Presented at International Weathering Bridge Steels Symposium, Dalian, China October 30-November 2, 2014

NIOBIUM CONTAINING WEATHERING BRIDGE STEELS AND PERFORMANCE BENEFITS

Steven G. Jansto[1]

CBMM North America, Inc., 1000 Old Pond Road, Bridgeville, PA 15017, USA

Keywords: Cost Effectiveness, Low Carbon, Niobium

Abstract

Niobium-containing weathering bridge steels have been developed globally for application throughout the world. These steels possess a combination of exceptional properties with high strength, excellent weldability, high toughness at low temperature, good ductility, excellent corrosion resistance, and high formability. These high-performance weathering bridge steels (HPS) possess an optimized balance of these properties to provide maximum cost effective performance in bridge structures at strength levels from 355 to 700MPa with excellent corrosion resistance. This combination of a good strength - toughness balance, excellent weathering properties and reduced preheat temperatures for welding in these low carbon Nb-bridge steels result in significant cost savings. For both new bridge and reconstruction of older bridges, these Nb-containing low carbon bridge steels are produced in the form of near net shape cast beams and/or welded plate sections that result in lighter and more corrosion-resistant superstructures. These enhancements provide structural engineers the opportunity to further improve the structural design and performance. Lower carbon Nb-alloy designs have exhibited reduced operational production cost at the steel mill, thereby embracing the value-added attribute Nb provides to benefit both the producer and the end user throughout the supply chain. Through the adoption of these Nb-containing structural bridge materials, several design-manufacturing companies are initiating new bridge steel designs that will further provide improved overall bridge lifetime and cost performance at reduced maintenance expense.

Introduction

The development of weathering steels initiated in the early 1960's in the United States. Over the subsequent decades, quality improvements in steel internal cleanliness, surface quality, improved mechanical properties and enhanced corrosion resistance were developed. The designers and fabricators require a keen understanding of the proper steel selection for a given environmental condition when specifying weathering bridge steels. The majority of weathering bridge steels is in the 355 and 420MPa yield strength level. Although at times, critical connection components approach yield strength levels up to 700MPa and may be specified such as (HPS100W with copper). The selection of weathering steel for a given application is based upon material cost and fabrication, material availability, site location weather conditions and a cost benefit economic analysis. Specific case examples are presented to illustrate these key analysis factors for design of bridges for a 50 to 100 year life span.

Weathering Bridge Steel Development History

Since 1964, weathering bridges steels have been a materials choice of construction for bridges because of performance benefits, economics and environmental conditions for varying corrosive conditions. As a result, approximately 2300 bridges have been constructed over the past 40 years in the United States. Studies have indicated that weathering steels reduce both the initial and life cycle bridge cost. Current highway legislation in the USA requires a life cycle assessment in the highway materials selection process.

From an economics perspective, Grade 50W, which is a 355MPa microalloyed steel, costs approximately $US60 per tonne more than non-weathering steel. However, the initial painting of the non-weathering Grade 50 costs nearly two times the difference per tonne of steel. Furthermore, the application of weathering steel precludes the need for future maintenance re-painting costs is significantly more expensive than the first painting. Weathering steel is a material that provides a great potential advantage for use in bridges in terms of improved durability and lower construction and maintenance costs.

As of 2013, there are 607,380 highway bridges in the United States. The materials of bridge construction are 200,000 with steel, 235,000 with conventional reinforced concrete, 108,000 bridges constructed using pre-stressed concrete, and the balance is made using other materials of construction. [1] Currently, approximately 30 percent of the bridges in the USA are structurally deficient, primarily due to corrosion of steel and steel reinforcement. Many of these bridges were constructed several decades ago before these weathering bridge steels were developed, not specified or incorrectly applied. The annual direct cost of corrosion for USA highway bridges is estimated at $13.6 billion. Although not all bridge collapse or bridge failure incidents are caused by corrosion, corrosion poses a growing threat as bridge infrastructure continues to age and spending on maintenance and repair has been deferred not only in the USA, but also in many different regions of the world.

