ADVANCED HIGH STRENGTH NIOBIUM BEARING CIVIL ENGINEERING STEELS IN CONCRETE AND STEEL CONSTRUCTION APPLICATIONS[1]

Steven George Jansto [2]

Abstract

Niobium steel technology is applied in both concrete and steel structural products. Niobium structural steels are displacing conventional higher carbon lower strength structural steels that did not contain Nb. The diverse application of lower strength Nb-bearing angles, beams and sections is well established. The technological development of value-added applications for niobium (Nb) microalloyed construction steels continues globally for advanced high yield strength applications. The civil engineering and end user community demands even higher strength structural bars, shapes, beams and plates with improved properties. Properties such as toughness, improved fire and seismic resistance, better fatigue and fracture toughness properties, more consistent yield-to-tensile ratios and improved weldability are end user demands for both low and high yield strength construction applications. Advanced high strength Nb-bearing steel structural members are being incorporated into buildings, bridges, and heavy equipment applications. Nb-containing high carbon reinforced concrete wire rods and seismic rebars offer improved properties and performance. Finally within construction sector, the shift from the high volume heavier gauge S235 and S275 construction grades to higher strength low carbon Nb-bearing S355 and S420 light gauge steels offer further potential to reduce construction cost with a favorable environmental impact on the carbon footprint.

Key words: Carbon footprint, Fatigue, Fire resistance, Niobium

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[2] *Market Development Manager CBMM – North America, Inc. Pittsburgh, PA. USA.*

1 INTRODUCTION

Value-added niobium (Nb) bearing microalloyed plate steels continue to be researched, developed and commercially implemented throughout the world. These steels successfully meet the ever-increasing material demands for improved mechanical properties and in-service performance for demanding 21st century structural applications. Future material and civil engineering designs will further stretch the mechanical property requirements and performance for these demanding structural applications. Historically, Nb-bearing steels result in structural steel's higher strength at thinner cross sections, improved toughness at both ambient and extremely low tempeatures, better fracture toughness and fire resistance, improved fatigue resistance, reduced yield-to-tensile variation and improved weldability. Such Nb-bearing construction steel applications span diverse global construction market segments such as buildings, skyscrapers and industrial complexes, wind towers, reinforcing bars and pre-stressed concrete wire rods. These steels continue to provide an important role in building construction because of their enhanced properties compare to lower strength conventional construction steels. Another key consideration is the ever-growing concern about the environment and resources. The application of these new, advanced high-strength Nb-bearing steels for structural applications contributes to a significant reduction in the carbon footprint and enhances material resource sustainability.

The unique metallurgical attributes that niobium provides to 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. However, over the last two decades, through 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. For example, through such collaborative activites and global projects. Grades S460 through S960 have been succesfully produced and incorporated into buildings and other structures, such as bridges, offshore platforms and heavy equipment around the world. This diverse array of Nb-bearing construction steel markets and future potential is discussed herein.

1.1 Background Information

The selection of building materials may significantly influence the overall construction cost, construction time, life cycle assessment and sustainability criteria. From a sustainability criteria perspective, specifically the life cycle costs, resource efficiency, recyclability and environmental impact are of keen relevance. Until now, the potential of steel with its wide range of strength classes, mechanical and technological properties has been utilized in some civil engineering applications, but the opportunity to increase its usage within this sector is immense. For example, both the automotive and large diameter pipeline segments have made tremendous technological progress in reducing the weight of components compared to the civil engineering segment.

The carbon steel structural construction segment is by far one of the largest product segments within the global structural market segment in the world. In 2013, over 10 percent of the 950 million metric tons of structural plate and long products production in 2013 contained Nb. The major structural steel product segment distribution for 2013 is shown in Figure 1.

