rolling. This paper reviews the results of such developments.

Keywords: HSLA Structural Steel; Niobium; Manganese; Alloy Design.

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1 INTRODUCTION

In principle, the alloy design of a steel, that is, its combination of alloying elements, must guarantee that its specified properties and characteristics are met, and in the most economical way possible. But other requirements must also be satisfied. For example, the steel refining, forming and processing steps at the plant should be as simplified, economical and consistent as possible. The availability of the corresponding ferroalloys on the market, as well as the value and stability of their quotations over time, are also an important factor to be considered. Finally, the issue of sustainability is assuming significant importance, particularly regarding the resulting carbon footprint and recyclability of steel.
This work focuses on rethinking the use of manganese in structural steel alloy designs. Its beneficial effects on steel, known for many decades, together with its low cost, have established its use in this class of materials, to the point of hamper the proposal of studies aiming at its replacement, even if only partially. Manganese provides increase in mechanical strength due to the various hardening mechanisms it promotes: solid solution, increase in the fraction of pearlite in the microstructure and a discrete grain size refinement, since it reduces the temperature of the transformation of austenite into ferrite (A_{r3}). This last effect is not very strong in the case of structural steels, which are air-cooled after hot rolling. In addition, manganese combines with the sulfur present in steel, preventing the formation of iron sulfide inclusions, which are liquid at typical hot-rolling temperatures and reduces the ductility of the material during this process [1].
On the other hand, the use of manganese brings some problems. In older oxygen steelworks, which do not have a ladle furnace, additions of this element above 0.8% increase the amount of cold charge to be incorporated into the liquid steel, which requires raising the tapping temperature, intensifying thus the risk of rephosphorization of the liquid steel and reducing the life of the LD converter's refractory lining. And, even in plants which have a ladle furnace, its use implies a longer manufacturing route and greater consumption of electricity. In addition, manganese tends to intensely segregate in the core of the slabs during its solidification in continuous casting, which can affect the performance of the finished product due to the massive formation of MnS inclusions in this location [2]. Other inconveniences are the increase in the degree of banding of the microstructure and reduction in weldability due to the higher value of carbon equivalent [3]. The literature reports successful experiences involving the reduction of manganese content in structural steels, with the objective of reducing costs and avoiding the mentioned problems [4,5].
But these problems have not constrained the increasing use of manganese in structural steels. As can be seen in Figure 1 [6], the average Mn content in crude steel has been increasing on a global scale, step by step with the production volume of this material in the BRIC group countries, resulting in an exceptional increase consumption of that alloying element. This is mainly due to the strong demand for structural steels with higher mechanical resistance in developing countries, as they are necessary for the implementation of infrastructure and in civil construction. In addition, steels with medium to high contents of Mn (3 to 20%), with exceptional mechanical properties, have been developed and progressively entering commercial manufacture, with emphasis on TRIP (Transformation Induced Plasticity) and TWIP (Twinning Induced Plasticity) AHSS steels [2].

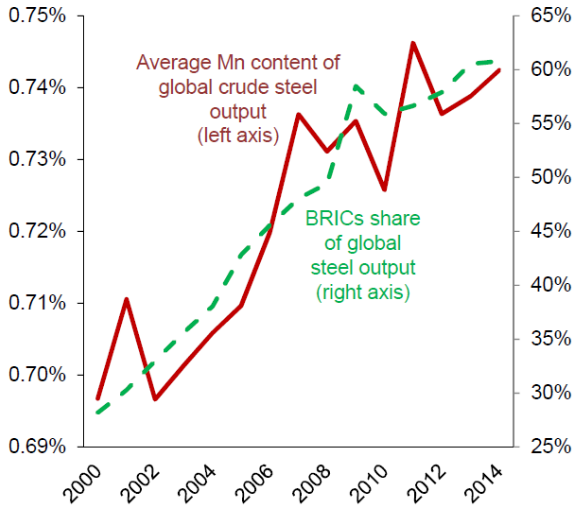


Figure 1: Evolution over time of the average Mn content and the participation of countries in the BRIC group in crude steel production [6].

This increase in demand for manganese naturally stresses its supply, making its ferroalloy prices volatile, as shown in Figure 2. Between October 2020 and July 2021, the cost of this input rose by around 75% in Europe and North America, and by 26% in China. These strong fluctuations in the value of FeMn have been taking place for some years now [7]. This situation encouraged the development of new structural steels where this element is partially replaced by others, which have lower and more stable prices over time, such as niobium, which, moreover, can be used at contents one hundred times lower than manganese. Niobium, traditionally used in special applications and sophisticated steels, can also provide cost reduction benefits in commodity steels, without the need to amend the rolling processes or the use of controlled rolling.

