WHITE PAPER

Meeting Global Demand for Safe Trustworthy Infrastructures with Low-Cost Niobium-Containing Steels

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Niobium is taking the lead in a new generation of structural steel. No other microalloy offers the unparalleled combination of higher strength, better toughness, superior bendability, and improved energy absorption for structural support.

KEY TAKEAWAYS

- Governments, the insurance industry, designers, and end users are demanding better structural materials with improved energy absorption, fracture toughness, and fatigue properties in response to seismic, fire, and extreme-weather events.
- Within the building, bridge, and rebar sector, there is a shift toward lower carbon-niobium (Nb) containing steels, which meet these demands with significantly improved toughness, formability, consistency, energy absorption, and weldability.
- The increased strength and toughness of Nb-containing infrastructure steels enable a reduction in size and weight of structural products resulting in lower transportation, fabrication, and erection costs; a reduced carbon footprint; and a more efficient project build.
- Commodity, construction-grade steels made with niobium make it possible for steelmakers to meet or exceed yield strength specifications while saving on production costs through Mn reduction, and lessened or eliminated CaS treatment.
- Steelmakers are responding to the growing demand of better infrastructures with Nb-microalloyed steel, which can be produced at a lower total cost through low carbon-low alloy (LCLA) chemistry with selective accelerated cooling and better control of reheat furnace temperatures.

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ABSTRACT

The new generation of value-added low carbon niobium (Nb) microalloyed beam, plate and rebar construction steels for both low and high yield strength and energy absorption infrastructure applications are shifting designers to new lower cost materials. The civil engineering and end user community demand structural reinforcing bars, shapes, beams and plates with improved energy absorption, fracture toughness and fatigue properties. The future market demands improved fire and seismic resistance, yield-totensile ratio consistency, improved bendability and weldability. Recent catastrophic climate events of fires in California to flooding in Manhattan to hurricanes in Florida to earthquakes in Alaska, Oklahoma and Mexico City are driving these changes.

These fire and seismic resistant steels are difficult to obtain from steel producers today with their current higher carbon higher cost microalloyed steel traditional designs. There also is a recent global shift in manganese reductions approaching a 30% decrease for low strength construction steels. This dynamic global shift is in motion moving towards lower C-lower Mn-MicroNb containing construction steel, thereby displacing traditional materials. For example, in the construction beam sector and rebar sector improved properties result for 0.02 to 0.04%Nb in low carbon steel for S355 and S420 beams and for S500 and S600 low carbon reinforcing bars. In S235 and S275 construction steels, manganese is being reduced to as low as 0.60%, with .06-.08%C and less than 0.020%Nb addition.

Through the grain refinement transformation from the Nb addition, strength and ductility is achieved via microstructure and fine grain size instead of alloy additions such as V, Ti, and others, thereby reducing the construction materials cost. The lower C to less than 0.10%C in combination with Nb for metallurgical grain refinement for infrastructure steels directly improves weldabililty, toughness ductility and robustness.

Lower strength, commodity steelmakers are meeting the demand for weather-resilient building construction with niobium, while lowering their overall production costs.

Niobium higher-strength steels are important to new infrastructure designs that anticipate seismic activity, sea level rise, coastal flooding, and higher levels of corrosive water acidity.

Introduction

The lean alloy approach for low strength commodity steels is often not thought to have a fit for Nb-containing infrastructure steels. Much of the prior Nb-development in construction steels was focused upon a multiplicative microalloy approach in which Nb was eventually added to conventional C-Mn low strength or C-Mn-V steels after V and/or after Ti and Mn were added when very high strength construction steels could not be achieved. Strength levels exceeding 420 to 460MPa were the target. However this multiplicative approach is outdated technology and economics is driving this change. With the evolution of Nb replacing V in 355MPa plate steels in low C-Mn construction grades for buildings and windtowers, the evolution has initiated. Today depending upon a given steel mill's rolling capability, up to 460MPa steels can be produced with a straight C-Mn-Nb alloy approach, displacing the multiplicative approach.