Life-cycle analysis has become a standard step in the design and materials selection process. Life cycle estimates indirect costs to the user due to traffic delays and lost productivity at more than 10 times the direct cost of corrosion maintenance, repair, and rehabilitation. Through the employment of relatively low cost corrosion control measures during the initial construction stage, low-maintenance bridges with service lives of 75 to 100 years may be achieved. One must fully understand the return on investment and capital cost benefit relationships. [2]

Some of the first uses of intentional additions of copper to steels were provoked by the increased need for atmospheric-corrosion resistance. Consequently, the use of copper in amounts over 0.2 percent to strengthen structural steels also goes back to at least the 1940s, when it was used in some ships. The ASTM A242 (Standard Specification for High-Strength Low-Alloy Structural Steel) and A588 (Standard Specification for High-Strength Low-Alloy Structural Steel, up to 50 ksi [345 MPa] Minimum Yield Point, with Atmospheric Corrosion Resistance) steels possess at least four to as much as eight times the atmospheric-corrosion resistance of structural carbon steel, which has a low copper content. When properly exposed to the atmosphere, such bare steels will develop a tight, adherent, protective-oxide coating during the first several months of weathering. Thereafter, little additional steel corrosion occurs. However, copper is known to have the potential to cause hot shortness problems due to molten iron-copper phases at the scale interface during heating in oxidizing atmospheres. [3]

Structural steels with copper additions for precipitation strengthening, forerunners of the current A710-type grades, were introduced in the 1960s, but generated little interest among engineers and the construction industry at that time. The COR-TEN series then evolved through the 1980's and 1990's.

Copper Bearing COR-TEN Steel A and B

Weathering steel is best known under the trademark COR-TEN steel which was developed to eliminate the need for painting. The steel forms a stable rust-like appearance when exposed to the weather for several years. United States Steel Corporation (USS) was developed may years ago and USS holds the registered trademark. [4,5] A weathering steel known as COR-TEN A, containing between 0.07 and 0.15% phosphorus had very good weatherability and was used for buildings. However, the fracture toughness was very low because phosphorus will diffuse to grain boundaries, resulting in steel embrittlement. As a result of this drawback, the concentration of phosphorus in the newer steel, known as COR-TEN B, was reduced to 0.030 % or less to improve the fracture toughness. COR-TEN B obtains its good weatherability by having alloying elements such as chromium, copper, and nickel. The yield strength of both COR-TEN steels is around 350 MPa (50 ksi).

The original COR-TEN A received the standard ASTM A242 designation from the ASTM International standards group. Newer ASTM grades include A588 (COR-TEN B) and ASTM A606 for thin sheet. The chemical composition of the A242 and A588 is specified in Table 1.

Table 1. ASTM A242 and A588 Chemical Specifications [6]

	Cmax	Mnmax	Pmax	Smax	Cumin	Si	Ni	Cr	Mo	V	Nb
A242*	0.15	1.00	0.040	0.050	0.20						
A588GrA	0.19	0.80/1.25	0.040	0.050	0.25/0.40	0.30/0.65	0.40max	0.40/0.65	-	0.02/0.10	-
Grade B	0.20	0.75/1.35	0.040	0.050	0.20/0.40	0.15/0.50	0.50max	0.40/0.70	-	0.01/0.10	-
Grade C	0.15	0.80/1.35	0.040	0.050	0.25/0.50	0.15/0.50	0.25/0.50	0.30/0.50	-	0.01/0.10	-
Grade K	0.17	0.50/1.20	0.040	0.050	0.30/0.50	0.25/0.50	0.40max	0.40/0.70	0.10max	-	0.005/0.050

* Elements commonly added include: chromium, nickel, niobium, silicon, vanadium and titanium.

Other chemical elements that may be added include nickel, niobium, silicon, vanadium and titanium. The addition of nickel prevents this problem and also improves toughness, but increases the material cost. Chromium and molybdenum are added to control the epsilon-copper precipitate nucleation and growth such that consistent properties can be achieved. Chromium and molybdenum also provide additional hardenability that helps promote a fine ferritic/bainitic/martensitic microstructure. Niobium helps retard austenite recrystallization during hot rolling and makes grain refinement possible. Some precipitation hardening occurs as well. Grain size control during austenitization is facilitated by the niobium carbo-nitride precipitates. Note that niobium is added in some cases to both the A242 and A588 Grades A, B and C in the 0.015 to 0.030%Nb range and considered to be a residual element under the specification. The mill is not required to report the MicroNb level as it is considered a residual element per the specifications, unless otherwise specified.

The tensile requirements are shown in Table 2.