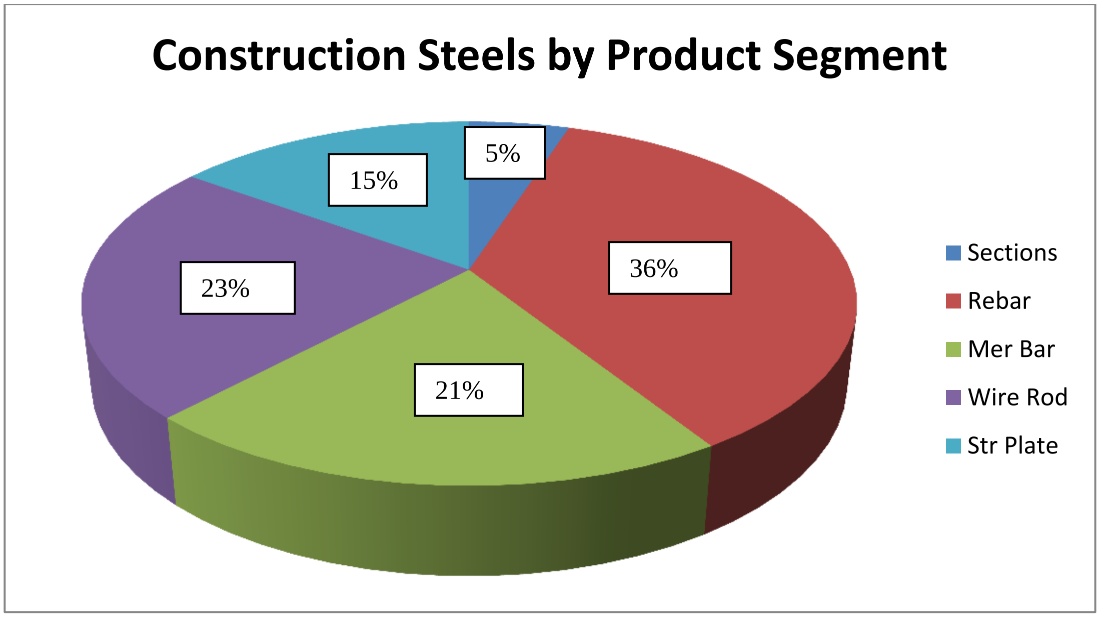

Figure 1. 2013 Construction steel distribution by product sector.

Within the construction steel segment, approximately 70 percent of the steel currently produced is still non-alloyed carbon manganese (C-Mn) steel grades. The highest Nb usage is currently within the structural sections segment (beams, angles and channels) in grade S355 and S420 structural plate for windtower and construction plate for both industrial and non-industrial buildings. Since the building sector consumes large amounts of lower yield strength materials, a huge opportunity exists to transition from the commodity low strength the S235/S275 to S355/S420 and then to S460 and higher. This strategy would increase the application of high strength steel not only improving life cycle assessment and economy of construction, but also improving the competitiveness of steel structures and the technological advantage of the companies involved in the value added process.[(1)] Niobium is applied in most of the advanced high strength microalloyed construction grades from S460 to S980.

Another major construction market segment is reinforcing bars. Within the reinforcing bar market, niobium containing products are evolving replacing vanadium in lower strength rebar where toughness is a requirement of the specification. Another recent value added rebar development involves the commercialization of value-added S500 and S600 seismic and fire resistant rebar. The design trend will continue with traditional lower strength rebar grades by higher strength-higher toughness Nb containing rebar grades. This chemistry is taking advantage of Nb in order to reduce rebar weight on projects as well as improve on the nesting aspect in concrete structures.

Finally, within the merchant bar and wire rod sector, although Nb usage has been quite limited to date, recent developments in the long products sector have resulted in the addition of Nb in high carbon (1085) and alloy (5160, 9260, etc.) long products. The materials development has increased global interest, popularity and application.

1.2 Urban Infrastructure Challenge

It is vital to the well-being of urbanites that infrastructure must reliably provide shelter, energy, water, transportation, waste management and access to food and manufactured goods and services. Building construction in urban areas continues to advance with more of the global population moving to large urban centers. For example, in the United States, 76 percent of the U.S. population lives in cities with that number projected to increase further.(2) In order to ensure that urban centers continue to thrive, architects, designers, engineers and builders will need to think differently about how to build the 21st century infrastructure. The community needs to consider how infrastructure is planned, designed, built and managed such that it creates and connects communities in a sustainable, environmental-friendly and resilient manner. Materials engineering and design play an important role during the planning process. This connection of materials and design requires total integration to meet high performance building standards of excellence. Specifically, attempts to do more with existing lower strength conventional materials and traditional design and connection methods are not the ultimate solution.

