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DEVELOPMENT AND MARKETING OF LOW-COST, HIGH-PERFORMANCE STEELS FOR INFRASTRUCTURE APPLICATIONS

Final Report

by

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Introduction

This project addressed the goal of National Strategy for Surface Transportation Research to improve highway structures by enhanced materials, in particular by design and implementation of new, drastically improved steels with respect to strength, low-temperature-fracture toughness, weldability, and weatherability.

The goal of the project was to develop, standardize and commercialize a family of low-cost, high-performance steels for infrastructure applications. As a result we developed steels with yield strength of 50 to 80 ksi, with Charpy absorbed fracture energy significantly exceeding requirements of bridge construction codes at temperatures down to -100°F, steels that are easy to weld without pre-heat or post-heat, steels that exhibit best weathering performance among other commercially available steels. In addition these steels are easy to produce; production does not involve any heat treatment or thermo-mechanically controlled processing which is available only to several US Steel companies. The steels developed in this project were commercially produced in the form of plate and wide-flange I-beams. The steels were used for seismic retrofitting of one bridge (in 2000) and for construction of two new bridges (in 2006 and 2010).

Accomplishments

Development and commercialization of lower-cost, high-performance steel

Our original A710B steel, developed in the past under ITI and FHWA sponsorship, is 70-ksi-yield strength steel. To achieve this strength 1.5% Cu and up to 1.0% Ni are used in the composition. The cost of the steel is approximately the same as A709 steels currently used in bridge construction. Illinois Department of Transportation (IDOT) suggested that we develop and test less expensive variation of our original A710B steel. To achieve that, we reduced the amount of Cu and Ni to below 1.0% and 0.5% respectively. To compensate for the reduction in the concentration of these elements we slightly increased the amount of Mn (inexpensive element). Since different steel companies use different elements (Nb or V) for grain refinement, we produced two 100-lb laboratory heats that contained either Nb or V (Table 1).

Table 1. Chemical Composition (wt. %)

Steel	C	Mn	Si	Cu	Ni	Nb	V	Ti	P	S
w/Nb	0.07	0.87	0.30	0.94	0.49	0.07	….	0.03	0.013	<0.005
w/V	0.05	0.98	0.29	0.90	0.42	….	0.05	…..	<0.010	<0.005

The mechanical properties of both these “lean” steels significantly exceeded the requirements for 50-ksi-yield-strength bridge steel (Table 2). The fracture properties of the steels were excellent at low temperatures; the Charpy specimens did not fracture down to -40°F (the limit of the Charpy machine is 264 ft-lbs). ASTM A709 “Standard Specification for Structural Steel for Bridges” requires Charpy absorbed fracture energy to exceed 30 ft-lbs at 10°F for fracture critical tension components.

IDOT specified this “lean” steel for construction of a bridge on Dixie Highway over Butterfield Creek in Westmont, IL. To further reduce the cost of bridge construction by eliminating welding, the steel was produced by hot-rolling and air cooling in the form of wide-flange I-beams at Steel Dynamics, Ft. Wayne, IN. The composition of the steel is given in Table 3. The properties are given in Table 4.

Table 2. Mechanical properties of the laboratory steels

	Steel with Nb	Steel with V
Yield Stress, ksi	61	53
UTS, ksi	75	64
Elongation to Failure, %	28	35

Table 3. Composition of the steel for Dixie Highway Bridge

C	Mn	Si	Cu	Ni	V	Ti	P	S
0.07	0.87	0.30	0.94	0.49	0.03	0.03	0.013	<0.005

Table 4. Mechanical properties of the steel for Dixie Highway Bridge

Yield Stress, ksi	69
UTS, ksi	81
Elongation to Failure, %	28

Charpy absorbed impact energy was measured at Northwestern University in wide temperature range. At room temperature the Charpy energy of as-received steel was very high, 150 ft-lbs. It dropped to 100 ft-lbs at 10ºF. It reached the lower plateau at -10ºF and remained in 40 to 48 ft-lbs range down to -62ºF. Thus, while the fracture toughness of the commercially produced steel was less than that for laboratory-produced steels, it significantly exceeded fracture requirements for bridge steel.

