WHITE PAPER

Steel Producers Respond to Demand for High Performance Bridge Steels with Niobium

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Øresund Bridge connects Denmark and Sweden and was constructed with 82,000 tonne of high strength steel. With a 0.02% Nb addition, a 15,000 tonne reduction in weight and a cost savings of $25 million were realized.

** Hillenbrand, H.G., Gräf, I.M., and Kalwa, I.C. "Development and Production of High Strength Pipeline Steels." Proceedings of The International Symposium Niobium 2001. Orlando, Florida, USA. December 2 – 5, 2001.*

KEY TAKEAWAYS

- The civil engineering community is looking toward steel producers to provide the next generation of bridge materials that meet robust performance standards, offer design-flexibility, provide durability and resiliency, and allow for faster, lower cost bridge construction. Steel producers are responding with alloyed, high performance steels containing Niobium (Nb).
- Nb-containing bridge steels have demonstrated a consistency in the base mechanical properties, as well as exhibiting outstanding toughness, weldability and corrosion resistance.
- Lower carbon Nb-alloy steel designs are cost-effective in mill production, enabling the entire supply chain, from designer through to the end user, to realize the benefits of Nb as an additive.
- Nb-containing weathering steels for bridge construction are proving to be economical and extremely valuable as a carbon footprint environmental asset. Eliminating the need for steel painting generates an initial 10 percent cost saving. Without painting, exposure to contaminated blast debris or volatile organic compounds (VOC) is eliminated. Life cycle cost savings can exceed 30 percent due to extended corrosion resistance and less overall maintenance.

CBMM North America, Inc. can partner with your facility by providing niobium products and value-added steel solutions to help you meet the demand for high performance bridge steels.

To discover how niobium can add value to your steel production, contact:

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The Viaduct de Millau bridge in southern France stands as the tallest bridge in the world at 343 m (1,125 ft). Niobium was used at the rate of 0.025% per tonne of steel to reduce its overall weight by some 60 percent.

** Fitzgerald, Barry. "Globe Takes great Stride with Niobium." Sydney Morning Herald. September 4, 2011.*

ABSTRACT

Nb-containing bridge steels are being produced by steelmakers to respond to the demand for better performing, value-added bridge materials. These steels possess a combination of exceptional properties – high strength, excellent weldability, impressive toughness at low temperature, desired ductility, superb corrosion resistance and high formability. High performance steels (HPS) that include weathering steels for bridge structures, possess an optimized balance of these primary properties, providing a cost-effective product for bridge structures at strength levels from 355MPa to 700MPa, and demonstrating excellent corrosion resistance. The combination of a desirable strength-toughness balance, favorable weathering properties and reduced pre-heat temperatures for welding in these low carbon Nb-bridge steels generates significant cost savings. When selected for new bridge construction or the rehabilitation of existing bridges, Nb-containing low carbon bridge steels are made in the form of net shape cast beams and/or welded plate sections that ensure lighter, more corrosion-resistant superstructures. The enhancements give designers and structural engineers the opportunity to specify HPS to further improve bridge structure design and performance.

Introduction

Materials and structural engineering bridge designers are currently focused on developing high performance bridges that feature excellent loading behavior, effective resistance to vibration, superb fabrication and corrosion resistance qualities, as well as improved fatigue and fracture toughness. Nb-containing steels improve the consistency of the base mechanical properties, and exhibit ideal toughness, weldability and corrosion resistance. Over the past 20 years, quality improvements relating to steel cleanliness, surface quality, mechanical properties and corrosion resistance have become increasingly evident.

