Niobium-Bearing Plate Steels for the 21st Century

Steven G. Jansto
CBMM-Reference Metals Company
1000 Old Pond Road, Bridgeville, PA 15017, USA
Phone: (412) 220-3041 Fax: (412) 221-7355
email: jansto@referencemetals.com

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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. 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 include boiler, bridge, container, heavy equipment, off-shore platform, oil and gas pipeline, pressure vessel, ship, storage tank and windtower applications. Metallurgical Operational Implementation (MOI©) links the product requirements to mill capability to process metallurgy implementation. This integrative process connects the process and physical metallurgy necessary to the desired ultrafine grain, homogeneous plate steel microstructures that result in superior toughness, strength and weldability. 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 reduction in the carbon footprint and material resource sustainability. A bridge sustainability case study is presented.

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 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. Nb-bearing structural products are now specified in a variety of applications and markets. The diverse array of structural steel markets and future potential is discussed herein. Finally, the process metallurgy required to consistently and cost effectively maximize the effectiveness in the melting, casting and rolling operation is outlined.

BACKGROUND

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. 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 are specified for different end-user requirements. Today's structural steels demand properties such as: 1) improved toughness at lower temperatures, 2) higher yield strengths for lower cross-sectional area of structure, 3) higher elongations, 4) improved weldability to reduce construction time, 5) improved elevated temperature properties, 6) improved fracture toughness, 7) seismic-resistance and 8) improved fatigue resistance. Cross-application of Nb-bearing steels has resulted in a variety of large-scale structural designs with improved properties for diverse products from beams to storage tanks.

Niobium-bearing Steel Structural Application Overview

The carbon steel structural segment is by far the largest global steel segment in the world. In 2010, over 10 percent of the 760 million metric tons of structural plate and long products production in 2010 contained Nb. The major structural steel product segment distribution for 2010 is shown in Figure 1.

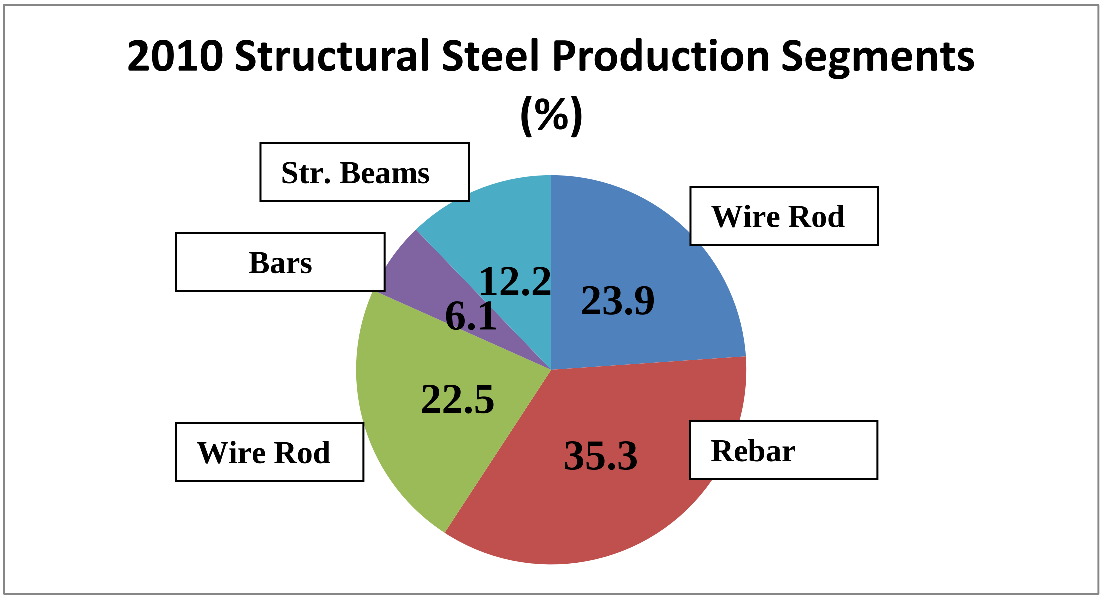

Figure 1. Global steel long products and plate production steel segment distribution

The current application of Nb in structural steels is more predominant in the structural plate and beam segment than in the long product segments such as wire rod, rebar and merchant bar. Current and future product development activities are making technological advancements within the Nb-bearing high carbon and alloy long product segment. For example, with the increasing demand for fire-resistant and seismic-resistant construction materials, the S500 and S600 Nb-Mo reinforcing bar research and industrial trials support applications in reinforced-concrete bridge, building and tunnel construction.

