Niobium reducing alloying costs for 355 MPa grade structural flat products

Discover the benefits of niobium microalloying design for structural applications

PARTIAL REPLACEMENT OF MANGANESE BY NIOBIUM IN LOW CARBON STRUCTURAL STEELS: A REVIEW

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INTRODUCTION

- Requirements to be satisfied by a steel alloy design:

  ✓ Meet specified requirements as cost-effectively as possible.

  ✓ Refining, rolling and application steps as simplified, economical and consistent as possible.

  ✓ Use alloy elements readily available on the market, with low and stable quotations over time.

  ✓ Present minimal carbon footprint and high recyclability.

INTRODUCTION

- The focus of this work is to **rethink** the use of manganese in structural steels:

  - ✓ Established alloy element due to its largely favorable **cost:benefit ratio** for decades.

  - ✓ It promotes **solid solution hardening**, an increase in the **pearlite fraction** in the microstructure and **discrete grain refinement** due to the lowering of A_{r3}.

  - ✓ It combines with the sulfur in the steel, preventing the **formation of iron sulfide** which is liquid at the usual hot working temperatures of steel and promotes embrittlement.

INTRODUCTION

- But the use of Mn presents some **drawbacks**:

  - ✓ Manganese contents above 0.8% require the addition of large amounts of FeMn, requiring an **increase in the BOF tapping temperature**, reducing the life of the refractory linings and intensifying liquid steel rephosphorization.

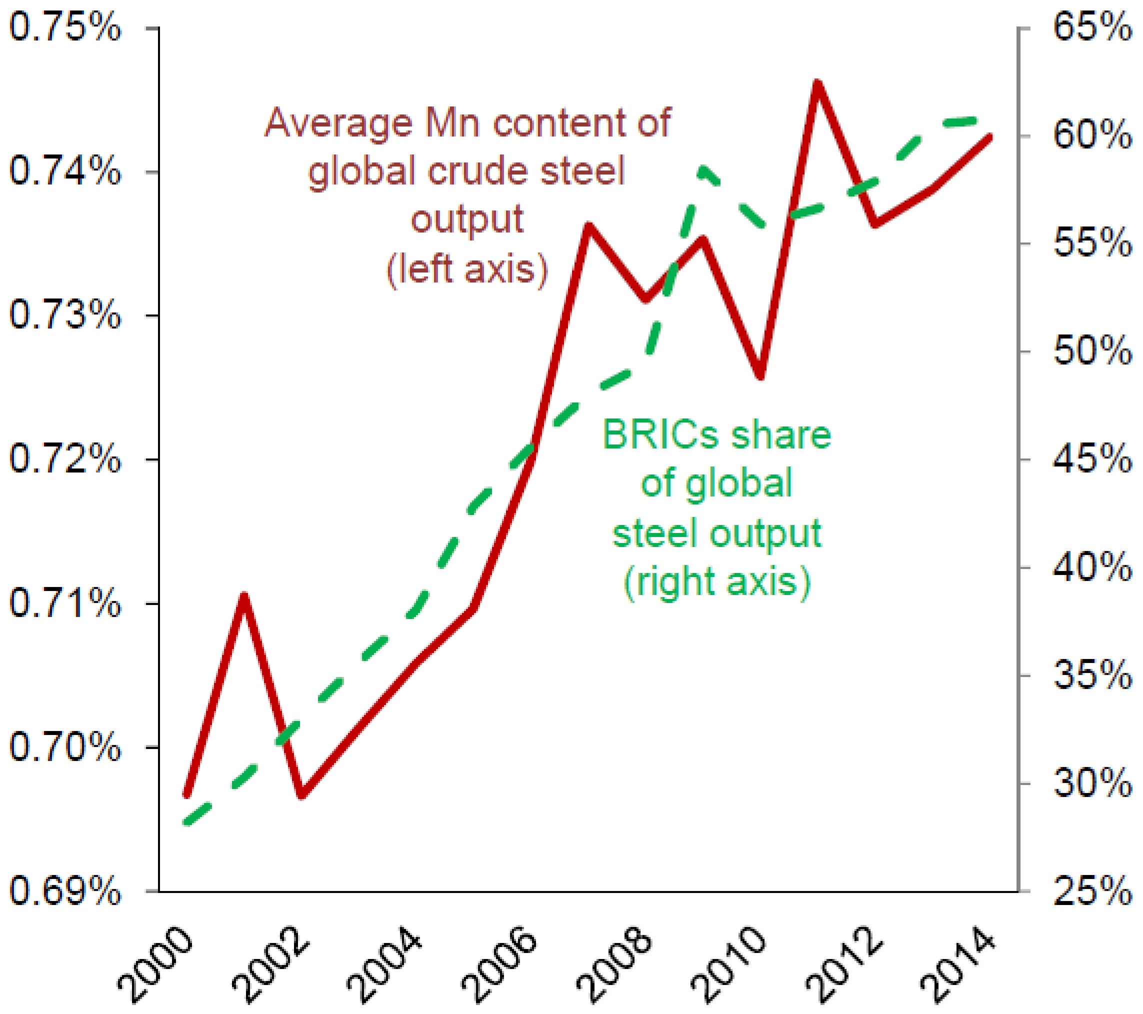
  - ✓ This problem can be avoided by adding FeMn in a **ladle furnace**, but the associated electricity costs are considerable, besides production restrictions.