The transformation attribute of Nb involves the phase transformation (approximately 75% of its purpose) and precipitation is less (at only 25% of its purpose). With this understanding, the fine grained desired microstructure can be achieved at reduced alloy, C and Mn compositions. This new technology is evolving globally within the infrastructure segment for several reasons discussed in this white paper. The primary process metallurgical driver is a series of simpler lower cost infrastructure steel compositions. The physical metallurgical driver is a more robust, homogeneous and finer grain microstructure in the final component. Since most structures contain lower strength steels, the Nb connection in low strength steels is advantageous and beneficial from a cost basis compared to traditional steel construction chemistries. The solution is a carbon reduction, then a manganese reduction followed by a Nb addition.

For example, structural beams, reinforcing bar and plate applications account for over 500 million tonnes of global steel production. Chemical and mechanical property requirements are quite diverse to accommodate the end user application. Traditional steels have been applied for decades with relatively insignificant mechanical performance enhancements for the end user. Over half of these structural plate and beam sections are intermediate carbon levels from 0.15 to 0.22% which results in increased operational cost, quality and welding issues. The solution is a gradual shift at some mills participating within the structural plate and beam segment to switch to lower cost Nb-bearing structural grades at less than 0.10%C thereby producing lower carbon base alloys for both plate and some long product applications. The benefits are not only improved mechanical properties and functional performance, but also the opportunity to reduce overall steelmaking cost per tonne through improved productivity, reduced diverts and improved product quality [1].

The incorporation of Nb into numerous steel grades is displacing traditional higher carbon (greater than 0.11%C) and higher manganese structural steels. The application of Nbtechnology in long products depends upon the design criterion of the end user. Often the customer may desire improved toughness (i.e energy absorption for the civil engineering community), better fracture toughness, improved cyclic fatigue performance (seismic), more homogeneous grain size and microstructure. On the processing side, with additions of Nb for structural steel plate and long product applications, normalizing and heat treatment cycles can be shortened or entirely eliminated for bridge and other infrastructure applications, thereby increasing throughput, productivity, capacity and realizing operational cost reductions between 5-15%.

Background Information

Traditional steels have been applied for decades in the lower strength infrastructure segment with relatively insignificant mechanical performance enhancements for the end user. The incorporation of Nb into numerous steel grades is now beginning to displace traditional higher carbon and higher manganese V-bearing structural steels. Within the building, bridge and rebar sector, there is a shift to lower carbon-Nb containing steels which significantly improve toughness, formability, consistency, energy absorption and weldability at a more economical cost in S235 through S460Mpa grades. Not known to many, niobium is also a key element in high carbon infrastructure steel grades for eutectoid (0.80%C) compositions for rail and prestressed concrete wire rod for concrete beams. The improved ductility is remarkable.

The application of Nb-technology in long products depends upon the design criterion of the end user. Often the customer may desire improved toughness, better fracture toughness, improved cyclic fatigue performance, more homogeneous grain size and microstructure. These improved mechanical property attributes are the primary drivers for Nb additions and an increasing market trend demand within the long product global segment.

Since nearly 50% of the structural plate and beam sections are within this intermediate carbon range from 0.15 to 0.22%, there a transitional shift at some mills seeking participation reducing cost and improving the robustness of these value-added structural plate and beam products. This segment shift to Nb-bearing structural grades containing less than 0.10%C has been virtually seamless within the production steps of the steel mill. Another attractive driver is that with increasing raw material and energy costs, the effects of processing parameters such as reheating temperature and cooling rate after hot rolling to achieve improved mechanical properties result in significant savings. A lower total cost of production may be achieved through low carbon-low alloy (LCLA) chemistry with selective accelerated cooling and better control of reheat furnace temperatures. [2]