These civil engineering infrastructure considerations have increased the recent demand for larger-scale and longer–span designs in high rise buildings and hence the increased demand for higher strength construction steels. Replacement of traditional low strength construction steels with advanced high strength microalloy steel beams, columns, sections, plates, rebar and pre-stressed concrete wire rod is a new trend to address these challenges. Niobium bearing construction products are part of the urban infrastructure challenge solution. Traditional lower strength construction steels are being replaced by microalloyed advanced high strength construction steels. Many of these challenges and opportunities that will define the 21st century will happen in our cities. It is apparent that given the challenges that the major global cities faces, infrastructure, as it is defined, designed, and constructed, needs to evolve from the practices of the earlier century from both civil and materials engineering perspective.

1.3 Historical Development of High Strength Steel Production Processes

The preferred microstructure and desired balance of mechanical properties have been progressively improved over the past several decades through a suitable combination of alloying additions and appropriately designed Thermo-Mechanical Controlled Processing (TMCP). The resultant microstructure of the structural plate can vary significantly depending upon the hot rolling thermal regime and hot reduction schedule. In general, our research has shown that a low carbon bainitic steel offers the optimal solution for most mills producing plates with enhanced strength in combination with adequate toughness. A tempering heat treatment has also been applied to optimize properties, but this approach at times requires a higher carbon steel. Thus, efforts continue to design steels at lower carbon levels for improved weldability. The historical development of these different processing routes and its influence on higher strength steels is shown in Figure 2.

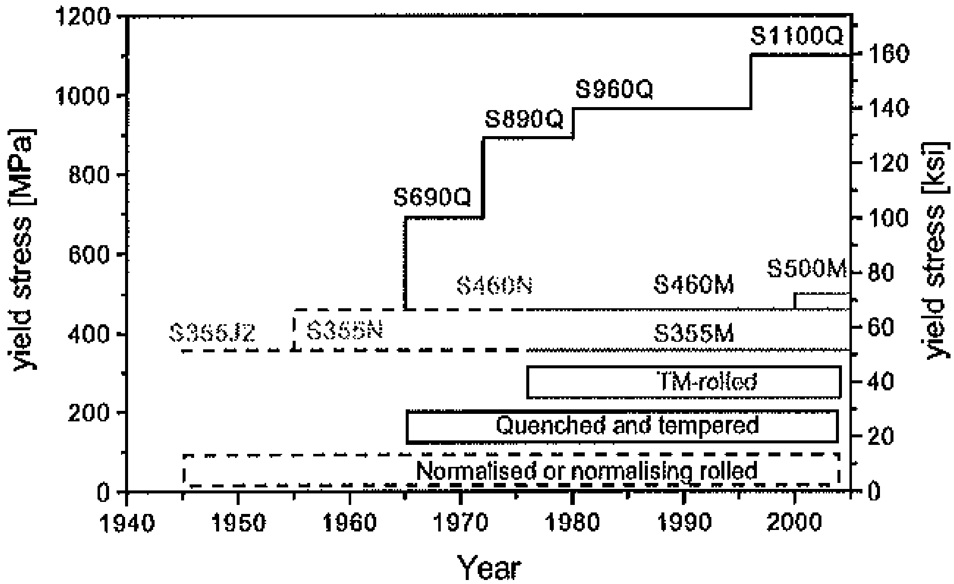

Figure 2. Historical development of production processes for rolled steel products.(3)

