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Evaluation of the Use of Painted and Unpainted Weathering Steel on Bridges

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Evaluation of the Use of Painted and Unpainted Weathering Steel on Bridges

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16. Abstract

KTC researchers studied the use of unpainted weathering steel on bridges, using findings of inspections performed on Kentucky Transportation Cabinet (KYTC) bridges constructed with both painted and unpainted weathering steel as well as laboratory testing. Laboratory tests were conducted on test panels of conventional and weathering grades of steel to determine the performance of barrier and zinc-based coatings over abrasive-blasted substrates of those steel types in both the new and corroded conditions. The report provides the following recommendations for the use of painted and unpainted weathering steel on Kentucky bridges based upon both the field and laboratory findings:

- KYTC should develop a consistent policy on the use of painted and UWS bridges.
- The use of UWS bridges should be restricted to deck girder types using jointless designs or the current KYTC detail that incorporates concrete diaphragms. KYTC should use the FHWA T5240.22 guidelines to determine where to use unpainted weathering steel. The use of UWS bridges with fracture-critical members is discouraged.
- KYTC should investigate the performance of existing UWS bridges. As part of this work, the Cabinet should determine the most effective means of assessing patina performance. Baseline inspections should be performed on all KYTC UWS bridges to identify locations where patinas are not performing correctly. Based on these observations, recommendations could be advanced for remedial measures (including zone and total painting). Special emphasis should be placed on the two UWS truss bridges (KY 81 and KY 90).
- Guidelines should be prepared for bridge inspectors so they may properly evaluate patinas. Additional guidance should be provided to KYTC maintenance personnel to properly maintain UWS bridges.

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EXECUTIVE SUMMARY

Compared to conventional structural steels, weathering steels provide improved corrosion resistance on bridges when properly employed — not unrestricted use. They have been used in Kentucky bridges in both painted and unpainted applications since the mid-1970s. Nationwide, initial applications of unpainted weathering steel (UWS) were sometimes found to be problematic because their corrosion resistance diminished in response to unfavorable exposures, including industrial and marine atmospheres and areas of high and extremely low humidity. Additionally, localized siting issues such as at-grade crossings, sheltered areas and low stream clearance negatively have impacted weathering steel performance. The use of deicing chemicals on bridge decks and roadways also proved troublesome. Runoff and aerosols contaminated with salt has caused progressive corrosion of UWS bridges at locations where it came in contact with the weathering steel. An early example of this problem occurred on the KY 1893 Bridge at Shawhan in Bourbon County where there was complete section loss on some steel components.

UWS forms a brownish, mildly protective coating — termed a patina — that resists normal atmospheric corrosion. The maintenance of that patina is the key to obtaining continued protection for the underlying steel. A patina is a complex mixture of oxides that constantly erodes and is regenerated due to the alloy content of the steel. It provides a barrier that hinders progressive corrosion and provides weathering steel with its unique properties. The patina requires short intervals of wetting and drying termed *bold exposure*. Bridge designs sometimes incorporate features that make achieving this process difficult. In these cases, the resulting patinas do not offer the anticipated corrosion resistance.

KTC researchers visually inspected 21 UWS bridges throughout Kentucky to assess the performance of their weathering steel. Access issues prevented researchers from conducting close inspections on several bridges, although the weathering steel on these structures was viewed from a distance. Of the bridges inspected, six had progressive corrosion or poorly formed patinas. In most cases, these areas were localized. KTC also found debris build-up and water ponding on some structural members that would negatively impact patina formation while promoting progressive corrosion.