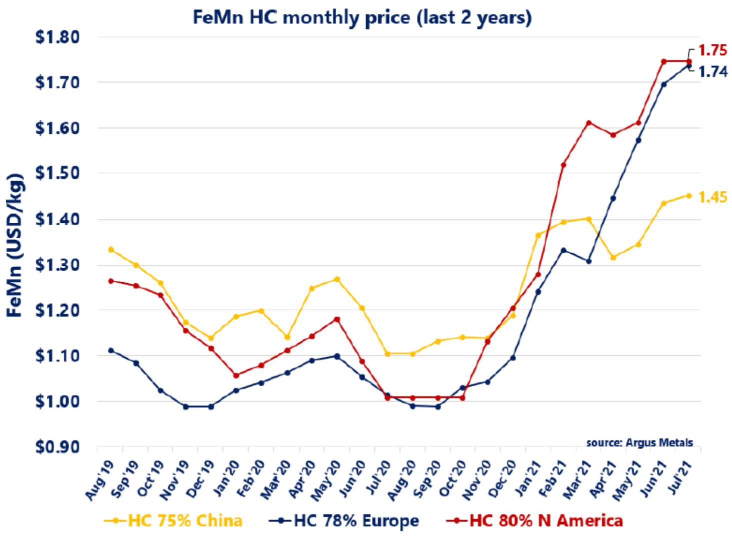
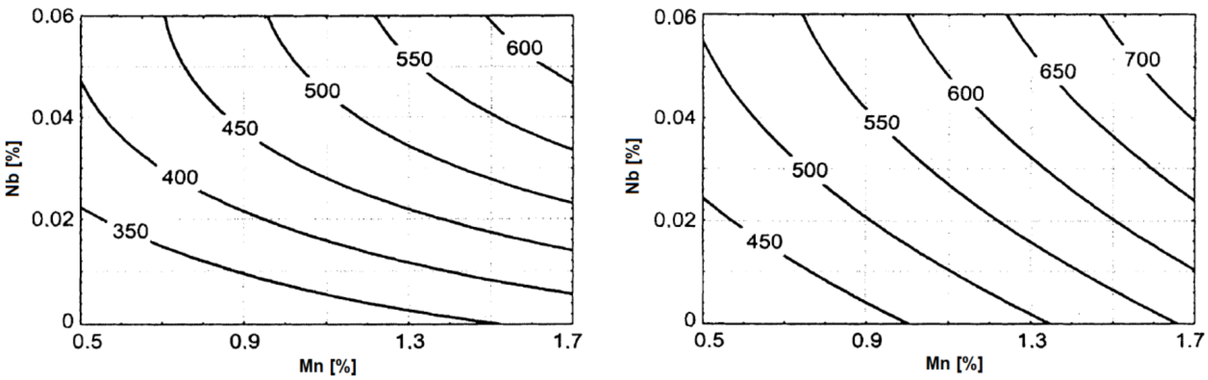


Figure 2: Evolution of monthly quotations for FeMn High Carbon in various regions of the world. Data from Argus Metals.

2 EMPIRICAL EQUIVALENCE BETWEEN NIOBIUM AND MANGANESE

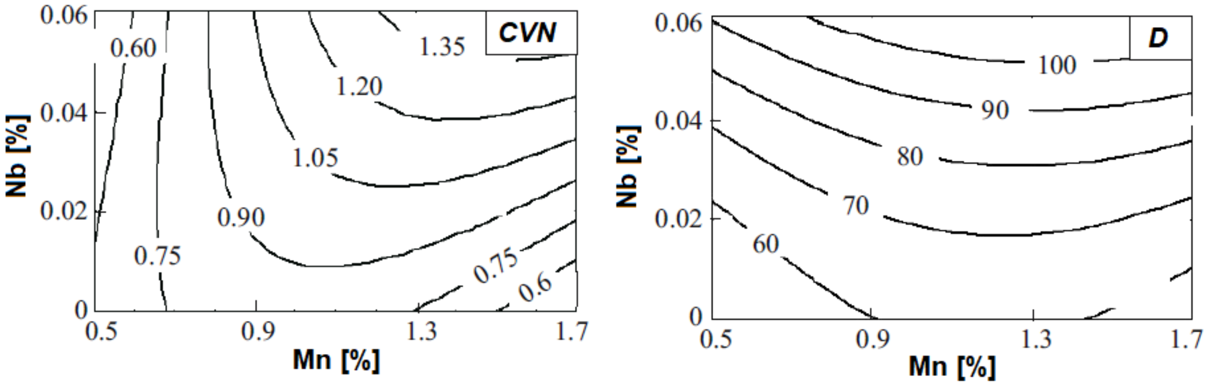
The proposal for partial replacement of manganese by niobium in structural steels is not exactly new [8]. According to that reference, in terms of the yield strength, a 0.30-0.40% reduction in the manganese content could be compensated by an addition of 0.010% niobium. In turn, to keep the tensile strength constant, the corresponding reduction in manganese content could be from 0.10 to 0.20%. Figure 3 shows complete equivalence curves between niobium and manganese established in that reference for these two mechanical properties.



(a) (b)

Figure 3: Dependence of yield (a) and tensile (b) strength, both expressed in MPa, as a function of Nb and Mn contents, for 0.10% C steel plates with thickness between 8 and 12 mm [8].

As a complement to this work, equivalence relationships were established between niobium and manganese in terms of plate toughness, which can be seen in Figure 4 [9]. These graphics shows that it is not possible to establish exceptional toughness levels below 0.90% Mn, but this is not a problem in the case of the most common structural steels, which do not have a high toughness specifications. A cost reduction around US$ 16 per ton of steel was also estimated by replacing 1.0% Mn with 0.020% Nb.



(a) (b)

Figure 4: Dependence on specific energy absorbed (CVN, expressed in MJ/m²) and ductile fracture area (D, percentage) determined in Charpy tests at -40°C [9].

It is possible to determine the manganese content that can be replaced by an addition of 0.010% Nb, without impairing yield or tensile strength. Therefore, statistical regression equations adjusted from the chemical composition of the steel and relevant hot rolling parameters are used. Table 1 shows a list of these values obtained based on data available from the literature. The values of manganese content equivalent to 0.010% Nb varied significantly between the various papers, since they were obtained from steels with different alloy designs and subjected to different rolling and heat treatment processes. The values of manganese that could be replaced by 0.010% Nb were higher for the yield strength case than the tensile strength, Table 1.