1.3 Construction Materials Engineering Paradigm Shift for the 21st Century

The global construction steel market development, research and industrial implementation programs require a shift in the traditional metallurgical approach. Current challenges confronting structural and long product steelmakers are nearly identical in nature to the challenges automotive steel producers confronted in their development of advanced high strength steels over the last two decades. Also, during the evolution of new pipeline steel grades over the last three decades from X-52 through X-100, a shift in both materials and construction design technologies were in order and successfully implemented. For example, in the pipeline sector, successful implementation of appropriate steelmaking and processing operational and cultural changes to apply the High Temperature Processing (HTP) methodology with Nb-bearing steels were achieved in order to overcome production and product quality challenges. Similar challenges currently exist for the construction steel structural segments. Much of this pipeline niobium technology can be transferred to the structural steel production of Nb-bearing construction steels. For example, the adaptation from S355 and S420 to higher strength grades exceeding S460 is quite feasible. The metallurgical and production techniques have already been mastered in the steelmaking and hot rolling operations in many regions of the world.

2.0 Niobium Bearing High Strength Construction Steel Differentiation

A variety of Nb technological structural steel approaches are applied to advanced high strength steels for the construction steel sector. Yield strengths from 355-960MPa have been developed. Depending upon the desired yield-to-tensile ratio requirement, different processing routes are employed. Advanced high strength steel construction steels are defined at 460 to 960MPa and currently represent approximately 5% of the construction steel sector as shown Table 1.

Table 1. Construction Segment Strength Grade Distribution

Timetable Period	Commodity C-Mn	Low Strength HSLA	Advanced High Strength
	S235/S275	S355/S420	S460 to S960
2012-2013	70%	25%	5%
2014-2016	60%	30%	10%
2017-2018	50%	35%	15%

Within the construction steel segment, approximately 70 percent of the steel currently produced is still non-alloyed carbon manganese (C-Mn) steel grades. The largest Nb usage is currently within the structural sections segment (beams, angles and channels) in grade S355 and S420 structural plate for windtower and construction plate for both industrial and non-industrial buildings. There is an evolution of S355/420 moving to advanced high strength microalloyed construction grades from S460 to S960. Over the next five years, drivers for this advanced high strength steel evolution will further evolve from an increased demand for improved fracture and fatigue resistance, lower yield-to-tensile ratios for seismic regions and longer spans, reduced steel weight and overall reduced construction cost. Construction costs may be significantly reduced by up to 20-25% through the adoption of the application of higher strength steels. Table 1 above forecasts the projected shift in steel grade types in the next five years.

2.1 Advanced High Strength Niobium Bearing Construction Steels

In response to these increased infrastructure demands, several structural steel producers from around the world have already developed a family of high performance Nb containing construction plate steels at strength levels of 460 to 960MPa. Microstructures will vary of course dependent upon the production route and a given mill's capability. Also, some steels are designed with lower yield strength to tensile strength ratios for seismic building conditions in regions such as China, Japan and Korea. For example, in order to provide resistance to fracture during earthquakes, the low yield ratio (yield strength/tensile strength) typically lower than 80% is preferable in steel plates for building construction as registered in Japanese Industrial Standards (JIS G 3136).[(4)]

The new version of the Chinese code for design of steel structures provides more flexilibity for newly developed steel materials for building construction. It is no doubt that Nb microalloyed steels with the outstanding mechanical properties will play an even more important role in the construction of high-rise buildings in China and hence, the increased Nb levels as illustrated in Table 2.

Table 2. Chemical composition construction steel specifications-GB/T 1591(5)

