NIOBIUM-BEARING CONSTRUCTION STEELS AND GLOBAL APPLICATION TRENDS

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Abstract

The technological development of value-added applications for Nb-microalloyed construction steels continues globally for both low and high yield strength applications. The civil engineering and end user community demands structural bars, shapes, beams and plates with improved properties. Properties such as increased toughness, better fire and seismic resistance, yield-to-tensile ratio consistency and improved weldability are end user requirements for both low and high yield strength construction applications. Nb-bearing construction steels have been, and will continue to be developed to address these more demanding requirements in both the low and high yield strength construction sector. Various Nb structural steel technologies are applied dependent upon the specification requirements, cost benefit considerations and competitive market conditions. These technologies and market dynamics are described in this paper. For example, several mills within the construction beam sector have adopted a 0.02 to 0.04%Nb chemistry and reduced the C content for lower strength (S355 and S420) steels with improved mechanical property performance and weldability, compared to traditional higher C (peritectic) construction steel grades. Operational cost reductions are also experienced by the steel producer when the Nb, low C, low alloy concept is adopted. Advanced Nb-bearing high strength structural steels have also been developed. Another evolving Nb product segment involves the high C, long product, pre-stressed, concrete wire rod market. Micro additions of 0.005 to 0.020%Nb exhibit improved wire drawability during manufacturing, as well as improved mechanical properties, compared to traditional non Nb-bearing high C steels. Finally, within the low C construction sector, the shift from the high volume, heavier gauge S235 and S275 construction grades to lower C, Nb-bearing S355 lighter gauge steels offers the potential to reduce construction costs with a favorable environmental impact on the carbon footprint.

Introduction

Value-added Nb-bearing microalloyed plate steels continue to be researched, developed and commercially implemented throughout the world. These steels successfully meet the ever-increasing material requirements for improved mechanical properties and in-service performance for demanding 21st century structural applications. Such material and civil engineering design demands require Nb-bearing steels that deliver higher strength at thinner cross sections, improved toughness, fracture and fire resistance, reduced yield-to-tensile variation and improved weldability. Applications span diverse global construction market segments such as buildings, skyscrapers and industrial complexes, wind towers, reinforcing bars, pre-stressed concrete wire rods and several other uses in which Nb continues to provide an important role because of the enhanced properties that can be attained compared with conventional construction steels.

Another key consideration is the ever-growing concern about the environment and resources. Structural design in the 21st century must take these environmental responsibilities into consideration. The application of these new advanced high strength Nb-bearing steels for structural applications contributes to a reduction in the carbon footprint and material resource sustainability. In addition to the steelmaking impact, construction activity can cause significant emissions of CO_2 gas. The structural designers will endeavor to reduce emissions of greenhouse gases through the selection of green materials, including steel, as structural components.

The unique metallurgical attributes that Nb provides in structural steels create the opportunity to not only meet future environmental challenges and demands, but also successfully meet stringent mechanical, corrosion and elevated temperature construction demands. Historically, Nb-based structural steels were in limited production during the 1980s. Over the last two decades, through the numerous Nb-bearing structural steel global research and development project activities conducted by steel mills, universities, research institutions and CBMM, significant progress has been achieved in the development of more environmentally friendly construction steels. Nb-bearing structural products are now specified in a variety of applications and markets. The diverse array of structural steel markets, future potential and application trends are discussed herein. Application of microalloyed steel designs to steel construction projects will make a significant positive contribution to the long term carbon footprint. Applications of value-added Nb-bearing steels can reduce the overall material and construction costs for many advanced high strength structural and civil engineering applications.

Background

Increasing the longevity of structures is a very effective means of reducing the carbon footprint and long-term infrastructure cost. Usually the lifetime of buildings is determined by deterioration and out-of-date facilities. The deterioration of structural components is not always the reason for demolition, but rather the structural framework becomes inadequate for users.

Approximately 350 million tonnes of construction steels were produced in 2011 as simple, thick gauge carbon manganese (C-Mn) steels that did not contain microalloys and hence, were not defined as High Strength Low Alloy (HSLA). These C-Mn steels are used for structural sections, angle and channel long products and plates. Replacement of these thick-section C-Mn steels provides an enormous opportunity to reduce weight and cross sectional thickness of structural components through the adoption of HSLA steels and hence, the reduction of greenhouse gases and carbon footprint.

Although there are different civil engineering designs and many diverse product applications in the structural market, the Nb metallurgy and production strategy to manufacture these steels often remain the same. Cross-application of similar Nb microalloy steel grade systems is specified for different end user requirements. Today's structural steels require properties such as:

i. Improved toughness at lower temperature;
ii. Higher yield strengths for lower cross sectional area of structure;
iii. Higher elongations;
iv. Improved weldability to reduce construction time;
v. Improved elevated temperature properties for fire resistance;
vi. Improved fracture toughness;
vii. Seismic resistance;
viii. Improved fatigue resistance.

Considering the requirements for structural design previously discussed, steel is the preferred structural material. Steel can be produced in large quantities and usually to a relatively consistent quality, although there are still areas for improvement concerning residual and impurity contents in the commodity S235 and S275 C-Mn grades and in some cases, even the HSLA S355 low strength construction grades, depending upon the steel producer. Of course, steel members are recycled. However, further improvements are still sought, aiming at producing anti-corrosion steel, fire-resistant steel and also steel with high fracture toughness. High fracture toughness demands of common structural materials such as S355 structural components led to the comprehensive wind tower development project.

The cross-application of microalloy-bearing HSLA steels has been applied for many years in steel mills throughout the world. This practice has resulted in limited structural design enhancements with improved properties for some construction products when the steel cannot be used for offshore platforms or oil and gas pipelines.

Nb-bearing Construction Steel - Structural Application Overview

The C steel construction segment is one of the largest product segments within the global structural steel market. In 2011, nearly 500 million tonnes of construction steel bar, beam, plate, section and wire rod were supplied to the global construction industry including C/Mn steel shapes, plates and bars of structural quality applied in riveted, bolted, or welded construction of buildings and for general structural purposes. Nucor's applications specifically include both bar and narrow plate (maximum width of 355 mm) for construction frames, metal building systems, structural steel shapes, trusses and weldable construction systems. The distribution of major construction steel product segments for 2011 is shown in Figure 1.