Table 2. ASTM A242 and A588 Mechanical Properties [6]

	Plates and Bars			**Structural Shapes**		
ASTM A242	**<20mm**	**20-40mm**	**>40-100mm**	**For flange or leg thicknesses ≤ 40mm**	**For flange thicknesses > 40mm to ≤50mm**	**For flange thicknesses > 50mm***
Yield Strength (MPa)	345	315	290	345	315	290
Tensile Strength (MPa)	480	460	435	485	460	435
% Elongation 250mm	18	18	18	18	18	18
%Elongation 50mm	21	21	21	21	21	21

* For wide flange shapes over 426 lb/ft [634 kg/m], elongation in 2 in. [50 mm] of 18 % minimum applies.

	Plates and Bars			**Structural Shapes**
ASTM 588	**≤100mm**	**>100-≤125mm**	**>125mm**	**Includes all thicknesses**
Yield Strength (MPa)	345	315	290	345
Tensile Strength (MPa)	485	460	435	485
% Elongation 250mm	18	-	-	18
%Elongation 50mm	21	21	21	21

* For wide flange shapes with flange thickness over 3 in. [75 mm], elongation in 2 in. [50 mm] of 18 % minimum applies.

The atmospheric corrosion-resistance index is calculated on the basis of the heat analysis of the steel, as described in Guide G101–Predictive Method Based on the Data of Larabee and Coburn, shall be 6.0 or higher. The user is cautioned that the Guide G101 predictive equation (Predictive Method Based on the Data of Larabee and Coburn) for calculation of an atmospheric corrosion-resistance index has only been verified for the composition limits stated in the guide. [6]

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

The use of copper in amounts over 0.2 percent to strengthen structural steels also goes back to at least the 1940s, when it was used in some ships. Structural steels with copper additions for precipitation strengthening have already been described and were forerunners of the current A710-type grades. Low-carbon, copper precipitation-aged plate steels were introduced in the late 1960s by the International Nickel Company as IN-787. They were introduced in the 1960s, but generated little interest among engineers and the construction industry at that time. The current ASTM specification (A710) for structural applications was developed in the mid-1980's. [7] Engineering needs began to change in the 1990's especially with designers seeking improved corrosion resistant structural steels for ships and bridges.

High-strength low-alloy (HSLA) steels were introduced and used extensively in U.S. Naval shipbuilding. The A710 grades substituted for the quenched and tempered HY-80 steel plate, which was the material of choice for ship plate. Based upon the success of these ship plate applications, the U.S. Army Corps of Engineers then considered the A710 grades for military construction projects. [7] The low-carbon, fine grained microstructure that results from typical processing yields a favorable combination of excellent fabricability, strength, and toughness to HSLA steel that adds to its usefulness and gives it clear advantages over quenched and tempered construction steels. For pressure vessel applications, this material is covered by ASTM specification A736. Both A710 and A736 steels can be supplied in three different classes: Class 1, as-rolled; Class 2, normalized; and Class 3, quenched. All three classes are precipitation heat treated at 1000 to 1300 °F (540 to 705 °C) for 30 to 60 minutes. They exhibit a wide range of tensile strength, 65 to 120 ksi (450 to 650 MPa) as well as good impact toughness at low temperatures.

In some instances, improved toughness at low temperature for certain regions of Canada and the northern United States was desired as well. Thus, the research and development of weathering resistant copper age-hardening steels of the A710 type ensued. Table 3 lists the compositions of the three ASTM grades of these A710-type steels and the HSLA-80 and HSLA-100 of the MIL-S-24645.Table 3 below illustrates the finalized plate steel compositions.

Table 3. Low Carbon Niobium-Copper Bearing Bridge Steels [8]

Where elemental chemistry not listed, consider as maximum.	ASTM* A710/736	ASTM A710	ASTM A710/736	MIL-S-24645**	
	Grade A	Grade B	Grade C	HSLA-80	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	---	---	0.60-0.90	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.

These moderate alloy additions of manganese, nickel, molybdenum, and chromium (with copper exceeding 1.00%), provides the age-hardening characteristics for this weather resistant steel. Copper has a high solubility in austenite at the typical austenitizing temperatures, 870 to 950 °C (1600 to 1750 °F. Ferrite formed at high temperature also has a relatively high solubility for copper, slightly over 2 percent maximum. However, due to the sloping solvus line in the phase diagram, the copper solubility drops significantly at lower temperatures. Thus, a rapidly cooled alloy contains copper in a supersaturated condition. When reheated, copper-rich precipitates form as fine spherical particles and cause the precipitation-hardening of the steel. These particles usually are referred to as epsilon-copper. Steels containing more than 0.60 percent of copper are capable of exhibiting precipitation hardening of the ferrite. It is important to be aware that copper is known to have the potential to cause hot shortness problems due to molten iron-copper phases at the scale interface during heating in oxidizing atmospheres. [3] Certainly, the addition of nickel prevents this problem, but adds to the material cost.