Table 1: Manganese contents that can be substituted by 0.010% Nb, without affecting the yield or tensile strength, which have been determined for various hot rolling processes (TM: controlled rolling; QST: Quench and Self Tempering; AcC: Accelerated Cooling)

Product	Process	x (*x*% Mn = 0.010% Nb)		Observations	Ref
		Y.S.	T.S.		
Profile 0.018 ≤ Nb ≤ 0.038%	Hot Rolling	0.20%	0.08%	Finishing Temperature: 1050°C	[10]
	Normalizing	0.24%	0.24%	Austenitization: 900-1050°C	
	TM	0.43%	0.18%	Finishing Temperature: 800-900°C	
	QST	0.08%	0.12%	End AcC Temperature: 600°C	
Profile	Hot Rolling	0.17%	0.07%	0,020 ≤ Nb ≤ 0,036% Finishing Temperature: 940-1010°C	[11]
Heavy Plate	TM + AcC	0.41%	0.13%		[12]
Heavy Plate	TM + AcC	0.25%	0.13%	Nb ≤ 0.040% 0.45 ≤ Mn ≤ 1.60% 755 ≤ End AcC Temperature ≤ 850°C	[13]
Hot Strip	Hot Rolling	0.31%	0.11%	0.006 ≤ Nb ≤ 0.076% 0.21 ≤ Mn ≤ 1.59% 795 ≤ Finish Temperature ≤ 937°C 500 ≤ Coil Temperature ≤ 812°C	[14]
Hot Strip	Hot Rolling	0.75%	0.53%	Nb ≤ 0.041% 0.05 ≤ Mn ≤ 1.41% 700 ≤ Finish Temperature ≤ 930°C 449 ≤ Coil Temperature ≤ 695°C	[15]

More recently, an abacus was proposed, specifically for structural steels with a yield point lower than 355 MPa, where it is possible to determine the niobium content necessary to compensate for a given reduction in the manganese content, which is shown in Figure 5 [16]. Here the point (1) in the graph indicates the original CMn steel, with 1.50% Mn and without niobium; a reduction in this content to 1.20%, corresponding to the point (2), implies a reduction of 26 MPa in the yield strength, which can be neutralized by an addition of about 0.006% Nb to the steel – point (3).

3 METALLURGICAL FUNDAMENTALS

A few years ago, with the increasing volatility of manganese ferroalloy prices, recent studies were started about the partial replacement of this element by niobium, but with more consistent metallurgical fundamentals. The main objective was to make such substitution feasible in commodity structural steels, with light or no toughness requirements, using conventional rolling processes and Nb contents below 0.020%. The idea was to prove that the adoption of niobium can be an excellent way to reduce structural steel costs without the need for controlled rolling.
The main microstructural hardening mechanisms in structural steels are evidenced by Pickering's formulas for the calculation of yield and strength limits (Equations 1 and 2, both expressed in MPa) of microstructures constituted by polygonal ferrite and

pearlite, as a function weight of alloying elements, percentage fraction of pearlite and grain size (in mm) [17]:

$$LE = 53{,}9 + 32{,}3\ Mn + 83{,}2\ Si + 354.2\sqrt{N_{sol}} + \frac{17{,}4}{\sqrt{d}} \qquad (1)$$

$$LR = 294{,}1 + 27{,}7\ Mn + 83{,}2\ Si + 2.85\ f_{Pearlite} + \frac{7{,}7}{\sqrt{d}} \qquad (2)$$

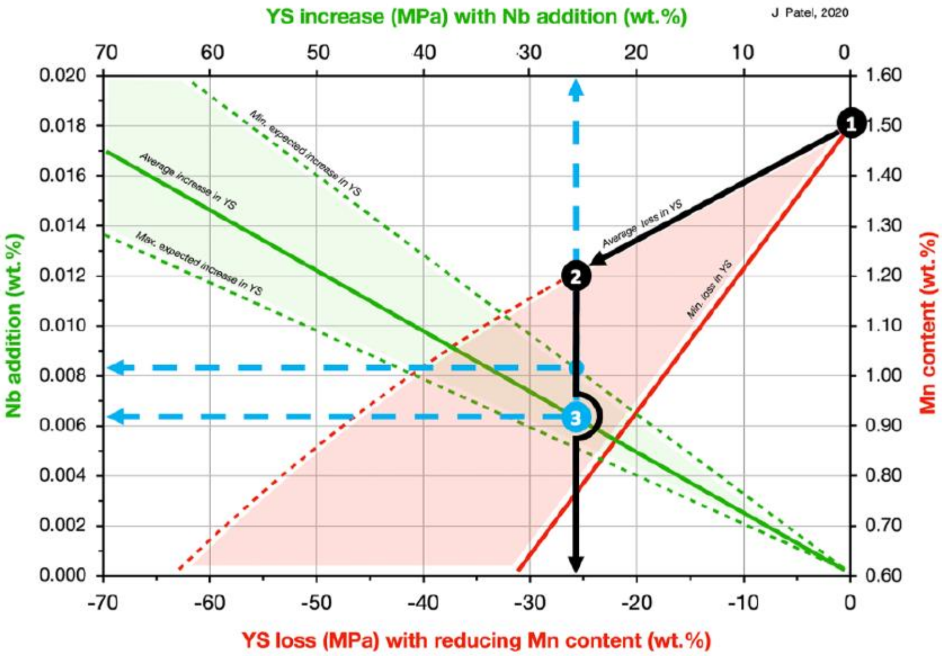


Figure 5: Abacus to determine the addition of niobium that is necessary to compensate for the loss of yield strength resulting from the reduction of the manganese content in structural steels with yield strength less than or equal to 355 MPa [16].