  - ✓ Manganese **segregates intensely in the center** of the thickness of the slabs produced by continuous casting, impairing the quality of the final product.

  - ✓ Increased **microstructure banding**, affecting toughness.

  - ✓ Increase in **carbon-equivalent**, affecting weldability.

INTRODUCTION



Even so, the use of Mn in structural steels has been increasing rapidly, both **due to the increase in its content** in steels and to the **increase in production**, especially in developing countries.

Fowkes 2015

INTRODUCTION

RESOURCEWORLD magazine

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Manganese consumption aligned with steel and lithium-ion battery demand

12 months ago Staff Writer

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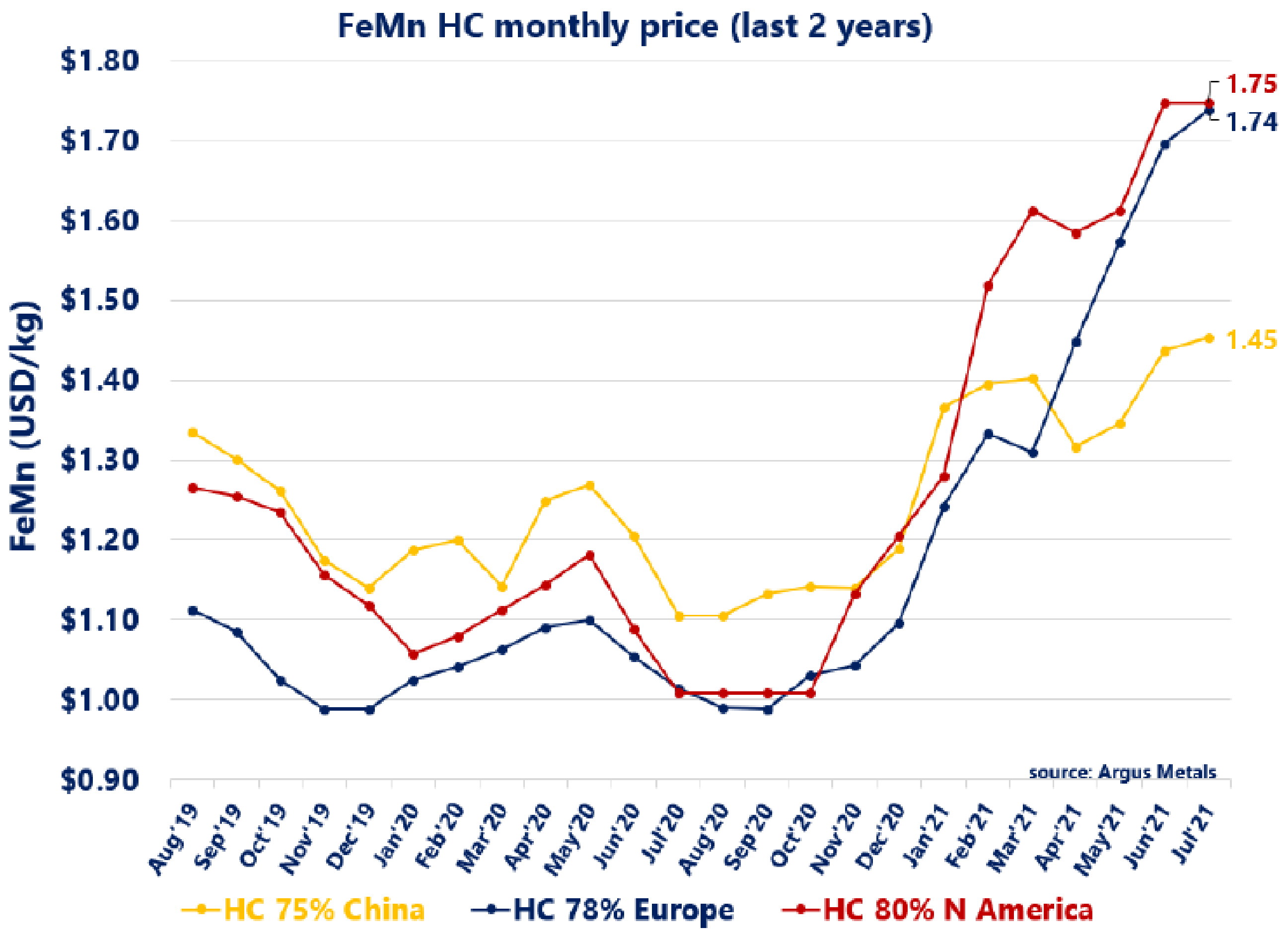
By David Duval