Nearly one third of the globally produced structural flat and long structural construction products are in the 0.11 to 0.16% carbon range. By definition, numerous steelmakers globally define this approximate carbon range as peritectic in their melting grade family definition within their organization. The metallurgical consequence is the result of numerous global structural specifications which allow low wide carbon ranges resulting in quality issues at both the steel producer and the end user. For example, such specifications as the weathering construction steels, ASTM A588, set no minimum and a 0.15 to 0.20%C maximum depending on the specific grade. From the steelmaker's perspective, this peritectic region may be specifically challengingdepending ontheir equipment and expertise as solidification issues and a higher propensity for slab or billet cracking occurs during continuous casting. The relative steelmaking operational cost of production then is higher for these peritectic grades compared to the lower carbon (i.e. non-peritectic carbon compositions) for a given specification. [3]

Infrastructure Steel Economics and Methodical Transitional Production Steps Which Enhance Cost Reduction Opportunities

There are numerous transitional steps a steel producer may make in incrementally reducing their overall operations and steel production cost within this extremely competitive infrastructure global materials market. Within this infrastructure product sector, there are four drivers, market- and operational cost-related that require consideration if mills expect to improve profitability. These drivers are: 1) many ASTM construction steel chemistry specifications have very wide chemistry ranges especially for carbon and manganese; 2) both the mill producer and end user experience higher costs due to quality and production deficiences, 3) infrastructure market is demanding more value added higher performance materials due to ever changing more sever climatic events and 4) the threat of substitute construction materials replacing low strength commodity steels.

The current transition to lower Mn levels is also driven by the continuing increase in FeMn pricing due to the current supply-demand situation. FeMn prices have risen by as much as 30% due to the evolution of Third Generation automotive steel development which consumes Mn at levels of 3 to 6%. The structural steel producers have absorbed the increased cost and delivery may be an issue in some cases as well. Figure 1 below shows the FeMn pricing situation.

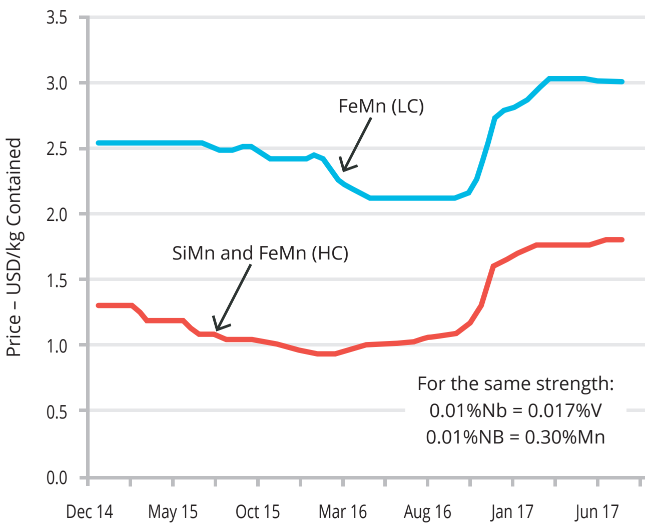

Figure 1. FeMn and SiMn Price Trend [4]

Structural ASTM Steel Specification Allowable Maximum Carbon Content:

Numerous steel specifications applied to structural applications allow C maximum levels as high as 0.26%. Peritectic grades in the range of 0.11-0.16%C are quite often applied globally for structural long and plate products. There have been cases of some structural mill producers shifting back from low C to peritectic. However, this peritectic-choice results in increased Total Activity Based Cost for steelmaking, casting and hot rolling operations. A lack of measuring and understanding the actual cost makes it difficult to calculate the benefits of this change to less than 0.10%C. Table 1 illustrates some ASTM specifications allowing for grades produced within this peritectic region.

Table 1. Selected ASTM Specification Carbon Maximum Levels [3]

ASTM Spec	A242	A514[1]	A529	A572[2]	A588	A913[3]	A992
%C maximum	0.15	0.10-0.21	0.27	0.21-0.26	0.15-0.20	0.12-0.16	0.23

1 Eight different grades with different maximum %carbon depending on grade
2 Carbon maximum varies with cross sectional area
3 Carbon maximum increases with high yield strength grades

The definition of lower carbon steels in this white paper is a carbon content less than 0.10%. For example, the current problem is that when customers place a steel order to a specification such as ASTM A572, unless a 0.10% maximum is specified by the customer, the mill can produce up to the maximum carbon level in lieu of the better material property performance achieved from lower carbon steels. For even higher yield strength grades, ASTM A913 allows up to maximum 0.16%C for Grade 65 and 70. This change has also created some import situations in different global regions and conflicts with poor end user performance.

