New Generation Niobium Bearing Structural Steels for Future Infrastructure Demands

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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 applications are shifting designers to these new high performance lower cost materials. The civil engineering and end user community demand structural reinforcing bars, shapes, beams and plates with improved energy absorption and fatigue properties. The future market demands better fire and seismic resistance, yield-to-tensile ratio consistency, improved bendability and weldability. These attributes are difficult to obtain from steel producers today with their current higher carbon microalloyed steel approach. However, there is a global shift in motion to low C-Nb bearing construction steels 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.

Introduction

Beam, reinforcing bar, plate and other infrastructure structural applications account for over 500 million tonnes of global steel production. With environmental climate change, more severe weather conditions around the globe and increased seismic activity, construction materials experience increased load, stress, strain and fatigue levels. These climatic changes often drive the customer to request improved low temperature toughness, better fracture toughness, improved cyclic fatigue performance, more homogeneous grain size and better resistance to earthquake, typhoon and hurricane environments. These mechanical property attributes are primary drivers for the increased use of Nb-containing structural steels the long product global segment.

Chemical and mechanical property requirements are quite diverse to accommodate the end user infrastructure requirements. Nb-bearing steels are being methodically introduced into beams, plates, rail, rebar, shapes and pre-stressed concrete wire rod. These products can now meet the ever increasing end user infrastructure demands for improved mechanical properties and tighter specifications compared to the traditional construction steels produced today. Traditional construction steels have been applied for decades with relatively insignificant mechanical performance enhancements for the end user. Recently, the incorporation of more Nb into numerous steel grades is displacing traditional higher carbon-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 improves toughness, formability, consistency, energy absorption and weldability at a more economical cost of construction than traditional structural steels. Niobium may be a key element in eutectoid (0.80%C) compositions for rail and pre-stressed concrete wire rod for improved fracture toughness in both heavy haul and light rail. In the end, the application of Nb-technology in long products depends upon the design criterion of the end user. On the metallurgical 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 operational cost reductions between 5-10%.

Other steel sectors, such as energy pipelines, have adopted the lower carbon approach years ago. End user performance and cost considerations drove the development of HSLA steels to allow higher operating pressures and gas transmission production rates through the development of lighter wall, higher strength low carbon steel pipelines. Although the introduction of HSLA into the structural sector is being done, the rate of product development and implementation is significantly slower. The technology is already proven; it is the implementation that is necessary. Right now, there is a compelling need to accelerate this adaptation of the Nb-HSLA infrastructure technology within the structural market with the same intensity that has been experienced within the global automotive and energy pipeline sectors.

Niobium Infrastructure Structural Steel Metallurgical Approach

The unique metallurgical attributes that niobium provides in structural steels create the opportunity to successfully meet stringent mechanical, corrosion and elevated temperature demands. Nb-based structural steels were in limited production during the 1980's. Different from the automotive or pipeline segment where carbon levels are typically less than 0.10%, many of the plate structural products still exceed 0.10%C approaching allowable specification maximum carbon levels of 0.22%. Also, a large volume of structural steels are produced within the higher carbon peritectic regions (i.e. 0.11-0.16%C). Some mills choose this higher carbon level approach to achieve strength, but sacrifice toughness, weldability and end user product performance at an increased cost. Mills which have not yet adopted the low carbon-Nb approach are missing out on the inherent advantages Nb provides in yield strength, ductility, toughness and weldability at a lower overall operational cost. [1] Several case applications are presented which exhibit the quality and production advantages of producing Nb-LCLA structural steels at less than 0.10%C. Specific case application examples involve medium and heavy section structural beams for high rise structures such as the Freedom Tower in New York City, wind tower structural supports with improved fatigue and fracture toughness and high carbon eutectoid pre-stressed concrete wire rod. The seismic-resistant rebar sector can also benefit through the adoption of low carbon Nb-containing rebar. This sub-segment of the structural market has the potential to significantly further reduce the carbon footprint and simultaneously improve fatigue and seismic performance.

All of these described applications will translate into less raw materials consumption, lower emissions and less overall energy consumption. With the global infrastructure construction segment, the opportunity exists to further reduce the carbon footprint by an additional 5 to 10% HSLA usage in the S355 and S420 strength grades. For example, through the application of Nb-microalloyed structural steels, the opportunity exists today to reduce the total weight of a given structure, such as a bridge, compared to a non-microalloyed steel construction design. The cost savings associated with less beam, plate or rebar material and lower construction cost translates into lower overall project cost. The reduction of the carbon footprint through the application of Nb-bearing steels can contribute to the beneficial reduction in CO_2 emissions and energy consumption in that less steel is required to construct the structure.