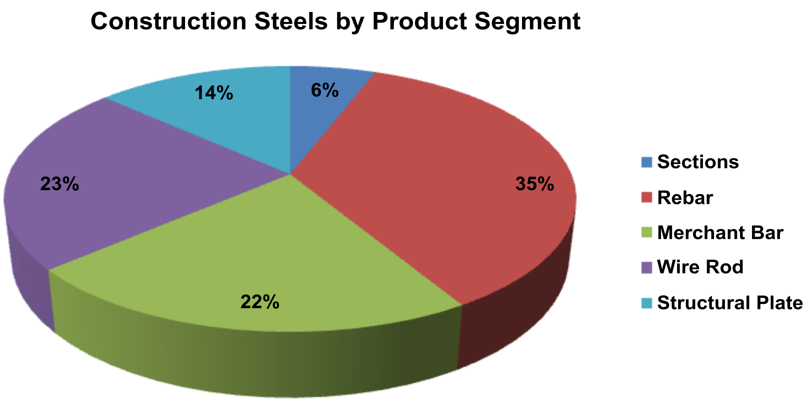

Figure 1. 2011 Construction steel distribution by product sector.

Within the construction steel segment, approximately 70 percent of the steel currently produced is still non-alloyed C-Mn grades. The highest Nb usage is currently within the structural sections segment (beams, angles and channels), in grade S355 and S420 structural plate for wind towers and construction plate for both industrial and non-industrial buildings. Advanced high strength microalloyed construction grades from S460 to S890 represent the balance.

Nb usage in the rebar product area is an evolving, recently developed market. Traditional lower strength grades are taking advantage of Nb to reduce rebar weight in projects as well as to improve the nesting in concrete structures. A recent development is the commercialization of value-added S500 and S600 seismic and fire-resistant rebar.

Within the merchant bar and wire rod sector, Nb usage has been quite limited to date. Within the long products sector, the addition of Nb in high C and alloy long products has been limited to date, but is increasing in popularity and application.

Low Strength and Advanced High Strength Construction Steel Differentiation

Different from the automotive or pipeline segment where C levels are typically less than 0.10%, many of the plate structural products exceed 0.15%C, approaching allowable specification maximum C levels of 0.22% in many S355 grades and some S420 grades, due to the perceived lower cost. Consequently, there is still a preponderance of structural plates and beams produced throughout the world with C levels greater than 0.18%. There are various reasons for this relating to miscalculated cost, process metallurgy, mill configuration and furnace reheating efficiency and performance. Some mills choose the higher C level approach to achieve strength, but sacrifice toughness, weldability and product performance [1]. Some mills decided against the adoption of a more efficient heating and rolling operation which is needed to accommodate low C, microalloy, mechanical metallurgy practices. Similar situations also exist in several plate mills rolling construction plate, hence they have not taken full advantage of the Nb solution to lower C levels which increases yield strength, ductility, toughness and improves weldability.

Within the higher strength or advanced higher strength construction grades, defined as S500, S550, S690 and S890, low C and traditional microalloyed TMCP practices have been adopted. In these cases, the application of higher Nb-bearing steels influences the grain refinement and toughness since rolling takes place at higher temperatures. Furthermore, high strength structural steel grades with yield strengths up to 960 MPa have been produced with different levels of Nb [2].

Some sectors of the construction design and steelmaking sector perceive that Nb is only required in higher strength constructional steels exceeding approximately 420 MPa. This misapprehension is quite evident within the end user and civil engineering community. However, recent Nb technological innovations have been developed for beam and plate applications with enhanced fatigue and fracture toughness in low C low alloy (LCLA) S355 grades for construction applications. Some case studies involving the use of these lower strength Nb-bearing structural grades are presented below.

The adoption of the as-rolled Nb-LCLA technology is replacing the traditional higher C, Nb or V normalized heat treated route for lower strength construction beam applications used for skyscrapers and structural plates for wind towers. The distribution of the family of structural steel grades is illustrated below in Table I.

Table I. Construction Segment Strength Grade Distribution

Commodity C-Mn	Low Strength HSLA	Advanced High Strength
S235/S275	S355/S420	S460 to S890
70%	25%	5%

Because of the potential problems with the peritectic chemistry, a significant amount of approximately 100 million tonnes of constructional steel received a normalize heat treatment in 2011. Elimination of this heat treatment step would realize a massive reduction in the carbon footprint, reduced energy consumption and a reduction in the production cost per tonne. The Nb wind tower structural support case study is discussed later.

Microalloy Design Considerations for Low Strength Low C Construction Steel Sections and Plates Applications

In view of the recent demand for alternative high strength structural beam chemistries and associated economic and processing cost factors, the Nb-microalloying approach has been adopted and considered for the production of large structural beams with improved mechanical properties. Structural S355 beams with the desired strength-toughness combination can be successfully obtained by the effective use of the Nb-microalloying design approach and TMCP rolling practices. The Nb-microalloyed steels exhibit outstanding notch-toughness at -40 °C compared to other traditional V-microalloy design systems. Detailed investigations involved stereological analysis and electron microscopy validating that toughness is strongly influenced by microstructural features.

The first objective for this work was a concerted effort to differentiate the Nb-bearing S355 structural beams from the V-bearing beams in terms of product quality performance. The reduction in C content from 0.15%C, typical for older type construction grades, to the 0.08-0.10%C range, coupled with the Nb-addition (0.02-0.04%), provide both improved weldability and toughness at reduced cost. The second objective was driven by the civil engineering and design community who demanded beams with improved toughness. The beam chemical composition range is congruent with the ASTM A992 chemistry specification and is outlined below in Table II.

