The Use of ASTM A1010 – a Dual-phase Martensitic/Ferritic Stainless Steel for Bridges in the United States

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Abstract

ASTM A1010 is a low-grade stainless steel which is gaining popularity in the US bridge market due to its corrosion resistance and potential for life-cycle cost savings. Several recent research studies and pilot bridge construction projects have been initiated across several different states and agencies. Recent research has primarily focused on corrosion resistance and galvanic corrosion when in contact with dissimilar metals commonly used in the steel bridge industry. Ongoing research is investigating the structural behaviour of connections such as pretensioned joints and welds. Six bridges have been constructed in the US using A1010 material by five different states. Several other agencies are considering or have initiated discussions on the use of this new material in an effort to reduce maintenance costs, particularly in highly corrosive environments where other common bridge materials and coating systems require costly corrosion protection maintenance.

Keywords

Stainless steel, ASTM A1010, steel bridge, fabrication, corrosion

1 Background

Steel bridges comprise a major percentage of the United States (US) bridge inventory. A 2002 study funded by the Federal Highway Administration (FHWA) found that the annual real cost of corrosion for highway bridges in the US was approximately $8.3 billion, of which $500 million annually is spent on maintenance painting of steel bridges (Koch, Brongers, Thompson, Virmani, & Payer, 2002). Corrosion protection of steel bridges has long been a critical issue in life expectancy, resulting in an evolution of methods and materials to combat deterioration. Since the early 2000’s the US bridge industry has begun to investigate the use of stainless steels for primary bridge members to minimize and eliminate much of the maintenance, labour, and cost associated with steel bridges, specifically in highly corrosive environments where other alternatives have been less successful. This paper addresses the early research and implementation of one specific grade of stainless steel, ASTM A1010, which has begun to see widespread interest by the FHWA and many departments of transportation (DOTs) across the US.

2 History

Corrosion protection of bridges in corrosive environments has been one of the primary motivators toward the development of new protection systems and steel alloys in the United States for many years. Until the mid-1960’s oil or alkyd-based paints were used to protect bridges through the use of lead or chromium compounds, and typically had a service life of 8 to 10 years (Kline, 2009). Since then, combinations consisting of an inorganic zinc-rich primer, epoxy midcoat, and urethane topcoat (IOZ/E/U) have been widely used with an expected service life of 20 to 30 years before required recoating. Since the mid-1960’s, several grades of weathering steel have been developed and used heavily in the US, with the hope that they would provide a low or no-maintenance solution for corrosion protection. While they have a relatively good track record in many areas, these steels have exhibited some cases of poor performance in specific climates, leading to a technical advisory written in 1989 by the Federal Highway Administration (FHWA) which detailed areas in which uncoated weathering steel should not be expected to perform as intended, such as near marine coastal areas, areas of frequent rainfall or fog, and industrial areas (FHWA, 1989). The combination of cases of poor performance and the FHWA technical advisory has resulted in some state and federal agencies having a somewhat negative opinion regarding uncoated weathering steel use since the 1980’s (Kogler, 2015).

In the early 2000’s FHWA began considering the use of stainless steel as a candidate for bridges in highly corrosive environments, where other corrosion protection systems had not performed to expectations. In 2004 a low-grade stainless steel, ASTM A1010, was selected for an accelerated bridge construction (ABC) project in California. A1010 had been developed by ArcelorMittal in the 1990’s for other industrial applications under the Duracorr® tradename (ArcelorMittal, 2015; Okasha, Frangopol, Fletcher, & Wilson, 2012). Much of A1010’s use had been in industrial applications such as coal hopper cars, truck salt spreaders, and slurry pipelines. The bridge industry began investigating its use due to its good performance in these highly corrosive environments. ASTM A1010 is classified as a *dual-phase stainless steel* since it is composed of both ferrite and tempered martensite grain structures, and contains 10.5-12% chromium and 1.5% nickel. The combination of the microstructure and chemical properties allow A1010 to provide high strength, excellent toughness, and good weldability, while still maintaining a lower cost than austenitic and duplex steels.

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A1010 steel is designated under the Unified Numbering System (UNS) as S41003, and conforms to the ASTM A1010 specification, which provides chemical composition, heat treatment, and mechanical property requirements (ASTM, 2013). Two grades of this plate steel are included in the specification: 275 MPa (40 ksi) and 345 MPa (50 ksi). Although both grades are produced in Europe, only the 345 MPa (50 ksi) grade is produced in the United States. Current practice limits the maximum thickness of the plates in this specification to 50 mm (2 in). The steel must be heat treated by tempering to meet the mechanical property requirements. Prior to tempering, the steel can be left as-rolled, normalized, or quenched. The chemical and mechanical property requirements of ASTM A1010 Grade 50 are shown in Table 1 and Table 2, respectively.