Niobium and copper-containing bridge steels have been used successfully, especially with weathering steel grades. Many weathering bridge steels belong to the family of 355, 420, 460 and 500MPa yield strength levels. Critical connection components occasionally approach yield strength levels reaching 700MPa and may be specified (for example, HPS 100 W with niobium and copper). Selection of a weathering steel for a specific application is based on material availability and cost, fabrication, site location, weather conditions and a cost-benefit economic analysis. When specifying Nb-containing steels, the hybrid component – combination of high strength and mild steel grades – of structural design is simplified. This design can also achieve overall bridge steel dead weight reduction by integrating S355 with higher strength grades such as 420, 460 and 500MPa.

Niobium-containing Bridge Applications

A high performance bridge steel (Q370qE-HPS) comprising low carbon content (<0.10wt%), Nb microalloying (0.025-0.050wt%) and low carbon equivalent (CEV) (<0.38%) has been produced using the thermomechanical controlled process (TMCP) for railway bridge applications. The results show the microstructure consists of fine-grained, quasi-polygonal ferrite (QPF), less pearlite and many finely dispersed Nb-rich nano-precipitates. Consequently, an excellent combination of high strength, high toughness and low yield-to-tensile strength ratio (YR) is obtained. TMCP of a low carbon Nb-microalloyed steel can lead to a significant refinement of ferrite grain, and simultaneously, less pearlite and even degeneration of the pearlite structure. [1] These events are likely to heighten interest to achieve a better balance of the final combination of YS, TS, YR and toughness.

Successful commercialization has led to Nb-bearing beams replacing V-bearing beams with substantial toughness improvements in beams and plates produced to various specifications, including ASTM992, ASTM572, ASTM588, ASTM710, Q345e and S355. Implementing Nb technology has vastly improved toughness properties through grain refinement and strategic cooling practices during rolling. Low carbon low alloy (LCLA) chemistry for a S355 bridge steel is less than the following: 0.10%C, 0.025-0.035%Nb, 0.010%S, 0.015%P, 1.40%Mn, with residuals less than 0.70% (i.e., Cr + Ni + Cu + Mo). The addition of Nb refines the grain by two ASTM sizes, lowers the carbon equivalent by 0.07% and significantly improves the toughness compared to V-bearing low C steels as shown in Figures 1 (a) [2] and (b). [3]

Low carbon Nb-containing bainitic steels also offer a solution to produce bridge steel plates with excellent properties. The favored microstructure and desired balance of mechanical properties are being achieved through an optimal combination of alloying additions and appropriately designed TMCP. Bainite is obtained in bridge steels by means of retarding the ferrite formation. [4] Nb is also effective for increasing the volume fraction of bainite. [5, 6] As in lower strength bridge steels, reducing the carbon to less than 0.10% is essential for maintaining toughness and sufficient HAZ (heat affected zone) properties. However, a minimum amount of alloying is necessary to prevent extensive softening while retaining adequate toughness. [7, 8]

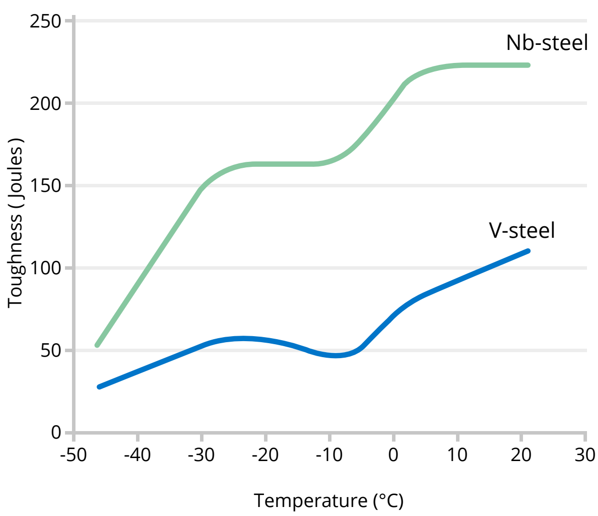

Figure 1. (a) Charpy V-notch impact strength comparison - Nb vs. V at Mill #1 [2]