Figure 1 shows the assembly of the bridge. Since the welding was not used, the assembly lasted just two days. Figure 2 shows the finished bridge in November, 2010. Our A710 steel is the best weathering steel used for bridges today (as shown in the following section), therefore it should be used unpainted. However, IDOT made a decision to paint the bridge, so bridge was painted by epoxy paint. We demonstrated in the past that paint subjected to accelerated salt-spray-test stays much longer on our A710 steel than on other weathering bridge steels such as A588 and A709 HPS70W.

Monitoring of the Lake Villa, IL Bridge

The weathering performance of the unpainted A710 B steel in the Lake Villa Bridge (built in 2006) was monitored by periodic site visits. We performed visual observations, took photographs of the different sections of the bridge and collected rust samples for X-ray diffraction analysis and scanning electron microscopy. We found that unpainted A710 B steel weathers very uniformly on vertical and horizontal surfaces of the girders. Over the last few years the color progressively changed from bright red-brown when the bridge was assembled (Figure 3) to dark black-brown now (Figure 4 and 5). The rust is compact, very hard and well adhered to the steel surface giving the steel good protection against further corrosion. X-ray diffraction analysis of the rust shows changes of the rust from mostly amorphous state when the bridge was just erected to a fine-grained crystalline state now. This progression is typically observed in advanced weathering steels during 10-15 years after erection. Our steel achieved this look in just few years. Figure 6 shows two bridges built in states of Pennsylvania and New York with A709 HPS70W steel. The contrast between our steel and the best weathering steel on the market is staggering; the protective rust on our steel is very uniform while the rust on A709 HPS70W steel is non-uniform. Our steel achieved this look in just few years.

Figure 1. Assembly of the Dixie Highway Bridge using wide-flange beams produced from lean A710B steel

Figure 2. Completed Dixie Highway Bridge (November 2010)

Figure 3. Assembly of Lake Villa Bridge (Fall 2006)

Figure 4. Lake Villa Bridge after 6 years after assembly

Figure 5. Weathered steel section of Lake Villa Bridge after 6 years in service

Figure 6. Bridges built with A709 HPS70W steel

Improvement of the steel weatherability

According to a study performed by the US Federal Highway Administration (FHWA) in 1998 the total annual estimated direct cost of corrosion in the US is a staggering $276 billion—approximately 3.1% of the nation's Gross Domestic Product (GDP) at that time. The study reveals that, although corrosion management has improved over the past several decades, the U.S. must find more and better ways to encourage, support, and implement optimal corrosion control practices. One of the ways to reduce this cost is to develop better corrosion resistant steels, weathering steels. "Weathering steels" are steels that exhibit enhanced resistance to atmospheric corrosion due to the formation of a protective oxide/hydroxide layer on the steel surface exposed to the ambient atmosphere. These steels are used in buildings, bridges, and other structures and can provide significant cost savings and environmental benefits when used unpainted. For example, for bridge construction without painting, one can realize an initial cost saving of more than 10 percent, with the additional benefit of easier installation and handling during assembly. The life cycle cost savings are more than 30 percent because weathering steels require less maintenance and are more durable than common construction steels. Since painting is not required, there are no volatile organic compounds (VOC's) from paints to deal with, and there is no need for the removal or disposal of contaminated blast debris over the life span of the structure. Because of these cost and environmental benefits, the use of weathering steels specifically for the construction of highway bridges has increased over the years. With the deterioration of the Nation's infrastructure, there is considerable interest in having weathering steels with improved durability. The other challenge is that current weathering steels are not considered adequate for marine and other high saline environments.

A few years ago, Federal Highway Administration expressed interest in the development of a "super" weathering steel for bridges in highly corrosive chloride-laden environments. We were sponsored by FHWA to develop a knowledge-based theoretical design of such a "super" weathering steel. We found that some elements that were not used in weathering steels in the past could significantly boost corrosion resistance of steels. Under ITI sponsorship we performed an experimental work to design "superweathering" steel with ASTM G101 corrosion index of more than 9. The typical weathering steels have this index in 5-6.5 range.