Steel grades	level	Chemical composition (percentage) (%) ← Maximum level of elemental concentration (percentage) →														
		C	Si	Mn	P	S	Nb	V	Ti	Cr	Ni	Cu	N	Mo	B	Als
					≤											≥
Q345	A	≤0.20	≤0.50	≤1.70	0.035	0.035	0.07	0.15	0.20	0.30	0.50	0.30	0.012	0.10	—	—
	B				0.035	0.035										
	C				0.030	0.030										0.015
	D	≤0.18			0.030	0.025										
	E				0.025	0.020										
Q390	A	≤0.20	≤0.50	≤1.70	0.035	0.035	0.07	0.20	0.20	0.30	0.50	0.30	0.015	0.10	—	—
	B				0.035	0.035										
	C				0.030	0.030										0.015
	D				0.030	0.025										
	E				0.025	0.020										
Q420	A	≤0.20	≤0.50	≤1.70	0.035	0.035	0.07	0.20	0.20	0.30	0.80	0.30	0.015	0.20	—	—
	B				0.035	0.035										
	C				0.030	0.030										0.015
	D				0.030	0.025										
	E				0.025	0.020										
Q460	C	≤0.20	≤0.60	≤1.80	0.030	0.030	0.11	0.20	0.20	0.30	0.80	0.55	0.015	0.20	0.004	0.015
	D				0.030	0.025										
	E				0.025	0.020										
Q500	C	≤0.18	≤0.60	≤1.80	0.030	0.030	0.11	0.12	0.20	0.60	0.80	0.55	0.015	0.20	0.004	0.015
	D				0.030	0.025										
	E				0.025	0.020										
Q550	C	≤0.18	≤0.60	≤2.00	0.030	0.030	0.11	0.12	0.20	0.80	0.80	0.80	0.015	0.30	0.004	0.015
	D				0.030	0.025										
	E				0.025	0.020										
Q620	C	≤0.18	≤0.60	≤2.00	0.030	0.030	0.11	0.12	0.20	1.00	0.80	0.80	0.015	0.30	0.004	0.015
	D				0.030	0.025										
	E				0.025	0.020										
Q690	C	≤0.18	≤0.60	≤2.00	0.030	0.030	0.11	0.12	0.20	1.00	0.80	0.80	0.015	0.30	0.004	0.015
	D				0.030	0.025										
	E				0.025	0.020										

The specifications for the Q460 to Q690 allow up to a 0.11% maximum Nb and the lower strength structural steels up to 0.07% Nb maximum. Elevated Nb levels are important for the further development of advanced high strength structural steels. These Chinese specifications are unique to other regions of the world that limits the Nb to a 0.05% maximum level for construction steels.

Within the construction sector, there is a parallel with the developmental and evolution scenario that occurred for Nb-bearing high strength HTP pipeline steels. However, one major diffence involves the specification issue just discussed in other regions of the world. Projects such as the East West pipeline in China and the Cheyenne plains in the USA successfully adopted these grades. The steel’s quality and standards in China are continuously advanced. As a result, more niobium micro-alloyed high performance steel will be used. The current Nb alloy structural steel development being performed in China exceeds 590Mpa yielding a low carbon bainitic microstructure at 0.08%Nb. These steels offer four common characteristics of structural steels which are versatility, economy, strength, and endurance. Their widespread use can be accounted for by these characteristics, either individually or in combination

It is quite challenging for some steel producers to obtain a low yield ratio in high strength steels, even in 590MPa (tensile strength) construction steel plate. Consequently, complex heat treatments are usually employed in the manufacturing process in other regions of the world which significantly increases the production cost and extends delivery times. A second benefit is the replacement of lower strength structural steels, thereby reducing the weight and cross section of the members. The stress and strain behavior for the HT780 is shown below compared to lower strength steels in Figure 3. [6]