Manganese is also increasingly being used in **batteries** for electric vehicles.

https://resourceworld.com/manganese-consumption-aligned-steel-and-lithium-ion-battery-demand/

INTRODUCTION



The high consumption of FeMn in structural and AHSS steels (these with extra-high manganese content), as electric batteries, is causing a considerable increase in the value and volatility of this raw material prices.

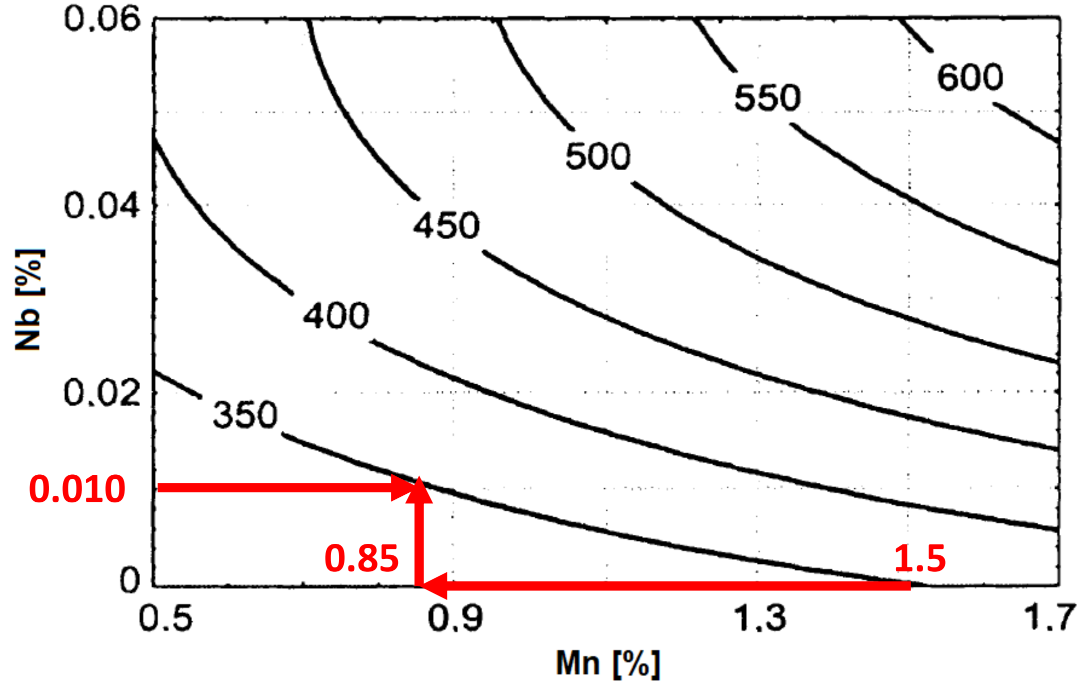
Proposed solution: **partial replacement of manganese by niobium in structural steels.**

Argus Metals 2021

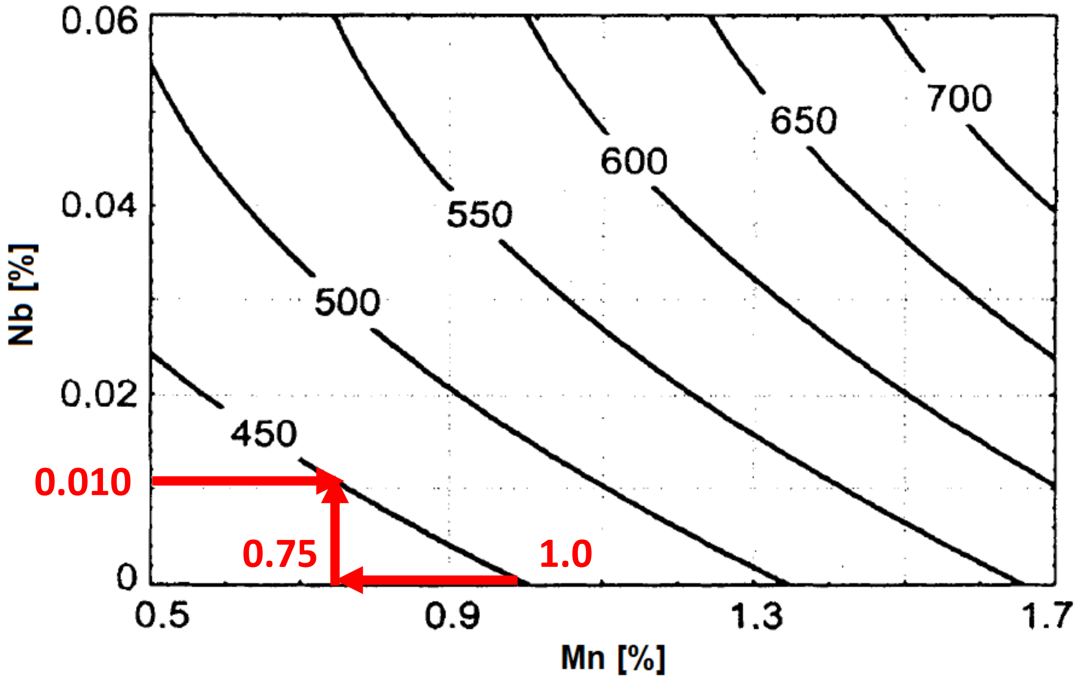
EMPIRICAL EQUIVALENCES BETWEEN NB AND MN