The global structural steel market development, research and industrial implementation requires a shift in the traditional metallurgical approach. Current challenges confronting structural and long product steelmakers are similar in nature to the challenges faced by automotive steel producers in their development of advanced high-strength steels in the last decade. Similarly, during the evolution of pipeline steel development from X52 through X100, similar challenges resulted in steelmaking and processing changes to successfully apply High Temperature Processing (HTP) to overcome production and product quality challenges. Much of this developed technology can be transferred to the structural steel production of Nb-bearing steels.

The successful production of value-added structural products requires the application of meltshop and rolling mill practices that in many cases are similar to practices for value-added automotive, pipeline and structural grades. Tighter process control during the melting, casting, slab/bloom/billet heating and rolling is necessary to make improved properties. Different control strategies are required for the production of these high-quality construction steels. These strategies include lower residual element levels, scrap segregation, lower sulfur and phosphorous levels, the adoption of a low-carbon approach, control of nitrogen levels at the basic oxygen furnace (BOF) or electric arc furnace (EAF) and at the billet/bloom/slab caster. Such operational and metallurgical practices were once considered unnecessary in long product structural production. However, the future generation of value-added long products will demand changes in operational practices similar to the adaptive developmental progression within the automotive, pipeline and plate producer community.

Nb-bearing structural plate, beams, rod and bar find their niche and application in numerous end-user segments and are entering some new product development segments as illustrated in Table 1.

Table I. Nb-bearing end-user steel application and development by structural segment

Structural Plate	Beams & Str. Shapes	Bar	Wire Rod	Structural Pipe & Tube	Rebar
Windtower supports	Light to jumbo beams	Spring steels	High carbon pre-stressed	Structural scaffolding	Seismic resistant
Bridge	Bridge	Forging quality	Engineering	Construction	Fire-resistant
Pressure vessels & containers	Buildings (Freedom Tower)	Automotive suspension systems	Cold headed	Irrigation and utilities	Bridges
Railway tank cars & rail cars	Power plants	Carburized gears & shafts	High-strength bolts	Boiler tubing	Buildings
Ship plate/Offshore platforms	Trailer support rails	Quench & Temper	Wire rope	Utility power plants	Tunnels
Heavy machinery	Rails				

21st Century Niobium-Bearing Structural Steels: Challenges, Changes and Opportunities

Different from the automotive or pipeline segment where carbon levels are typically less than 0.10%, many of the plate structural products exceed 0.15%C approaching allowable specification maximum carbon levels of 0.22%. There is a still a preponderance of structural plates and beams produced throughout the world with carbon levels greater than 0.18%C. There are various reasons for this including the process metallurgy, mill configuration and furnace reheating efficiency and performance. Some mills choose the higher carbon level approach to achieve strength, but sacrifice toughness, weldability, product performance and increased operational expense. [1]

Some mills have been unable to adapt their heating and rolling operations to accommodate low-carbon microalloy mechanical metallurgy practices. In these cases, the plate production approach has not taken full advantage of the Nb solution to lower carbon levels which increases yield strength, ductility, toughness and weldability. The introduction of new process metallurgy technology and practices offer attractive cost benefits when incorporating a low-carbon low-alloy (LCLA)© grade strategy. Specific LCLA Nb-bearing microalloy value-added steel applications and future development activities play a key role in the improvement of product quality, properties and operational margins. Within the long products sector, the addition of Nb in high-carbon and alloy long products is increasing in popularity and application as evident in Table 1.

Niobium Product Development Opportunities

Steel value-added markets require; 1) exceptional toughness and low temperature properties, 2) excellent yield strength to tensile strength balance with minimal σ_{ys} to σ_{ts} ratio variation, 3) ultrafine grain microstructure, 4) excellent weldability and 5) exceptional fatigue resistance. More consistent low sulfur and low phosphorous steels with calcium shape control and restricted residual levels are required to produce the demanding toughness requirements at low temperature, reduce yield to tensile variation, improve fatigue performance and improve weldability.

These are opportunities and challenges for the adaptation of Nb technology in the following areas:

- Development of a more economical Low-Carbon Low-Alloy (LCLA) steel incorporating accelerated cooling in the rolling mill to replace some rich alloy steel grades.
- Shift more construction structural grades to less than 0.10%C incorporating TMCP and Nb technology (i.e. S355 and S460 LCLA-accelerated controlled cooling approach).
- Further develop the application of 0.005-0.020%Nb for fine grain refinement in over 0.50%C steels (rail steels, heavy equipment, abrasion-resistant plate).
- Take advantage of the Nb-Mo nano co-precipitation synergy to develop a family of fire-resistant and seismic-resistant S500 and S600 rebar.
- Commercialization of fire-resistant plate/beam construction steels.
- Grain refinement of Ni bearing pressure vessel steels with improved creep and fatigue performance.