The contributions of manganese through solid solution hardening in the iron lattice are 32.3 MPa/%Mn or 27.7 MPa/%Mn, respectively for the yield and tensile strength. They are not so pronounced, since the atomic diameter of manganese is very close to that of iron, being greater for the yield strength than for the tensile strength. These equations do not directly predict the effects provided by niobium on steel, which promotes intense refining of the austenitic grain size during rolling, which is inherited by the final ferritic microstructure. Niobium restricts (in the form of a solute, by dragging) or even interrupts (in the form of fine NbC precipitates) the migration of the austenite recrystallization boundaries, delaying its kinetics. This grain refining is the main contribution of niobium to the strength of steel, which is expressed in the last term of Equations 1 and 2. Note that the effect of hardening mechanisms is smaller in the case of the tensile strength than in the yield strength, that is, 14% less in the case of hardening by solid solution of manganese and 56% less in the case of grain boundaries (Hall-Petch effect). Furthermore, it is likely that the reduction in the Mn content reduces the fraction of pearlite present in the microstructure, which would be reflected in the lower strengthening effect of this constituent. This can explain the fact that the manganese contents equivalent to 0.010% Nb (parameter “x” from Table 1) are systematically smaller in the case of the tensile strength in relation to the yield strength.

The interchangeability between manganese and niobium contents can be metallurgically evaluated by determining the reduction in grain size promoted by this last element under the conditions of hot forming. From there, it is possible to calculate the contribution of this microstructural refining to the yield and tensile strengths and then calculate the possible reduction in the manganese content, using the respective factors in Equations 1 and 2.
A first example of this calculation can be seen in [18], where the experimental results obtained by [19] were used, which can be seen in Figure 6. They were obtained from flat compression tests where a roughing pass (0.3 true strain) and a finishing pass (0.2 true strain) were applied at temperatures of 1050°C, 1000°C or 950° C, followed by a delay of 20 s and then quenching in water to preserve the austenitic microstructure.

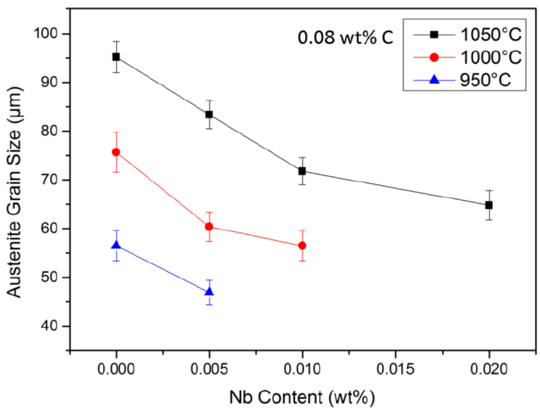


Figure 6: Austenitic grain sizes of a steel with 0.08% C, obtained after a holding period of 20 s following the application of the last pass, as a function of their niobium content. The legend shows the finishing temperatures [19].

It can be seen in Figure 6 that, for a finishing temperature of 1000°C, an addition of 0.010% Nb promoted a reduction in the final austenitic grain size from 80 to 60 microns. Niobium reduces the final grain size of the austenite, which implies refining of the resulting microstructure after the material has cooled, as can be seen in Figure 7 [20]. This figure relates the ferritic grain size obtained after the transformation of the recrystallized austenite with the effective interfacial area per unit volume (S_V) of austenite. Considering a reduction from 16 to 14 microns in the ferritic grain size, according to Equation 1, there is an increase of 9 MPa in the yield strength, which would allow a reduction of 0.28% of Mn in the chemical composition of steel. Applying the same reasoning to the tensile strength, the reduction in the ferritic grain size would lead to an increase of 4 MPa in this property, allowing, according to Equation 2, a reduction in the manganese content of the steel of 0.14%. These values are in good agreement with those presented in Table 1.
This same approach was adopted by other authors, but assuming other experimental results [21]. The grain refining provided by an extra low niobium content was calculated by comparing the microstructures obtained by a CMn steel (0.20% C, 1.03% Mn, 0.20% Si, 0.0058% N) and another one with a similar composition, but with an extra low addition of Nb (0.0066%) [22]. Specimens of these steels were subjected to hot flat compression tests, being reheated at 1250°C for 120 seconds, cooled in air and deformed at 950°C by two passes under true strain of 0.40 and a delay of 5 s between them, followed by water quenching. The microstructures thus

obtained revealed that the austenitic grain size after the test was equal to 20.7 microns for the CMn steel and 17.5 microns for the 0.0066% Nb steel. These parameters, expressed in terms of the effective interfacial area per unit volume (S_V), are equal to 100 and 77 1/mm, respectively. It is now possible to estimate the ferritic grain size values that can be obtained from these microstructures after cooling to air, applying the graph in Figure 8 [20], obtaining respectively 10.5 microns and 9.0 microns – that is, the addition of Nb promoted a 1.5 micron reduction in the average ferritic grain size.