Table II. Chemical Composition Range of Nb- and V-microalloyed Construction Steels

Elements	Nb-microalloyed Steel (wt.%)	V-microalloyed Steel (wt.%)
C	0.030-0.100	0.030-0.100
Mn	0.500-1.500	0.500-1.500
V	0.001	0.020-0.050
Nb	0.020-0.050	0.001
Si	0.15-0.25	0.15-0.25
P	0.010-0.020	0.010-0.020
S*	0.015-0.025	0.015-0.025
N**	0.009-0.010	0.009-0.010

*≤0.008%S dependent upon design and beam application
**Electric arc furnace steels

Research and development resulted in the successful commercialization of Nb-bearing beams, replacing V-bearing beams, with significant toughness improvements. The adoption of this Nb-Low Carbon Low Alloy (LCLA) technology has facilitated over 20 million tonnes of structural beam production globally to-date. The ASTM A992 beam (S355) study was based on industrial heats which then led to the commercialization of low C, Nb-bearing beams in place of higher C, V-only bearing beams. The incorporation of Nb technology has significantly improved the beam toughness properties through grain refinement and strategic cooling practices during rolling. The Nb addition refines the average grain size by 2 ASTM numbers, lowers the carbon equivalent by 0.07% and improves the toughness. Near-net shape cast structural beams containing only a Nb microalloy addition exhibit double the impact toughness at room temperature compared to a V-only microalloy system at similar S, P and N levels and cooling rates, as illustrated in Figure 2 [3].

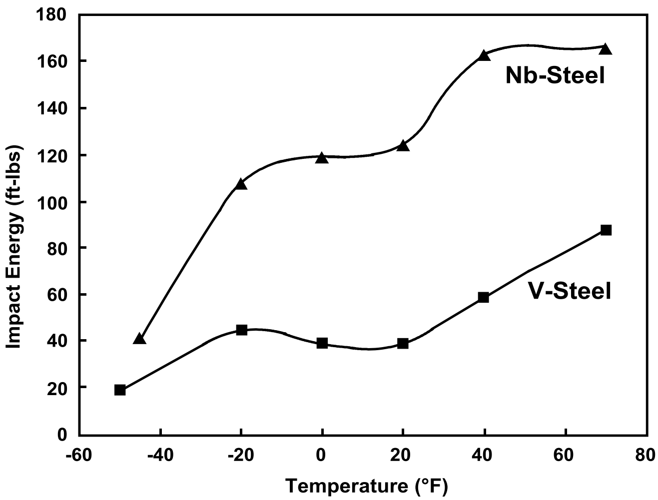

Figure 2. Charpy V-notch impact toughness comparison – Nb vs. V.

A second part of the study investigated a comparison of different post rolling cooling rates. Micrographic analysis revealed that the primary microstructural constituents at a low cooling rate were polygonal ferrite and pearlite. At intermediate and high cooling rates, the microstructure consisted of lath-type bainitic ferrite and some degenerate pearlite, together with conventional ferrite-pearlite, degenerate pearlite being most prominent in the Nb steel. With an increase in cooling rate, there was an increased tendency towards the formation of lath ferrite/bainitic ferrite with a consequential decrease in the conventional ferrite-pearlite microstructure. [4] Figure 3 illustrates the influence of Nb on the transformation to degenerate pearlite which contributes to the improved toughness. No degenerate pearlite was observed in the V-bearing steel grade except at the highest cooling rate.

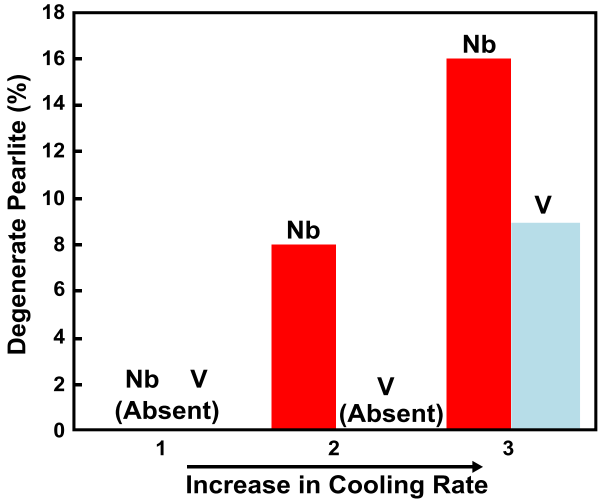

Figure 3. Percent degenerate pearlite versus cooling rate – Nb and V comparison.

A combined Nb-V microalloy approach is currently under development for heavy beam S420 sections with industrial trials currently in progress. The application of low S and Ca shape control is also being employed to further improve the toughness of the low C grade.

Nb-LCLA (Low Carbon Low Alloy) Wind Tower Application

Within the wind tower sector, the end user requirement to improve power generation efficiency requires construction of towers to higher elevation. However, at around 2005, fatigue and fracture toughness limitations of the traditional steel structural supports moved designers to consider carbon fiber composites. As a result of this threat from carbon fiber composite 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-LCLA as-hot rolled product provided a viable, cost effective solution.

Wind Tower Design Trends and Challenges

This decade will see a further increase in the height of wind towers presenting new materials and civil engineering challenges. In the past 15 years of wind energy growth, the current trends of the industry are to 80, 90 and now over 100 meter towers being introduced in Europe and North America. Turbines have increased in size to 2.0 MW, 2.5 MW, 3.0 MW and are increasing to 4.5 MW. The dead load of these higher elevation structures is surpassing 2600 kN (600 kips). Consequently, structural dynamics, frequency response, fatigue and fracture toughness properties of materials and soil-structure interactions become increasingly important.

With these industry demands, the designers and fabricators must consider the current market demographics including such issues as budget constraints, alternative materials for these higher towers, the necessity for cost-effective design and materials of construction. The wind tower growth trend will continue for the next ten years in both the mature as well as evolving markets around the world. Many of these countries embrace wind energy as a sustainable, cost effective and environmentally-friendly, green solution.

Wind tower designs will transcend the traditional pole-tube design into special shapes with the need for improved materials, not only for both S355 and S420 but in some cases higher strength steels, that will better accommodate the higher dynamic stresses, complex loading and vibrational fatigue conditions experienced during the operation of these higher structures.

Increased value-added material cost is required to ensure that fatigue and fracture toughness properties are met for higher efficiency wind tower design. Considering these increased structural steel demands, structural steels with enhanced fatigue and fracture toughness properties were examined. A joint research study on fatigue and fracture toughness was performed comparing normalized versus as-rolled, industrially-produced Grade S355 plate steels for wind tower construction [5]. There has been very little recently published data on the fatigue and fracture toughness properties of these structural steels. Therefore, such data was determined in this research programme for S355 structural steel plate produced via 21st century steelmaking and hot rolling practices.