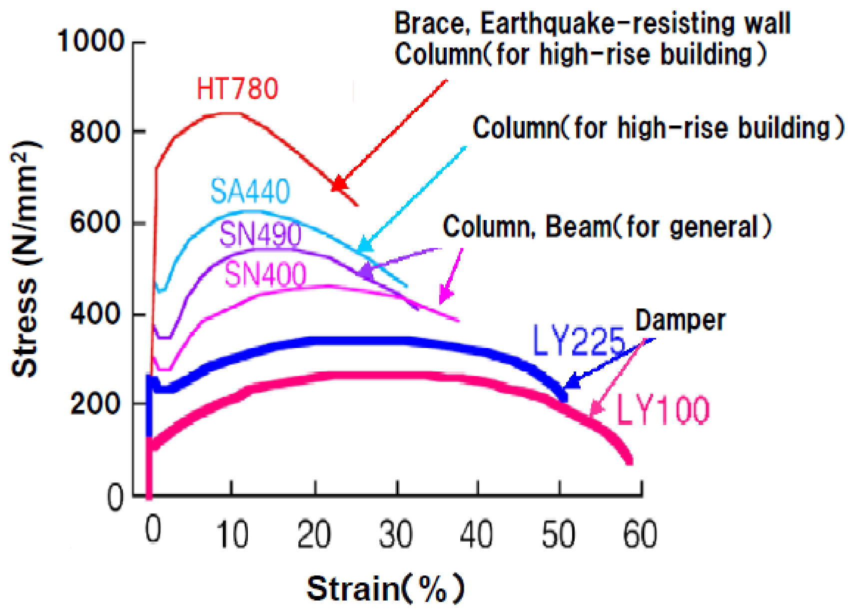

Figure 3. Variety of low yield ratio construction steels

In South Korea, building height is getting higher and the span is longer requiring the application of high performance microalloyed steels. These Nb-bearing steels have been developed to maintain the increased loads and secure high safety and durability. HSA800 is a new niobium (Nb) microalloyed high strength steel plate for building structures was developed by POSCO and RIST in 2011.[7] It has upper and lower bounds for yield (F_y) and tensile (F_u) strength of 650-770MPa and 800-950MPa, respectively, with a yield ratio (F_y/F_u) limit of 0.85. These yield and tensile characteristics improve steel quality, increase building reliability and enhance the seismic resistance of the structure.

High strength, water-quench and tempered structural steels can meet very high strength and toughness requirements. These steel grades have minimum yield strengths ranging from about 550 MPa to approximately 1100 MPa. The temper heat treat process is a critical process step in achieving the appropriate desired strength to toughness balances as well as the specified yield-to-tensile ratio. Table 3 illustrates some chemical compositions for Basic Oxygen Furnace (BOF) produced structural steels at various yield strengths via the TMCP and the Q&T processing scheme.

Table 3. Chemical compositions of BOF produced high strength construction steel grades (Maximum %)

	C	Mn	Si	P	S	Al	N	Ti	Nb	V	Cu	Cr	Ni	Mo
S355TMCP	0.07	1.50	0.30	0.015	0.005	0.02	0.005	0.015	0.030	-	res	res	res	res
S420TMCP	0.06	1.60	0.25	0.015	0.005	0.02		0.015	0.035	-	res	res	res	res
S460Q&T	0.08	1.50	0.35	0.015	0.005	0.03	0.005	0.015	0.025	-	res	res	res	res
S460TMCP	0.08	1,55	0.25	0.015	0.005	0.02	0.005	0.015	0.025	0.05	res	res	res	res
S500TMCP	0.10	1.65	0.40	0.015	0.005	0.02	0.005	0.015	0.040	0.07	res	res	res	res
S500Q&T	0.10	1.40	0.30	0.015	0.005	0.03	0.005	0.015	0.025	0.05	0.20	0.15	0.60	0.20
S690TMCP	0.08	1.80	0.30	0.015	0.005	0.02	0.005	0.015	0.030	0.05	0.30	res	0.50	0.25

S690Q&T	0.12	0.90	0.30	0.015	0.005	0.03	0.005	0.015	0.025	0.04	0.25	0.40	1.00	0.35
S960Q&T	0.12	1.90	0.25	0.005	0.003	0.04	0.004	0.015	0.045	0.08	0.25	1.10	1.15	0.35

3 PRESTRESSED HIGH CARBON WIRE ROD FOR REINFORCED CONCRETE

Several Nb-containing high carbon steel applications over the past several years have employed the Thermomechanical Controlled Processing (TMCP) approach in higher carbon equivalent engineering tool steels. Generally, the TMCP route in some lower carbon engineering steels apply Nb at concentrations of 0.030% to 0.045%, successful Nb additions of 0.010-0.020%Nb have demonstrated improvements in mechanical property behavior, particularly fatigue, fracture toughness and manufacturability. Although the Nb-solubility is lower in higher carbon steels compared to low carbon steels, the grain refinement attribute of Nb still applies. Through empirical evidence and actual operating data, the MicroNiobium® Alloy Approach has demonstrated some very positive results on high carbon grades such as steel wire rods and bars, eutectoid steels such as rail, and other medium carbon engineering alloy applications. This technology has been introduced at an accelerated pace throughout the world and gaining interest around the world.(8)