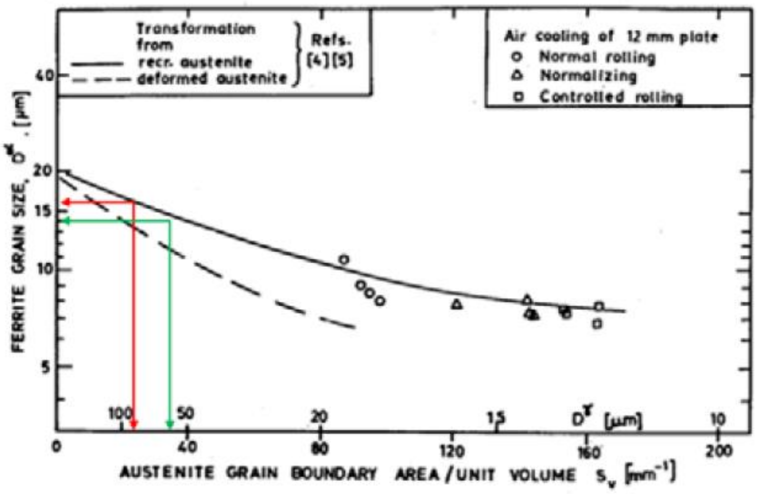


Figure 7: Dependence of ferritic grain size on the total area of austenitic grain boundaries per unit volume obtained from air-cooled samples [20].

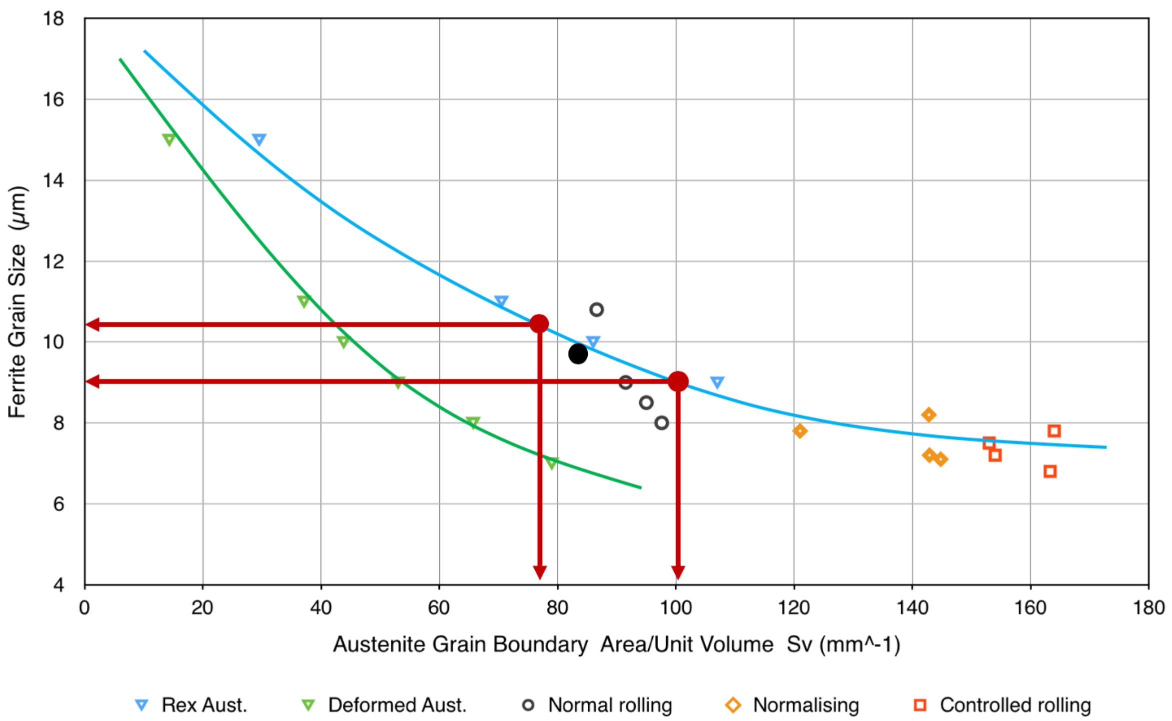


Figure 8: Dependence of ferritic grain size on the total area of austenitic grain boundaries per unit volume obtained from air-cooled samples [23].

According to Equation 1, this reduction in ferritic grain size corresponds to an increase of 14 MPa in the yield strength. Using this same equation, this allows, in theory, a reduction in the Mn content of the order of 0.40%. Or, to put it another way, 0.010% Nb would correspond to 0.57% Mn in terms of yield strength equivalence – a value of the same order of magnitude as those listed in Table 1, albeit higher than most of them. This is since this factor was determined from laboratory tests, under controlled conditions, while the values in Table 1 were determined from regression equations adjusted for steels with different alloy designs and subjected to different industrial thermomechanical conditions.