Table 1 ASTM A1010 Chemical Composition Requirements (% max, unless range is indicated)

C	*Mn*	*P*	*S*	*Si*	*Ni*	*Cr*	*N*
0.030	1.50	0.040	0.01	1.00	1.50	10.5 - 12.5	0.03

Table 2 ASTM A1010 Mechanical Test Requirements

Grade	Minimum Yield Strength, F_y MPa (ksi)	Minimum Tensile Strength, F_u MPa (ksi)	Elongation in 50 mm (2 in) (% minimum)
50	345 (50)	485 (70)	18

The ASTM A1010 specification also includes two supplementary requirements suitable to agreement between the steel supplier and the purchaser. The first of these requirements allows for CVN testing where the number of tests, test temperature, and impact energy requirements are specified by the purchaser. For bridge applications, the CVN requirements for A1010 are equivalent to those found in ASTM A709, the ASTM designation for bridge steel commonly used in the US (ASTM, 2010). The second supplemental requirement allows the steel to be inspected via ultrasonic testing when specified by the purchaser.

The stress vs. strain behaviour of A1010 Grade 50 has some notable differences when compared to A709 Grade 50 steel. The Virginia Transportation Research Council (VTRC) at the Virginia Department of Transportation (VDOT) recently performed tensile tests on A1010 coupons; the test data were then compared to a typical A709 steel tensile test. Both tests were performed on 25 mm (0.5 in) thick specimens. The test results of the two types of steel are shown in Fig. 1. For small strains (less than 1%), the A709 steel exhibited linear elastic behaviour up to its yield stress before undergoing strain hardening. In comparison, the A1010 steel also demonstrated a linear elastic behaviour, but had a more rounded response with no clear yield point. The A1010 steel also did not display a flat yield plateau as the A709 steel does. It was observed that the A1010 steel experienced a significantly greater amount of ductility of approximately 35% strain prior to fracture, while the A709 steel fractured at approximately 25% strain.

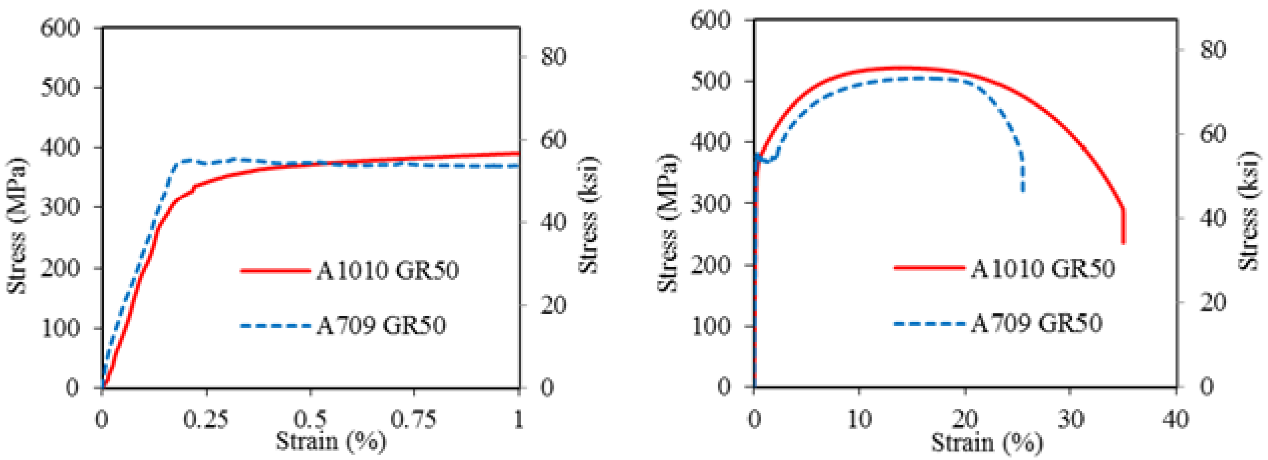

Fig. 1 Stress-strain comparison of ASTM A1010 Gr50 steel and ASTM A709 Gr50 steel to strains of 1% (left) and 40% (right)

Another important observation from the A1010 tensile tests was the presence of a delamination within the gauge length of the tensile specimen as shown in Fig. 2. Similar delaminations were observed on tensile tests of welded A1010 samples conducted by the Oregon Department of Transportation (ODOT) (Seradj, 2010). Although this delamination behaviour has not been observed in typical A709 steels, all of the A1010 tensile tests conducted at VTRC have met or exceeded the minimum specified mechanical property values of the ASTM A1010 specification.