<u>Industrial Trial Rolling Comparison</u>

Since the higher 0.15%C plate steels are very popular globally for this application, industrial heats were produced for both the low and medium C grades. Medium C S355 grades are produced by the normalizing heat treatment route due to the requirement in some wind tower specifications. Figure 4 illustrates the loss in strength due to heat treatment.

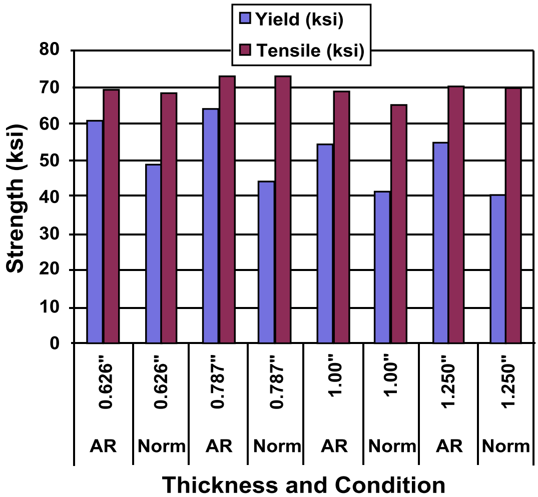

Figure 4. Effective loss of yield strength due to Normalize Heat Treatment compared to Normalized Rolled Condition for a 0.15%C steel.

Industrial heats were produced to compare low C-Nb control rolled, medium C-Nb normalized rolled products and medium C-Nb normalized rolled and heat treated products. The compositions are listed below in Table III.

Table III. Chemical Compositions of Nb-LCLA vs. Medium C, wt.% [5]

Steel	C	Mn	P	S	Si	Cu	Ni+Cr+Mo	Nb	CE[1]
Low C–Nb Control Rolled	0.06	1.27	0.011	0.001	0.34	0.27	0.41	0.031	0.35
Med C–Nb Normalized Rolled	0.15	1.39	0.012	0.003	0.22	0.20	0.32	0.019	0.43
Med C–Nb Normalized Rolled and Heat Treated	0.15	1.32	0.011	0.003	0.21	0.22	0.23	0.014	0.42
ASTM A572-50 and A709-50 (max)	0.23	1.35	0.04	0.05	0.40	-	-	-	-
EN 10025-2 S355K2 (max)	0.23	1.70	0.035	0.035	0.60	0.60	-	-	0.45

[1]CE = C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15

A comparison of the impact properties of the three steels exhibits a consistent upper shelf for the low C-Nb steel in both the transverse and longitudinal directions with superior impact toughness of 265 ft-lb in the longitudinal direction and 250 ft-lb in the transverse direction at -100 °F as shown in Figure 5.

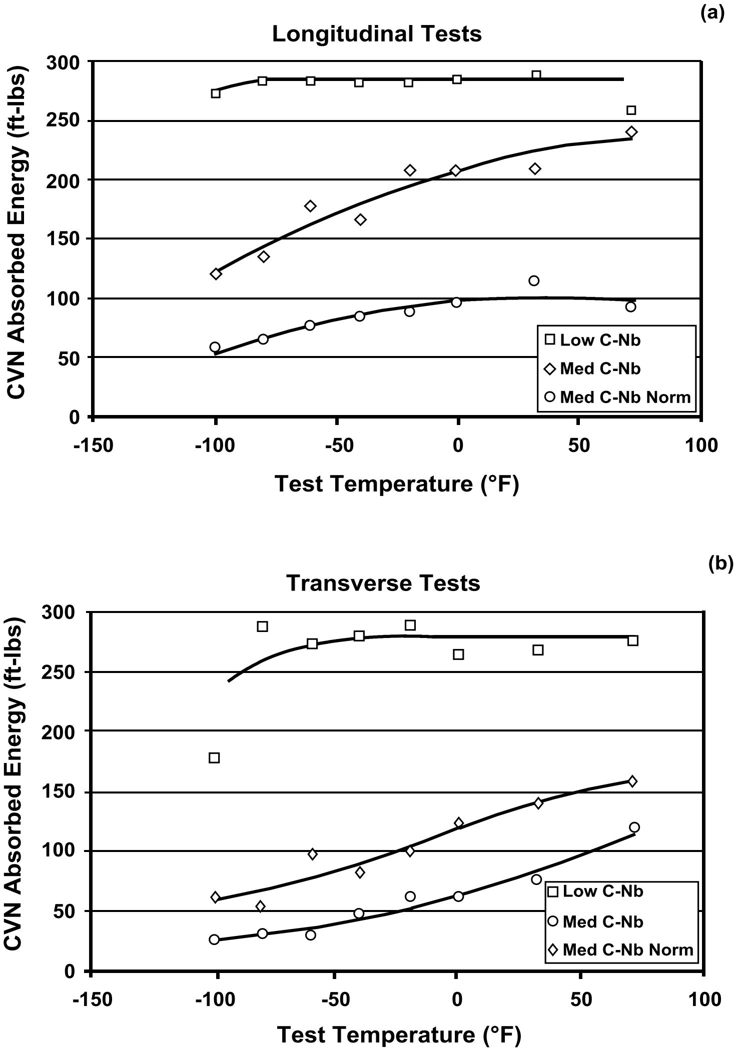

Figure 5. Charpy V-notch absorbed energy; (a) Longitudinal tests, (b) Transverse tests [5].

Fatigue and Fracture Toughness Implications of As-rolled vs. Normalize Heat Treated

There is very little fatigue and fracture toughness data available in the literature for 21st century produced structural plate steels such as S355. Hence, this research work on industrially produced heats was performed to determine the fatigue and fracture toughness of these important parameters for designers. Improved fatigue and fracture toughness properties of the as-rolled low C-Nb steel compared to the as-rolled medium C-Nb and medium C-Nb heat treated steels are remarkable. Table IV summarizes the mechanical property results for the industrial heats.

Table IV. Mechanical Property Comparison [5]

Steel	YS (ksi)	UTS (ksi)	-60 °F TCVN (ft-lbs)	Upper Shelf TCVN (ft-lbs)	Fracture Toughness, K_{Ic} (ksi/√in)	Fatigue Endurance Limit, S_e (ksi)
Low C–Nb	65	76	270	280	375	44
Medium C–Nb	64	82	30	120	235	39
Medium C–Nb Normalized Heat Treatment	57	77	80	160	250	35

The fatigue and fracture toughness performance of the medium C normalized rolled and/or normalized heat treated plate steels is inferior in comparison to the as-rolled low C, Nb-bearing wind tower plates.

