TECHBRIEF

Improved Corrosion-Resistant Steel for Highway Bridge Construction

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This document is a technical summary of the Federal Highway Administration report, *Improved Corrosion-Resistant Steel for Highway Bridge Construction* (FHWA-HRT-11-062).

Introduction

Plate girder bridges are usually fabricated from painted carbon steels or unpainted weathering steels. Weathering steels, including the modern high-performance steels, offer the lowest life-cycle cost (LCC) over the design life of the bridge because, in most service environments, ongoing maintenance due to steel deterioration is not necessary. However, where the bridge is subject to high time-of-wetness or high chloride exposures—coastal areas and areas that use large quantities of deicing salt—weathering steels are not effective because the protective patina does not develop and the steel has a high corrosion rate.[1] In these conditions, structural stainless steel ASTM A1010 (UNS S41003) provides sufficient corrosion protection so that painting is not necessary and the bridge structure is maintenance free over its design life.[2] The initial cost of stainless steel is more than twice the cost of carbon or weathering steel. Reducing the cost of stainless steel would improve the LCC of bridges in severe corrosion service conditions. This study identifies steels with lower potential cost than ASTM A1010 that could be candidates for bridge construction while still providing low corrosion rates.

Approach

The alloy steel design selected to reduce the cost of ASTM A1010—that contains 11 percent chromium (Cr)—was to reduce the Cr content to 9, 7, and 5 percent. To compensate for the diminished corrosion resistance from lower Cr, additions of 2 percent silicon (Si), 2 percent aluminum (Al), or a combination of 2 percent Si plus 2 percent Al were made in the lower Cr experimental steels. After making and hot rolling the steels, the resulting plates were heat treated. These were tested for strength and impact resistance to determine which steels can meet the steel specifications for steel bridges.[3] The corrosion resistance of the alloyed steels was studied in the laboratory using accelerated test methods. In addition to measuring the corrosion rates, the corrosion products that developed on each of the steels were identified. Several steels were studied further by exposing them for 1 year on an existing weathering steel bridge that has a high corrosion rate due to deicing salt use.

Additionally, a LCC analysis was conducted to examine the benefits of using maintenance-free, corrosion-resistant steel in place of regularly repainting conventional steel. Both deterministic and probabilistic LCC

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analyses were conducted for a bridge intended to have a 125-year service life.

Results

Experimental Steels

Melting of six experimental steels was performed in an induction furnace under vacuum. The aim compositions of all heats was 0.015 percent carbon (C), 1.29 percent manganese (Mn), 0.022 percent phosphorus (P), 0.004 percent sulfur (S), 0.08 percent copper (Cu), 0.43 percent nickel (Ni), 0.24 percent molybdenum (Mo), 0.020 percent vanadium (V), and 0.0150 percent nitrogen (N). Table 1 shows the nominal compositions of each experimental steel.

Heats weighing 100 lb (45 kg) were poured into iron molds. The resulting ingots measured approximately 5 x 5 x 13 inches (125 x 125 x 350 mm). The ingots were heated one at a time in an electric furnace to 2,300 °F (1,260 °C) and hot rolled to 0.5625-inch (14.3-mm)-thick plates. These plates were normalized by heating to 1,650 °F (900 °C) and then cooling in air.

Mechanical Properties

The results of standard Brinell hardness tests on the as-normalized plates are presented in table 2. Most of the experimental steels exhibited the desired dual-phase or martensite microstructure, but the two Al-containing steels had an all ferrite microstructure, and they were relatively soft.

In the as-normalized condition, martensitic and dual-phase steels exhibited relatively high hardness, tensile strength, and yield strength. It was necessary to determine the temperature at which each steel needed to be tempered to achieve the two targeted yield strength levels of 50 to 65 ksi (344.5 to 447.9 MPa) and 70 to 85 ksi (482.3 to 585.7 MPa). This was accomplished by systematic heat treatment studies for each experimental steel using hardness testing and tensile testing. All the steels could be normalized and tempered to achieve the targeted 50 to 65 ksi (344.5 to 447.9 MPa) yield strength range representative of ASTM A709 50W, except 5Cr2Si2Al. All the steels could be normalized and tempered to achieve the ASTM A709 70W target yield strength of 70 ksi to 85 ksi (482.3 to 585.7 MPa), except 5Cr2Si2Al and 7Cr2Al.

The Charpy V-notch (CVN) impact test is specified for bridge steels.[3] Figure 1 presents the results of this test for the experimental steels. At the 50 ksi (344.5 MPa) strength level, only 11Cr, representing the ASTM A1010 steel, exhibited sufficient impact toughness to be a candidate for bridge construction. Similar behavior was observed for the 70 to 85 ksi (482.3 to 585.7 MPa) yield strength plates. The impact toughness results for the experimental steels are disappointing, but they may be explained by the optimum dual-phase microstructure of 11Cr with fine grain size compared to the other steels.