Background

Over 50% of the structural plate and beam sections currently produced today are intermediate carbon levels from 0.11 to 0.22%. There is a gradual shift at some mills seeking participation in the value-added structural plate and beam segment to produce Nb-bearing structural grades at less than 0.10%C to make 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]. With increasing raw material and energy costs, the focus on processing parameters, such as reheating temperature and cooling rate after hot rolling to achieve improved mechanical properties can result in significant savings. A lower total cost of production may be achieved through low carbon-low alloy (LCLA) chemistries with selective accelerated cooling and better control of reheat furnace temperatures.

Structural Plates and Beams

Successful commercialization has resulted in the production of Nb-bearing beams for the Freedom Tower in New York City replacing V-bearing beams. Significant toughness improvements are realized in beams and plates produced to such specifications as ASTM992, ASTM572, ASTM588, ASTM710, Q345e, and S355 to name a few. The incorporation of Nb technology has significantly improved toughness properties through grain refinement and strategic cooling practices during rolling. The LCLA chemistry is comprised of less than 0.10%C, 0.025-0.035%Nb, less than 0.010%S, less than 0.015%P, less than 1.40%Mn and residuals less than 0.70% (i.e. Cr+Ni+Cu+Mo). The Nb addition refines the grain by 2-3 ASTM sizes, lowers the carbon equivalent by 0.07% and significantly improves the beam toughness compared to V-bearing low C steels as shown below in Figure 1(a) and 1(b).

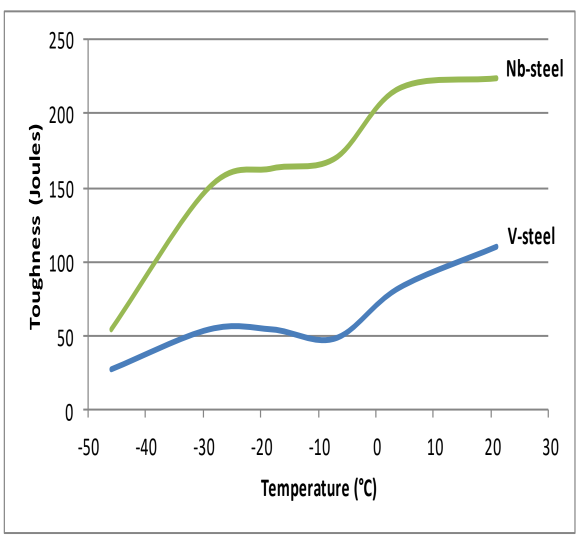


Figure 1. (a)Charpy V-notch impact strength comparison – Nb vs. V at Mill #1 [2]

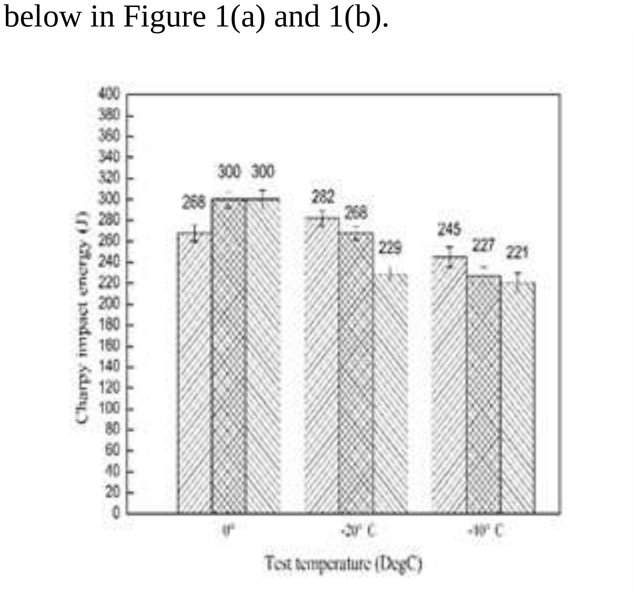


Figure 1. (b) Charpy V-notch impact strength toughness Nb steel at Mill #2

Results from various mills in different geographic regions have been congruent. Near net shape cast structural beams containing only a single Nb microalloy exhibit double to triple the Charpy impact strength energy at room temperature compared to a V-only microalloy system at similar sulfur, phosphorous and nitrogen levels and cooling rates as illustrated in Figure 1. At mill #2 in China, an even higher cooling rate was employed and Charpy values increased more.