- Adapt the automotive approach to reduce the mass of a vehicle for fuel economy and reduced emissions to the application of high-strength low-alloy steels to accommodate lighter cross-sectional thicknesses in civil engineering design to result in less mass in the structure. This also results in reduced emissions and reduced energy consumption in the steel producing and welding operations.
- Reinforced concrete versus steel bridge design approach continues to be closely analyzed from a carbon footprint perspective considering the resource sustainability and emissions considerations.
- Use Nb grain refinement (Micro Niobium AlloyApproach©) to create a finer grain microstructure in virtually all carbon steel grades for improved processability at the steel mill (i.e. reduced cobbles, reduced diverts, higher productivity).
- The concentration of Nb in structural applications must be carefully controlled at lower levels compared to the higher Nb levels currently used in automotive and pipeline steels.

Nb-Bearing Structural Beams

Over 50% of the structural plate and beam sections are intermediate carbon levels from 0.15 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. [2]

Excellent research and development progress has resulted in the successful commercialization of lower carbon Nb-bearing microalloyed plate steel and near net shape cast and rolled beams throughout the world. Many of these progressive metallurgical accomplishments are presented within this text. With increasing raw material and energy costs, the effects of processing parameters such as reheating temperature and cooling rate after hot rolling to achieve improved mechanical properties can result in significant savings. A lower total cost of production may be achieved through a low-carbon low-alloy (LCLA©) chemistry with selective accelerated cooling and better control of reheat furnace temperatures. [2]

The ASTM 992 beam (S355) study was based on industrial heats which then lead to the commercialization of low-carbon Nb-bearing beam in place of a low-carbon V-only bearing beam. 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 grain by two ASTM sizes, lowers the carbon equivalent by 0.07% and improves the toughness. Near-net-shape cast structural beams containing only a single Nb microalloy exhibit double the impact strength at room temperature compared to a V-only microalloy system at similar carbon, sulfur, phosphorous and nitrogen levels and cooling rates as illustrated in Figure 2. [3]

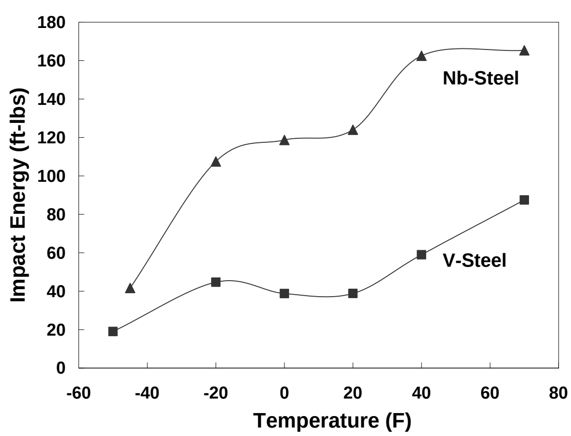

Figure 2. Charpy V-notch impact strength comparison

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 degenerate pearlite together with conventional ferrite-pearlite. With increase in cooling rate, there was an increased tendency towards the formation of lath ferrite/bainitic ferrite with consequent decrease in conventional ferrite-pearlite microstructure. [4] Figure 3 illustrates the influence of Nb on the transformation to the formation of degenerate pearlite which contributes to the improved toughness. No degenerate pearlite was observed in the V-bearing steel grade.

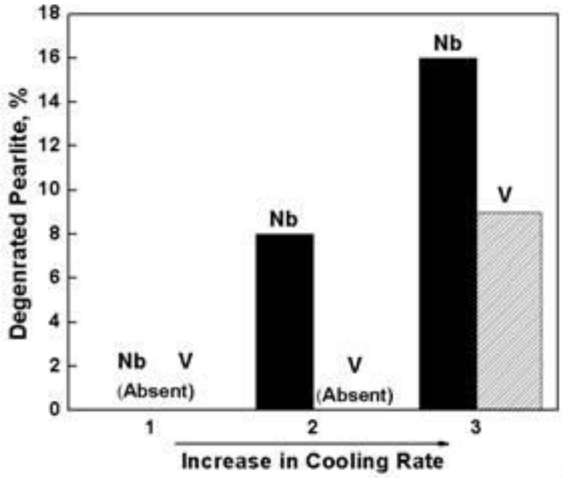

Figure 3. % degenerate pearlite of Nb- and V-microalloyed steels. [5]