Subsequently, a copper-precipitation-hardened, high performance Grade 70 weathering steel, NUCu 70W (Northwestern University Cu-Precipitation-Strengthened) steel, now standardized as ASTM A710 Grade B, was developed at Northwestern University with the support of the Federal Highway Administration, the Illinois Department of Transportation, and Northwestern University's Infrastructure Technology Institute. Initially the steel did not contain Nb. [9,10] Specifically, the corrosion properties of unpainted steel was compared. The newly developed NUCu steel has the lowest loss in thickness among commercial construction and weathering steels in the accelerated automotive SAE J2334 salt, wet/dry, eight-week corrosion tests performed at that time by Bethlehem Steel Corporation. [11] Figure 1 shows the corrosion salt spray comparison results.

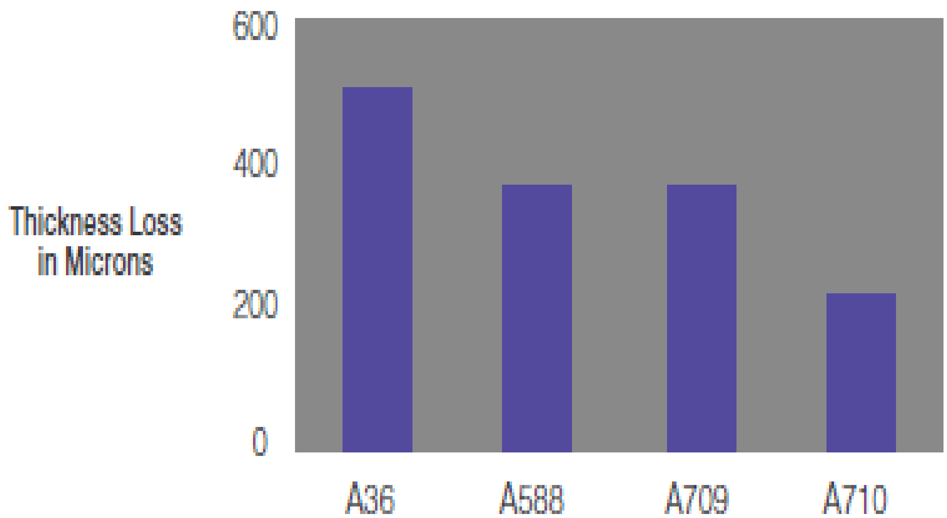

Figure 1. Corrosion Comparison of Structural Bridge Steels [11]

The A710 steel was designed to achieve a minimum 500MPa yield strength on air cooling from hot rolling without quenching and tempering (Q&T), accelerated cooling or thermomechanically-controlled processing (TMCP). The carbon content was lowered well below 0.10% to a range of 0.06-0.07%C. The carbon and alloy composition is leaner resulting in a very low carbon equivalent for excellent weldability, toughness and formability. Figure 2 illustrates that the NUCu 9ASTM A710 Grade B) steel has far superior corrosion resistance than any other commercially available weathering bridge steel. Also, both the paint adherence is better and corrosion resistance is even better than the popular HPS 70W bridge steels as exhibited below in Figure 2.