To supplement field observations, laboratory coatings tests were performed on conventional and weathering steel test panels. The steel panels were tested in the new and preconditioned (corroded) condition. Panels using both types of steel and surface conditions were coated after abrasive blast surface preparation. Barrier and organic zinc coatings were applied to test panels of both steel types and surface conditions to assess their relative performance based on rusting and scribe undercutting. The painted test panels were corroded in a test chamber for 5,000 hours. Most of the barrier-coated specimens failed in several thousand hours, and none made it to the 5,000-hour test limit. All of the organic zinc coated panels passed the 5,000-hour test, although their paint was chalked. Testing indicated that irrespective of steel type or initial surface condition (after abrasive blasting), the choice of paint was the major factor.

Other corrosion tests used half-coated panels where half of the steel substrate was left exposed. Those specimens were also corroded in test chamber for 5,000 hours. After the test, the paint and exposed/corroded steel areas were cleaned and the thicknesses of the steel were measured in the two different areas. The half-painted test panels revealed several things. For all steels painted with the organic zinc coating, the differences in thicknesses between the painted and unpainted (exposed) steel were greater than those for steels with the barrier coatings due to barrier coating failure and corrosion of the underlying steel. The conventional steel with the organic zinc coatings (blasted only & blasted and washed) had greater thickness differences between the painted and unpainted portions than the weathering steel due to the greater amount of corrosion occurring on the exposed conventional steel.

KTC researchers reached the following conclusions based on their literature reviews, field observations and laboratory testing:

1. UWS bridges constructed using current KYTC design practices may require some degree of follow-up painting after being placed into service. This may involve painting high-stress areas (e.g., areas lacking good drying and bold exposure — at or adjacent to abutments).
2. It may take up to 10 years of service to assess the performance of patinas on UWS bridges. Biennial inspections should be suitable to assess their performance and provide the opportunity for any necessary maintenance. The biennial inspection should be focused on determining whether patinas are performing properly.
3. While UWS bridges may avoid one or more paint cycles, they are not maintenance-free and require attention, including clearing of brush adjacent to abutments to promote air flow, debris removal from bridge steel and upkeep of joint seals.
4. The guidelines in FHWA T5140.22, if followed, would eliminate most, but not all of those problems. Low water clearances should be avoided as well as grade crossings less than 20 feet over a roadway.
5. The concept of building a UWS bridge and subsequently considering maintenance painting if the patina becomes unstable appears to be a practical option. Maintenance painting of problematic bridge locations will provide suitable performance, especially if abrasive blasting and multi-coat systems are used, including organic zinc-based primers.
6. UWS bridges can be investigated in more detail, including a focus on baseline steel section measurements and the investigation of patina corrosion products to identify bridges/locations where the weathering steel is not functioning properly.

KTC makes the following recommendations:

1. KYTC should develop a consistent policy on the use of painted and UWS bridges.
2. The use of UWS bridges should be restricted to deck girder types using jointless designs or the current KYTC detail that incorporates concrete diaphragms. KYTC should use the FHWA T5240.22 guidelines to determine where to use unpainted weathering steel. The use of UWS bridges with fracture-critical members is discouraged.

3. KYTC should investigate the performance of existing UWS bridges. As part of this work, the Cabinet should determine the most effective means of assessing patina performance. Baseline inspections should be performed on all KYTC UWS bridges to identify locations where patinas are not performing correctly. Based on these observations, recommendations could be advanced for remedial measures (including zone and total painting). Special emphasis should be placed on the two UWS truss bridges (KY 81 and KY 90).
4. Guidelines should be prepared for bridge inspectors so they may properly evaluate patinas. Additional guidance should be provided to KYTC maintenance personnel to properly maintain UWS bridges.

1. INTRODUCTION

1.1 GENERAL BACKGROUND — WEATHERING STEEL ON BRIDGES

Weathering steel is a term used to describe structural steels with better atmospheric corrosion resistance than conventional carbon and copper structural steels. Weathering steels were developed over 80 years ago and are widely used in unpainted structural applications that are exposed to the environment. They are typically low carbon steels containing alloys including chrome, nickel, phosphorus and copper in amounts up to 2 percent. In applications involving bold exposure and continuous wetting and drying, unpainted weathering steel (UWS) in ASTM A242*, A588 and A709 (Grades 50W, 70W and 100W) typically provide 1.5 to 2 times the corrosion resistance of conventional copper structural steels (ASTM A7*, A36, A440*, and A441*) (1). They provide about 4 times the corrosion resistance of plain carbon steels which includes some A36 steels where copper alloying was not specified.