If a producer opts that the peritectic approach is more cost effective, that particular mill is not properly analyzing or understanding their total cost of production for these carbonmicroalloyed steel grades. Since many end users rely on a given specification to meet their order requirements, as long as the specified chemical elements meet the composition range, the shipment is deemed acceptable. Herein, two potential problems might be experienced by the end user, specifically, material performance variability and major carbon level differences between heats and/or multiple suppliers and service centers. Recent communications with end users reveal that they do not realize the negative implications to their business when the peritectic grade is processed in their operation. Concurrently, the end users of these ASTM grades are demanding structural components with less mechanical property variability and consistence. For example, properties such as low temperature toughness, formability, bendability, weldability, fracture toughness and fatigue performance are impaired when these higher C grades are applied instead of the less than 0.10%C lower carbon steels.

Metallurgical Reasons for Higher Cost of Production:

The primary metallurgical reasons for higher production cost for this 0.11-0.16%C (hypoperitectic) microalloyed steel grades compared to low carbon microalloyed grades relate to negative implications at the steelmaking, casting and hot rolling steps of the process. Primary differences between the low carbon and peritectic grades are:

1. Differences in solidification behavior during continuous casting
2. Casting requires tighter control of primary and secondary cooling for peritectic due to heat flux differences
3. Increased slab conditioning with peritectic grades due to uneven surface solidification resulting in a variable equiaxed chill zone closer to the surface compared to low carbon microalloyed grades
4. Maximum austenite grain size occurs in the 0.11-0.16%C range
5. Surface quality generally worsens in hot roll product
6. Increased slab scarfing and potential to open cracks in peritectic grades
7. Often peritectic grades are normalized heat treated to homogeneous grain size, but not necessary in low carbon grades (eliminate heat treatment)
8. Grain size and mechanical property variability across the width and through the thickness
9. Peritectic grades are cast at slower speeds affecting productivity by as much as 10-20%
10. Increase in number of transition slabs and potential downgrades
11. Peritectic grades tend to exhibit more internal and centerline segregation, especially as Mn levels increase

Quality & Performance

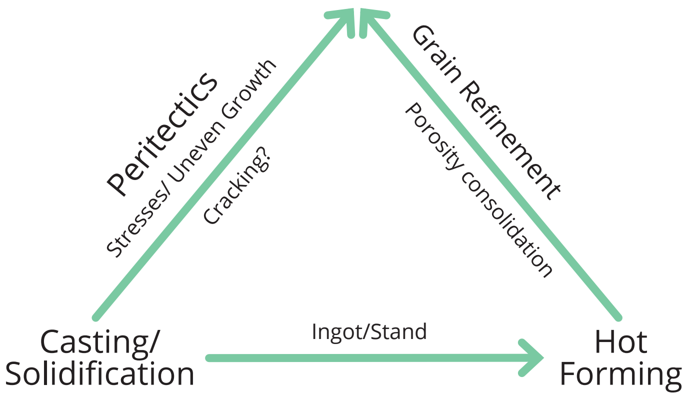

Figure 2. Peritectic steel implications.

Figure 2 schematically illustrates these inter-relationships in order to achieve enhanced mechanical and microstructural properties at an acceptable margin [3].