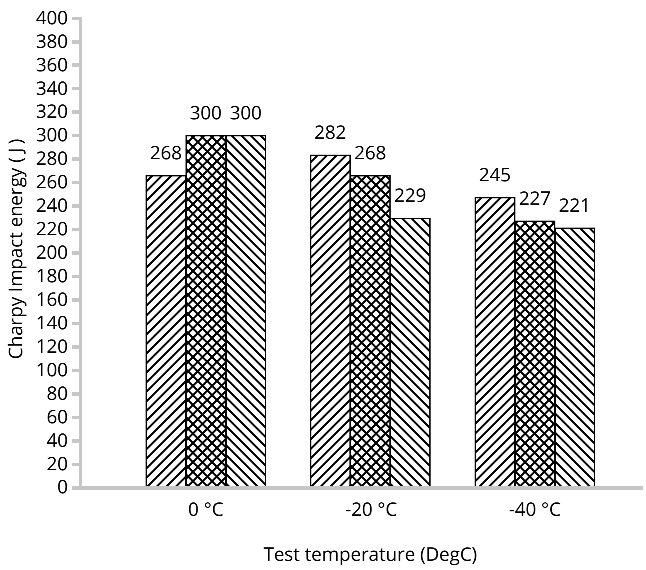

Figure 1. (b) Charpy V-notch impact strength toughness Nb steel at Mill #2 [3]

Table 1. Low Carbon Copper-Niobium Bearing Bridge Steels [12]

Where elemental chemistry not listed, consider as maximum.	ASTM* A710/736 Grade A	ASTM A710 Grade B	ASTM A710/736 Grade C	MIL-S-24645** HSLA-80	MIL-S-24645** HSLA-100
Carbon	0.07	0.06	0.07	0.06	0.06
Manganese	0.40-0.70	0.40-0.65	1.3-1.65	0.40-0.70	0.75-1.05
Phosphorus	0.025	0.025	0.025	0.020	0.020
Sulfur	0.025	0.025	0.025	0.006	0.006
Silicon	0.40	0.15-0.40	0.40	0.40	0.40
Nickel	0.07	0.06	0.07	0.06	0.06
Chromium	0.60-0.90	–	–	0.06-0.90	0.45-0.65
Molybdenum	0.15-0.25	–	0.15-0.25	0.15-0.25	0.55-0.65
Copper	1.00-1.30	1.00-1.30	1.00-1.30	1.00-1.30	1.45-1.75
Niobium	0.02 min	0.02 min	0.02 min	0.02-0.06	0.02-0.06

* ASTM specifications. ** Military specifications.

ASTM A710 Low Carbon Age Hardenable Copper-Niobium Bearing Structural Steels

NUCu 70W (Northwestern University Cu-Precipitation–Strengthened) steel, which is a copper precipitation-hardened, high performance Grade 70 weathering product, has been standardized as A710 Grade B. Research studies began at Northwestern University during the late 1990s with the support of the Federal Highway Administration, Illinois Department of Transportation and the school's Infrastructure Technology Institute. Initially, the steel did not contain Nb. [9, 10] Specifically, the corrosion properties of unpainted steel were compared. The newly developed NUCu steel features the lowest loss in thickness among commercial construction and weathering steels in accelerated automotive SAE J2334 salt, wet/dry, eight-week corrosion tests performed by Bethlehem Steel Corporation. [11] Both A710 and A736 steels are available in three different classes: Class 1, as rolled; Class 2, normalized; and Class 3, quenched.

In some instances, improved toughness at low temperature is desired for certain regions of Canada and the northern United States. To meet the demand, research and development of weathering resistant copper age-hardening steels (A710 type) has ensued. Table 1 compares the composition of the three ASTM grades involving A710-type steels with HSLA-80 and HSLA-100 of the MIL-S-24645. Note the minimum 0.02%Nb level.