Bridge Steels

The opportunity exists for the global steel industry to further develop value-added high-performance bridge steel materials that will meet future construction and performance needs of the market. Because of increasing raw material, fabricating and steelmaking costs, the civil engineering community demands bridge steels that result in faster and lower cost replacement for bridges in the USA and Europe, as well as for new bridge construction in Brazil, China, Russia and India. There is a major opportunity and demand for the development of even lower carbon-lean alloy bridge steels. Many current High-Performance Steels of 490 and 700MPa compositions are rich alloy compositions resulting in high cost to the end-user. Global research activity in some areas of the world is focused upon the development of a lower cost Nb-bearing LCLA bridge steels meeting the properties of HPS 50W, HPS 70W and HPS 100W.

The World Bridge Symposium assembled the civil engineering community in 2007 to present their viewpoints on current global bridge design and fabrication. [6] As in Europe and the USA, China has evolved through the progression of low-strength 16Mnq series (345MPa) steels which lacked grain refinement and controlled rolling to its current focus on bridge steels using high-strength steels (530 and 690MPa) to sustain loads, provide seismic and corrosion resistance and improve fabrication. Currently, through the application of clean steel-low carbon Nb technology, the development of such grades as the WQ530E (14MnNbq), WNG 570 and WNQ690 has been applied in many bridges such as the construction of the Nanjing Dashengguan Yangtze River Bridge. The weathering steel grades of WNG 570 and WNQ690 are specifically designed to offer high yield strength, good toughness and excellent corrosion resistance for long-span bridges. [7]

In addition to the move toward lower carbon plate steels, additional research on new types of high-strength bridge steels with excellent weldability and low temperature toughness is necessary. Wuhan Iron and Steel Company has developed a series of high-strength bridge steels with an ultralow-carbon bainitic microstructure (WNQ570 steel and WNQ690 steel). The bainitic WNQ570 steel is successfully applied to Nanjing Dashengguan Yangtze River and the cantilever beam in an offshore drilling platform. The WNQ690 steel is successfully installed in the Floating Crane made at Shanghai Zhenhua Port Machinery Company. [7]

Some bridge steels in Europe typically contain 0.015 to 0.040% Nb. For example, Grade 460ML (EN10025) was utilized in thicknesses up to 100mm for the construction of the Ilverich bridge near Dusseldorf airport. The special high-strength pylon design was necessary due to the low flight paths with the bridge located in close proximity to the airport. Low-carbon CuNiMoNb steel with a carbon equivalent CE_{IIW} of about 0.39% was selected. The design exhibits superior toughness criterion of 27J at -80°C. [8]

The process metallurgy applied for these advanced high-strength weathering bridge steels necessitate ultralow-carbon acicular ferrite microstructures, strict secondary ladle metallurgy practices (i.e. less than .005%S and less than .020%P), selective scrap charge segregation to minimize residuals, and incorporation of TMCP practices regardless of the mill configuration.

The progression of bridge development is similar to the development of high-strength pipeline steels. This cross application of process and physical metallurgy first develops from a microstructure of ferrite and pearlite defined by large differences in grade composition, usually higher carbon levels and microstructure. The next development involves a bainite and ferrite microstructure in which the composition level does not vary much and carbon levels are reduced. Finally, the current plate production trend moves toward an acicular ferrite which transforms at intermediate temperatures with good uniformity of composition and microstructure. Through the progression of such process metallurgy development programs, an industrial trial may attempt to produce perhaps an X80 pipeline steel. If not successful, the material can be reapplied to a structural grade of similar dimension.

Bridge and Materials and Civil Engineering Feasibility Study

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

The following study illustrates the significant reduction in emissions (pounds of CO_2) and energy consumption (mmbtu) comparing a bridge constructed from 10,000 tons of S235 steel versus a 9,000 ton S355 Nb-bearing HSLA steel bridge at 0.03%Nb. The 10% weight savings is a conservative estimate considering bridge design stiffness, specification requirements and design considerations. The results of the analysis are shown in Table 2 (CO_2 emission reduction) and Table 5 (mmbtu savings) compares steel plates and beams melted via the BOF versus the EAF route. [9]