Since grain size and microstructure are of utmost importance in determining the strength, toughness, property variability and performance of a steel, poor cast slab quality translates directly into increased internal and external cost of quality. Also, these peritectic steel implications are of extreme importance and incongruent with the global initiative to adopt high- speed continuous casting. At higher casting speeds, the resultant increase in productivity of steel translates into reduced operational cost per tonne, improved hot ductility during casting, and improved quality which is a priority in today's competitive global steel environment. Specifically, within the peritectic family of grades, the hypo-peritectic steels (0.11-0.16%C) impose a bottleneck for the high-speed casting in numerous operations around the world due to the strand contraction during peritectic solidification that causes non uniform development of the shell in the continuous casting mould.

Business Case Example

There are three business examples one can study to reduce cost in three different low strength structural grades. Case I involves a Mn reduction in a S345. Case II involves a C reduction and Nb-addition in a normalize heat treated S355. Case 3 involves both a C and Mn reduction and a micro-Nb addition in a S355.

Case I: The low Mn-low Nb construction steels research and development recently being commercialized involves the application of quite simple conventional rolling schedules and reheat and hot rolling practices. In the past, there was limited research into such products for two primary reasons. First, when secondary and tertiary processes such as hot forging, drawing and cold forging are applied to medium and high carbon steels, the effects of controlled rolling may be lost through the process. Secondly, Nb has a lower solubility in austenite in comparison with low carbon steels at the same temperature. However, these past concerns have been alleviated via industrial production trials have exhibited excellent results even in medium carbon peritectic S355 structural steels applied to platforms and other structural supports at very economical cost as shown below in Table 2.

*Table 2. Medium C-Low Mn-MicroNiobium Mechanical Properties**

	Yield Strength MPa	Tensile Strength MPa	Elongation %	Impact Strength (Joules)		
				-20 °C	0 °C	20 °C
Aim	345	470	21	-	>34	-
II - 16mm	405	525	28.5	150	170	160
III - 16mm	410	535	33.0	150	170	160
IV - 40mm	455	615	22	100	155	180

** Mn level reduced from Standard 1.45 to 1.15%Mn and 0.010%Nb at 0.16%C (peritectic)*

The intent of this work is to study existing carbon (peritectic) compositions and replace the vanadium with niobium and make a significant reduction in the manganese level for these 345MPa grades. The next step is to consider a similar reduction in Mn strategy even for lower strength steels such as 235MPa and 275MPa as a cost reduction opportunity. The knowledge gained from this work is illustrating the possibility of making Mn reductions and significant cost savings. There have been situations where the aim is to produce S275 and the mill actually produced S420MPa structural grades.

Case II: This case involves the carbon and manganese reduction with an Nb addition. The similar reduction in C and Mn is then compared with V additions. Toughness, fatigue and fracture toughness limitations of traditional higher carbon (>0.11%) structural tower supports moved designers to consider alternative materials such as carbon fiber or high performance reinforced concrete. As a result of this threat of carbon fiber and concrete substitution for the HSLA S355 structural steel supports, a new steel material design was required to halt the threat. With the proven success of the beam applications, the Nb-Low Carbon Low Alloy (Nb-LCLA) as hot rolled product provided a viable, cost effective solution. Table 3 compares the mechanical properties of strength and toughness for low and medium C-Nb or -V for 20mm plate thickness. [5,6]

Table 3. Mechanical Properties of Low and Medium C-Nb Plate

Steel	Orientation	Yield Strength (MPa)	Tensile Strength (MPa)	Yield to Tensile Ratio	Elongation in 200mm (%)	CVN@-15 °C (Joules)
Low C-Nb	L	436	514	0.85	29.7	384
.06C-1.27Mn-.031Nb	T	450	521	0.86	28.1	371
Med C-Nb	L	439	561	0.78	21.9	103
.15C-1.39Mn-.019Nb	T	442	569	0.77	23.3	42
Med C-Norm	L	384	528	0.73	28.3	243
.15C-1.32Mn-.014Nb	T	391	530	0.74	27.6	132
Low C-V	L	404	492	0.82	25.8	390
.05C-1.18Mn-.04Nb	T	404	491	0.82	23.9	149
Med C-V	L	394	522	0.75	24.5	88
.14C-1.17Mn-.05Nb	T	393	523	0.75	26.1	33
ASTM A572 & A709-50 min requirement		345	448	0.77	18	34@ -12 °C
EN10025-2 S355 min requirement		345	468-627	0.74-0.55	20	41@ -20 °C