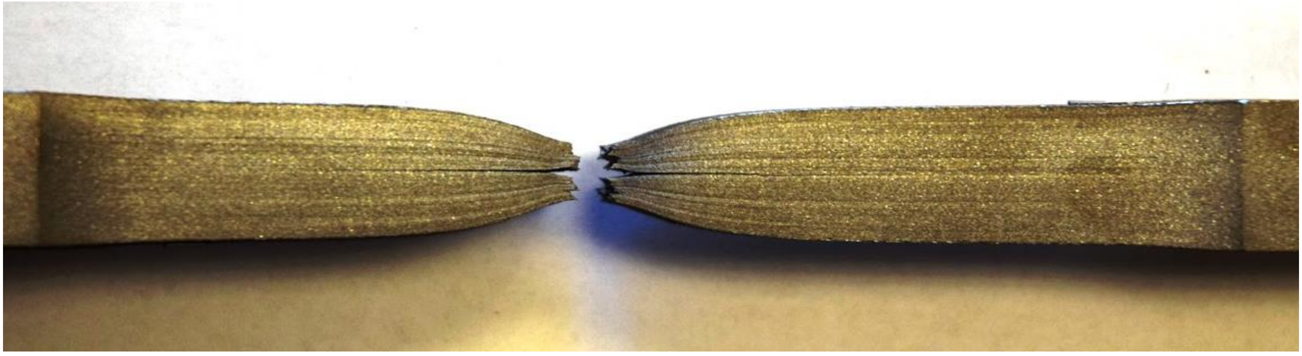

Fig. 2 Delamination fracture present within gauge length of ASTM A1010 tensile test specimen

3 A1010 Bridges in the US

To date, six bridges have been constructed in the US using A1010 steel. Each bridge has unique construction and fabrication features largely resulting from the experience of the limited A1010 construction experience and research of other DOTs. A1010 is currently produced by one supplier in the US, ArcelorMittal who produces only plate material. The availability of suitable material for secondary members and fasteners, along with the relatively new understanding of the behaviour of this material in different environments, has resulted in several investigations and incremental advances in this new industrial use of the material. Each of the bridges will be briefly discussed in chronological order.

3.1 Fairview Road Bridge over the Glenn-Colusa Canal, California

In 2004 the first vehicular bridge to use A1010 steel in the U.S. was constructed to carry Fairview Road over the Glenn-Colusa Main Canal in Colusa County, California. The approach roadway required a bridge with a clearance of approximately 0.3 m (1 ft) at high water events, as shown in Fig. 3. Since access below the bridge was limited due to the clearance, a bridge with minimal maintenance was desired. Colusa County engineers proposed the use of A1010 to the California Department of Transportation (Caltrans) as part of the FHWA Innovative Bridge Research and Construction (IBRC) program (Fletcher et al., 2005). Multi-cell bridge girders (MCBGs), composed of shallow steel modular c-shaped units, were selected for the structural system to reduce the height of the structure and significantly reduce the construction time. It was reported that the selection of A1010 for the material allowed the thickness (and weight) of the structural steel plates used to fabricate the modular units to be reduced by 50% due to the elimination of additional steel thickness for sacrificial corrosion resistance. A1010 was an available steel product in the US at that time, but until this point had not been used for bridge applications (Fletcher, 2011).

Fig. 3 Low clearance under the Fairview Road Bridge, Colusa County, CA (F. Fletcher, 2011)

The Fairview bridge was constructed with two 10.7 m (35 ft) spans and a total width of 9.6 m (31.5 ft). The MCBGs were fabricated using 4 mm (0.16 in) thick A1010 Grade 50 steel plate which was formed into C-shaped units by press brakes (Fletcher et al., 2005). The units were then longitudinally welded together using E309L consumable wire into modules of eight units for erection. Diaphragms and other attachments for rail post connections were also welded to the bridge modules. All plates were prepared using a water-jet to cut the material. The shear studs were of a low carbon steel, but were welded onto the top of the A1010 modules without any difficulty.

3.2 ArcelorMittal bridge

In 2012 ArcelorMittal, the only producer of A1010 in the US, funded the construction of a private two-span A1010 plate girder bridge over the West Branch of the Brandywine Creek at their Coatesville, Pennsylvania steel mill (ArcelorMittal, 2015). A1010 steel was used because the bridge was located adjacent to the mill, an industrially corrosive environment, with a high time-of-wetness. Additionally, ArcelorMittal wanted to demonstrate the corrosion resistance in an environment in which the bridge was subjected to a significant amount of heavy truck traffic, adjacent to the mill. An example of the heavy truck loads crossing the bridge is shown in Fig. 4.

Fig. 4 Heavy truck loads on ArcelorMittal Bridge, Coatesville, PA

The ArcelorMittal bridge was constructed with six girder lines consisting of welded plate girders with intermediate transverse stiffeners (ArcelorMittal, 2013). The bridge consists of two 14.9 m (49 ft) spans. Plate thicknesses ranging from 9.5 mm (0.375 in) to 38.1 mm (1.5 in) were used in the plate girder fabrication. Welds were performed using an E309L consumable for all A1010 material.