Table 2. CO_2 Emission savings – BOF vs. EAF comparison

Factor	**BOF (pounds CO_2 per ton of steel)**	**Emission Reduction (x 10^5 pounds CO_2)**	**EAF (pounds CO_2 per ton of steel)**	**Emission Reduction (x 10^5 pounds CO_2)**
Coke savings	102	1.02	0	-
Blast Furnace	2000	20.0	0	-
BOF	490	4.9	0	-
EAF	0	-	1012	10.12
V Degas/Ladle Met	78	0.78	141	1.41
Cont Cast	39	0.39	39	0.39
Hot Rolling	376	3.76	282	2.82
Pickling	155	1.55	85	0.85
CO2 Reduced Emissions	**-**	**32.40**	**-**	**15.59**
Reduced CO_2 Emissions 1,620 tons from BOF & 779.5 from EAF				

Table 3. Energy savings – BOF vs. EAF comparison

Factor	**BOF (mmbtu per ton of steel)**	**Energy Reduction (x 10^9 btu)**	**EAF (mmbtu per ton of steel)**	**Energy Reduction (x 10^9 btu)**
Coke savings	**3.35**	**3.35**	**0**	**0**
Blast Furnace	**10.73**	**10.73**	**0**	**0**
BOF	**0.88**	**0.88**	**0**	**0**
EAF	**-**	**-**	**5.25**	**5.25**
V Degas/Ladle Met	**0.62**	**0.62**	**1.07**	**1.07**
Cont Cast	**0.29**	**0.29**	**0.29**	**0.29**
Hot Rolling	**2.30**	**2.30**	**3.53**	**3.53**
Pickling	**1.21**	**1.21**	**0.68**	**0.68**
BTU Reduced Energy Consumption (x10^9)	**-**	**19.38**	**-**	**10.82**
Reduced Energy Consumption 19,380MMBTU - BOF & 10,820MMBTU - EAF				

Pressure Vessels

There is a growing global pressure vessel market that demands improved performance, fabricability and cost-containment. The pressure vessel plate market is quite diverse with end-market segments such as reaction vessels, heat exchanger vessels, storage containers, corrosion-resistant vessels and cylinders of multilayered clad high-pressure vessels. The market for LNG and LPG pressure vessels is increasing with the growing global demand for natural gas and propane. Boiler plates are used in the manufacture of cylinders and shell covers for low- and high-pressure boilers. Within some of these product segments, specifications are some of the most stringent for any plate steel. Non-alloyed or Nb-bearing microalloyed steels with minimum 460MPa yield strength are applied in many such products.

ThyssenKrupp Stahl produces high-quality Nb-bearing heavy plate for several pressure vessel products. The plate thicknesses are typically between 10mm to 50mm and are characterized by: 1) high-strength and toughness, 2) good cold formability, 3) high fatigue strength and 4) favorable weldability. For example, within the combination P265GH/ASTM A516 Grade 60 it is found that the minimum toughness (specified at 27J at -51°C) cannot be achieved with sufficient reliability when testing steels without Nb micro-alloying. Nb is added within the limit values in the range of up to 0.02% as specified in the standards. As a result of the grain refinement, toughness improves, and the mean increase of the impact energy at -51°C is approximately 60J. [10]

Figure 4 shows a list of the strength properties of plates of different thickness for the (pressure) vessel construction, which simultaneously cover the qualities S355J2+N, P355N (L) according to DIN EN 10028 and the ASTM A516 Gr. 70. It is evident here that, particularly regarding the tensile strength, there is a comparably narrow scatter width for acceptable values.