Nb x Mn for Steel Plates – 0.1% C, 8-10 mm thickness

YS [MPa]



TS [MPa]



Morozov 2002

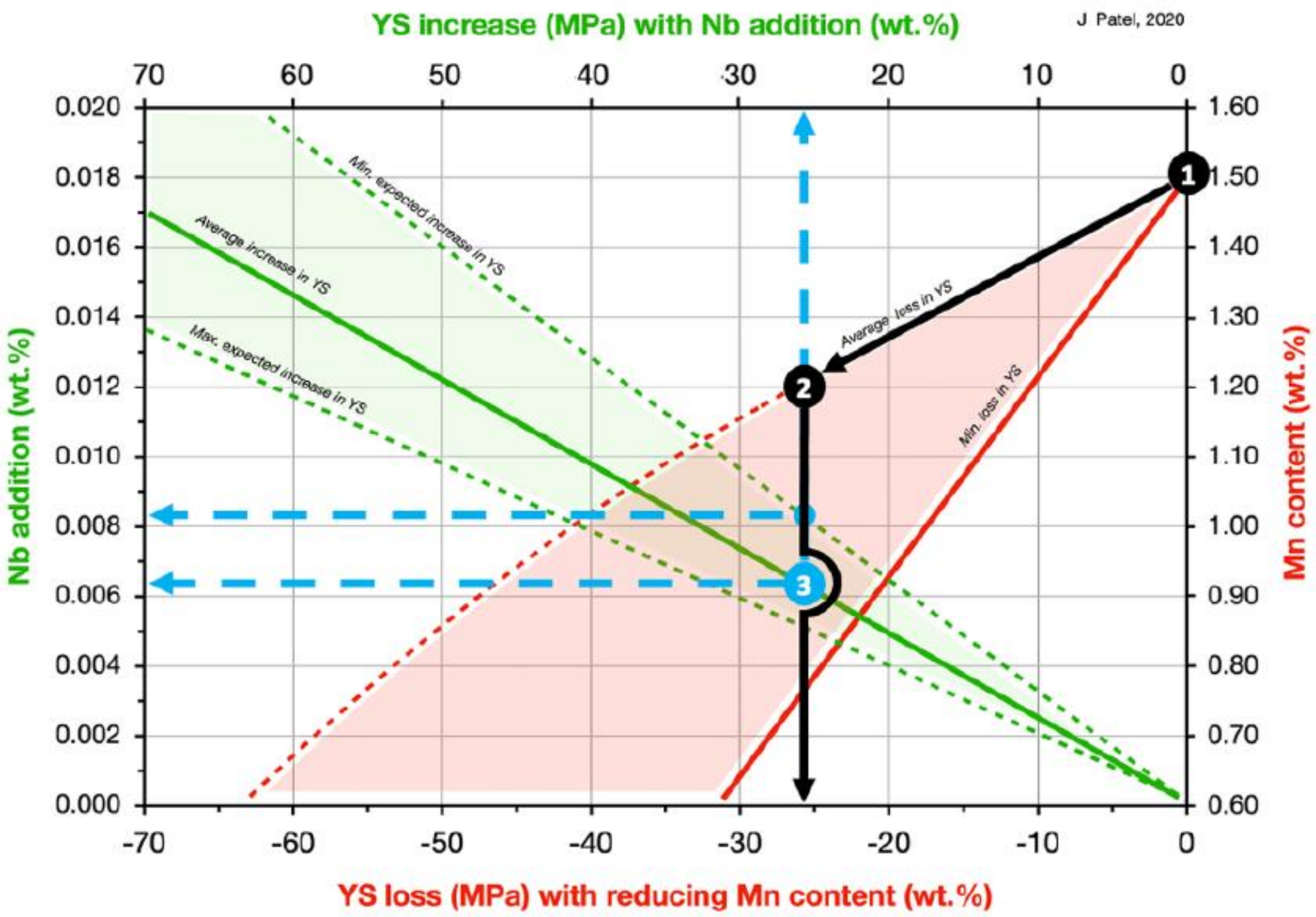
EMPIRICAL EQUIVALENCES BETWEEN NB AND MN

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]

In general, the replacement of Mn by Nb is more effective in the case of **Yield Strength**.