3.3 Dodge Creek Bridge & Mill Creek Bridge, Oregon

Champions of A1010 steel within the Oregon Department of Transportation (ODOT) performed several small experimental programs to better understand the material properties and fabrication needs of A1010 steel. They successfully promoted its corrosion resistance and obtained state and federal grants supporting the new material for two recently constructed bridges. ODOT's first A1010 bridge was constructed on Route 138 over Dodge Creek, near Sutherlin, Oregon in 2012. The single-span 40.4 m (132.5 ft) bridge was constructed with four plate girders, and a cast-in-place concrete deck having a width of 13 m (42.6 ft). A photograph of the bridge is shown in Fig. 5 (NSBA, 2014). This bridge had a high time-of-wetness and was chosen by ODOT as a trial location for their first A1010 venture. Due to limited material availability, weathering steel cross-frames with weathering steel bolts were used.

Fig. 5 Dodge Canyon Bridge, OR (NSBA, 2014)

One year later, in 2013, a similar single span 37.5 m (123 ft) A1010 plate girder bridge was completed over Mill Creek on Route 30 near Astoria, Oregon, as shown in Fig. 6 (Seradj, 2015). This bridge crosses the Mill Creek as it empties into the Columbia River Estuary, and is therefore in a corrosive marine environment making it an excellent location for additional corrosion resistance. It has four plate girders, and a total width of 13 m (42.6 ft). All A1010 material was cut using a plasma cutter and welded with ER309L welding consumables. Stainless steel fastener assemblies were specified for use during erection.

Fig. 6 Mill Creek Bridge, OR (Seradj, 2015)

3.4 Salix Interchange Bridge, Iowa

In 2016, the Iowa Department of Transportation constructed a four-span bridge composed of six plate girders carrying County Road K-25 over Interstate I-29 in Salix, Iowa. The bridge was being replaced due to low clearance and frequent vehicular strikes from interstate traffic below the bridge (Hytrek, 2014). The Iowa DOT used this bridge replacement to construct a bridge to evaluate their first A1010 bridge application. Two of the plate girders (one exterior and one interior) were fabricated with A1010 plate, and the remainder were fabricated with A709 Grade 50W (weathering steel) plate material. This will allow for a side-by-side comparison of the long-term corrosion behaviour of A1010 plate girders and A709 weathering steel plate girders. All cross frames were constructed with weathering steel, and all fasteners attached to the A1010 plate girders were specified as galvanized A325 bolts.

3.5 Route 340 Bridge, Virginia

In 2017, VDOT finished construction of the latest A1010 bridge constructed in the US. The bridge carries Route 340 over the South River in Waynesboro, Virginia. This project was the first time that A1010 steel had been used in a haunched plate girder bridge (see Fig. 7). It was also the first time that a US bridge design specified stainless steel for all secondary members and fasteners. Since A1010 angles were not available at the time of construction, bent A1010 plates were specified to be used in the fabrication of all cross-frames. Additionally, stainless steel fastener assemblies were specified throughout the bridge. A1010 material was selected for this location due to its proximity to an industrial area resulting in a corrosive environment, as well as the possibility of low water clearance over the South River.

Fig. 7 Route 340 Bridge Construction, VA

4 Recently Completed Research

4.1 Investigation of Cost-Effective Corrosion Resistant Bridge Steels, FHWA

The FHWA conducted a research study to develop a lower cost alternative to A1010 after its original use in the Fairview Road Bridge (F. Fletcher, 2011). The main objective of the study was to find a corrosion-resistant alloy that met the mechanical property requirements of ASTM A709, the specification for bridge steel used in the US. In the study, six similar alloys were produced, with decreasing amounts of chromium to reduce the material cost. Selected alloys were subjected to Brinell Hardness, Charpy V-Notch (CVN), and accelerated corrosion tests. Based on the test results none of the other alternatives completely met the A709 material test specifications, therefore it was concluded that A1010 was the most economical stainless steel for US bridges. Although the study did not reveal a better performing alternative to A1010, it did highlight the potential benefits of the material.

In the study, accelerated corrosion tests were conducted on each of the six experimental steels. ASTM A1010 and ASTM A588 steels were also included as control specimens (F. Fletcher, 2011). The cyclic corrosion tests as part of the study followed a modified SAE J2334 standard (SAE International, 2016), consisting of 1-day cycles for 100 days. Specimens were cycled using both a 5% sodium chloride (NaCl) and 3% NaCl spray solution. Thickness loss measurements were recorded periodically and showed linear behaviour. Table 3 shows the notable chemical compositions of the six experimental steels as well as the thickness loss determined through linear regression during the corrosion test. A predicted life compared to A588 was then made for each steel by comparing its thickness loss to that of A588. For the 5% NaCl solution cyclic corrosion tests, the A1010 had a corrosion rate of approximately one-tenth that of A588 steel.