A second part of the study investigated a comparison of different 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 degenerated pearlite together with conventional ferrite-pearlite. With an increase in cooling rate, there was an increased tendency towards formation of lath ferrite/bainitic ferrite with a consequential decrease in the conventional ferrite-pearlite microstructure. Figure 2 illustrates the influence of Nb on the transformation to the formation of degenerated pearlite (approaching a bainitic-type microstructure) which contributes to the improved toughness. No degenerated pearlite was observed in the V-bearing steel grade.

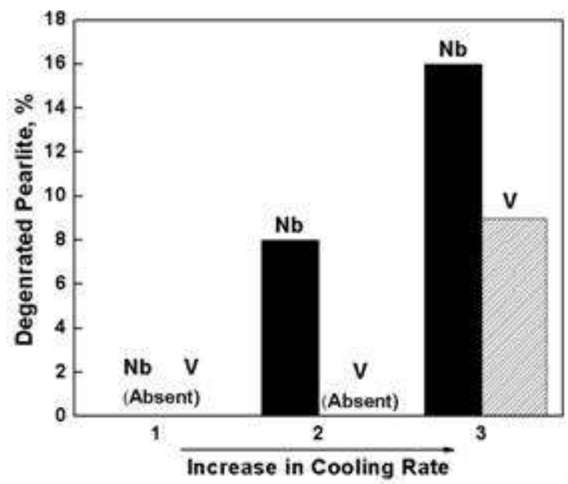


Figure 2. Percent degenerated pearlite versus cooling rate – Nb and V comparison [3]

Construction Plates for Wind tower Infrastructure

The wind tower end users require demand greater power generation efficiency which requires construction of towers to higher elevations. Fatigue and fracture toughness limitations of traditional steel higher carbon structural supports moved designers to consider carbon fiber composites. As a result of this threat of 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-Low Carbon Low Alloy (Nb-LCLA) hot rolled plate product provided a viable cost effective solution. Table 1 compares the mechanical properties of low C (0.06%C)-Nb (0.03%Nb) versus medium C (0.15%C)-Nb (0.02%Nb) containing wind tower plate for 20mm plate thickness.

Table 1. Mechanical Property Comparison [4]

Steel	Orientation	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation in 200mm (%)	CVN @ -15.5°C (Joules)
Low C-Nb	L	436	514	29.7	384
	T	450	521	28.1	371
Med C-Nb	L	439	561	21.9	103
	T	442	569	23.3	42

Med C-Nb Norm	L	384	528	28.3	243
	T	391	530	27.6	132
ASTM A572-50 ASTM A709-50		345min	448min	18min	34min LCVN @ -12.2°C
EN10025-2 S355K2		345min	469-627	20min	41min LCVN @ -20°C

Note the isotropic CVN toughness at 15.5°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. The comparison of low carbon-Nb and low carbon-V wind tower construction plates is illustrated in Figure 3(a) and 3(b). [4, 5]

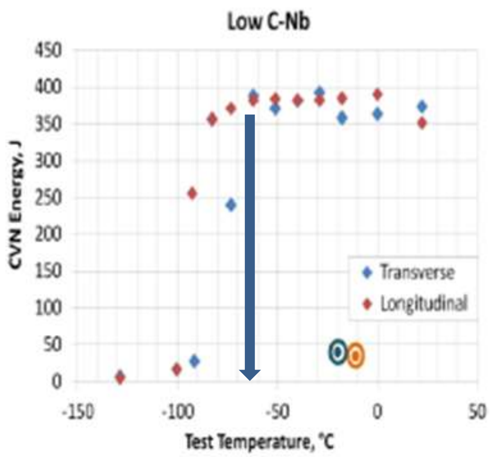


Figure 3. (a) Low C-Nb transverse and longitudinal impact toughness

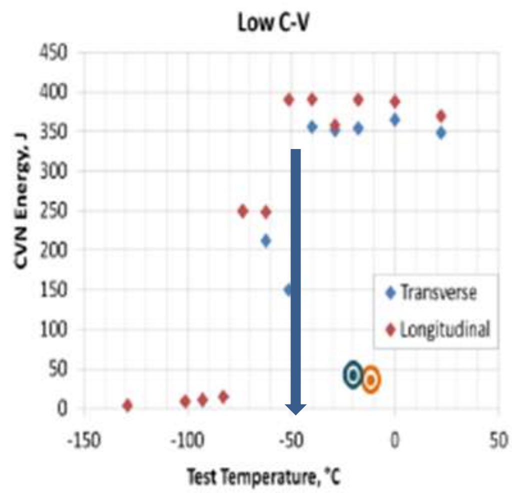


Figure 3. (b) Low C-V transverse and longitudinal impact toughness

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. Based upon the superior isotropic Nb-LCLA, the fatigue and fracture toughness was measured as shown in Table 2.