In these ferrite-pearlite steels, the damage generally occurs in the ferrite as opposed to the pearlite, which can prevent cracks from propagating [6]. Ferrite which has been more effectively strengthened by Nb(C,N) precipitates (eg. Low C-Nb steel) will exhibit greater cyclic hardening [7]. This greater cyclic hardening provides more resistance to slip, thereby leading to a higher fatigue endurance limit.

Based on the fatigue and fracture toughness data performance, the implications of specifying the EN 10025 normalized rolling delivery condition, which is common by wind tower designers, are clear. The steel chemical composition constraints imposed by the EN 10025 normalized rolling requirement result in wind turbine tower plates with reduced weldability, toughness and fatigue resistance.

Higher production costs are associated with the continuous casting of medium C steels, which are more susceptible to surface cracks due to the peritectic solidification reaction, compared to low C steels. These surface quality issues result in increased reject and conditioning costs compared to low C steels. Castability and slab surface quality are significantly improved for the Nb-LCLA composition based upon application of this approach in structural products such as beams, wind tower supports and other general construction steels. Improved castability results in increased casting speed and lower rejects due to surface and internal casting defects because the peritectic issues are eliminated.

There are several implications of this development relating to future wind tower designs involving specifications, the selected C level and steelmaking/rolling practices. Considering future civil engineering design challenges and market trends for higher elevation wind tower designs, several specification and chemistry issues need to be addressed. A further implication involves cost. The costs of steelmaking and welding of the low C steel are less compared to the medium 0.15%C steel. The as-rolled Nb-LCLA product exhibits both cost and metallurgical benefits compared to the traditional higher C structural steels.

Nb and/or Nb-Mo Steels for Earthquake Zones and Fire Resistance Requirements

The development of seismic-resistant rebar was initiated with the introduction of Nb to existing rebar grades. Increased sizes of reinforcing bars at greater than 40 mm in diameter, high yield strength (greater than 450 MPa) with improved weldability, are required for seismic zone construction. Microalloyed steels with V have been traditionally used in rebar, but recently, the strong grain refinement effect of Nb has resulted in the increased development of Nb-bearing steels in concrete reinforcing bars for 450 to 550 MPa strength levels, with improved ductility and toughness. The addition of Mo also offers improved fire-resistant properties for an evolving market.

Currently a large quantity of rebar is produced with no microalloys incorporating the Tempcore process, however, ductility is reduced. The cooling regime achieved through application of the Tempcore process with a Nb-Mo grade may be relaxed or eliminated in the lower strength grades, resulting in reduced operating costs and increased mill productivity. The Tempcore process is applied to reinforcing bars to increase the yield strength, but elongation, toughness and fatigue performance may be impaired due to the microstructure developed.

Fire-resistant (FR) Plate Steels

Fire-resistant constructional steels have been commercialized in some parts of the world (China and Japan) and are being examined in the USA. Current activities are focused on development of specifications for determination of elevated temperature properties. Some material specifications and niche applications (eg. high-rise building columns, structures where friable insulated coatings are undesirable) will follow. Selected metallurgical studies are reviewed, with a focus on Nb-containing steels that are intended to help understand the microstructure/property relationships that control fire-resistant (FR) properties. Specific examples are cited which illustrate the apparent benefit of Mo in suppressing precipitate coarsening rates at elevated temperature, beneficial effects of microstructure refinement, microalloy precipitation, and warm working of ferrite, on the FR properties.

Since structural steels usually maintain most of their strength at 350 °C (and indeed some steels may be stronger at 350 °C than at room temperature due to the strain aging effects caused by interstitials), this requirement is effective and conservative, but quite restrictive and it drove development and implementation of newer steels with improved properties at elevated temperature. The FR steels produced in Japan for the past several years guarantee a minimum yield strength at 600 °C that is 2/3 of the room temperature yield strength, ie. having a minimum FR yield strength ratio of 2/3, and these developments have already stimulated implementation of FR steels in some niche applications. Some other design codes cite minimum FR yield strength ratios of 50% at 600 °C [8].

With the evolving demand for fire resistance, it became apparent that a Nb-Mo based structural steel design could also improve fire resistance. Therefore, it was decided to study various compositions focused upon fire resistance behavior. So, the need for fire resistance in construction steels for high strength at elevated temperatures was defined in the USA. Also, there are very few commercially available fire-resistant plates produced globally. Simultaneously, work is being performed in China at the Baoshan Iron and Steel Company as a result of the increasing demand for high performance fire-resistant structural steels for use in commercial building type applications. A low Mo-Nb approach processed by TMCP has demonstrated acceptable high temperature strength in China [9].

Based upon the research and development in the USA as well as other previous developments in Japan, specifically Nippon Steel [10], it was decided to create a task force within ASTM to study the possibility of writing an ASTM specification. An ASTM Fire-Resistant Steel specification has been approved.

Experimental Nb-Mo Fire-resistant Steel Comparison

The new ASTM A1077/A1077M specification, "Standard Specification for Structural Steel with Improved Yield Strength at High Temperature for Use in Building," has been approved by the standards committee and was published in March 2012. The specification encompasses a Nb-Mo alloy design that retains two-thirds of its yield strength at 600 °C. Table V compares the compositions to the commercially available Japanese FRS plate.

Table V. Compositions of Experimental Fire-resistant Steels (FRS), wt.% [11]

	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Nb	Al	N
Base	0.11	1.16	0.018	0.013	0.19	0.25	0.08	0.17	0.020	0.004	0.001	0.02	0.010
Nb	0.10	1.06	0.005	0.031	0.27	0.39	0.16	0.09	0.047	0.001	0.021	0.03	0.016
Mo+Nb	0.10	0.98	0.008	0.028	0.30	0.38	0.15	0.10	0.480	-	0.017	0.04	0.010
V+Nb	0.08	1.13	0.005	0.030	0.27	0.32	0.11	0.13	0.036	0.047	0.021	0.03	-
Nippon I	0.11	1.14	0.009	0.020*	0.24	-	-	-	0.520	-	0.030	-	-
Nippon II	0.10	0.64	0.009	0.050*	0.10	-	-	-	0.510	-	-	-	-

* Maximum values

Figure 6 shows the superior elevated temperature properties of Nb-Mo plate steels compared to other ASTM A572 or ASTM A992 type construction steels.