4 FIRST INDUSTRIAL IMPLEMENTATIONS OF THE NEW ALLOY DESIGN

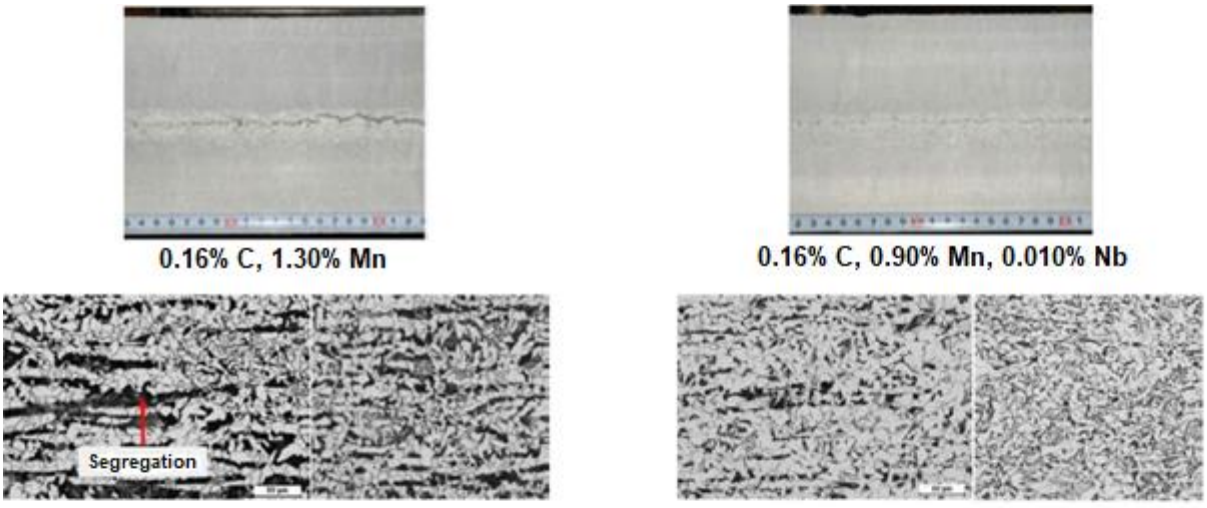
Table 2 shows examples of alloy design developments where manganese was partially replaced by niobium [18]. A36 and S355 steels were processed through hot strip rolling, while Q345 was used for heavy plate rolling. As can be seen, the mechanical properties between the two alloy designs for each standard were always very similar; the economy oscillated between 2.30 and 7.30 dollars per ton of steel, considering the prices of FeMn High-Carbon and FeNb in January 2018, when the material was rolled. The addition of 0.010% Nb allowed to reduce the manganese content between 0.25% and 0.50%; this decrease was proportional to the original content of this element. And, in the specific case of steel for the Q345 standard, the reduction in the Mn content was effectively beneficial in terms of reducing the central segregation and banding in the plate, as well as greater uniformity of the microstructure of the final product, as shown in Figure 9.

Table 2. Comparison between industrially laminated flat products with conventional alloy design or with Mn partially replaced by Nb [18].

Standard	Thickness [mm]	Alloy Design	C [%]	Mn [%]	Nb [%]	LE [MPa]	LR [MPa]	A [%]	CVN @0°C [J]
ASTM A36	2,3	Traditional	0.07	0.80	-	301	435	35.4	-
		New	0.07	0.50	0.012	321	420	34.8	-
EN S355	12,0	Traditional	0.15	1.20	-	356	499	26.0	-
		New	0.15	0.80	0.010	359	481	27.0	-
Q345	≤ 30	Traditional	0.16	1.40	-	383	525	27	164
		New	0.16	0.90	0.010	387	514	26	170

More recently, an application study of this new alloy design was conducted for the case of hot-rolled structural H-beams [16]. Again, a significant saving in steelmaking costs was achieved because it was possible to use the addition of Nb not only to compensate for the reduction in the Mn content, but also to suppress the addition of V that was previously done, as shown in Table 3. Due to the specific conditions of the long products rolling process, it is not possible to fully exploit the grain refining potential provided by niobium in comparison with what occurs in the hot rolling of flat products.
The same work [16] included an unprecedented approach, making the calculation of the Global Warming Potential (GWP, for a time horizon of one hundred years) referring to the chemical compositions of conventional steel and new alloys proposed, with lower Mn content and V suppression compensated by a micro addition of Nb. Although this calculation is controversial, as the values obtained depend on a myriad of factors, including the manufacturing route of each plant and

its energy sources, a life cycle analysis based on the ISO 10144 technical standard was adopted in that work, using the GaBi 6.0 program and databases such as IDEMAT and Ecoinvent 2.2. As shown in Table 4, the results obtained in terms of the Global Warming Potential for produce structural profiles were favorable for the new Nb steels, with an average reduction of 34 kg of CO_2 equivalents per ton of product, a not negligible bonus considering the pressure being put on the steel industry to reduce its carbon footprint.



(a) (b)

Figure 9: Effect of reducing manganese content in Q345 steel: (a) original Mn content; (b) reduced Mn, showing minimization of central segregation and greater uniformity of the microstructure of the final product [18].

Table 3. Comparison between industrially rolled H structural profiles according to S355 standard, with conventional alloy design or with Mn partially replaced by Nb and suppression of V. The calculated savings values were based on the quotation of ferroalloys in China [16].

Grade	Dimensions [mm,mm,kg/m]	C	Mn	V	Nb	YS	TS	El.	Alloy Costs	Economy
		%				MPa		%	US$/t	
S355J0	W 305 x 165 x 45	0.16	1.18	0.021	---	406	557	30	36.22	+8.80
	W 457 x 140 x 47	0.14	0.96	---	0.010	382	563	30	27.42	
S355J0	W 457 x 191 x 107	0.19	1.11	0.021	---	383	541	28	34.54	+0.63
		0.18	1.14	---	0.015	415	557	29	33.91	
S355JR	W 356 x 254 x 92	0.17	1.07	0.020	---	376	535	28	33.20	+11.03
		0.18	0.67	---	0.014	435	582	25	22.17	
S355JR	W 203 x 165 x 36	0.13	1.23	0.040	---	489	590	29	44.50	+13.57
		0.16	1.07	---	0.012	473	580	29	30.93	

5 IMPROVEMENT OF THE NEW CONCEPT

The partial replacement of manganese by niobium can usually be done without modifying the hot rolling processes adopted by the mill. However, leaving this comfort zone can allow to further refine the alloy design or manufacture products with improved mechanical properties. It is possible to optimize the microstructure obtained after the hot rolling processes using the MicroSim® tool, developed by the 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 [24]. This program determines the microstructural evolution occurred during the hot rolling of low carbon steels, in the form of austenitic grain size distribution and other additional stereological parameters, being available in specific versions for each type of industrial hot rolling process.