EMPIRICAL EQUIVALENCES BETWEEN NB AND MN

Abacus for Replacement of Mn by Nb - Steel S355



In this specific case, a reduction of **Mn content** from **1.50%** to **1.20%** is compensated by the addition of **0.006% Nb**.

Patel 2021

METALLURGICAL FUNDAMENTALS

- **Main hardening mechanisms** in structural steels:

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

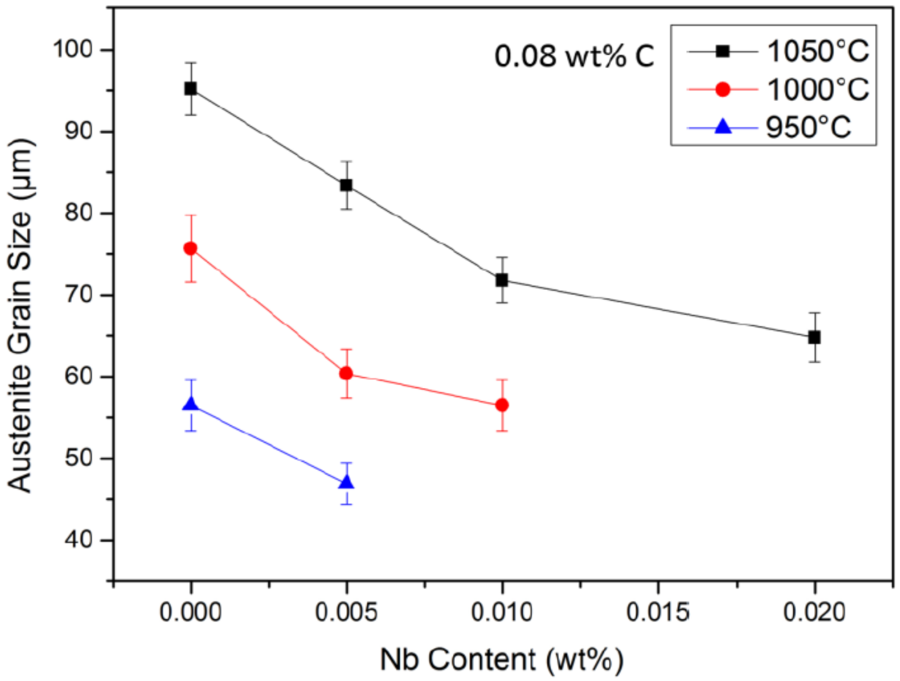
$$LR = 294{,}1 + 27{,}7\ Mn + 83{,}2\ Si + 2.85\ f_{Perlita} + \frac{7{,}7}{\sqrt{d}}$$