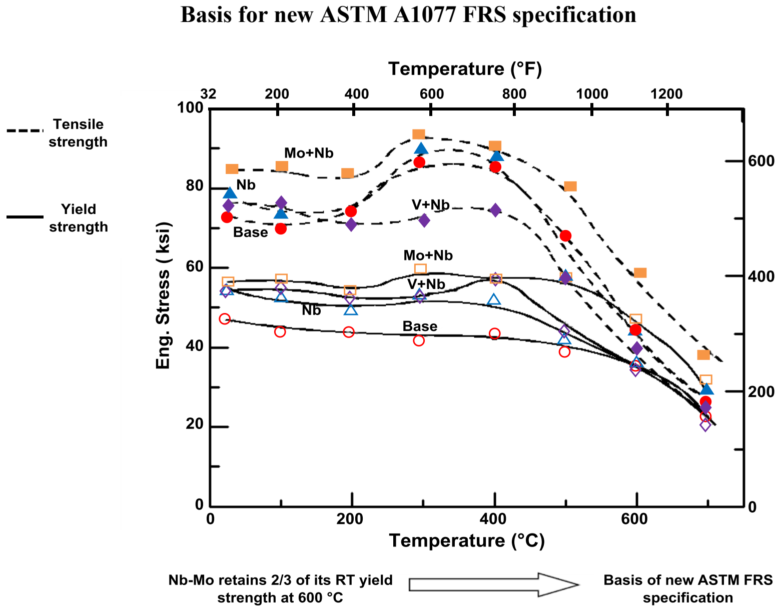

Figure 6. Yield and tensile strength vs. temperature (25-700 °C) for base, Nb, Mo+Nb and V+Nb alloys [11].

The Nb+Mo steel exhibits the best high temperature performance. The strengthening mechanism involves the co-precipitation of Nb,Mo(C,N) in a fine dispersion of 3 to 5 nm within the ferrite matrix. Figure 7 illustrates the co-precipitation of the Nb,Mo(C,N) precipitates.

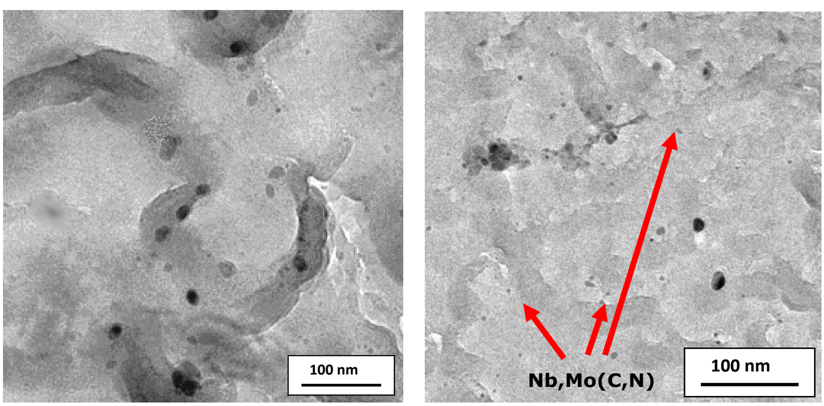

Figure 7. Co-precipitation of duplex Nb,Mo(C,N) precipitates in ferrite matrix.

The diffusion of Nb and Mo at different C concentrations influences the precipitation kinetics. Initially, solute Nb and Mo will retard dislocation climb, dislocation recovery and grain boundary migration. However, as the temperature increases, the dislocations can become mobile at approximately 400 to 500 ºC. Consequently, the yield strength reduction occurs as exhibited in Figure 6. Finally, as the fire ensues, the secondary precipitation of Nb,Mo(C,N) occurs and the traditional Ostwald ripening mechanism is in effect. These metallurgical principles are now being transferred into the rebar product sector.

Nb Microalloy in High C Construction Steels

In most cases, Nb has not been the microalloy of choice or even considered for that matter in most high C steels. The reason has typically been cited as the lower solubility of Nb in higher C steels. Although there is lower solubility, the effectiveness of Nb in the grain refinement and precipitation strengthening mechanisms in Nb, Nb-V and Nb-Mo steels has been demonstrated. Within the higher C steel segment in the past, research focused on Nb levels that were quite high with less than desirable results. Now, micro-Nb levels of 0.005-0.020% prove extremely effective in improving product performance. Applications include Nb in eutectoid pre-stressed concrete wire rod and rail, Nb-V for power transmission components in wind tower gear boxes and Nb-Mo in fire-resistant, value-added reinforcement bar [12,13].

Historically, higher Nb levels (especially exceeding 0.040%) were thought to be necessary in order to obtain proper grain refinement, microstructural control and strength in higher carbon equivalent steels. However, high C metallurgical and production research and experience indicates higher Nb levels in high C steels certainly make the processing more challenging and the resultant properties are not optimized. It is important to consider the synergistic precipitation behavior effect between the Nb and V and in some cases Mo which can contribute to the improved mechanical performance. This duplex or triplex complex microalloy precipitation behavior requires further study.

The application of the micro-Nb, high C steel technology mechanism, metallurgy and processing parameters has led to an enhancement of the opportunity to more widely introduce Nb into other high C steel products. This development has been invaluable for the implementation process to successfully incorporate these micro-levels of Nb (0.005-0.020%) in existing high C steels to improve fatigue, fracture toughness, ductility, manufacturability and overall product performance.

MicroNiobium Alloy Approach® on Pre-stressed High C Concrete Wire Rod

The application of the MicroNiobium Alloy Approach® in C steel long product and plate steels enhances both the metallurgical properties and processability and reduces the operational cost per tonne. The process and product metallurgical improvements relate to the pinning effect of the austenite grain boundaries by Nb. The metallurgical mechanism of the MicroNiobium Alloy Approach® is related to the retardation of austenite grain coarsening during reheat furnace soaking of the billet, slabs or shapes before rolling. Although the Nb-solubility is limited when increasing amounts of Nb are used in higher C steels compared to low C steels, through empirical evidence and actual operating data, the MicroNiobium Alloy Approach® has demonstrated very positive results in high C grades such as steel wire rods and bars, eutectoid steels, and other medium C engineering alloy applications.