The carbon content is reduced well below 0.10% to a range of 0.06-0.07%C. A lean carbon and alloy composition creates an extremely low carbon equivalent for excellent weldability, toughness and formability. Figure 2 illustrates that the NUCu (ASTM A710 Grade B) steel features a far superior corrosion resistant characteristic than any other commercially available weathering bridge steel. In addition, the paint adherence and corrosion resistance are markedly improved over popular HPS 70W bridge steels as shown below. Figure 2 illustrates corrosion and salt spray comparison results.

Figure 2. Painted Steel Corrosion Comparison [11]

Table 2 shows the values of the ASTM G101 corrosion index for several bridge steels. [13, 14] These are non-weatherable steel grades A36 and A572-50; weatherable and non-weatherable A588 steels used in bridge construction the past few decades; weatherable, high performance A709 50W and 70W used the past 15 years; and A710 Grade B steel developed at Northwestern University and used for bridge construction in Illinois. A588 weatherable steels derive their weatherability characteristic primarily from Cu (0-.20-0.50%) and Cr (0.30-0.60%); A709 HPS70W steel from Cu (0.25-0.40%) and Cr (0.45-0.70%); and A710 Grade B from Cu (1.20-1.40%). A710 Grade B possesses the highest G101 index among all weathering steels used today. Table 2 compares commercially produced bridge steels currently available for building bridges in North America. [13, 14]

Table 2. ASTM G101 Index for Commercially Produced Bridge Steels

Steel Grade	G101 New Index
A36	2.85
A572-50	3.24
CORTEN B	4.90
A588 Grade C	4.95
A588 Grade B	5.43
A709 50W	4.95-6.51
CORTEN A	5.88
A709 HPS 70W	6.62
A710B	7.33

The original ASTM Standard G101 corrosion index, based on the work of Legault and Leckie [15], was used to predict if a steel is weatherable. They utilized a portion of an extensive database published by Larrabee and Coburn. [16] The ASTM Standard G101 was established to estimate corrosion resistance of low-alloy weathering steels derived from chemical composition data and actual atmospheric exposure tests. Many high strength, low alloy steels are currently used in the development stage with chemical composition ranges extending beyond those covered by the ASTM Standard G101. These steels may contain more nickel and copper or elements not included in the Standard G101. Being able to estimate the weatherability of these steels is of primary interest today. As a result, new equations have been added to the revised ASTM Standard G101 corrosion index. [17]

Decades of structural and material neglect, lack of budget, end of design life, and the effects of weather and hazard events have produced an urgent need for bridge replacement and rehabilitation throughout the United States and abroad with new and improved higher toughness and more corrosion resistant steels.

Corrosion Behavior in Niobium-containing Steels

Continuing research involves the characterization of CuNb precipitates and grain refinement of Nb as to their potential role in improving corrosion performance. The composition of co-precipitated NbC carbide precipitates, Fe_3C iron carbide (cementite) and Cu-rich precipitates continues to be studied by atom-probe tomography (APT). [18] Cu-rich precipitates located at a grain boundary (GB) also are under study. ATP results for carbides are supplemented with computational thermodynamics predictions of composition at thermodynamic equilibrium. Two types of NbC carbide precipitates are identified based on their stoichiometric ratio and size.

Grain refinement is known to influence improvements affecting strength and wear resistance. Inherent processing involved in grain refinement alters both the bulk and surface of a material, leading to changes in grain boundary density, orientation and residual stress. Ultimately, these surface changes can impact electrochemical behavior and consequently, corrosion susceptibility as evidenced by the large number of studies addressing the effect of grain size on corrosion. These studies cover a broad range of materials and test environments. However,

The Hong Kong- Zhuhai-Macao bridge is the world's longest cross-sea project at 55Km (34 miles), incorporating a bridge and a 6.7Km (4 miles) seabed tunnel. The HBIS Group optimized levels of vanadium, chrome, niobium and copper to provide high strength, anti-seismic wire bars with an unprecedented anti-corrosion ability used for the immersed tunnel construction.