The first applications of UWS in bridges occurred in the 1960s (Figure 1). Its use has gradually increased — today there are approximately 10,000 bridges in the U.S. that employ UWS. Many other bridges are in service that have painted weathering steels. Currently, while weathering steels represent only about 0.3 percent of steel tonnage produced in the U.S., they account for approximately half of the tonnage of steel used by fabricators to produce bridges (2).

The use of UWS in bridges has not been without problems. Several of the earliest UWS bridges experienced progressive corrosion and were subsequently painted (Figures 2, 3). After about 2,000 UWS bridges were completed, many state departments of transportation (DOTs) placed moratoriums or restrictions on their use. The Michigan Department of Transportation (MDOT) was the first to do so, in 1980 (3). Numerous MDOT bridges experienced significant corrosion problems, including those located over sunken roadways and other grade separation structures.

The steel industry responded to that situation, and shortly after the American Iron and Steel Institute (AISI) initiated a Phase I project consisting of field evaluations of the performance of 52 UWS bridges in several states. The project found that:

- 30% of the bridges had good performance (e.g., proper patina function) in all areas
- 58% of the bridges had good overall performance with moderate corrosion in some areas
- 12% showed good overall performance with heavy corrosion in some areas.

Subsequently, the Steel Structures Painting Council (SSPC) working under an FHWA contract studied the maintenance painting of weathering steel (termed Phase II by the AISI).

* Steels no longer in production.

An overview article published at the time stated that UWS bridges had two problems: 1) not every site is suitable for a UWS bridge — only sites that provide the right amount of moisture, sunlight and fresh air for successful oxide formation are appropriate, and 2) maintenance departments have to take steps to protect UWS bridges. The article noted that rainwater must wash over the steel in many wet/dry cycles, and contaminants must be diluted regularly, followed by the passage of enough fresh air to promote the drying (4).

In 1988 the Federal Highway Administration (FHWA) sponsored a forum involving federal and state government officials along with industry representatives that developed guidance concerning the use of UWS in structures. Based upon that forum, the FHWA developed a Technical Advisory, *Uncoated Weathering Steel in Structures*, T5140.22 (5). That document provided specific guidance and recommendations about the use and maintenance of UWS in highway structures.

In 1993, the AISI began a Phase III project re-examining the 52 UWS bridges that were previously investigated as part of its sponsored Phase I work as well as 11 additional bridges that fit into specific categories and had features which concerned DOTs. That investigation determined UWS bridges conforming to the FHWA T5140.22 guidelines were performing well. The AISI report also noted several limitations in the FHWA guidelines that it considered overly restrictive, including height restrictions on low water crossings.

Since the issuance of T5140.22, most DOTs that previously placed moratoriums on UWS have resumed using it in bridges due to its economic appeal. The number of DOTs with moratoriums dropped from 14 in 1987 to 6 in 2014 (Alaska, Georgia, Hawaii, Michigan, Mississippi and Puerto Rico). In a recent survey of DOTs, 96 percent of respondents had a positive perception of UWS bridges, but 40 percent reported some corrosion issues, primarily related to the use of deicing agents on roadways beneath UWS overpass bridges. Literature has noted that as of 2014 UWS bridges have registered slightly better performance than other steel bridges (including those that were painted) for service lives less than 25 years. For steel bridges older than 25 years, the other (painted) steel bridges performed slightly better than those with UWS (6). Most state DOTs have been satisfied with the performance of their weathering steel bridges though significant problems have noted in some instances (7)