Table 2. Fatigue and Fracture Toughness Comparison [4, 5]

	Endurance Limit (MPa)	Fracture Toughness (MPa-$m^{1/2}$)
Low C-Nb	303	412
Med C-Nb	269	258
Med C-Normalized	245	275
Low C-V	245	Invalid test J integral*

***** due to anisotropy and microstructure inhomogeneity

The weldability of these low C-Nb plates is significantly improved as well with the move from Zone II for the medium carbon which requires preheating into Zone I which does not require any preheating as shown below in Figure 4.

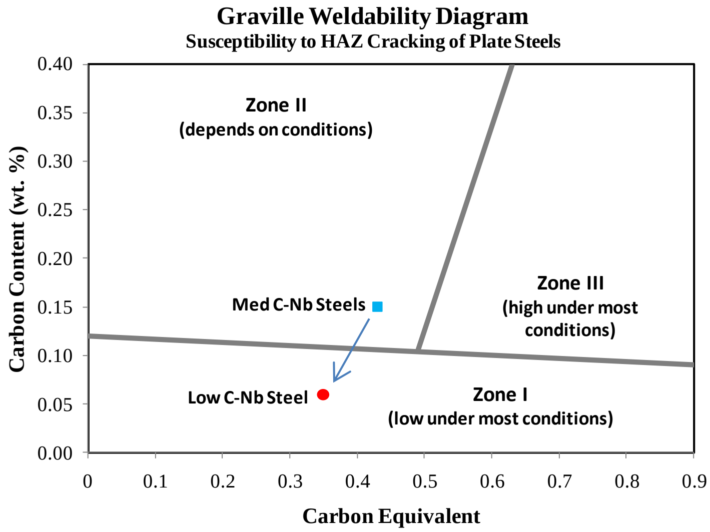


Figure 4. Graville diagram [4]

Nb-Low Carbon Weathering Bridge Steel

A high-performance Q370qE-HPS bridge steel in China with low carbon content (≤0.10wt%), Nb microalloying (0.025-0.050wt%) and low carbon equivalent (CEV) (≤0.38%) has been produced using TMCP procedure. The results show that the microstructure consists of fine-grained quasi-polygonal ferrite (QPF), less pearlite and a large number of finely dispersed 5 to 10 nanometer Nb-rich precipitates. As shown in Figure 5(a) and 5(b), the *E*KV2 (-40°C) of Q370qE-HPS steel plate increases significantly with the decreasing *dα* (interlammelar spacing) or P% (pearlite area fraction). These effects can be described quantitatively by the Boltzmann model.

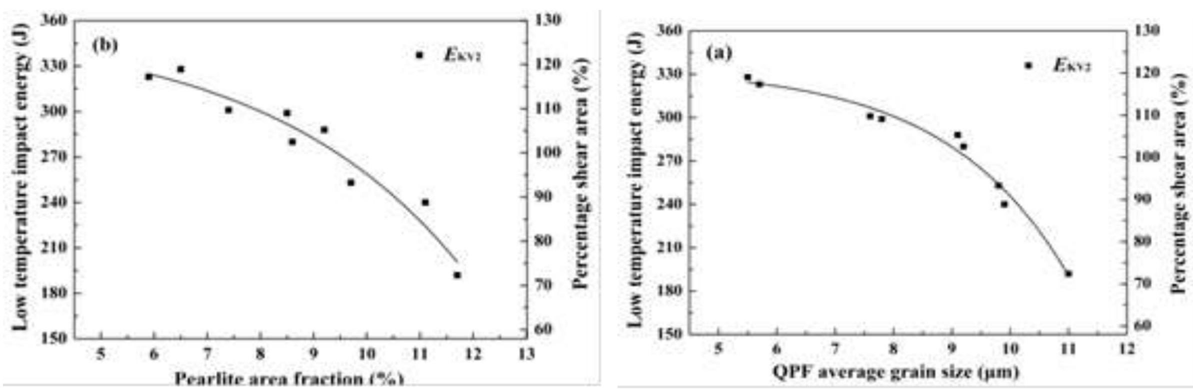


Figure 5. Effects of (a) pearlite area fraction (b) QPF grain size on *E*KV2 (-40°C) [6]