In addition to corrosion resistance, we must consider other factors in the design of better weathering steels. These factors include (i) excellent mechanical properties such as strength, ductility and high fracture resistance at low temperatures, (ii) the ability of steel companies to produce the steel by existing steel-making processes, (iii) ease of steel structure fabrication such as weldability and machinability, (iv) no adverse health effects during steel production and structures fabrication, and (v) cost-competitive with existing weathering steels. Therefore, one cannot design steels requiring complicated thermomechanical treatments not available to most steel companies. Likewise, one must be cautious about specific types and amounts of alloying elements incorporated into the steel to improve weatherability. For example, phosphorus is the most potent element in increasing the weatherability of steels, as seen from the ASTM G101 Standard [2]. However, when the concentration exceeds 0.05 wt.%, it causes embrittlement. Chromium provides excellent corrosion performance, but steels containing chromium release carcinogenic fumes during welding, so the concentration must be kept to some reasonable level. Molybdenum increases alloy strength and toughness, but it is expensive.

To utilize significant effect of P on weatherability, weathering steel known as COR-TEN A was developed many years ago by US Steel Company, containing between 0.07 and 0.15% P. While the steel had very good weatherability and was used for buildings, the fracture toughness was very low. This arises from the diffusion of phosphorus to grain boundaries, resulting in steel embrittlement. Because of this drawback, the concentration of phosphorus in the newer alloy, 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 Cr, Cu and Ni.

The issue is how one can retain the excellent weathering performance due to P while maintaining good mechanical properties, in terms of yield strength, ductility, and fracture toughness. We came with an idea to add an optimum concentration of titanium (Ti) as an efficient P getter, forming titanium phosphides (Ti_3P and/or Ti_2P) inside the steel grains, thus minimizing dissolved phosphorous diffusing to grain boundaries and causing embrittlement. This is feasible because the Ti-P bond is stronger than Fe-P (the Ti-P bond dissociation energy is estimated to be 431 kJ/mole compared with 313 kJ/mole for the Fe-P bond). Thus, we anticipated that an optimal combination of phosphorus and titanium can markedly improve weatherability while maintaining fracture toughness. We designed few new steel compositions based on the A710 Grade B steel with addition of more phosphorous and titanium. One-hundred-pound laboratory steel heats were produced and their mechanical, fracture and weathering properties being tested. The compositions of the original A710B steel and newly developed “superweathering” steels (SW) are given in Table 5. The concentration of P was varied from 0.08 to 0.11 %, which significantly exceeds that in commercial steels (e.g., almost four times higher than in COR-TEN B). The concentration of Ti was up to 0.68 %, slightly more than necessary to form stoichiometric titanium phosphide (Ti_3P). The ultimate tensile strength of the steels SW1 to SW3 (tested to date) depended on steel composition and was up to 660 MPa, and the yield strength was up to 520 MPa, thus suitable as a direct replacement of existing weathering steels. The ductility of these steels was very good; the elongation to failure exceeded 20% in all steels. Figure 7 summarizes the results of Charpy absorbed fracture energy tests for SW1, 2, and 3 performed down to -100°F. Charpy values for all steels significantly exceed the absorbed fracture energy requirement of ASTM A709 standard for bridge steels; Charpy values of 35 ft-lbs at −10°F for fracture-critical components. SW2 and 3 exceed this requirement down to at least −60°F. These are remarkable performance numbers, especially considering that the steel contains 0.11 % P!

Table 1. Chemical Composition, wt.%

Steel	C	Mn	Si	Cu	Ni	Cr	Mo	Nb	S	P	Ti	CI*
A710B**	0.05	0.50	0.50	1.30	0.80	NA	NA	0.07	<0.005	<0.005	NA	7.3
SW1	0.04	0.49	0.45	1.25	0.55	NA	NA	0.07	<0.005	0.11	0.68	8.1
SW2	0.07	1.29	0.59	0.71	0.37	0.53	0.10	0.05	<0.005	0.08	0.45	8.1
SW3	0.05	1.16	0.51	1.15	0.86	0.51	0.11	0.08	<0.005	0.08	0.53	8.6

* ASTM G101 Corrosion Index
** Typical A710B composition

So far only SW1 together with A710B steel was investigated in 2000 hours standard accelerated weathering test performed at the Kentucky Transportation Center. Addition of P and Ti to SW1 resulted in corrosion loss about 40% less than in A710B steel (Figure 8). It is very impressive considering that A710B is the best weathering steel used in bridges to date; A710B shows about 40% less corrosion loss than typical weathering steels A709HPS or A588. The weathering properties of SW2 and SW3 steels will be tested soon under new Transportation Research Board grant.