Table 3 Comparison of thickness loss in 5% NaCl cyclic corrosion tests (F. Fletcher, 2011)

Steel	Wt. % Cr	Wt. % Si	Wt. % Al	Mil Lost Per Cycle	Predicted Life vs. ASTM A588
ASTM A588				0.519	1.0
ASTM A1010				0.050	10.4
11Cr	11.4	0.5	-	0.056	9.3
9Cr	9.0	0.5	-	0.147	3.5
9Cr2Si	9.0	2.0	-	0.197	2.6
7Cr2Si	7.0	0.5	2.0	0.304	1.7
7CrAl	7.0	2.0	-	0.152	3.4
5Cr2Si2Al	5.0	2.0	2.0	0.275	1.9

Field exposure tests were also conducted on the Moore Drive Bridge in Rochester, NY (F. Fletcher, 2011). This site was chosen due to the large amount of de-icing salt used on the interstate passing beneath the bridge. Test specimens of three of the experimental steels (9Cr, 7Cr2Si, and 7Cr2Al), ASTM A1010, and ASTM A588 were mounted to exposure racks on the bottom flange of the bridge. Thickness loss rates of each of the steels were compared, and it was determined that A1010 steel corroded at approximately one-fourth the rate of A588 while each of the experimental steels corroded at approximately one-half the rate of A588.

A life cycle cost (LCC) analysis was also performed in the study to evaluate the benefits of using a corrosion-resistant A1010 steel in place of regularly repainting A709 steel. Probabilistic LCC analysis was performed on a typical steel girder bridge with a design life of 125 years. The analysis showed that in year 15 of the bridge's life, there is a 50% probability that an A1010 steel girder would cost less than an A588 steel girder due to the need for maintenance actions such as repainting, necessary for the A588 girder. By year 40, there was a nearly 100% probability that the A1010 girder would be the least expensive material. The study concluded that the increased material cost of A1010 compared to weathering steel would likely be offset in only one or two repainting cycles.

4.2 Weldability & fabrication study, Oregon Department of Transportation

Prior to the construction of the Dodge Creek and Mill Creek Bridges, ODOT performed a study to investigate several concerns specific to the fabrication of A1010 plate girders (Seradj, 2010). Welding procedures were developed and evaluated for A1010 plate material. The machinability of A1010 plate material was also investigated along with an accelerated corrosion test of plain plate specimens.

4.2.1 Welding procedure development

ODOT decided to investigate welding procedures after a review of existing A1010 welding guidelines (Kelley, 2003) indicated an interpass temperature tolerance which allowed little variation, as well as strict pre- and post-heat requirements. The weld study was initiated to determine the effects of relaxing the weld heat requirements to reduce fabrication costs. The existing welding guidelines were based on meeting the procedure qualification records (PQRs) from the American Welding Society (AWS) D1.6/D1.6M Structural Welding Code – Stainless Steel (AWS, 2007). This study also investigated whether the required PQRs for the A1010 plate could be met for the AASHTO/AWS D1.5M/D1.5 – Bridge Welding Code (AASHTO/AWS, 2008).

An initial set of PQRs for a single bevel groove weld was completed using conditions recommended by Kelley (2003) including an interpass temperature of 107°C (225°F) and an ER309L weld metal. Pressurized air was directed at the bottom of the weld joint to decrease the time required to meet the interpass temperature and reduce the overall weld time. It was noted that the E309L consumable resulted in a significant amount of weld distortion and it was recommended that measures be taken during fabrication to limit such distortion in welded joints. All tested specimens met the PQR requirements of D1.5 and so three additional sets of specimens were created using interpass temperatures of 149°C (300°F), 204°C (400°F), and 232°C (450°F). At each test temperature, all required PQR tests were satisfactory; the required weld tests included tensile coupons on all weld-metal, CVN tests, macroetching, radiographic inspection, reduced section tensile coupons, and side bend tests. While the tests were all satisfactory for all three additional interpass temperatures, the tensile tests were observed to have a delamination-like surface at the point of fracture similar to the one shown in Fig. 2. A resulting straight beam ultrasonic test was conducted by the fabricator on theses specimens, but did not reveal any lamellar tearing in the material.

4.2.2 Accelerated corrosion test

During the corrosion tests, A1010 plate was compared to weathering steel and high-performance steel (HPS) in three different solutions over a duration of two years. All specimens consisted of 2.5 cm x 3.8 cm x 6.4 cm (1 in x 1.5 in x 2.5 in) plates which were ground to a surface roughness of 0.013 mm (0.0005 in). The first set of specimens were subjected to a daily set of four cycles of fresh water spray followed by drying with fans oriented on the specimens. The second set of specimens were subjected to the same cycles as the first set of specimens, but with an additional salt spray applied twice per week. The final set of specimens were exposed to a salt spray twice per week, and were not allowed to dry, but instead were stored in a sealed container with an internal water reservoir to represent a high humidity environment. The visual observations at the end of the study were reported. For specimens exposed to fresh water only, all specimens performed well with limited corrosion noted on the weathering steel and HPS specimens, and almost no corrosion product on the A1010 specimens. The specimens subjected to a salt spray had a significant amount of corrosion and suggested that for even the A1010 plates, a passive surface layer did not form. However, the corrosion product on the A1010 steel was much lower than on both the weathering steel and the HPS. ODOT is following up this investigation with a study expected to produce more quantifiable results.