In T5140.22, bridge designers were apprised of macroenvironments that are problematic for UWS bridges, including marine coastal areas, locations with high rainfall, high humidity or persistent fog and industrial areas where concentrated chemical fumes could drift onto a structure. There are microenvironments surrounding bridges that can be problematic as well. T5140.22 noted siting conditions to be avoided, including grade separations where *tunnel-like* conditions occurred and low level water crossings (less than 10 feet over stagnant water or 8 feet over moving water). *Tunnel-like* conditions are produced by a combination of narrow, depressed roads and minimum-width shoulders between vertical retaining walls, and wide bridges with minimum headroom and full-height abutments. Those conditions are typically encountered in urban/suburban grade separations. Other problematic microenvironment conditions include abutments where beam ends and bearings are sheltered. Those locations can be exposed to high humidities and poor airflow that inhibits drying. Vegetation situated around abutments can also restrict airflow.

Design details requiring emphasis included:
- Elimination of bridge joints
- Use of troughs under joints to divert water from the steel
- Painting all superstructure steel within 1-1/2 times the depth of girders from bridge joints
- Avoiding drip bars where fatigue is a concern
- Minimizing the number of scuppers
- Eliminating details that served as water traps
- Sealing box members where possible, or providing weep holes for drainage
- Covering or screening box members that are not sealed
- Protecting pier caps to minimize staining
- Sealing overlapping surfaces exposed to water (to prevent capillary penetration action)

An example of design accommodations for UWS is the New York State DOT's (NYSDOT) New Schoharie Creek Bridge on the New York State Throughway. To preclude problematic girder design details in using UWS, NYSDOT eliminated structural stiffeners and limited the number of flange splices by using oversized beams.

Not all DOTs strictly adhere to T5140.22. Some have elected to use UWS for all bridge applications, while others have restricted its use from specific structure types (e.g., box girder bridges, grade separation structures or trusses), at particular locations (marine, industrial or urban environments) and for specified traffic densities (e.g., Missouri DOT's urban restriction of ADT > 10,000) (8). In 1989, Albrecht et al (9) reported that for DOTs using UWS, the number of bridges on which it had been adopted varied from 100 percent (Vermont) to a few (Pennsylvania and Tennessee).

In the case of DOTs practicing unrestricted use of UWS, the option exists to paint a bridge or portions of it that exhibit progressive/unhindered corrosion. Another option would be to increase the section of structural members to accommodate for potential corrosion. An Ontario Transportation Ministry study recommended a slight increase in the section thicknesses of UWS on structural members at risk of higher corrosion rates than achieved when properly functioning (10). In addition to limiting the applications of UWS, the NYSDOT Bridge Manual contains a similar provision, specifying an extra 1/16" in flange and web thickness "where excessive salt spray may compromise structural performance" (11).

Maintenance actions recommended in T5140.22 included:
- Implementing maintenance and inspection procedures to detect and minimize corrosion
- Controlling roadway drainage (by diverting drainage away from the structure)

- Cleaning troughs or resealing deck joints
- Maintaining deck drainage systems
- Periodically cleaning (e.g., washing) and repainting steel within 1-1/2 times the depth of girders from bridge joints
- Regularly removing dirt, debris and other deposits that trap moisture
- Regularly removing all vegetation which impedes the drying of bridge steel
- Maintaining covers and screens on access holes

1.2 CORROSION OF UNPAINTED WEATHERING STEEL

For corrosion resistance, A242 > A588 > copper steels > carbon steels. However, environmental factors influence corrosion more than alloy composition (op. cit. 1). Corrosion requires oxygen and moisture. A key factor which promotes corrosion is time-of-wetness (TOW). TOW is related to relative humidity. TOW is in part a product of the duration and frequency of steel's exposure to fog, dew, rain and snowfall. Moisture can be deposited by the capillary action of porous rust, corrosion products and salt deposits. Pores and cracks in the rust coating, as well as crevices and small pits, also foster capillary action, which puts moisture into contact with the uncorroded steel (Figure 4). Atmospheric corrosion in moist conditions takes place when a thin invisible film of electrolyte forms on the surface at an ambient relative humidity well below 100%. The critical relative humidity above which atmospheric corrosion of structural steel increases sharply depends on the alloy type, surface contaminants, atmospheric pollutants and the nature of the corrosion product.