Pickering 1980

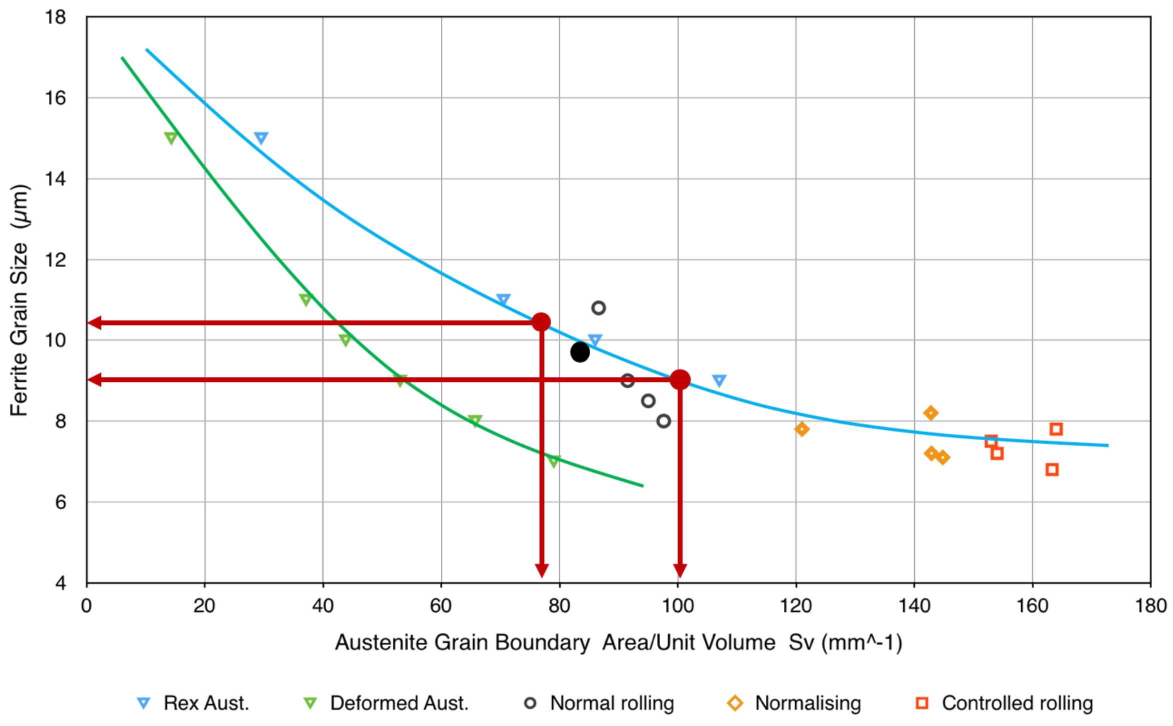
- ✓ **Yield Strength:** the modest contribution of Mn solid solution hardening must be compensated by the greater grain refining promoted by Nb.
- ✓ **Tensile Strength:** here the contributions of the hardening mechanisms are **smaller**, particularly that provided by the grain boundaries (Hall-Petch). This fact, plus the probable reduction in the pearlite fraction resulting from the decrease in Mn content, explain the **lower effectiveness** of the replacement of Mn by Nb in this property.

METALLURGICAL FUNDAMENTALS

Grain size refining promoted by niobium:



Cui 2016



Sandberg 1980

Additional contributions (precipitation, hardenability) are being studied.