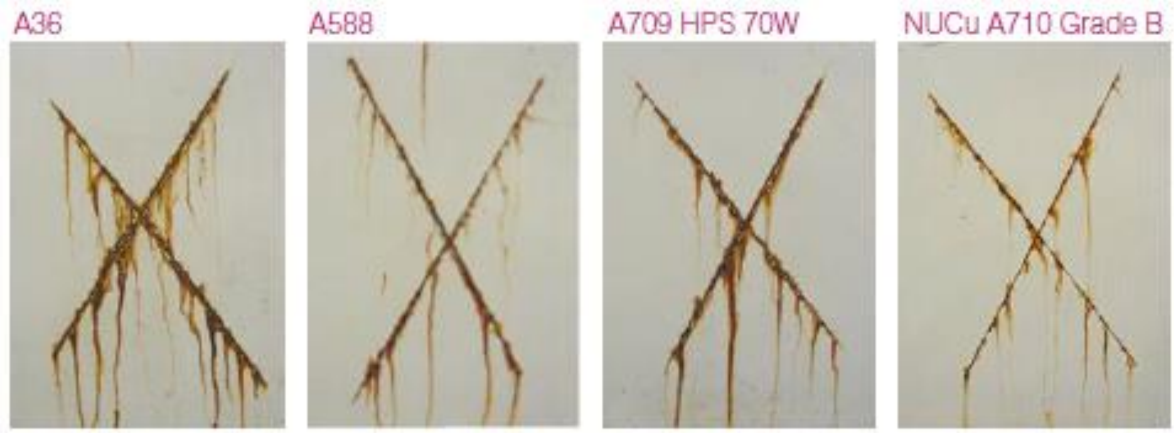

Figure 2. Painted Steel Corrosion Comparison [11]

Table 4 shows the values of ASTM G101 corrosion index for a number of bridge steels. [12] These grades are A36 and A572-50 which are non-weatherable steels, weatherable and non-weatherable A588 steels that have been used in bridges for few decades, weatherable high-performance A709 50W and 70W that are used in bridges in the last 15 years, and A710 Grade B steel that was developed by us at Northwestern University and has been used in bridges in Illinois. A588 weatherable steels derive their weatherability mainly from Cu (0.2-0.5%) and Cr (0.3-0.5%), A709 HPS70W steel from Cu (0.25-0.40%) and Cr (0.45-70%), A710 Grade B from Cu (1.20-1.40%). A710 Grade B has the highest G101 index among all weathering steels in use today. Table 4 below compares the currently commercially produced bridge steels for North America. [13]

Table 4. 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 G101 corrosion index, which is used to predict whether a steel is mweatherable, is based on the work of Legault and Leckie. [14] They utilized part of an extensive database published by Larrabee and Coburn. [15] This ASTM G101 standard was developed to estimate the corrosion resistance of low-alloy weathering steels from chemical composition data and from actual atmospheric exposure tests. There were many high-strength, low-alloy steels that are used at the present time or that are under development with chemical composition ranges extending beyond the chemical compositions of steels covered by the ASTM Standard G101. These steels may contain more nickel and more copper or elements not included in the G101

Standard. Ability to estimate the weatherability of these steels is of current interest. Hence new equations were developed and added to the revised ASTM G101 corrosion index. [16]

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

The high performance steel (HPS) grades were developed through a cooperative agreement between the Federal Highway Administration, the U.S. Navy, and the American Iron and Steel Institute. The goal was to enhance weldability and toughness compared to previous versions of grade 70 and 100 steel. [17] Prior to HPS, steels with yield strength greater than 355MPa (A 852 and A 514) were very sensitive to welding conditions and fabricators often encountered welding problems. The HPS grades have essentially eliminated base metal weldability concerns through the lower carbon approach. In addition, HPS grades provide enhanced fracture toughness compared to non-HPS grades and replaced the A852 grades.

The properties of HPS are largely achieved by dramatically lowering the percentage of carbon in the steel chemistry. Since carbon is traditionally one of the primary strengthening elements in steel, the composition of other alloying elements must be more precisely controlled to meet the required strength and compensate for the reduced carbon content. There are also stricter controls on steel making practice and requirements for thermal and/or mechanical processing to meet the required strength. These refinements in steel making practice result in a very high quality product, especially through lower sulfur and phosphorous contents. However, this also limits the number of steel mills that have the capability of producing HPS steels in the USA. However, experience is showing that HPS steels, due to their higher strength, can result in more efficient bridges with lower cost. This benefit generally is greater as the size and span length of bridges increase. Since the HPS cost is higher than conventional steel, use of HPS should be carefully considered and thoroughly understood by the designer to insure the benefits outweigh the additional cost of the product.

HPS 50W is an as-rolled steel produced to the same chemical composition requirements as grade HPS 70W. Similar to the higher strength HPS grades, HPS 50W has enhanced weldability and toughness compared to grades 50, 50W, and 50S. However, the need for enhanced weldability is questionable at this strength level since few weldability problems are reported for the non-HPS grades. The primary advantage of HPS 50W is that it can be delivered with high toughness that exceeds the current AASHTO specification requirements for grades 50 and 50W. Enhanced toughness may be beneficial for certain fracture critical members with low redundancy such as the tension ties in tied arch bridges.

Table 5 outlines comparison of the old and new chemical compositions for the 70W and the carbon reduction.