The macroenvironment in which a structure is located can significantly impact the atmospheric corrosion rate of steel. Macroenvironments include 1) marine, 2) industrial, 3) urban and 4) rural locations. That ordering also represents the normally anticipated aggressiveness of the attendant atmospheres, from worst to least. Nearly all marine environments aggressively corrode steel (both unpainted and painted). Pollution regulations have reduced the corrosivity of many industrial environments by lessening the amount of airborne sulphur compounds, which are most damaging to UWS. However, it can be misleading to characterize an environment's propensity to generate corrosion based solely upon location — a rural environment with high rainfall can prove as corrosive as an industrial environment.

ISO standard 9224, "Corrosion of Metals and Alloys-Corrosivity of Atmospheres," establishes a classification system to assess the corrosivity of atmospheric environments. It specifies average corrosion rates during the first 10 years of a metal or alloy's exposure. After 10 years, the corrosion rate attains a steady state (op. cit. 1). A modified ISO standard for weathering steels in the steady state corrosion range (after 10 years) establishes a medium corrosion band for weathering steels with an upper bounded loss per surface of 0.005 mm (0.20 mils)/yr. and a lower bounded loss per surface of 0.001 mm (0.04 mils)/yr. For carbon steels, the band values are 0.006 mm (0.24 mils)/yr. (upper bound) and 0.0015 mm (0.06 mils)/yr. (lower bound). Tests show that orientation can have an effect on environmental corrosion as well. On plates oriented 30^o from horizontal, skyward surfaces accounted for 38% of thickness loss while downward-facing surfaces accounted for 62% (Figures 5, 6).

In the presence of moisture, all low alloy steels have a tendency to rust. Many steels form surface layers of corrosion products that may provide some degree of corrosion resistance, but not to the degree provided by UWS. The rate of corrosion depends on the access of oxygen, moisture and contaminants (atmospheric and bridge run-off) to the metal surface. As corrosion progresses, the rust layer forms a barrier, hindering the ingress of those corrosion sources. For non-weathering steels, this layer of rust consists of coarse, porous and flakey oxides that eventually detach, allowing moisture to continue penetrating and corroding the underlying steel. This results in a repetitive corrosion cycle of high initial corrosion, rust formation (corrosion rate mitigation), exfoliation of the rust and renewed corrosion of the underlying steel at a high rate (12).

UWSs are used in atmospheric exposures because of they can develop a surface layer of a dense adherent corrosion product that resists/retards further corrosion. Unlike the tenacious oxide layers formed on other metals/alloys that are typically stable in many atmospheric exposures (e.g. aluminum alloys, stainless steel and gold), UWS's corrosion layer is relatively stable only in environments that are generally mild and under specific conditions.

The protective corrosion product (rust) layer on weathering steel is called a *patina*. The patina does not form immediately on UWS (assuming the mill scale layer is removed). Its formation is gradual, often taking five or more years. In the proper environmental conditions, it remains relatively stable, which results in the steel corroding at a relatively low uniform rate throughout the structure's remaining life. Certain environmental/ atmospheric conditions falling outside the ideal conditions will result in higher corrosion rates. In severe exposures, UWS corrodes unstably, at the same rate of a conventional carbon steel.