Many researchers and designers do not consider current applications of Nb in concrete beams, structures and other construction products. In developing a new steel product application, such as the MicroNiobium® Approach in 1080 wire rods for prestressed concrete wire rods, attention must be paid to the important issues such as the following:

(1) The possibility to design a steel grade that will assist in the elimination or simplification of one or more secondary and ternary processing steps, thereby improving productivity and reducing manufacturing costs;

(2) The possible improvement of the new product functionality, extension of the service life, reduces the weight and/or introduces advantages to the final product;

(3) Whether it is possible to eliminate environmentally harmful substances during the processing.

These requirements are not always mutually compatible. Therefore, it is important to proceed with developmental steps based on good understanding of the operational conditions at each of the processing stages, the use condition and the characteristics of the final product for which the steel will be applied. Most recently, the MicroNiobium Alloy Approach new product developmental activity with Nb concentrations of 0.005 to 0.020%Nb have been successfully applied to the following medium and high carbon steel grades and applications; 1) AISI 5160 and 9259 automotive coil springs, 2) AISI1050 automotive fasteners, 3) S500 earthquake/fire-resistant reinforcing bars, 4) 0.20%C abrasion resistant plates for heavy machinery and agricultural, 5) eutectoid steels for rail and pre-stressed wire rod, and 6) carburized steel power transmission components such as 4130 and 6250 grades.(8)

3.1 MICRONIOBIUM IN HIGH STRENGTH PRESTRESSED CONCRETE WIRE ROD

Experimental laboratory heats were produced with Nb, V and Nb+V and then cast in a vacuum furnace. The objective was to compare the mechanical properties and drawability during wire rod production of a single microalloy addition of Nb against a V addition against a dual Nb+V combination. The compositions melted are shown in Table 4.

Table 4. Chemical compositions of experimental heats

	S_0	V1	V2	VNB	NB1	NB2	NB3	NB4
C	0.829	0.778	0.776	0.781	0.811	0.770	0.805	0.791
Mn	0.756	0.707	0.731	0.730	0.760	0.635	0.736	0.723
Si	0.221	0.234	0.218	0.205	0.221	0.193	0.228	0.230
Al	0.004	0.003	0.002	0.002	0.005	0.002	0.008	0.005
Cr	0.144	0.138	0.152	0.150	0.152	0.124	0.156	0.157
Nb	0.002	0	0.002	0.021	0.023	0.038	0.087	0.119
V	0.002	0.092	0.053	0.050	0.003	0	0	0
N (ppm)	69	73	67	73	70	70	70	85

The microstructure of the laboratory produced wire rods were homogeneous and pearlitic for all of the experimental steels. Optical observation did not reveal any incidence of the Nb addition on segregation, decarburization and microstructure homogeneity. The levels of surface defects on the Nb wire rods were compared to the V-containing wire rods and the Nb+V containing wire rods is shown in Table 5.

Table 5. Mechanical properties based on tensile tests

Wire Rod Sample	Yield Strength 0.2% (N/mm^2)	Tensile Strength (N/mm^2)	Reduction of Area (%)
SO	627	1086	30.4
V1	733	1154	26.8
V2	719	1154	22.9
VNB	740	1169	38.0
NB1	648	1139	45.1
NB2	680	1102	41.4
NB3	666	1115	38.4
NB4	709	1150	35.8

Review of the mechanical property data shows the best elongation with Sample NB1 which is the 0.02%Nb MicroNiobium Alloy design at 45.1% reduction of area. The yield strength, tensile strength and reduction of area is met as defined by SO in Table 5. The mechanism of this optimization of the Nb concentration in this high carbon eutectoid steel is the refinement of the lamellar spacing. As exhibited in Figure 2, the refinement of the lamellar spacing is the finest at 75nm with 0.02%Nb directly linking the superior elongation. The optimized composition of NB1 exhibits nearly double the %RA. Figure 4 illustrates the significant refinement of the pearlite. The NB1 composition exhibits the finest interlamellar spacing at 72ɥm.