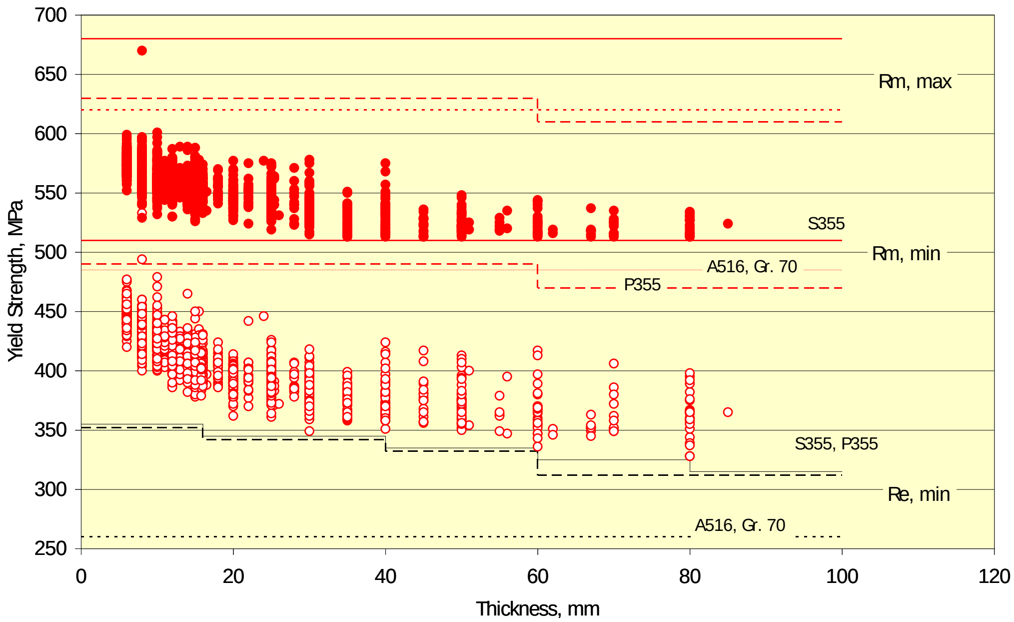

Figure 4. Strength properties of multi-grade S355N/P355N/ASTM516Gr.70 [10].

Microalloying with Nb inhibits grain growth due to the formed carbides and carbonitrides, and the critical temperature for the initiation of the grain growth is shifted to higher temperatures. [11]

Pressure vessel steel production in China initiated with development of the 370MPa grade. Subsequently, improvements were made on Charpy Vee-notch at -20°C and weldability and fabricability with the development of the 15MnNbR grade (570MPa) by WISCO. This grade is applied to LPG and propylene spherical pressure vessels with a maximum volume of 3,000 cubic meters. [12]

Ship Plate

The shipbuilding industry is focused upon increasing productivity, reliability and quality while simultaneously improving the safety, efficiency and environmental performance at an optimal cost. There exists a compelling need to further improve the resistance to brittle fracture, fatigue performance and improved saltwater corrosion resistance. These demands apply to a variety of ship types including oil tankers, container ships, LNG ships, bulk carriers, LPG ships, chemical tankers and automobile transport vessels. The welding of ship plate has made remarkable progress over the past few years. Welding methods have been developed which allow for the application of high heat inputs per pass on heavy thickness Nb-bearing plates so that shipbuilding productivity is more efficient.

Bainitic steels have inherently become a more popular microstructural solution characterized by high-strength with high toughness and adequate weldability. Certainly, the process metallurgy practices discussed earlier involving clean steel practices, residual element restrictions, casting and thermomechanical control are of paramount importance. The clean steel and TMCP route at Dillinger is an excellent example. [8]

Value-added Nb-bearing ship plate has been successfully developed by Nippon Steel. Grade YP460MPa heavy ship plate has high toughness, excellent crack arrestability and large input weldability for hull structures of mega-container ships. [13] EH47 Nb-bearing plate with the appropriate welding techniques, which have been developed for mega-container ships, provide a compelling solution for three major challenges in heavy plate: 1) improved reliability of fracture toughness preventing brittle fracture and improve the ability of the base metal to arrest the brittle crack propagation, 2) improved fuel efficiency by reduced weight with less plate cross-sectional area and 3) improved productivity in shipbuilding by welding with a large heat input.[14]

These heavy thickness steel ship plates offer an excellent balance of strength, toughness and weldability for large container ships. High-strength steel plates with heavy gauges of EH36, EH40 and EH47 have been developed by POSCO through the optimization of chemical compositions and TMCP process parameters with 0.02%Nb levels in all three grades. Also, the EH36 steel plates are designed for high welding heat input rates over 550kJ/cm with the addition of TiN particles to improve HAZ toughness. [15] The strength of base plates of EH40 and EH47 significantly increased due to the synergistic effect of Nb and B, since the soluble Nb complements the effect of B on the mechanical properties. [16]

Anshan Iron and Steel Group in China has embraced the low-carbon – Nb microalloying approach and optimized TMCP in the successful production of steels for shipbuilding and cross-application into offshore platforms using C levels between 0.03-0.05% in a Mn-Nb system with low-alloy contents (Cr, Ni, Cu and Mo) for a family of 420MPa, 460MPa, 500MPa and 550MPa grades which provide excellent toughness down to -60°C (250J at 14mm thickness and 200J at 80mm thickness). [17] This low-carbon approach allows flexibility for the steel producer to obtain a homogeneous fine grained intermediate transformation microstructure of bainite and/or acicular ferrite microstructure over a wide cooling range during the accelerated cooling of heavy gauge plate.