4.2.3 Fabrication study

A fabrication mini-study was performed by ODOT and Fought & Company, Inc., the fabricator for the Dodge Creek Bridge. The purpose of the study was to compare the use of common fabrication tools on A1010 relative to traditional bridge steels. Holes were drilled with a Cincinnati Bickford drill machine and compared for A1010 steel plate and A572 steel plate, both having a 2.5 cm (1 in) thickness. The fabricator noted that the holes could be drilled at the same speed and feed rate for both materials with no noticeable difference in wear of the drill bit or quality of finished hole. Additionally, a Do-All commercial handsaw was used to compare the cutting performance of A1010 steel plate relative to A572 steel plate. It was noted that the A1010 plate was more difficult to cut and that more time was required. However, no additional wear was observed on the saw blade.

4.3 Corrosion studies, Virginia Tech

Cost and availability of material played a role in the decision making of the secondary members in each of the A1010 bridges previously constructed in the US. In all cases except for the Route 340 bride in Virginia, the designers selected A1010 as the primary members, but specified alternative materials which were connected to the primary members. The combination of dissimilar metals therefore affected the corrosion resistance of the primary members, secondary members, and fasteners. Virginia Tech performed an accelerated corrosion study to investigate the effects of galvanic corrosion between the A1010 material and various connected materials, consisting of both plate material in direct contact, and fastener assemblies connecting materials together (Groshek, 2017). Each material was selected based upon commonly used and available materials in the bridge industry, as well as applications having been used in recently constructed A1010 steel bridges in the US.

Each phase of the accelerated corrosion study was performed using a modified SAE J2334 Surface Vehicle Standard corrosion test, similar to the procedure performed by Fletcher in the FHWA corrosion study (2011). In the modified SAE J2334 test procedure, a sodium chloride (NaCl) concentration of 5.0% by weight was used based on findings which showed the correlation to corrosion rates of in-service bridges. Specimens were handled in a three-step daily process consisting of a humid stage (6 hours), salt solution application stage (0.25 hours), and a dry stage (17.75 hours) in accordance with SAE J2334 test procedure (SAE International, 2016). Control specimens were subjected to the same process to compare relative corrosion rates. Each set of specimens was subjected to eighty cycles, with intermediate specimen cleaning at twenty cycle intervals. Each cleaning cycle was performed to quantify the mass loss resulting from corrosion on each specimen as specified by ASTM G1 (ASTM, 2011).

4.3.1 Galvanic corrosion of plates

In phase one of the study, twenty-four 10.2 cm x 15.2 cm x 1.0 cm (4 in x 6 in x 0.375 in) ASTM A1010 Gr50 plates were secured to dissimilar plate material consisting of ASTM A709 Gr50, Gr50W, and Gr50 Hot Dipped Galvanized (HDG). Each set consisted of eight specimens, two of which were attached with a nylon plate between materials as control specimens preventing galvanic corrosion, but allowing atmospheric corrosion. The remaining six specimens in each set were connected to the dissimilar steels having three different plate sizes to investigate the effects of varying anode sizes. Each specimen configuration was connected using a nylon bolt through the centre of the plates to prevent galvanic corrosion contribution from the fastener. The specimens were placed at an angle of 5° from horizontal to simulate poor conditions when connected materials prevent drainage and therefore experience high time-of-wetness.

The results of the first phase of corrosion testing indicated that the A709 Gr50 HDG plate had the best outcome when attached to the A1010 steel plate specimens. Table 4 shows the relationship between the A1010 steel plates and the dissimilar steel plates. An increasing rate of corrosion was observed for all A1010 plates when connected to dissimilar plates. Both the Gr50 and the Gr50W had similar results from the aggressive corrosive environment that prevented creation of a passive surface layer. Crevice corrosion was observed on both the Gr50 and Gr50W specimens where the edges of the smaller dissimilar plate came into contact with the A1010 plate. The cyclic nature of crevice corrosion appeared to be a contributing factor to the increase in corrosion rate of the A1010 plate. The HDG assemblies were observed to experience migration of the zinc to the A1010 plate, as shown in Fig. 8. Additionally, the assemblies with HDG plates were observed to have a linear rate of corrosion until the zinc coating was depleted, at which point the rate of corrosion dramatically increased to a linear rate similar to the A709 Gr50. However, while there was a large increase in the rate of corrosion for the HDG specimens, the actual corrosion loss was much lower than both the Gr50 and Gr50W specimens. No clear change in corrosion rate was found for any of the specimens when the dissimilar plate sizes were varied.