The developmental chemistries were evaluated to determine the effectiveness of Nb, V or Nb-V concentrations on the pearlite interlamellar spacing and mechanical properties in a eutectoid steel. Table VI shows the aim chemistries and Table VII the mechanical properties.

Table VI. Nb and V Eutectoid Chemistries, wt.%

	C	**Mn**	**Si**	**Cr**	**Nb**	**V**
V1	0.80	0.70	0.20	0.15	0.0	0.09
V2	0.80	0.70	0.20	0.15	0.0	0.05
VN	0.80	0.70	0.20	0.15	0.02	0.05
N1	0.80	0.70	0.20	0.15	0.02	0.00
N2	0.80	0.70	0.20	0.15	0.04	0.00
N3	0.80	0.70	0.20	0.15	0.09	0.00
N4	0.80	0.70	0.20	0.15	0.12	0.00

Table VII. Mechanical Properties

Steel	**YS 0.2% (MPa)**	**TS (MPa)**	**Reduction of Area (%)**
S0	627	1086	30.4
V1	733	1154	26.8
V2	719	1154	22.9
VN	740	1169	38.0
N1	648	1139	45.1
N2	680	1102	41.4
N3	666	1115	38.4
N4	709	1150	35.8

Review of the mechanical property data shows the best ductility in Sample N1 which is the 0.02%Nb MicroNiobium Alloy design, at 45.1% reduction of area. The yield strength, tensile strength and reduction of area meet the specification as defined by S0 in Table VII. The mechanism of this optimization of the Nb concentration and properties in this high C eutectoid steel is the refinement of the lamellar spacing. As shown in Figure 8, the lowest lamellar spacing (λ), 75 nm, is attained in the 0.02%Nb steel and this directly links to the superior ductility.

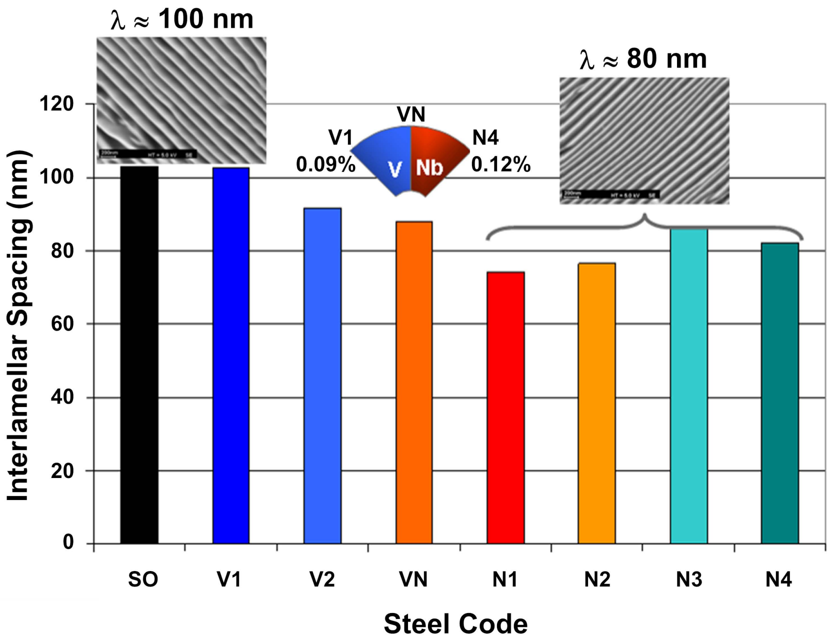

Figure 8. Interlamellar spacing refinement with MicroNiobium (μ-Nb) addition in 1080 steel.

The master rods were then drawn into the final pre-stressed wire rod product. Figure 9 relates the reduction of area to the strain ratio of the initial diameter (S_0) to the final product diameter (S). The optimum strain ratio for the industrial wire drawing operation is between 1.50-1.80. The consistent 55 percent reduction of area (μ-Nb with the 0.02%Nb eutectoid chemistry – N1) over this strain ratio range is excellent (ie. flat) and results in increased productivity at the wire rod mill.

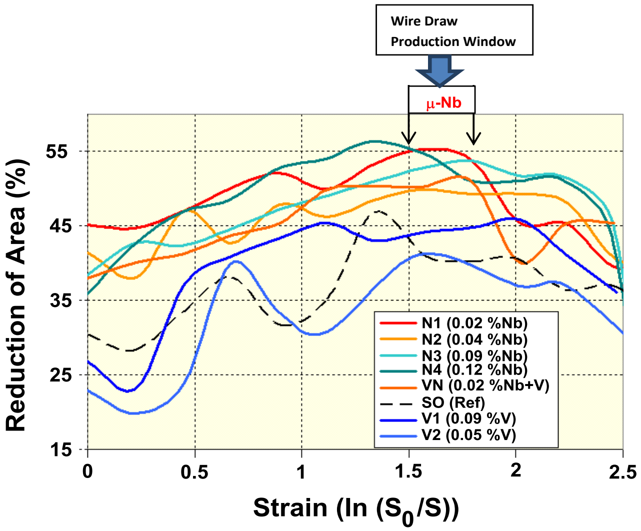

Figure 9. Drawability performance.

C-Mn versus C-Mn-Nb Microalloyed Bridge Steel - Sustainability Comparison

The application of Nb-microalloyed structural steels offers the opportunity to reduce the total weight of a given structure, such as a building or bridge, compared to non-microalloy steel construction. Generally, one considers the cost savings are due to less material (reduced gauges) and lower costs associated with construction which translates into significant overall cost savings. However, the intangible benefit is the significant reduction in emissions and energy consumption from the fact that less steel is produced as a result of the weight reduction in the structure.