Table 5. Chemical Compositions of Weathering HPS Grades [18]

		C	**Mn**	**P**	**S**	**Si**	**Cu**	**Ni**	**Cr**	**Mo**	**V**	**Nb**	**Al**
Old70W	Min	-	.80	-	-	.25	.20	-	.40	-	.02	-	-
	Max	.19	1.35	.035	.040	.65	.40	.50	.70	-	.10	*	-
HPS70W and HPS 50W	Min	-	1.10	-	-	.30	.25	.25	.45	.02	.04	-	-
	Max	.11	1.35	.020	.006	.50	.40	.40	.70	.08	.08	*	-

* Nb added by discretion of steel producer at 0.01-0.03%Nb in HPS 50W and 70W for grain refinement.

Table 6 and 7 outline the A709 chemical and mechanical property specification.

Table 6. ASTM A709 Chemical Specifications [19]

Element	**Composition %**	
	Grades HPS 50W [HPS 345MPa] HPS 70W [HPS 485W}	HPS 100W [HPS 690MPa]
Carbon	0.11max	0.08max
Manganese <65mm **>65mm**	1.10-1.35 1.10-1.50	0.95-1.50 0.95-1.50
Phosphorous	0.020max	0.015max
Sulfur	0.006max[A]	0.006max[A]
Silicon	0.30-0.50	0.15-0.35
Copper	0.25-0.40	0.90-1.20
Nickel	0.25-0.40	0.65-0.90
Chromium	0.45-0.70	0.40-0.65
Molybdenum	0.02-0.08	0.40-0.65
Vanadium	0.04-0.08	0.04-0.08
Niobium	*	0.01-0.03
Aluminum	0.010-0.040	0.030-0.050
Nitrogen	0.015max	0.015max

[A] The steel shall be calcium treated for sulfide shape control.
* Nb added by steel producers for grain refinement in 0.01-0.03% range and considered a residual element in spec.

Table 7. Mechanical Property Specifications for HPS Weathering Steels [19]

Grade	**Plate Thickness [mm]**	**Structural Shape Flange or Leg[mm]**	**Yield Strength [MPa]**	**Tensile Strength {MPa]**	**Elongation %**				**Reduction of Area min, %**
					Plates and Bars		**Shapes**		
test section					200mm	50mm	200mm	50mm	
HPS 345W	<100	all	345min	485min	18	21	18	21[J]	-
HPS 485W	<100	a	485min	585-760	-	19[K]	-	-	-
HPS 690 W	<65 >65-<100	a a	690min 620min	760-895 690-85	- -	18[K] 16[K]	-	-	L L

a – See specimen orientation and preparation subsection in the tension tests section in Specification A6/A6M
J – For wide flange shapes with flange thickness over 75mm, elongation in 50mm of 18% minimum applies
K- 40%minimum applies if measured on 40mm wide specimens; 50% minimum applies on 12.5mm round test specimens.

Table 8 shows all of the available bridge steels currently available in North America.

Table 8. Overview of Available Bridge Steels in North America

M 270 A 709 GRADE	ASTM Specification	Description	Atmospheric Corrosion Resistance	Product Categories			
				Plates	Shapes	Bars	Sheet Piles
36	A 36	Carbon Steel	No	X	X	X	
50	A 572	HSLA Steel	No	X	X	X	X
50S	A 992	Structural Steel	No		X		
50W	A 588	HSLA Steel	Yes	X	X	X	
HPS 50W	A 709	HSLA Steel(*)	Yes	X			
HPS 70W	A 709	Heat Treated(*) HSLA Steel	Yes	X			
HPS 100W	A 709	Q&T Cu-Ni Steel(*)	Yes	X			

(*) High Performance Steel (HPS) grades with enhanced weldability and toughness
HSLA High Strength Low-Alloy
Q&T Cu-Ni Quenched & Tempered Copper-Nickel Steel

Future Trends and Opportunities for Weathering 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, alloy and steelmaking cost, 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 series of Nb-bearing LCLA bridge steels further improving the properties of HPS 50W, HPS 70W and HPS 100W, especially fracture toughness, fatigue and low temperature impact properties

From a materials engineering perspective, the following list outlines requested material and fabrication demands from the civil engineering community and end users. These objectives are intended for those steel producers' consideration in future bridge steel development of the next generation of bridge steels; many of which represent opportunities for Nb-bearing steels:

- Reduce weight of bridge assemblies for faster installation time.
- Civil engineering goal: two crane lifts of bridge assembly to span 6-lane highway (reducing traffic closure time).
- Improved weldability to increase productivity at fabricator and in the field erection.
- Increase use of hot forming for curved bridge beams.
- Improved corrosion resistance with excellent toughness
- Reduce cost of High Performance Bridge steel materials.
- Fire resistive steel (rebar) for tunnel & long span bridge applications (Class II flammable truck traffic).