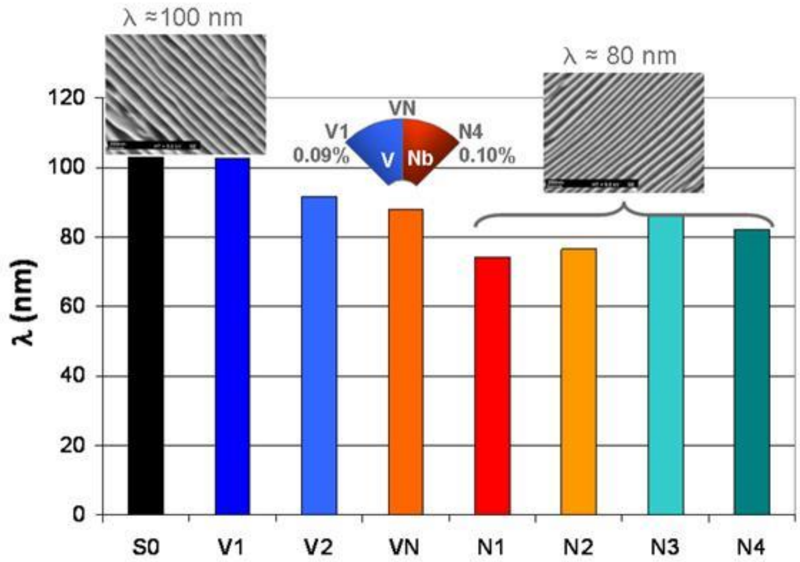

Figure 4. Interlammelar spacing of pearlite in microstructure of as rolled wire rods.

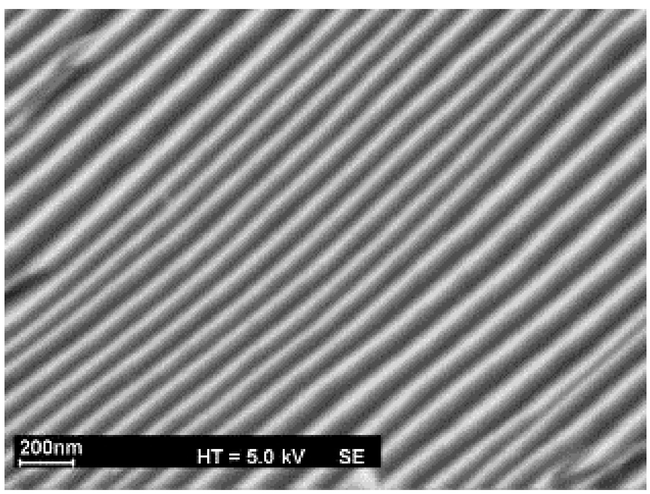

Figure 5. SEM micrograph of sample NB1(0.023%Nb) with finest interlammelar spacing.

5. CONCLUSIONS

The technological development of value-added applications for niobium (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. Nb-bearing construction steels have been and will continue to be developed to address these more demanding applications 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. Advanced Nb-bearing high strength structural steels have been developed and commercialized up to S960. Another evolving Nb product segment involves the high carbon long product prestressed concrete wire rod market. Micro additions of .005 to .020%Nb exhibit improved wire drawability during manufacturing as well as improved mechanical properties compared to traditional non-Nb bearing high carbon steels. Finally, within the construction sector, the shift from the high volume heavier gauge S235 and S275 construction grades to lower carbon Nb-bearing S355 lighter gauge steels and then the next transition to S460 and greater offer tremendous potential to reduce construction cost with a favorable environmental impact on the carbon footprint.

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