Further steel development and marketing for other than bridges infrastructure and non-infrastructure applications

Since the market for steels for infrastructure applications such as bridges is not big enough, other markets need to be explored to make production of new steels more attractive to steel makers.

Under ITI and CCITT sponsorship we modified A710B steel by addition of Ti. This addition resulted in the interstitial-free steel with significantly increased the Charpy absorbed energy of the steel down to -100°F; the steel bent but did not fracture in testing apparatus (Figure 9). Over the last few years this, “supertough” steel is being tested in the “Next-Generation Rail Tank Car Project”, an innovative joint initiative of three companies (Dow, Union Pacific and Union Tank Car Company (UTLX)) and the US Government that is focused on the design and implementation of a next-generation rail tank car with enhanced ability to safely transport hazardous chemicals like liquid chlorine at cryogenic temperatures. The steel significantly outperformed other commercial steel tested. At the present time the steel undergoes rigorous welding studies performed under tank car industry standards at UTLX. Pending welding studies results the steel will be tried for construction and testing of experimental tank cars (Figure 10).

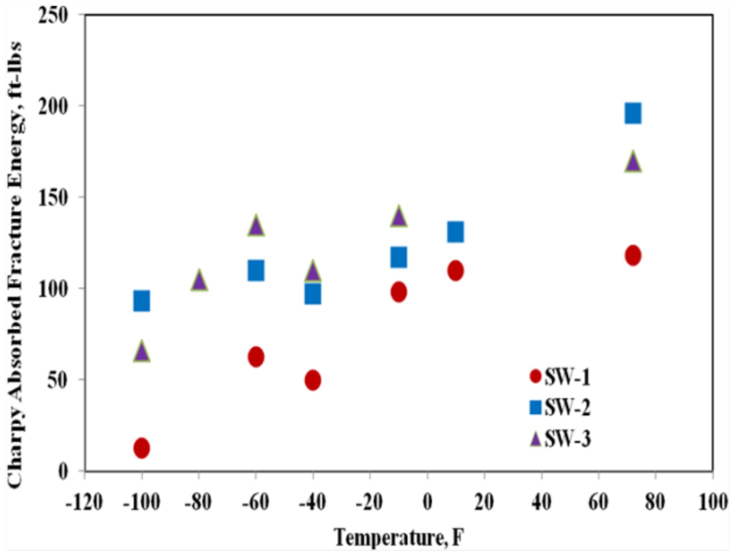

Figure 7. Charpy absorbed fracture energy of Northwestern experimental superweathering steels

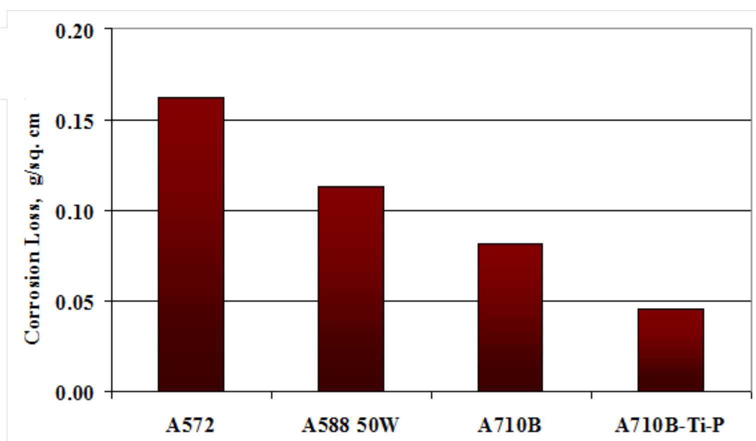

Figure 8. Accelerated weathering Prohesion test (ASTM G85 annex A) performed at the Kentucky Transportation Center