-Improve structural performance (i.e. deflection, expansion).

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. [20]

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 ultra-low 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. [20]

Some bridge steels in Europe typically contain 0.015 to 0.040% Nb. For example, Grade 460ML (EN10025) was utilized in thicknesses up to 100 mm 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 weathering resistance and a carbon equivalent CE_{IIW} of about 0.39 % was selected. The design exhibits superior toughness criterion of 27J at -80°C. [21]

The process metallurgy applied for these advanced high strength weathering bridge steels necessitate ultra-low 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 United States bridge industry sought steels with improved weldability and higher toughness. The original development of the quench and temper (Q&T) High Performance Steel (HPS) 100W did not initially incorporate Nb. It was later changed to incorporate an addition of 0.01 to 0.03%Nb with clean steel, low carbon practices. As a result, excellent impact properties at -30°C could be realized. [22]

The progression of bridge development is similar to the development of high strength pipeline steels. This cross application of process and physical metallurgy firsts 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 weathering steel structural grade of similar dimension. In this manner, unsuccessful trials for one product may be cross applied to a prime structural plate product.

Steel vs. Reinforced Concrete Bridge Design

In any bridge design, the civil engineer makes the material decision of steel versus concrete. Ultimately, it is the overall material, labor, fabrication, welding and construction costs that drive the final decision. With the introduction of Nb-bearing high strength bridge steels, creative design can result in a lower cost bridge constructed from steel instead of pre-stressed concrete. An excellent illustration of such an application of the 460M/ML grade is evident at the Viaduct de Millau bridge in France. This bridge represents a new world record with a total height of 342m, a length of 2460m and a roadway height of 270m over the Tarn valley. Originally, the civil engineers specified a pre-stressed concrete bridge.

The new design incorporated a multiple-cable-stayed bridge consisting of a steel bridge deck and towers. The cost benefit analysis revealed a shorter construction period with steel, lighter weight (36,000mt of steel versus 120,000mt of concrete), a reduced box girder height of 4.20m, minimization of the number of inclined tension cable and less foundation work. Nearly half the structure consists of high strength fine grained S460ML structural steel in thicknesses of 10 to 120mm. [21]

Corrosion Problem With Reinforced Concrete Bridges

For reinforced concrete (RC) structures, reinforcement corrosion induced by chloride contamination is a leading cause of structural damage and premature degradation. For example, approximately 90,000 bridges built in the U.S. are currently classified as structurally deficient and/or functionally obsolete. This estimate represents approximately 15% of the total number of bridges in the United States.

Remediation projects for concrete bridges undertaken as a direct result of chloride-induced rebar corrosion was estimated to cost the U.S. highway departments $5 billion per year, aside from the safety and reliability implications. The corrosion concern is even greater in coastal and northern states where these structures are exposed to marine environments or deicing salts respectively. In addition to infrastructure bridges for interstates and highways, the Department of Transportation (DOT) of different states along the coastline has historic RC bridges that experience serious corrosion and degradation. They are faced with the difficult and expensive task of more frequent routine corrosion inspection of existing aging infrastructure to enhance on-time maintenance decision making. Corrosion of reinforcing steel is common in reinforced concrete structures around the world. It causes premature deterioration of civil infrastructures such as highway and railway bridges, offshore platforms, pipelines, and dams. Chloride mainly comes from road deicing salts in winter for highways and bridges, and marine climate for offshore and coastal structures.

Conclusions

The use of weathering steels for bridge construction provides cost savings as well as environmental benefits. The initial cost savings of more than 10 percent are realized since there is no need in painting. The steel is easier to install and handle during the construction. Life cycle cost savings are more than 30 percent because weathering steels require less maintenance and are more durable than common construction steels. The use of weathering steels provides significant environmental benefits also because there are no volatile organic compounds (VOC) from paints. Also, there is no need in removal or disposal of contaminated blast debris due to preparation of the bridge steel surface over the life span of the structure. Due to these benefits, the use of weathering steels increases specifically for the construction of new highway bridges. Current weathering steels are not considered adequate for marine and other high saline environments and consequently, further development continues with low carbon, copper and niobium bearing steels While the corrosion resistance is an important factor for steels, toughness, weldability and low temperature performance are key attributes for new weathering bridge steels currently under development. These developments will build off the success of the ASTM A710B bridge steel grade.