Low Carbon Nb Containing Seismic-Resistant Rebar

Weldable and non-weldable reinforcing steel bars are one of the most important steel products widely applied in civil construction approaching over 240 million tons of usage in 2016. The compelling need for the development of even higher quality rebar for seismic applications is driven by recent catastrophic earthquakes in Haiti, Japan, Peru and China. Therefore, research projects are in progress around the world with a focus on the development of a family of low C-Nb-containing S500 and S600 grades with superior toughness, excellent low temperature energy absorption, fatigue resistance and less yield to tensile ratio variation. The available strength levels of Nb-bearing rebar has increased progressively from S345, S390, S500 and S600 grades. Traditionally, higher strength grades were produced with vanadium. However, recent niobium bearing rebar developments combine clean steelmaking practices of lower carbon steels at the melt shop with selective accelerated and controlled cooling practices at the rolling mill to produce low carbon equivalent high strength and earthquake resistant reinforcing bars. Typical chemistries are shown below in Table 3. The goal is to eventually progress to a "New Generation" ultra-low carbon-Nb-B rebar for the most demanding seismic conditions after the successful evaluation of the less than 0.10%C rebar.

Table 3. Nb-Rebar Technological Development Progression to "New Generation" Nb-Rebar

	C	**Mn**	**Si**	**V**	**Nb**	**S**	**P**	**Cr**	**Ni**	**Cu**	**B**	**N(ppm)**
W/Nb	0.18-0.21	1.10-1.30	0.25 max	-	0.025-0.050	0.015 max	0.020 max	0.20-0.30	0.20 max	0.30 max	-	110 max
LowC+Nb	0.08-0.10	1.10-1.30	0.25 max	-	0.040-0.050	0.007 max	0.020 max	0.20-0.30	0.20 max	0.30 max	-	110 max
New Generation*	0.03-0.05	0.90-1.20	0.25 max	-	0.10 max	0.007 max	0.015 max	0.20-0.30	0.20 max	0.30 max	0.002	90 max

*Not yet industrially produced

The production practices from the melting stage through the crack-free continuous casting of the billets through the hot rolling and accelerated cooling are keys to maximize the niobium effectiveness when producing these high quality, high strength reinforcing bar grades. One major obstacle to improved fatigue and fracture toughness performance involves the traditional Tempcore® produced reinforcing bar which results in a tempered martensite shell and a pearlitic or bainitic core mixed microstructure. This segregated microstructure is old technology and is incongruent with the fundamental goal of a uniform fine grain microstructure to accommodate high fatigue and fracture toughness environments.

There has been limited reliable published research on the impact and toughness properties of rebar. Some fundamental process metallurgy considerations should be incorporated into the production scheme to effectively manufacture homogeneous fine grain size across the entire cross section of S355, S420, S500 and S600 seismic rebars. There is a need to reduce carbon levels of rebar to improve fatigue and fracture behavior is seismic regions. It is initially a two-step process, first moving to 0.20%C and then to 0.10%C. The reduction of sulfur and phosphorous is imperative. The homogeneous fine-grain refinement that results from the Nb addition is critical. Figure 6 schematically captures these three critical success factors in designing and producing consistent high quality rebar with exceptional properties over the currently produced earthquake resistant rebars.