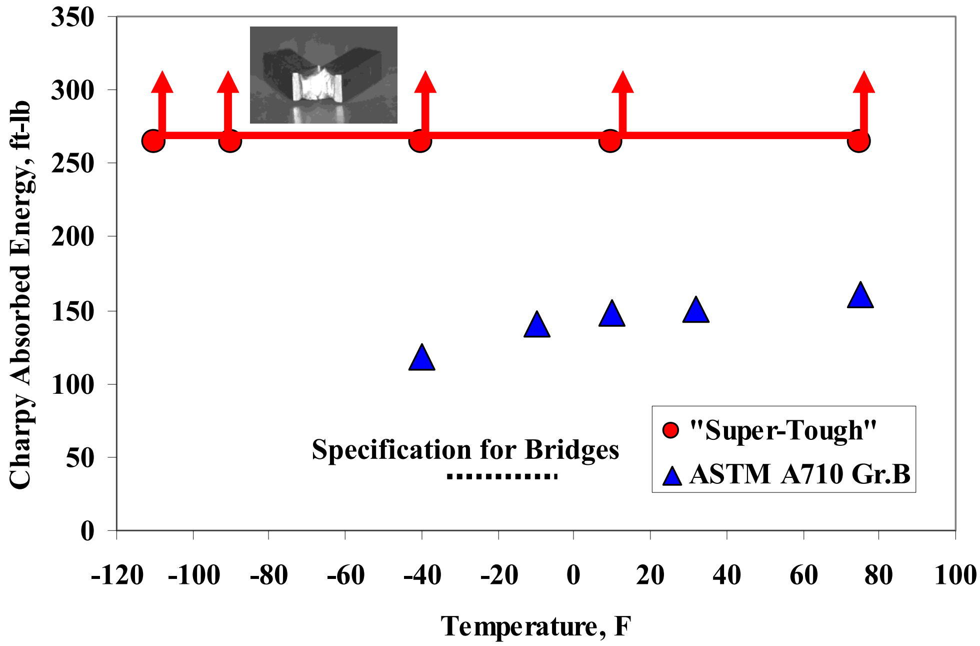

Figure 9. Variation of Charpy absorbed fracture energy with temperature for A710B and "superweathering" steel

Our original A710B steel is being considered by Siemens Light Rail Car Division for weight reduction of Siemens S70 low-floor light rail vehicle (LRV) (Figure 11). Siemens uses 50-ksi-yield-strength steel at the present time. Switch to stronger, 70-ksi-yield-strength will result in significant weight reduction of the rail car leading to energy savings. The mechanical and welding tests of A710B steel already performed at Siemens demonstrated that steel significantly exceed the requirements for light rail car construction. Siemens is ready to use the steel for their upcoming projects.

Recently IDOT sponsored through Illinois Center for Transportation a study at Northwestern University of formability of our "lean" A710B steel. The steel is being compared to ASTM A606 weathering steel that is used for sign and signal structures, light poles and other highway structures in Illinois. The A606 unpainted weathering steel could not be placed close to the roadways because the salt in the winter non-uniformly attacks the protective rust-layer on the steel's surface thus leading to the excessive steel corrosion. Galvanized highway structures are expensive and since the protective galvanic layer is consumed in time by corrosion the structure rusts after comparatively short time in service. Painted highway steel structures are expensive to maintain due to corrosion. Currently used steels do not have high fracture toughness; therefore the corroded structure might collapse due to cracking (Figure 12). A710B steel with its high fracture toughness and excellent weathering characteristics seems to be a great candidate for these applications pending the results of formability studies. Since our steel has excellent ductility it is expected to easily pass the formability requirements for construction steel.