Table 4 **Plate galvanic corrosion loss relative to control specimens**

	A1010 Plate		Dissimilar Plate	
	Avg. mils/cycle	% Increase	Avg. mils/cycle	% Increase
A709 Gr50	0.08	416%	0.35	147%
A709 Gr50W	0.10	494%	0.36	172%
A709 Gr50 HDG	0.05	229%	0.16	777%

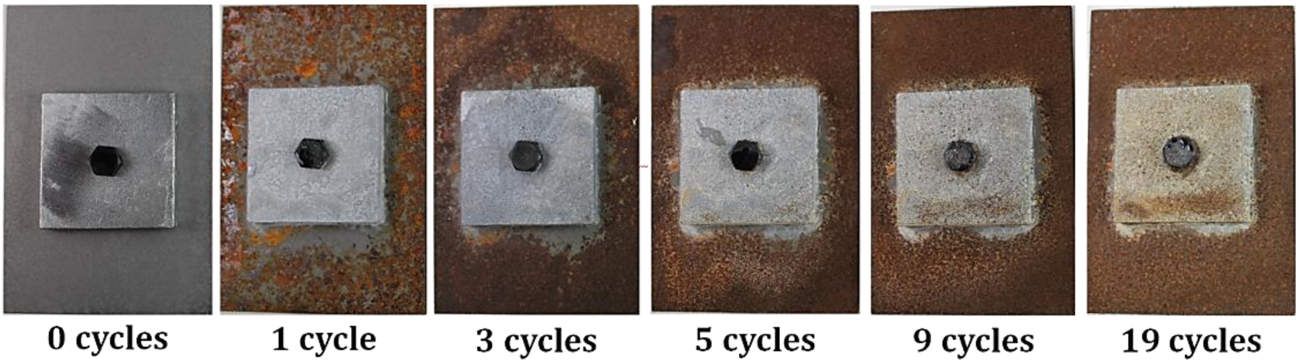

Fig. 8 **Migration of zinc from HDG specimens**

4.3.2 Galvanic corrosion of fasteners

Phase two of the study focused on the galvanic corrosion effects between dissimilar fastener materials and A1010 steel. Thirty-six specimens were tested, with eighteen 10.2 cm x 10.2 cm x 1.0 cm (4 in x 4 in x 0.375 in) A1010 plates attached to different fastener assemblies, and the remaining eighteen fastener assemblies attached to nylon plate material as control specimens. Six different fastener types were selected; four common types in the US bridge industry, and two recommended stainless steel fasteners. Table 5 shows the fastener component designations that were tested.

Table 5 **Fastener assemblies for galvanic corrosion test**

Bolt Type	Nut Type	Washer Type
A325 Type 1	A563 C	F436 Type 1
A325 Type 3	A563 C3	F436 Type 3
A325 Type 1 HDG	A563 DH HDG	F436 Type 1 HDG
A490 Type 1	A563 DH	F436 Type 1
A193 B8 Class 2	A194 Gr8 Class 2	410SS
A193 B6	A194 Gr6	410SS

The results from phase 2 indicated little difference in corrosion rates for the A1010 plate connected to fasteners of dissimilar metals. However, most of the fastener types experienced some change in corrosion rate as a result of the galvanic corrosion. While the uncoated carbon and weathering steel bolts (A325 Type 1, A325 Type 3, and A490 Type 1) had the largest initial corrosion rates (nearly double that of the next fastener), the A325 bolts were the least affected by the galvanic corrosion, with less than a 6% change for both the Type 1 and Type 3 bolts. The zinc on the HDG bolts was observed to migrate to the A1010 plate, and, similar to phase 1, the corrosion rate of the HDG bolts was linear until the zinc was depleted, and then had a corrosion rate similar to the uncoated A325 Type 1 bolts. The A490 bolts, A193 B8 Class 2 bolts, and A193 B6 bolts had the largest increase in corrosion rates as a result of the galvanic corrosion, with an increase of approximately 160%. However, the B8 bolts still had the lowest overall corrosion rate.

Table 6 Fastener galvanic corrosion loss relative to control specimens

Bolt Type	Avg. mils/cycle	% Increase
A325 Type 1	0.19	94%
A325 Type 3	0.19	104%
A325 Type 1 HDG	0.05	135%
A490 Type 1	0.23	160%
A193 B8 Class 2	0.01	160%
A193 B6	0.11	161%

4.3.3 Crevice corrosion

The third phase of the study investigated the effect of crevice corrosion when two adjacent A1010 steel plates were connected by a fastener. Crevice corrosion is a concern when a small isolated gap exists between components (such as a faying surface) in which corrosive substances along with reactants can be trapped, preventing passive surface layer formation (NACE, 2012). Six specimens consisting of a 10.2 cm x 10.2 cm x 1.0 cm (4 in x 4 in x 0.375 in) plate connected to a 7.6 mm x 7.6mm x 1.0 cm (3 in x 3in x 0.375 in) plate with a nylon bolt were tested. Each specimen assembly was tested at an angle of 5° from horizontal to maximize the time-of-wetness. Specimens were monitored for localized corrosion at the intersecting boundary edge of the two A1010 plates.