Note the isotropic CVN toughness at 15°C for the low C-Nb compared to the anisotropic toughness behavior of the medium C-V in the transverse direction. A closer analysis of the upper shelf energy difference between the Nb and V is quite remarkable. A significant difference is exhibited in upper shelf CVN energy performance for the Nb LCLA compared to the low carbon V wind tower constructional plate in both directions. At -65°C test temperature, the CVN energy of the Nb wind tower supports is 400 Joules in both directions compared to V wind tower plate which is only 250J in the longitudinal direction and 200J in the transverse direction. With the Nb-containing microstructure, the isotropic properties are excellent with 400 Joules in both the longitudinal and transverse directions. [6]

Case III: This case studies the simple reduction in Mn and the Nb addition for a 315MPa (45ksi yield strength) commodity construction grade. Table 4 below shows the mechanical property results.

Table 4. Mechanical Properties of Medium C-Low Mn-Nb Commodity Plate

	C	Ma	Nb	Yield Strength (MPa)	Tensile Strength (MPa)	Comments
Base I	0.14	1.50	-	330-420	500-565	Wider range in strength
Lower Mn-Nb	0.14	1.10	0.01	350-390	530-560	Less variability in strength
Lower Mn-Nb	0.15	1.35	0.01	389	535	Average strength
Lower Mn-Nb	0.15	1.05	0.02	392	522	Average strength

Essentially, a 0.40% Mn reduction and 0.01%Nb addition exceeds the minimum 315MPA by 35 to 75MPa easily meeting and exceeding the yield strength specification minimum translating to $3 to $5/tonne reduction in cost. Also, the opportunity exists to further reduce the Mn by another 0.30 to 0.40% if the steel is hot rolled at lower finishing temperatures.

Future Cost Reduction Opportunity: A36 with MicroNb Addition to Offset Deleterious High Sulfur and Phosphorous Levels.

This case involves the opportunity for the grain refinement of a Microaddition of Nb to allow for the higher sulfur and phosphorous levels in commodity grades. The specification allows 0.040%S and 0.040%P maximums. A steelmaking operation may be able to reduce or eliminate its CaS treatment for sulfur reduction and by making an addition of Nb result in an additional savings approaching $10 to $15/tonne by meeting properties at higher sulfur levels in commodity steels.

Table 5. Cost Benefit Metallurgical Analysis

Nb Case Strategy	Grade	Process Met Benefit	Physical Met Benefit	$ per Tonne Benefit
I-reduce Mn + Peritectic C + MicroNb	345MPa	Less MnS segregation + less hot rolled banding	More homogeneous microstructure + finer grain size + improved robustness	4.00-8.00
II-reduce Mn + reduce C + replace V with Nb	355MPa	Eliminate slab continuous cast cracks + less hot rolled banding + eliminate normalize heat treatment	More homogeneous microstructure + finer grain size + improved robustness	25.00-35.00
III-reduce Mn + MicroNb for Commodity Low Strength S315 Grade	315MPa	Less MnS segregation and finer grain	Improved robustness & reduced internal diverts and scrap	10.00-15.00
IV-Research Step	235 & 275MPa	Increase S+P levels and possible elimination of CaSi treatment	Simple commodity grade with more robustness	20.00-30.00

The Nb-Case Strategy IV shows the transitional cost reduction that a mill can make for a commodity S235 or S275MPa construction steel or ASTM A36 which is 250MPa yield strength.

Conclusions

This new generation of value-added low carbon-low manganese-niobium microalloyed structural steels for both low and high yield strength, energy absorption, fatigue and fracture resistant applications is the future low cost, economic and quality choice. The process metallurgy of reducing carbon and avoidance of peritectic structural grades improves the steel robustness coupled with the MicroNb addition for grain refinement to better serve the increasing demands of the infrastructure sector.

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