METALLURGICAL OPERATIONAL IMPLEMENTATION (MOI) ©

The process metallurgy, physical metallurgy and resultant properties are significantly determined by mill capabilities, mill practices, operational understanding and the culture of the steel mill. The optimal combination and implementation aspects that are unique to each mill we call metallurgical operational integration (MOI). MOI is the bridge that links the product requirements to mill capability and process implementation. Product research and development from the laboratory to the mill production floor requires a disciplined transfer of technology from research to the mill. Fully appreciating a given mill's melting and heating strategy by steel grade, rolling mill horsepower limitations, reheat furnace practices and resultant thermal profiles throughout the rolling operation are key. [2] Even with all that, unless the leadership of a steel mill takes initiative and remains committed, the development of newer, more challenging grades may not happen. Figure 5 schematically illustrates the five key parts of the MOI process.

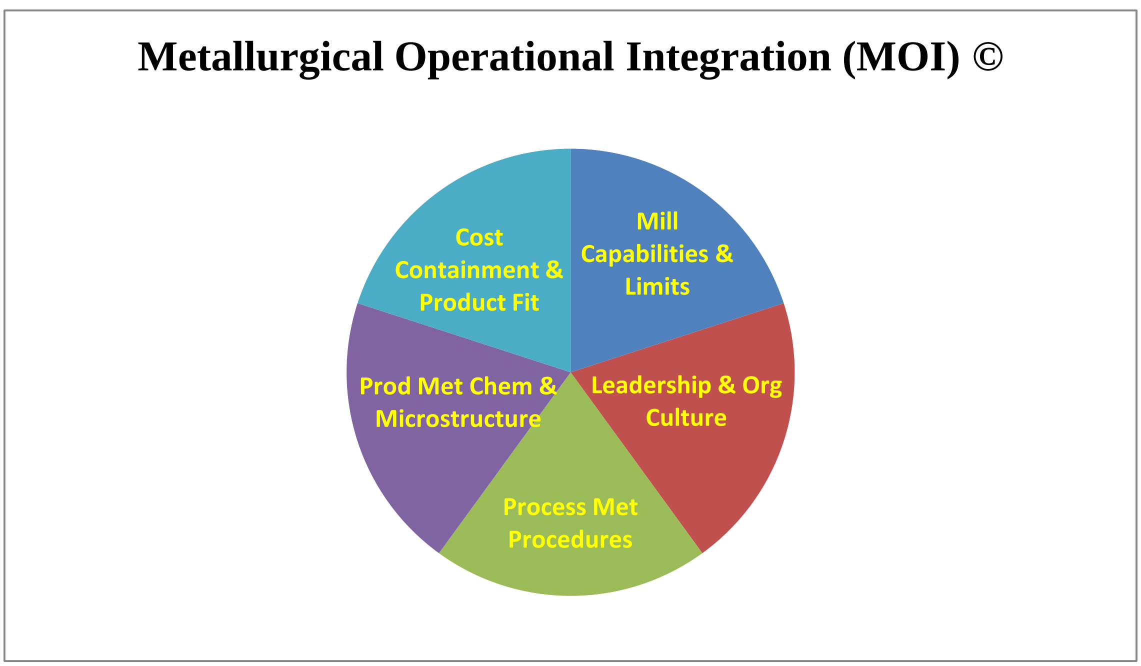

Figure 5. Metallurgical Operational Integration

Process metallurgy to use Nb specifically relates to a few critical parameters which can significantly affect product property quality and variability: 1) melting practices and controlled residual elements, 2) clean steel, 3) continuous casting quality, 4) homogeneous heating of slabs, billets and blooms, 5) consistent thermomechanical rolling practices, 6) consistent quenching to minimize property variation and 7) possible incorporation of accelerated cooling. The physical metallurgy includes: 1) microstructural control through grain refinement, 2) controlled phase transformations, 3) fine precipitate distributions, 4) minimization of carbon levels on plate grades and 5) through thickness microstructural/grain size consistency. The mechanical property attribute relates to: 1) consistent yield to tensile ratio balance, 2) toughness and low-temperature performance, 3) weldability, 4) corrosion, 5) fire and seismic resistance and 6) improved manufacturability at the mill and end-user. Every mill is different, and a particular new product may or may not fit as cost effectively from one mill compared to another. This makes a significant difference in margin maximization and mill productivity.

Experience indicates that laboratory simulations or models do not exactly represent actual mill melting and rolling operations. Although many times the results are close, often they are not good enough for the first trial so more than one industrial trial may be necessary to successfully execute new product development. The MOI analysis increases the probability of success. Data from trials of the process and physical metallurgy parameters previously discussed must be examined closely to correlate process parameters with resulting properties to develop Standard Operating Practices (SOP's). Since each mill is unique, there is no universal scheme regarding the chemical composition, melting practice, reheat furnace soak temperature, and hot rolling regime. Carefully controlled mill trials should integrate the actual melting, casting, furnace and rolling mill operational results and variations of the process into the final analysis to refine standard practices to achieve desired mechanical and high-temperature properties.