**"HBIS Fine Steel Applied in Hong Kong-Zhuhai-Macao Bridge," HBIS Group, last modified 2017. http://www.hbisco.com/site/en/groupnewssub/info/2017/13455.html*

limited research has been conducted to gain a fundamental understanding of the grain refinement mechanism with Nb. Generally, the studies seek to determine how grain size affects corrosion resistance of an alloy. Existing literature is often contradictory, even within the same alloy class, and a coherent understanding of how grain size influences corrosion response is noticeably lacking. [19] Cross-application and development of additional global corrosion on weathering bridge steels are highly recommended to better understand enhanced corrosion behavior and corrosion behavior via Nb-grain refinement and NbC precipitation.

HPS 50W, 70W and 100W HPS Bridge Steels

Development of HPS grades was initiated through a cooperative agreement involving the Federal Highway Administration, the U.S. Navy, and American Iron and Steel Institute. The goal was to enhance weldability and toughness over previous versions of grade 70 and 100 steel. [20] Prior to HPS, steels with yield strength greater than 355MPa (A852 and A514) were extremely sensitive to welding conditions. As a result, fabricators often encountered welding problems. HPS grades essentially have eliminated such concerns due to the lower carbon approach. In addition, these grades provide enhanced fracture toughness compared to non-HPS grades and have replaced A852 grades.

HPS properties are achieved largely by dramatically lowering the percentage of carbon in the steel chemistry. Since carbon is traditionally a primary strengthening element in steel, the composition of other alloying elements becomes more precisely controlled in order to meet the required strength and compensate for the reduced carbon content. Lower carbon levels are essential to improving steel mechanical properties and weldability. Recently, incorporating Nb into numerous steel grades is displacing the traditional practice of using higher carbon (greater than 0.11%C) and higher manganese structural steels. The application of Nb-technology in bridge steels, as well as cross-application into lower strength plate, section and long products, depend on the design criterion of the end user. The customer often desires improved toughness (i.e., energy absorption for the civil engineering community), a higher level of fracture toughness, improved cyclic fatigue performance (seismic), greater homogeneous grain size and microstructure.

On the processing side, adding 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. The impressive results are increased throughput, productivity, capacity and achieving operational cost reduction of 5-15 percent. [21]

For reference, the finer grain size produced with the Nb addition in plate or section steel may

Table 3. Chemical Compositions of Weathering HPS Grades [22]

		C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Nb	Al	N
Old 70W	Min	–	.80	–	–	.25	.20	–	.40	–	.02	–	–	–
	Max	.19	1.35	.035	.040	.65	.40	.50	.70	–	.10	*	–	–
HPS70W and HPS50W	Min	–	1.10	–	–	.30	.25	.25	.45	.02	.04	–	.010	–
	Max	.11	1.35	.020	.006[A]	.50	.40	.40	.70	.08	.08	*	.040	.015
HPS100W	Min	–	.95	–	–	.15	.90	.65	.40	.40	.04	.01	.020	–
	Max	.08	1.50	.015	.006[A]	.35	1.20	.90	.65	.65	.08	.03	.050	.015

[A] The steel shall be calcium treated for sulfide shape control.

* Nb added by discretion of steel producer at 0.01-0.02%Nb in HPS 50W and 70W for grain refinement.

allow the mill to adjust its chemistry to a leaner alloy system with reduced Mn levels. In 2018, CBMM North America, Inc. published a white paper that outlines the production process for lowering Mn levels in infrastructure steels. [21] Cross-application for bridge steels is progressing. Experience is proving that HPS steels, due to their higher strength, can deliver more cost-effective bridge projects. The scope of this benefit generally equates to the size and span length of the bridge. The longer the bridge, the greater the cost saving. Since the price of HPS steel is higher than conventional steel, the designer should carefully consider all the project details to ensure that the benefits outweigh an additional product cost.