FIRST INDUSTRIAL IMPLEMENTATIONS

Application of the New Concept to Flat Products

A36, S355: Hot Coils

Q345: Plates

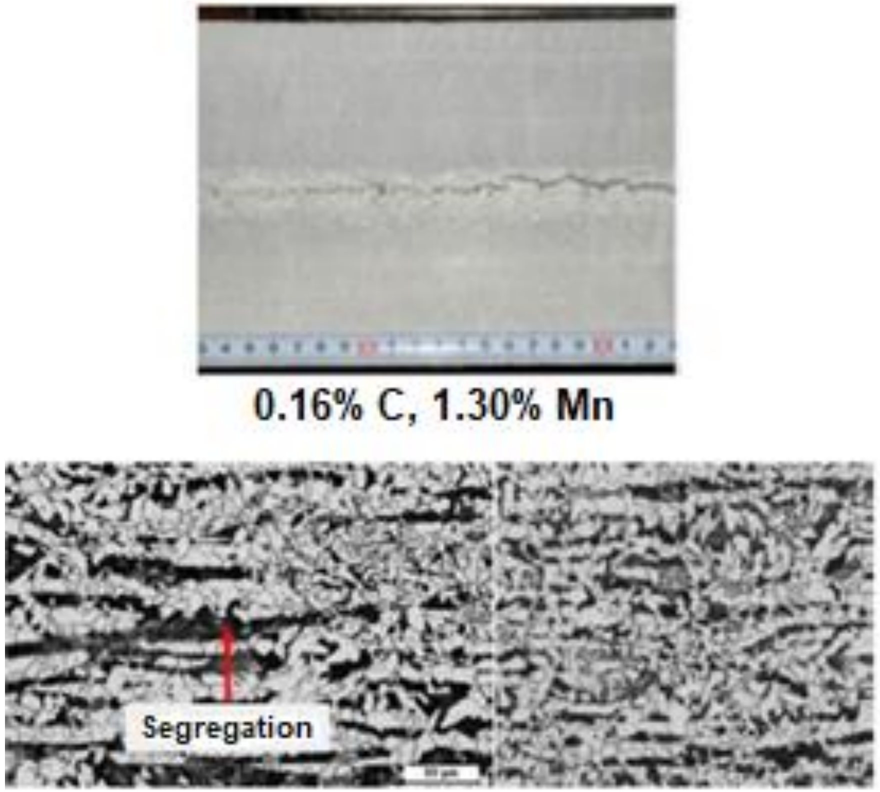
Cost Reduction: US$ 2.30 a 7.30/t steel

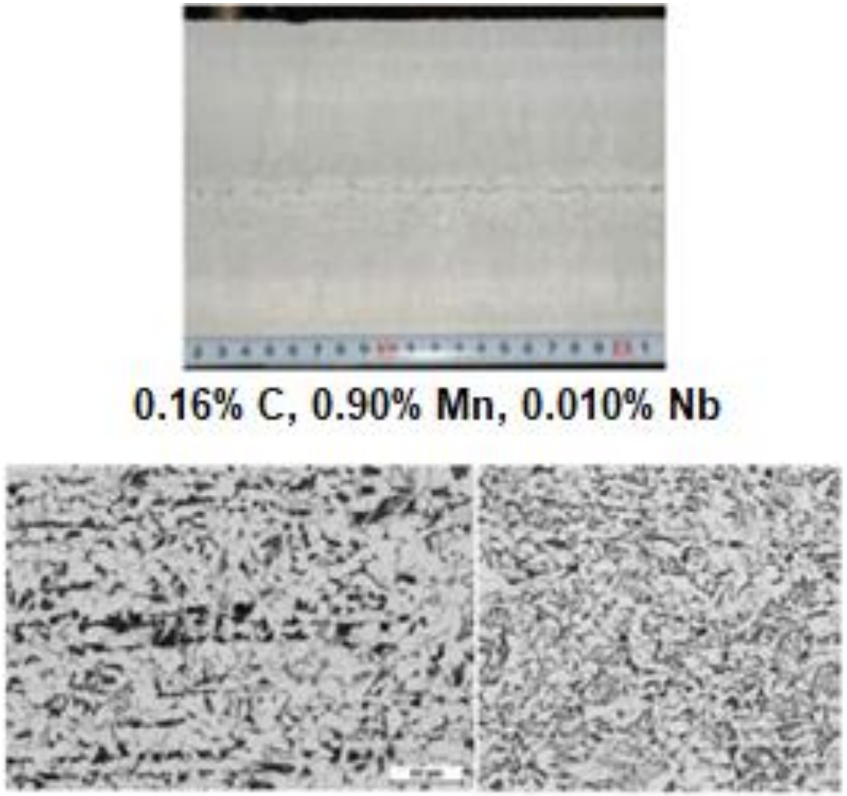
Standard	Thickness [mm]	Alloy Design	C [%]	Mn [%]	Nb [%]	LE [MPa]	LR [MPa]	A [%]	CVN @0°C [J]
ASTM A36	2,3	Traditional	0.07	0.80	-	301	435	35.4	-
		New	0.07	0.50	0.012	321	420	34.8	-
EN S355	12,0	Traditional	0.15	1.20	-	356	499	26.0	-
		New	0.15	0.80	0.010	359	481	27.0	-
Q345	≤ 30	Traditional	0.16	1.40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

Stalheim 2018

FIRST INDUSTRIAL IMPLEMENTATIONS

Beneficial Effects on Segregation and Microstructure Resulting from the Reduction of Mn Content





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FIRST INDUSTRIAL IMPLEMENTATIONS

Application of the New Concept to "H" Beams
It even allowed the suppression of the use of vanadium

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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	

FIRST INDUSTRIAL IMPLEMENTATIONS

Application of the New Concept to "H" Beams

Global Warming Potential Reduction (kg CO2e/t steel)

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

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IMPROVEMENT OF THE NEW CONCEPT

- The use of Nb in this approach **does not necessarily imply** the adoption of **special rolling processes** to provide favorable results.
- However, the **optimization of pass schedules**, aiming at even more intense austenitic (and ferritic) grain refining, allows to obtain products with **even better performance**.
- A metallurgical tool that allows to easily determine the microstructural evolution that occurs during the hot rolling of steels is the **MicroSim**, developed by the Centro de Estudios e Investigaciones Técnicas de Gipuzkoa – CEIT, under the sponsorship of the Companhia Brasileira de Metalurgia e Mineração – CBMM.

IMPROVEMENT OF THE NEW CONCEPT

Optimization of Pass Schedules by MicroSim

S355 Grade Plates, 30 mm Thickness, 0.010% Nb

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

→

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

- Optimization results carried out by MicroSim:
  - Average Grain Size: **21.3 → 15.9 microns**
  - Maximum Grain Size: **274 → 232 microns**
  - Limit Grain Size (for the thinnest 90%, $Dc_{0.1}$): **60.1 → 41.7 mícrons**