The following comparative study illustrates the significant reduction in emissions (kilograms of CO_2) and energy consumption (Gigajoules) comparing a structure constructed from 10,000 tonnes of S235 steel to one with 9,000 tonnes of S355 Nb-bearing HSLA steel at 0.03%Nb. The 10% weight saving is a conservative estimate considering bridge design stiffness, specification requirements and design considerations. The results of the analysis are shown in Table VIII (CO_2 emission reduction) and Table IX (GJ savings) and compares steel plates and beams melted via the BOF and the EAF route [14].

Table VIII. CO_2 Emission Savings - BOF versus EAF

Factor	BOF kilograms CO_2 per tonne Steel	Emission Reduction x10^4 kilograms CO_2	EAF kilograms CO_2 per tonne Steel	Emission Reduction x10^4 kilograms CO_2
Coke Savings	51.1	5.11	0	-
Blast Furnace	1000	100.0	0	-
BOF	244.7	24.47	0	-
EAF	0	-	506.1	50.61
V Degas/ Ladle Met	38.6	3.86	70.5	7.05
Cont Cast	19.8	1.98	19.5	1.95
Hot Rolling	188.5	18.85	141.1	14.11
Pickling	77.2	7.72	42.5	4.25
CO_2 Reduced Emissions	-	**161.99**	-	**77.97**
Reduced CO_2 Emissions - 1,620 metric tons at BOF and 780 metric tons at EAF comparing a structure made from either 10,000 tonnes of S235 or 9000 tonnes of S355				

Table IX. Energy Savings – BOF versus EAF

Factor	BOF GJ Per Tonne of Steel	Energy Reduction (x10^3 GJ)	EAF GJ Per Tonne of Steel	Energy Reduction (x10^3 GJ)
Coke Savings	3.89	3.89	0	0
Blast Furnace	12.48	12.48	0	0
BOF	1.02	1.02	0	0
EAF	-	-	6.11	6.11
V Degas/ Ladle Met	0.72	0.72	1.25	1.25
Cont Cast	0.34	0.34	0.34	0.34
Hot Rolling	2.67	2.67	4.10	4.10
Pickling	1.40	1.40	0.79	0.79
CO_2 Reduced Emissions	-	**22.52**	-	**12.59**
Reduced Energy Consumption 22,520 GJ at BOF and 12,590 GJ at EAF comparing a structure made from either 10,000 tonnes of S235 or 9000 tonnes of S355				

The integrated mills' opportunity to reduce C emissions and energy usage is nearly two times higher than for the EAF operations. However, this analysis does not consider the C emissions from the generation of power for the electrodes to melt the 100% scrap charge or the production of direct reduced iron pellets for the EAF. With this in mind, it becomes apparent that the potential C savings are significant for both operational routes.

The construction case study is just one example of the cost and environmental impact resulting from the simple substitution of S235 with S355. Upgrading some critical member sections of a structure to S460 may result in an additional 3% reduction in emissions and energy consumption. However, there are civil engineering considerations such as the stiffness, slenderness and twist of the sections, which must be defined by the designer.

Advanced High Strength Structural Steel Development Trend

The application of advanced high strength structural steels is a further opportunity to reduce weight, but the application is somewhat limited based upon the relationship between the allowable stress/load and the structural member's slenderness. This relationship and convergence of the allowable stress/load for advanced high strength steels compared with lower strength structural steels is illustrated in Figure 10 as the slenderness parameter increases.

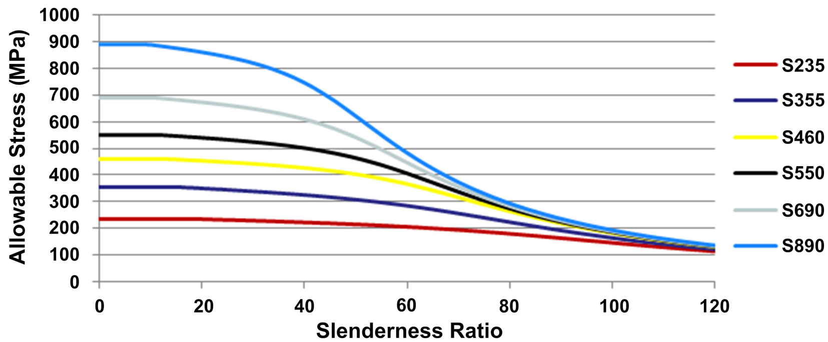

Figure 10. Slenderness of structural member versus allowable stress.

The effect of a column's unbraced length and radius of gyration is combined in the slenderness ratio calculation. The slenderness ratio for steel columns is defined as the ratio of a column's length (l) to the radius of gyration (r).

$$\text{Slenderness ratio} = l/r \quad (1)$$

In general, the greater the slenderness ratio, the greater the tendency for the member to fail under buckling, therefore, less load can be tolerated since most steel columns are not symmetrical about both axes (wide flange) and the least radius of gyration governs for design purposes because it is about this axis where the column will fail first. The radii of gyration, r, about both axes are given in the AISC manual. Hence, under certain circumstances, advanced high strength constructional steels cannot be cost effectively applied and lower strength Nb-low C steels are appropriate. These design decisions are governed by the end user.

Conclusions

The civil engineering and end user community demands structural bars, shapes, beams and plates with improved properties. These properties include increased fatigue resistance, fracture toughness, Charpy energy absorption, improved fire and seismic resistance and higher yield and tensile strengths. Nb-microalloying has contributed to the improvement in these properties and has ensured that low carbon steels (less than 0.10%) can achieve the equivalent yield and tensile properties in the as rolled condition compared to normalized rolled, higher C (ie. peritectic) steels. Near net shape constructional beams and wind tower supports are now adopting this low C-Nb technology.

The application of the MicroNiobium Alloy Approach® in C steel long product and plate steels enhances both the metallurgical properties and processability and reduces the operational cost per tonne. The process and product metallurgical improvements relate to the Nb-pinning effect of the austenite grain boundaries and the retardation of austenite grain coarsening during reheat soaking of the billet, slabs or shapes before rolling. The addition of Nb in high C pre-stressed concrete wire rod results in improved ductility, drawability and reduced operational costs.

The technological development of low C, Nb-bearing value-added construction steels continues globally for both low and high strength applications and within the construction sector, the shift from the high volume, heavier gauge S235 and S275 peritectic constructional grades to low C, Nb-bearing S355 thinner gauge steels offers the potential to reduce construction costs with a favorable environmental impact on the carbon footprint.

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