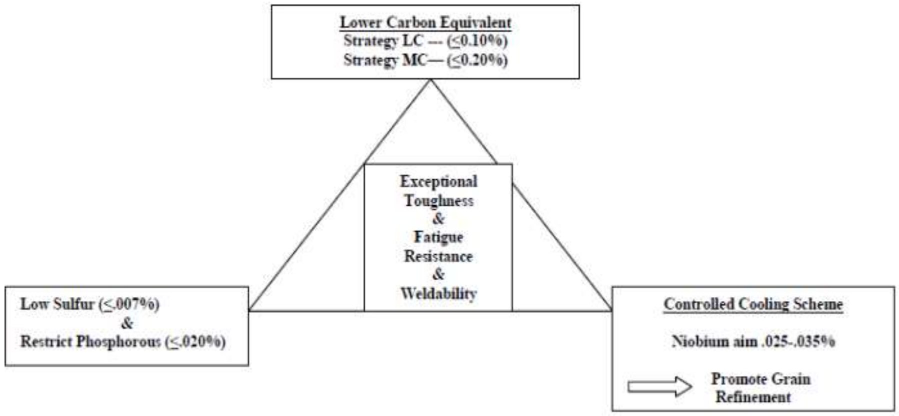
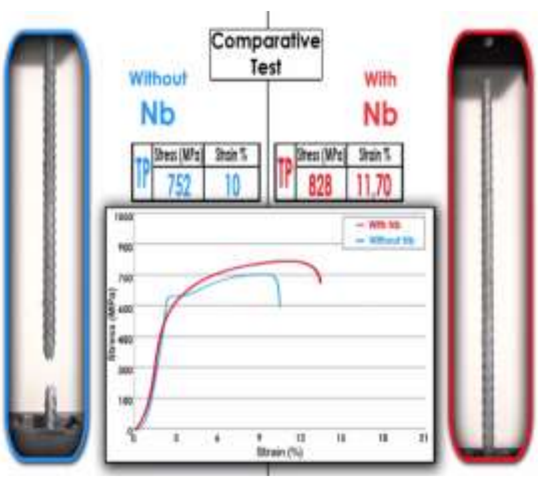


Figure 6. Ultra-tough seismic-resistant rebar approach

The goal is consistent production of lighter-weight reinforcing bar products at a lower carbon equivalent with improved weldability, higher elongation and better toughness at a lower cost. Low carbon grades with microalloys of Nb, Ti and Mo and the judicious application of accelerated/controlled cooling with or without the Tempcore® Process was compared to study the energy absorptive properties via the stress-strain curve behavior. Figure 7(a) below illustrates the stress-strain curve comparison of a high strength mixed microstructure Tempcore® rebar (0.26%C) compared to an air cooled homogeneous fine grain Nb-containing rebar at similar carbon content. Figure 7(b) illustrates the homogeneous fine grain microstructure compared to the discontinuous inhomogeneous Tempcore®-produced microstructure. [7]



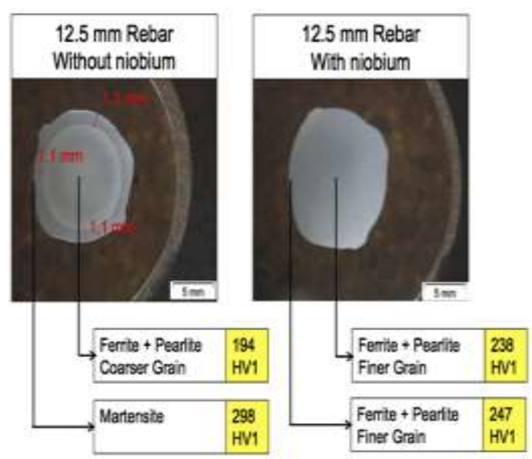


Figure 7. (a) Air cooled Nb-rebar versus conventional Tempcore® rebar

Figure 7. (b) Tempcore® vs. Nb-air cooled rebar microstructure

The chemistry and mechanical properties are shown below in Table 4.

Table 4. Non-Nb Tempcore® vs. Air Cool Nb Rebar

	C	Si	Mn	P	S	Nb	YS(MPa)	TS(MPa)	Elong(%)	TS/YS
Tempcore	0.25	0.15	0.65	0.041	0.034	0.00	620	752	10	1.21
Air-Nb	0.28	0.26	1.00	0.030	0.042	0.02	600	828	13	1.38

The homogeneous microstructure of the Nb-containing rebar is fundamentally favorable for fatigue and fracture toughness for earthquake resistant value added rebar

Conclusions

Several case applications including high rise buildings, wind towers and bridges are presented which exhibit the quality and production advantages of producing Nb-LCLA structural steels at less than 0.10%C compared to the traditional 0.11 to 0.16%C steels. As a result of documented environmental climate change, more severe weather conditions around the globe and increased seismic activity, upgraded construction materials are required in order to sustain increased load, stress, strain and fatigue levels. Niobium-containing low carbon structural steels can meet this need. Nb-steels promote homogenous fine grain microstructures which improve performance under more severe climatic conditions. The 240 million tonne global rebar market is a huge opportunity as well to apply lower carbon fine grained Nb-containing steels with improved fatigue and fracture toughness performance.

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