HPS 50W is an as-rolled steel produced to the same chemical composition requirements as grade HPS 70W. As with higher strength HPS grades, HPS 50W features enhanced weldability and toughness compared to grades 50, 50W and 50S. The primary advantage of HPS 50W is a high toughness that exceeds current American Association of State Highway & Transportation Officials specifications for grades 50 and 50W. Enhanced toughness may be beneficial for certain fracture critical members with low redundancy, such as tension ties in tied arch bridges. Table 3 compares old and new compositions for 70W and the carbon reduction.

As previously discussed, the trend toward production of a leaner alloy system has led to the adoption of a MicroNiobium addition (less than 0.02%) specifically to obtain grain refinement of at least two ASTM grain sizes. The system meets ASTM A20 specifications since Nb is considered a residual element in the 0.01% to 0.02% range and adheres to all HPS and ASTM A709 chemical requirements.

Future Opportunities for Weathering Bridge Steels

An opportunity exists for the global steel industry to further develop value-added HPS bridge materials that will meet future construction and performance needs across the marketplace. Because of increased raw material, alloy and steelmaking costs, the civil engineering community demands bridge steels that translate into faster, lower cost bridge replacement in the United States and Europe, as well as new bridge construction in Brazil, China, Russia and India. Another opportunity is to develop even lower carbon-lean alloy bridge steels. Many current HPS products of 490MPa and 700MPa are rich alloy compositions that drive up costs for the end user. Research activity in some areas of the world is focused on developing a series of Nb-bearing LCLA bridge steels that further improve HPS 50W, HPS 70W and HPS 100W, especially their fracture toughness, fatigue and low temperature impact properties.

From a materials engineering perspective, the following list outlines material and fabrication demands provided by the civil engineering community and end users. These objectives are intended for steel producers committed to next-generation bridge steel development. It is important to note that many of the listed opportunities represent potential for Nb-bearing steels.

- Improved corrosion resistance of weathering carbon steels
- Reduced weight of bridge assemblies for faster installation time
- Civil engineering goal: two crane lifts of bridge assembly to span a six-lane highway, thereby reducing traffic closure time

- Improved weldability to increase fabrication and field erection productivity
- Increased use of hot forming for cured bridge beams
- Improved corrosion resistance with excellent toughness
- Reduced cost of high-performance bridge steel materials
- Fire-resistant steel (rebar) for tunnel and long span bridge applications (Class II flammable truck traffic)
- Improved structural performance (i.e., deflection, expansion)

Nb-containing high performance bridge steels are providing engineers design flexibility, lowering initial costs through weight savings in transportation and fabrication, and resulting in life-cycle savings with fewer maintenance requirements and a longer service life.

Conclusion

The use of weathering steels for bridge construction provides substantial cost saving, as well as environmental benefits. A cost saving exceeding 10 percent is initially realized because the painting step is eliminated. The steel is also easier to handle and install during construction. Life cycle cost savings of more than 30 percent can be realized since weathering steels require less maintenance and have proven to be more durable than common construction steels. The use of weathering steels also provides major environmental benefits as no volatile organic compounds (VOC) associated with paints are involved.

Finally, over the life of the structure there is no need for removal or disposal of contaminated blast debris that is required in the use of non-weathering steels. The overall benefits have contributed to the growing popularity of selecting weathering steels for new highway bridge construction. A cautionary note is that such steels are not considered adequate for use in marine and other high saline environments. Research involving low carbon, copper and niobium-bearing steels is continuing to include these applications. While corrosion resistance remains a critical research subject, other key attributes being studied for weathering bridge steels are toughness, weldability and low temperature performance. Substantial progress can be traced to the success of the ASTM A710B bridge steel grade. Recent corrosion science activities are being advanced to better understand corrosion and corrosion-resistant behaviors via Nb-grain refinement and NbC precipitation in high strength low alloy steels.

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