References

[1] G.H. Koch, M.P.H. Brongers, N.G. Thompson, Y.P. Virmani, J.H. Payer, "Corrosion Costs and Preventive Strategies in the United States," Publication No. FHRD-01-156 (Washington, D.C.: FHWA, 2002).

[2] http://www.nace.org/Corrosion/Industries/Highways-and-Bridges/#sthash.kcKRL8ZN.pduf

[3 Jesseman, R.J., and G.J. Murphy, "Mechanical Properties and Precipitation Hardening Responses in ASTM A710 Grade A and A736 Alloy Steel Plates," Journal of Heat Treating, vol 3, no. 3 (June 1984), pp 228-236.

[4] "Trademarks and Ownership," United States Steel Corporation, retrieved 24 September 2010.

[5] Plate Products, 31 October 2013, archived from the original trademark on 28 December 2007.

[6] ASTM A242 and A588 Standards Specification, , "Steel-Structural, Reinforcing, Pressure Vessel and Railway," Volume 01.04, 2009.

[7] Weber, R. A., Somers, B. R. and Kaufmann, E. J., "Low Carbon, Age Hardenable Steels for Use in Construction: A Review," USACERL Technical Review Report 96/104, September, 1996.

[8] ASTM A710 Standards Specification, , "Steel-Structural, Reinforcing, Pressure Vessel and Railway," Volume 01.04, 2009.

[9] Vaynman, S., Fine, M.E., and Bhat, S.P. (2004) "High-Strength, Low-Carbon, Ferritic, Copper- Precipitation-Strengthening Steels for Tank Car Applications," Materials Science and Technology 2004 Conference Proceedings, AIST and TMS, 417, New Orleans, LA.

[10] Vaynman, S. et al. (2002). "High Performance Copper-Precipitation-Hardened Steel," Microalloyed Steels, ASM International, *43*.

[11] Vaynman, S., Fine, M.E., "High Perferomance Weatherable, Copper-Precipitation-Hardened Steel," Proceedings of International Symposium for Fabricated Structures," ASM International, 1999, p.59.

[12] ASTM G101-04 Standard Guide for Estimating the Atmospheric Corrosion Resistance of Low-Alloy Steels. ASTM, 2009.

[13] Vaynman, S., Fine, M.E. and Chung, Y-W, "Super-Weathering Steel for Infrastructure

Applications," Highway Idea Project #160, January 2014.

[14] Legault, R. A. and H.P. Leckie, H. P., "Corrosion in Natural Environment", ASTM STP 558, ASTM, Philadelphia, PA, 1974, pp. 334-47.

[15] C.P. Larrabee and S.K. Coburn, "1st International Congress on Corrosion," Butterworth and Co., London, 1962, pp. 276-85.

[16] S. Vaynman, R.S. Guico, M.E. Fine, and S.J. Manganello, "Estimation of Atmospheric Corrosion of High strength Low Alloy Steels," Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science Volume 28A, Number 5, May 1997.

[17] Wright, W.J. "High Performance Steel: Research to Practice Public Roads," Vol. 60, No. 4, Spring, 1997.

[18] Mistry, V.C., "High Performance Steels for Highway Bridges," Proceedings Advanced Materials for Construction of Bridges, Buildings and Other Structures III, Engineering Conferences International, 2002.

[19] ASTM A709 Standards Specification, "Steel-Structural, Reinforcing, Pressure Vessel and Railway," Volume 01.04, 2009.

[20] Guo, A. and Yi, L., "Development and Application of Steels for Bridges and Buildings in China," Niobium Bearing Structural Steels, CBMM, TMS, October, 2010.

[21] Fluess, R. Valentin, V. Schwinn, F. Hanus "Application of Nb in TMCP structural Steel Plates with Thicknesses up to 120mm," Niobium Bearing Structural Steels, CBMM, TMS, October, 2010.

[22] Wilson, A. D., Gross, J.H., R.D. Stout, Asfahani, R.L. and Manganello, S.J., "Development of an Improved HPS 100W Steel for Bridge Applications," International Symposium on Microalloyed Steels, ASM International, 2002.