Table 4. Reduction in terms of Global Warming Potential (GWP) values related to the steels shown in Table 3 [16].

Grade	Dimensions [mm,mm,kg/m]	Mn	V	Nb	Mn	V	Nb	Total GWP	Saving GWP
		%			kg ferro-alloy/tonne			kg CO_2e/tonne	
S355J0	W 305 x 165 x 45	1.18	0.021	---	21.36	0.29	---	158	37
	W 457 x 140 x 47	0.96	---	0.010	17.38	---	0.17	122	
S355J0	W 457 x 191 x 107	1.11	0.021	---	20.09	0.29	---	149	5
		1.14	---	0.015	20.63	---	0.25	145	
S355JR	W 356 x 254 x 92	1.07	0.020	---	19.37	0.27	---	144	58
		0.67	---	0.014	12.13	---	0.23	85	
S355JR	W 203 x 165 x 36	1.23	0.040	---	22.26	0.54	---	173	37
		1.07	---	0.012	19.37	---	0.20	135	
								Average:	34

Alloying recovery rates during steelmaking: SiMn65% = 85%, VN80% = 92% and FeNb65% = 92%
GWP (kg CO_2e/kg): SiMn65% = 34.1, VN80% = 34.1 and FeNb65% = 5.32
Sources: CBMM, GaBi Database

In this case, the MicroSim simulator aims to optimize the pass schedule applied to the heavy plate mill, to maximize and homogenize the grain size refining provided by the action of niobium, and thus achieve a simultaneous increase in mechanical strength and toughness. Table 5 shows a comparison of the results obtained by the MicroSim® simulations for the original and the optimized rolling of heavy steel plates of steel with reduced Mn content plus 0.010% Nb, with final thickness of 30 mm, meeting the standard S355 specifications. This table shows that, at the end of the optimized pass schedule, the plate would show austenitic microstructure with average grain size of 15.9 microns and a maximum of 232 microns, compared to 21.3 microns and 274 microns, respectively, of the original pass schedule. Furthermore, the austenitic microstructure obtained in the case of the optimized rolling process presented 10% of its coarsest grains above 41.7 microns, against 60.1 microns of the austenite obtained under conventional conditions, indicating greater microstructural homogeneity for the optimized rolling condition. The mean ferritic grain sizes after air-cooling corresponding to these mean austenitic grain size eventually can be determined using the graphs in Figures 7 or 8.
In this specific case, industrial rolling trials were conducted under the conventional and optimized pass schedules, and the corresponding ferritic grain size distributions were determined by EBSD in samples extracted from the plates, Figure 10. The average ferritic grain sizes obtained by the conventional process were 5.7 - 10.2 - 11.2 microns (respectively, at ½, ¼ and on the surface, 15° disorientation). These values were reduced to 5.3 - 6.9 - 7.9 microns by adopting the optimized pass

schedule. This allowed increasing the contribution of grain size to the yield strength from 181 MPa to 210 MPa [18].

Table 5. Results of the simulations carried out by the MicroSim ® program for the rolling of heavy plates with 30 mm thickness of steel with low manganese plus 0.010% Nb, meeting the S355 standard specifications: (a) original; (b) optimized rolling process [18].

Microstructural Evolution

Pass	Rex. Fraction	No Rex. (Prec.)	No Rex. (Drag)	D Mean (microns)	D Max (microns)	Dc (0.1) (microns)	ZD	Acc. Strain
R1	0.83	0	0.17	116.7	633.4	384.2	5.4	0.03
R2	0.92	0	0.08	84.4	737.9	358.8	8.7	0.02
R3	0.99	0	0.01	89.9	730.5	329.6	8.1	0
R4	1	0	0	100.6	702.9	301.2	7	0
R5	1	0	0	91.2	596	251.1	6.5	0
R6	1	0	0	87.5	562.4	235.3	6.4	0
R7	1	0	0	88.1	563.9	235.2	6.4	0
F1	0.32	0	0.68	70.1	450	191.5	6.4	0.14
F2	0.53	0	0.47	47	365.6	133.2	7.8	0.15
F3	0.43	0.04	0.53	35.5	312.7	98.9	8.8	0.15
F4	0.44	0.22	0.34	28.7	298.4	79.5	10.4	0.18
F5	0.29	0.37	0.34	23.6	280.6	68	11.9	0.29
F6	0.16	0.37	0.47	21.3	274.4	60.1	12.9	0.39

(a)

Microstructural Evolution

Pass	Rex. Fraction	No Rex. (Prec.)	No Rex. (Drag)	D Mean (microns)	D Max (microns)	Dc (0.1) (microns)	ZD	Acc. Strain
R1	0.16	0	0.84	162.1	808	384.4	5	0.08
R2	0.96	0	0.04	119.3	863.2	319.1	7.2	0.01
R3	0.94	0	0.06	117.2	852.7	347.2	7.3	0.01
R4	1	0	0	95.5	842.7	348	8.8	0
R5	0.98	0	0.02	116.1	765.2	332.2	6.6	0.01
R6	0.9	0	0.1	97.3	688	299	7.1	0.02
R7	0.85	0	0.15	66.4	627.2	260.9	9.4	0.04
R8	0.8	0	0.2	49	568.3	221.2	11.6	0.05
R9	1	0	0	54.3	678	248.4	12.5	0
F1	0.09	0	0.91	45.5	566.2	199.5	12.4	0.2
F2	0.23	0	0.77	34.9	468.3	141.7	13.4	0.31
F3	0.34	0	0.66	26.8	375.9	87.4	14	0.3
F4	0.36	0.15	0.49	21.2	287.3	58.7	13.6	0.25
F5	0.2	0.15	0.65	18.2	251.8	48.3	13.8	0.35
F6	0.2	0.15	0.65	15.9	232.1	41.7	14.6	0.38