The crevice corrosion of A1010 plates attached to one another resulted in an average corrosion rate increase of 463%. The presence of a crevice prevented the formation of a stable surface layer on the A1010 plates in the immediate vicinity of the faying surface. While the control specimens indicated the development of a stable surface layer with some pitting, crevice corrosion specimens experienced continuous corrosion product flaking where the plates were touching. The pitting was significantly more pronounced on the crevice corrosion specimens. However, since the specimen plates were very similar in size, it is expected that, when implemented, the crevice corrosion on a bridge would be localized and that the increased corrosion rate would only represent an area adjacent to the connection.

5 Ongoing Research/Implementation

5.1 Corrosion resistant steel for low maintenance bridge girders, VTRC

In recent years, VDOT has begun making bridge design decisions considering the life-cycle costs (including long-term maintenance costs), rather than only considering the initial cost of the materials. One example is with reinforcing steel bars (rebars) in bridge decks. Previously, general practice was to use epoxy-coated steel rebars for bridge decks, but VDOT has since transitioned to using more uncoated, corrosion-resistant alloyed steel rebars because the increased durability leads to lower life-cycle maintenance costs. This ongoing project is following a similar concept, but with steel bridge girders. The main objective is to compare the design and fabrication requirements of painted carbon, weathering, galvanized, and A1010 steel girders. It is anticipated that although the initial cost of A1010 steel is greater than other steel types, it will be a competitive product when considering the cost of maintenance actions, such as repainting and washing that other steels can require over the life of the structure.

5.2 Construction of the Waynesboro Route 340 Bridge, VTRC

The objective of this project is to document the construction of the U.S. Route 340 Bridge in Waynesboro, VA. This bridge was constructed using A1010 steel girders, cross-frames, and stainless-steel fastener assemblies. Documentation includes the mill process and rolling of the A1010 steel plate as well as the design, fabrication, and erection of the Route 340 bridge. Each step of the process includes a documented comparison to traditional materials and fabrication, such as for painted, weathering, and galvanized steel. A cost analysis will be performed to assess the associated cost savings with using a corrosion resistant steel such as A1010. Guidance will be provided to VDOT on the most suitable and economical use of low-maintenance, corrosion-resistant steel for future bridge projects.

5.3 Welding of A1010 Steel, VTRC

Since A1010 is a relatively new material to the US steel bridge industry, there has been limited research on its weldability, aside from the afore-mentioned ODOT research. During the fabrication of the Route 340 bridge, issues arose in finding enough domestically produced 309L consumable metal that met the Buy America requirements (FHWA, 2017). Buy America is a federal law that requires nearly all of the steel or iron products used in federally funded transportation projects to be domestically produced in the US. Sufficient quantities of filler metal were eventually acquired, but it led to discussions on whether other more readily available consumable metals could be used when welding A1010. This research project was initiated to investigate the use of different types of electrodes from different consumable suppliers. It will also test several other welding parameters such as heat input and interpass temperatures in hopes of developing easier and more efficient welding procedures for A1010.

5.4 Evaluation and performance of Salix Interchange Bridge, Iowa State University

As part of the construction of the Salix Interchange Bridge, Iowa DOT funded a research project to further investigate A1010 steel material for bridge use in the state of Iowa. The study will continue to assess the behaviour of the plate girders fabricated from A1010 steel material relative to the adjacent plate girders fabricated from A709 Gr50 steel in the Salix Interchange Bridge. Additionally, a galvanic corrosion study is being performed to investigate the behaviour of different fasteners attached to A1010 steel.

5.5 Slip coefficient of A1010 uniform and hybrid bolted connections, VTRC

During the design of the bolted field splice on the Route 340 bridge, questions arose about how to classify the slip coefficient of A1010 steel since it is not addressed in the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications (AASHTO, 2015). Standard slip-coefficient tests according to the Research Council on Structural Connections (RCSC) procedures are being conducted on A1010 steel surfaces in the following conditions: unblasted, blast-cleaned using steel shot, and blast-cleaned using garnet media (RCSC, 2014). Garnet media is included in the study since it was used for the surface preparation of the Route 340 bridge faying surfaces. Slip coefficient tests will also be conducted on hybrid steel bolted connections consisting of A1010 and A709 steels. The A709 steel will include both weathering and galvanized steel in the anticipation of future use of hybrid steel bridge concepts in which A1010 and A709 steel are used on the same bridge. Hybrid steel applications may consist of using A1010 steel material in targeted areas with high corrosive exposure such as beam ends and areas closer to water; A709 steel material would be used in other locations with lower corrosive exposure to allow for cost savings. The hybrid steel connections will include various surface preparations.

6 Conclusion

A growing number of US agencies are investigating ASTM A1010 for use in bridge construction in corrosive environments. Corrosion resistance of plain A1010 steel plates has been shown to be up to 10 times greater than for traditional weathering bridge steels. Both research and bridges constructed to-date have illustrated largely positive results for corrosive environments. A1010 is also being investigated as an attractive material to repair or rehabilitate bridges with severe corrosion issues since often the corrosion is localized and is a known issue due to years of deterioration.

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