Very importantly, there is a leadership and organization cultural aspect that contributes to higher success rates for new product development. These characteristics include initiative and commitment. This is another reason why some mills will be more successful than others in the development of new products.

In summary, MOI encompasses the process/physical metallurgy and specific mill culture and capabilities to achieve desired results for new product development. This integration necessitates a thorough understanding of melting, secondary metallurgy, reheat furnace combustion, hot rolling and quenching mill capabilities, along with a mill's cost drivers, culture and commitment to achieve success. A sophisticated understanding of how Nb can be used to achieve desired properties in 21st century structural steel markets promises to yield exciting opportunities and lucrative results for steelmakers who are dedicated to doing so.

REFERENCES

[1] S. Jansto, “Niobium Market and Technical Development for Civil Engineering Structural Applications,” *International Symposium of HSLA Steels for the Construction Industry*, Tianjin, China October 22-23, 2007.

[2] S. Jansto, “Cost-Effective Microalloy Structural Steel Balance of Process Metallurgy and Materials Engineering,” *MS&T Conference*, Pittsburgh, PA, October 2008.

[3] D. Misra, S. Shanmugam, T. Mannering, D. Panda, and S. Jansto, “Some Process and Physical Metallurgy Aspects of Niobium Microalloyed Steels for Heavy Structural Beams,” *International Conference on New Developments in Long Products*, 2006, pp. 179-187.

[4] D. Misra, T. Mannering, D. Panda and S. Jansto, “Physical Metallurgy of Nb Microalloyed Steels for Heavy Structural Beams,” *Niobium Bearing Structural Steels*, TMS, October 2010, pp. 123-138.

[5] S. Shanmugam, R.D.K. Misra, T. Mannering, D. Panda and S.G. Jansto, *Materials Science and Engineering A*, Vol 437**,** 2006, p436-445; and Vol 460-461**,** 2007, pp. 335- 343.

[6] *World Bridge Symposium* 2007, New Orleans, Louisiana.

[7] A. Guo and Lunxiong Yi, “Development and Application of Steels for Bridges and Buildings in China,” *Niobium Bearing Structural Steels*, TMS, October 2010, pp. 47-62.

[8] Fluess, R. Valentin, V. Schwinn, F. Hanus “Application of Nb in TMCP Structural Steel Plates with Thicknesses up to 120mm,” *Niobium Bearing Structural Steels*, TMS, October 2010, pp. 89-106.

[9] S. Jansto, “The Contribution of Niobium-Bearing Steels and Enhanced Sustainability,” *HSLA Steels 2011*, Beijing, China, May 2011.

[10] J. Gottlieb, A. Kern, U. Schriever and G. Steinbeck, “High-Performance Steels for Pressure Vessels,” ThyssenKrupp Steel AG, *Niobium Bearing Structural Steels*, TMS, October 2010, pp. 415-428.

[11] A. Kern, W. Reif: *Steel Research*, 57 (1985), Nr. 7, pp. 321-331.

[12] Q. Xu, “Present Status and Future Developments in Pressure Vessels and Steels in China,” *Niobium Bearing Structural Steels*, TMS, October 2010, pp. 395-400.

[13] A. Yoshie, “Recent Developments of Nb-Bearing Structural Steels for Ships and Infrastructure at Nippon Steel,” *Niobium Bearing Structural Steels*, TMS, October 2010, pp. 291-308.

[14] S.Sasaki et al., “Development of Two-Electrode Electro-Gas Arc Welding Process,” *Nippon Steel Tech. Report*, 380(2004), p. 57.

[15] O. Kwon, C. Lee, S. Kim and K. UM, “Niobium Thick Steel Plates for Large Container Shipbuilding,” *Niobium Bearing Structural Steels*, TMS, October 2010, pp. 333-346.

[16] Ph. Maitrepierre, J. Rofes-Vernis and D. Thivellier, Hardenability of Boron-Treated Low-Carbon Low-Alloy Steels, *Proc. Int.Symp. On Boron Steels*, TMS-AIME, Milwaukee, 1979, pp 1-18.

[17] W. Hua and, “Microstructure and Mechanical Properties of 420-550MPa Grade Heavy-Gauge Offshore Platform Steel,” *Niobium Bearing Structural Steels*, TMS, October 2010, pp. 351-364.