Table 1. Compositions of experimental steels.

Steel (Wt Percent)	Cr	Si	Al
11Cr (ASTM A1010)	11.4	0.5	—
9Cr	9.0	0.5	—
9Cr2Si	9.0	2.0	—
7Cr2Al	7.0	0.5	2.0
7Cr2Si	7.0	2.0	—
5Cr2Al2Si	5.0	2.0	2.0

— No (zero) aluminum present in these steels.

Table 2. As-normalized hardness and microstructures.

Steel (Wt Percent)	HBW	Microstructure
11Cr (ASTM A1010)	285	Dual-phase ferrite plus martensite
9Cr	313	All martensite
9Cr2Si	256	Dual-phase—more ferrite than 11 percent Cr
7Cr2Si	258	Dual-phase—more ferrite than 11 percent Cr
7Cr2Al	154	All ferrite
5Cr2Si2Al	200	All ferrite

HBW = Brinell hardness number (ASTM recognized).

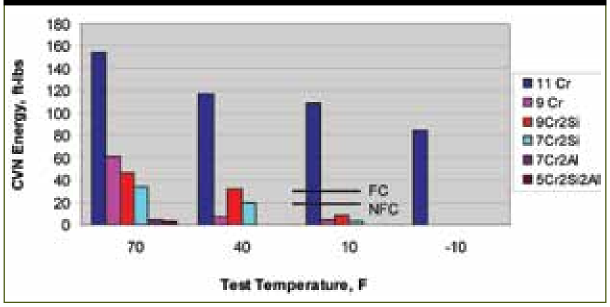
Laboratory Corrosion Evaluation

The atmospheric corrosion of bare structural bridge steels in chloride environments was simulated with the standard SAE J2334 cyclic corrosion test, consisting of 1-day cycles for 100 days.[4] Sets of coupons were run with a 5 percent sodium chloride (NaCl) spray solution, and another set of coupons was run with 3 percent NaCl solution to determine if a less severe chloride content in the spray solution might change the thickness loss rates from corrosion for any of the steels.[5] Thickness loss of test coupons and x-ray spectroscopic analysis of the corrosion products were both determined. Conventional ASTM A588 steel coupons representative of ASTM A709 50W bridge steel and ASTM A1010 coupons were tested along with the experimental steels.

The effect of yield strength on the thickness loss was measured for the 11Cr, 9Cr2Si, and 7Cr2Si steels. There was no significant difference in thickness loss for the two different yield strengths of the three steels. It was concluded that the corrosion behavior of these steels was not influenced by the steel yield strength.

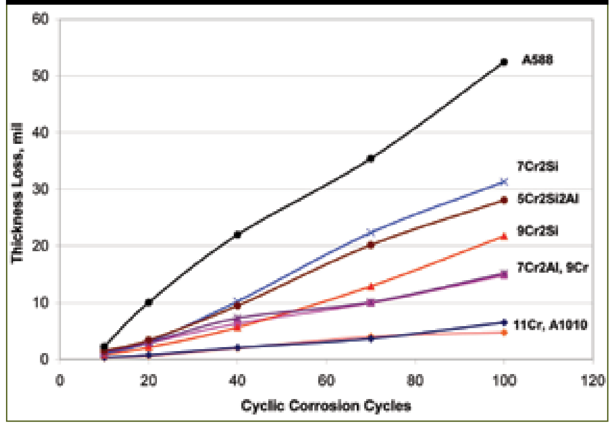
The comparative corrosion behavior of the steels is presented in figure 2. As the number of corrosion cycles increased, the total thickness loss increased

Figure 1. Average CVN absorbed energy values for experimental steels tempered to achieve yield strength greater than 50 ksi (344.5 MPa).



5*(F-32)/9 °F = °C
FC = Fracture Critical; NFC = Non-Fracture Critical

Figure 2. Summary of 5 percent NaCl cyclic corrosion test results.



1 mil = 25.4 µm

for all the steels. The experimental steels, as well as the control ASTM A588 weathering steel, experienced thickness loss at a relatively constant rate per cycle. This behavior demonstrates that the protective patina responsible for providing reduced corrosion rates for weathering steels does not form when the test is conducted with 5 percent NaCl. Similar behavior was observed using 3 percent NaCl.