Figure 10. Typical UTLX tank car for transportation of liquid chlorine at cryogenic temperatures

Figure 11. Siemens S70 low-floor light rail vehicle (LRV)

Figure 12. A606 steel sign structure collapse due to corrosion and low fracture toughness on IL-29

In 2011 we visited Nucor Steel Company in Decatur, AL and presented our work on strengthening and toughening of steels using nanosized copper precipitates. Subsequent discussion led Nucor to use our concept for addition of Cu and Ni to improve the strength and toughness of their coiled sheet steels. In accordance with our recommendations, Nucor produced two 170-ton commercial heats of the steel for structural support rails for truck frames, with increased yield and ultimate tensile strengths by about 15%, from 71 to 82 ksi and from 85 to 97 ksi respectively. The absorbed fracture energy of the steel was very high, more than 150 ft-lbs at -20°F in small, ¾-sized, Charpy specimens. The ASTM G101 corrosion index for the new Northwestern-modified Nucor steel increases from about 4.2 to 6.2. According to Table 1, the Northwestern-modified Nucor steel is more corrosion-resistant than A588 and A606 (used for signs, sign structures, light poles and other highway structures). This means that for example, under certain standard weathering conditions, the new Northwestern-modified Nucor steel will sustain only 70% of the corrosion loss of A606 steel.

Table 1. ASTM G101 Corrosion Index for Selected Steels

Steel Grade	G101 Index
A588 Grade B	5.4
A588 Grade C	5.0
A606	4.7
Nucor Steel	4.2
Nucor + 0.6Cu + 0.3Ni	6.2

Dissemination of information/steel marketing

Our steel development work was presented in conferences and published in proceedings and archival journals. These disseminations attracted interest from several steel producers, the bridge-building community, and companies involved in steel fabrication.

Development of material science engineers

Our ITI sponsored projects involved numerous undergraduate students that performed their senior research projects. Students were involved in steel development and characterization of mechanical, fracture and microstructural properties of the steels.

Publications

1. S. Vaynman, M. E. Fine, Y-W. Chung, S. P. Bhat, C. H. Hahin, "Low-Carbon, Cu-Precipitation-Strengthened Steel", "Low-Carbon, Cu-Precipitation-Strengthened Steel", Proceedings of International Symposium on the Recent Developments in Plate Steels, Winter Park, CO, June 2011, 181-188
2. M. E. Fine, S. Vaynman, D. Isheim, Y-W. Chung, S. P. Bhat, C. H. Hahin "A New Paradigm for Designing High-Fracture-Energy Steels", Materials and Metallurgical Transactions, **41A**, 2010, 3318-3325
3. W-J. Lee, W-J. Chia, J. Wang, Y. Chen, S. Vaynman, M.E. Fine, Y-W. Chung, Role of Surfaces and Interfaces in Controlling Mechanical Properties of Metallic Alloys", Langmuir, **26**, 2010, 16254 -16260
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5. S. Vaynman, Y-W. Chung, M. Fine, R. Asfahani, "Effect of Ti on Charpy Fracture Energy and Other Mechanical Properties of ASTM A 710 Grade B Cu-Precipitation-Strengthened Steel", Materials Science and Technology (MS&T) 2009 October 25-29, 2009, Pittsburgh, Pennsylvania, p. 1625-1632, TMS 2009
6. S. Vaynman, M.E. Fine, C. Hahin, N. Biondolilo, C. Crosby, "New Span, New Steel", Modern Steel Construction, 3, 2007, 16-20

Presentations

1. M.E. Fine, S. Vaynman, D. Isheim, Y-W. Chung, S.P. Bhat, "A New Paradigm for Lowering the Ductile-to-Brittle Transformation Temperature in Steels", presented at 2011 TMS Annual Meeting, San Diego, March, 2011
2. S. Vaynman, M. E. Fine, Y-W. Chung, S. P. Bhat, C. H. Hahin, "Low-Carbon, Cu-Precipitation-Strengthened Steel", presented at International Symposium on the Recent Developments in Plate Steels, Winter Park, CO, June 2011
3. S. Vaynman, M.E. Fine, Y-W. Chung, C. Hahin "High-Performance Steels for Infrastructure Applications", presented at 2010 FHWA Bridge Engineering Conference: Highways for LIFE and Accelerated Bridge Construction, Orlando, FL, April 2010, 561-569