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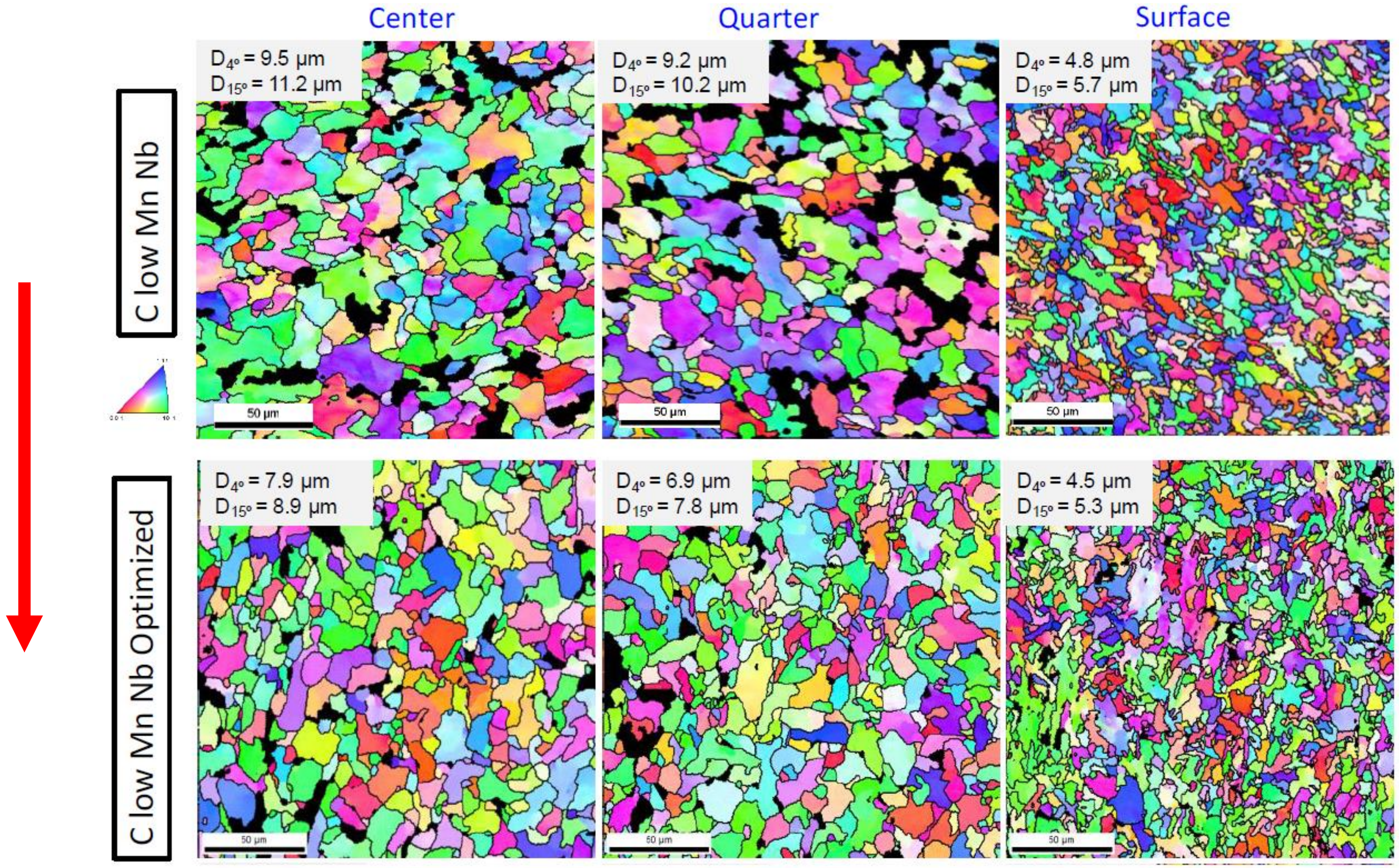
IMPROVEMENT OF THE NEW CONCEPT

Comparison of Grain Sizes Measured by EBSD

Non-Optimized Case x Optimized Case (Industrial Rolling)



The optimized pass schedule effectively led to more refined ferritic grain sizes in industrial rolling, confirming the results obtained in the MicroSim simulations.

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CONCLUSIONS

- The **world steel market is extremely competitive**, requiring a continuous search for opportunities to **reduce costs** and ensure the **competitiveness** of the plants.
- One of them arose from the **large increase in demand for Mn** that occurred in recent years, resulting from the **greater production of higher strength structural** and **AHSS steels**, as well electric batteries, which was reflected in the **magnitude** and **volatility of the prices** of its ferroalloys.
- The **replacement of 0.30-0.50% Mn by 0.010-0.020% Nb** in structural steels proved to be a **viable alternative** in technical, economic and environmental terms.
- The **optimization of hot rolling processes**, through the use of **metallurgical tools**, aiming at even more intense degrees of grain refining, amplifies these advantages.

CONCLUSIONS

- The work **Benefits for LD Steel Plant Resulting from the Partial Substitution of Manganese by Small Additions of Niobium**, that will be presented tomorrow at the **51th Melting, Refining & Casting of Metals Seminar**, part of this ABM Week edition, will bring more information about the additional advantages of this alloy design during the secondary refining and casting of liquid steel.

THANK YOU FOR YOUR ATTENTION! QUESTIONS?

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