All the reduced Cr experimental steels had significantly less corrosion resistance than the ASTM A1010 control sample and its laboratory analog, the 11Cr steel. As the Cr content of the experimental steels decreased from 11 to 5 percent Cr, the corrosion rate (thickness loss) increased. However, all the experimental steels exhibited better corrosion resistance than the ASTM A588 control sample. Adding 2 percent Si to the 9 and 7 percent Cr steels was detrimental to corrosion resistance. This is shown in figure 2 by comparing 9Cr to 9Cr2Si. Substituting 2 percent Al for 2 percent Si in the 7 percent Cr steel had a strong positive effect on the corrosion rate. Figure 2 shows that the 7Cr2Al steel had the same corrosion performance as the 9Cr steel, suggesting that 2 percent Al is equivalent to 2 percent Cr for cyclic corrosion resistance.

Since the corrosion rates in the cyclic corrosion tests appear to be linear, a regression equation was calculated for thickness loss as a function of cycles for each steel. The results of this analysis are presented in table 3. The values for the coefficient of determination (R^2) were all greater than 0.97, confirming that the corrosion rates of all the steels are linear with cycle number.

Under the conditions of the 5 percent NaCl cyclic corrosion tests, the corrosion rate of the ASTM A1010 steel is one-tenth that of ASTM A588, implying it will take 10 times longer for the same amount of thickness loss from ASTM A1010 as from ASTM A588.

Field Corrosion

In a field corrosion test site on the Moore Drive Bridge over I-394S in Rochester, NY, various steel coupons were exposed on racks mounted to the lower flange of the bridge.[6] The Moore Drive Bridge is in a location of high deicing salt use on interstate highway I-394S passing beneath the bridge. Following 4 years of exposure, ASTM A588 coupons experienced thickness loss of 10 mil (254 µm) or a rate of 2.5 mil per year (mpy) (60 µm per year), 10 times the generally accepted maximum rate for weathering steel of less than 0.25 mpy (less than 6 µm per year). At the same time, ASTM A1010 stainless steel coupons exposed for 2 years showed a corrosion rate of 0.58 mpy (14.7 µm per year).

Table 3. Linear regression equations for thickness loss in 5 percent NaCl cyclic corrosion tests.

Steel	Coefficient, Mil Per Cycle	Predicted Life Versus ASTM A588
ASTM A1010	0.050	10.4
11Cr	0.056	9.3
9Cr	0.147	3.5
9Cr2Si	0.197	2.6
7Cr2Si	0.304	1.7
7Cr2Al	0.152	3.4
5Cr2Si2Al	0.275	1.9
ASTM A588	0.519	1.0

1 mil = 25.4 µm

The experimental steels selected for exposure on the Moore Drive Bridge were 9Cr, 7Cr2Si, and 7Cr2Al. After 329 days of exposure on the bridge, thickness loss of the steels was determined. The corrosion rate of each of the three developmental steels was 1.07, 1.11, and 1.20 mpy (27, 28, and 30 µm per year), respectively. These rates are less than one-half the 2.5 mpy (64 µm per years) of ASTM A588 weathering steel. The rust composition was similar for all three of the experimental steels: Akaganeite was the most abundant oxyhydroxide, followed by goethite and lepidocrocite. Notably absent was maghemite, which was abundant on the cyclic corrosion test coupons. It was concluded that the cyclic corrosion test protocols used in this study were fundamentally different for Cr-containing steels than actual field environments for bridges exposed to deicing salts. It is likely the high time-of-wetness of the cyclic corrosion test promotes the formation of maghemite.

LCC Analysis

A LCC analysis examined the benefits of using a maintenance-free, corrosion-resistant steel in place of regularly repainting conventional steel. Deterministic LCC comparisons for a 125-year life span bridge girder made of painted carbon steel versus ASTM A1010 steel showed ASTM A1010 was more economical. Probabilistic LCC analysis determined that starting in about year 12 the probability that an ASTM A1010 steel girder costs less than a painted steel girder increases rapidly; the 50 percent probability occurs at year 15. By year 20 of service, the probability is over 90 percent that the ASTM A1010 steel girder is less expensive, and it becomes certain that the ASTM A1010 steel girder is less expensive than a painted conventional steel girder after year 40.

Summary

The efforts to develop a less costly but equally corrosion-resistant bridge steel than currently available ASTM A1010 were unsuccessful because the combination of strength and impact toughness required for steel bridge members could not be achieved with the lower Cr steels. The experimental steels were more corrosion resistant than ASTM A588. However, because ASTM A588 and other weathering steels do not develop a protective rust patina in the presence of high-salt exposure, bridges made from weathering steels or carbon steel must be painted and maintained by repainting at certain intervals for those service environments. Its corrosion resistance makes ASTM A1010 capable of lasting in structures for long periods of time—125 years, as considered in this study—without the need for initial painting or maintenance (i.e., repainting). Accordingly, the economic benefit of ASTM A1010 is gauged on its lower LCC compared to that of a conventional painted bridge steel.

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