(b)

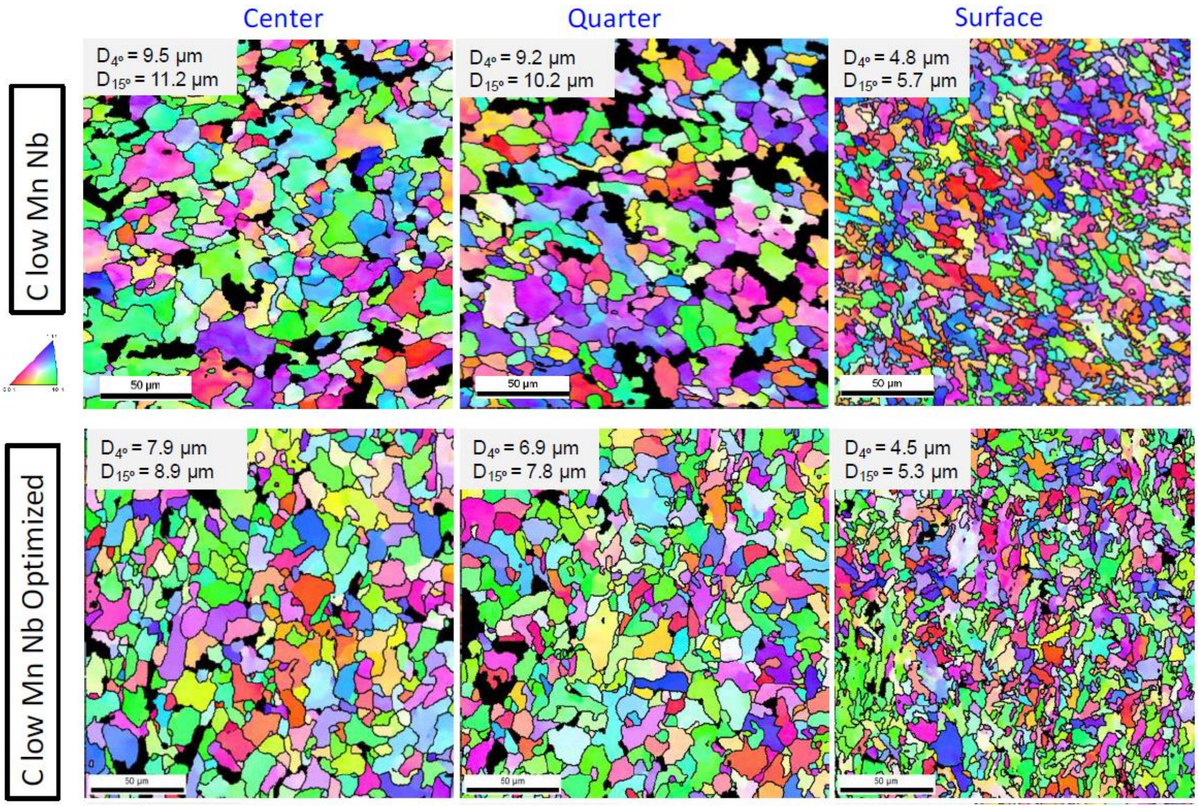


Figure 10. Results of the grain size distribution analysis done by EBSD for industrial heavy plates with thickness of 30 mm of steel with low Mn plus 0.010% Nb, satisfying the S355 standard specifications, rolled according to the conventional process (upper row) or optimized (lower row) [18].

This example showed how it is possible to further intensify the grain size refining effect exerted by niobium and the consequent increase in the mechanical properties of the rolled product, through the adoption of thermomechanical treatments whose optimized process parameters can be determined using tools with a solid metallurgical foundation for the determination of the evolution microstructural of low carbon steels during hot rolling.

6 FINAL CONSIDERATIONS

In recent decades, the robust growth of world steel production has led to the continuous search for profitability and even for the survival of companies involved in the steel segment. The impressive expansion of the Chinese steel industry only added more volatility to this scenario. This situation is changing the price relationships between ferroalloy prices and several cost reduction initiatives are being developed, as exemplified in this work for the case of partial replacement of manganese through small additions of niobium. More than ever, it is necessary to “think outside the box” and seek competitiveness in creative solutions, which are not always evident at a first glance. It is about decreasing contents in the order of 0.30 to 0.50% of manganese, an alloying element traditionally used in structural steel alloy designs, by adding 0.010% of niobium, an element used until then in the case of steels of high performance. In addition, new projects for structural steels with lower manganese content and the addition of niobium have lower Global Warming Potential, a not negligible bonus when the watchword in the steel industry is to minimize the emission of gases that promote the so-called greenhouse effect. New metallurgical tools, such as the MicroSim® model presented here, are allowing the optimization of thermomechanical treatments and, in this way, extract the maximum effect from niobium and other alloying elements from steels. The optimization of alloy steel designs will progressively require deeper knowledge in metallurgy and the boldness to experiment innovative approaches.

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