The patina layer consists of several main compounds — goethite (α-FeOOH; the most stable phase), akaganéite (β-FeOOH), lepidocrocite (γ-FeOOH), magnetite (Fe_3O_4) and other amorphous and nonstoichiometric compounds. Depending on the environmental conditions, some spinel types of iron oxides, such as magnetite (Fe_3O_4), are contained in the rust layer. Among the patina constituents, α-FeOOH forms a densely packed uniform layer of nano-sized particles, which are tightly bound to the underlying steel substrate. It contributes to the protective properties of the newly developed surface layer. Further, it inhibits penetrating water, oxygen and chloride ions from reaching the bottom layer of patina (13). Akaganéite occurs mainly in a macro- or microenvironments containing chlorides. Lepidocrocite is a non-stable component, which can transform into magnetite and maghemite in oxygen-rich environments.

A study of patina layers indicated the composition of layers that were most protective consisted mainly of nano-sized goethite and lower amounts of lepidocrocite (14). That occurs under ideal wet-dry cycling where the surface is wet for less than about 20% of the time (15). When the TOW > 40% or there are infrequent drying cycles, the UWS forms a rust coating that consists of a large amount of maghemite (a form of magnetite) and goethite that contains very little of the nano-sized goethite. Layered patinas formed by long-term humidity retention/exposure have magnetite as their main compound. The rust coating is not protective and disbonds in sheets. Where long-term accumulation of impurities occurs, especially chlorides, the content of individual patina compounds include goethite, magnetite and akaganéite. The resulting corrosion is progressive and, in conditions of severe chloride exposure, the UWS can experience corrosion 6 times greater than expected from weathering steel with a protective patina.

Weathering steels in most exposures are subject to electrochemical corrosion, requiring water, oxygen and an electrical path. Any disruption to those on the surface of a corroding material will halt or limit corrosion. The patina layers interact to protect the underlying steel from progressive corrosion by a number of complex properties and interactions (16). The general mechanism of weathering steels that limits corrosion is not fully understood but is related to stability of the patina. Signs of an unstable patina (scaling rust, coarse rust particles and pitting) indicate progressive corrosion.

As previously noted, UWSs are intended to corrode and loose section at a low, stable rate. If the corrosion rate is 0.3 mils/yr./surface or less, the patina is stable. Above that rate, the patina does not develop properly and the resulting corrosion product can result in corrosion rates as high as 5 mils/year/surface in corrosive exposures, causing localized pitting of up to 16 mils/year/surface (op. cit. 3). Damage to the patina occurs when moisture or corrodants (e.g., chlorides, sulfates), in conjunction with moisture, either come into contact with and weaken the inner layer of the patina or prevent it from forming properly. Albrecht and Naeemi found that corrosion of UWS, even in the absence of chlorides, can result in severe corrosion and pitting (17). Understanding how the weathering steel patina fails to form properly or what damages it causes provides insights into conditions on or around bridges that are problematic. General criteria for stable patinas include chloride exposures < 5 mg/m^2/day and TOW < 30% (18).

1.3 IMPACTS OF ENVIRONMENT AND DESIGN ON THE PERFORMANCE OF UWS BRIDGES

The performance of UWS on bridges relates to both the macro- and microenvironments around bridges as well as to structures' designs and maintainability. As previously noted, the development of patinas on weathering steel requires alternating wet-dry cycles and surface washing by periodic rains. On the macroenvironment side, UWS does not perform well in corrosive atmospheres (e.g., marine or near-coast locations, or aggressive industrial atmospheres); predominately dry atmospheres; or atmospheres with heavy rain, fog, or high humidity. These issues can be avoided by properly determining whether UWS is suitable for a bridge. On the microenvironment side, air flow, level of sheltering and vegetation can all restrict drying and may result in extended TOW. That includes not only when a surface is wet, but also when the relative humidity exceeds 80%. Another problem occurs when grade separation structures are exposed to the aforementioned tunnel-like conditions in which wind and traffic stir up aerosols that are laden with deicing salts, which are then deposited on girders. Proper siting/orientation of a bridge can typically improve those factors.

The service environments in which UWS structural members on bridges are commonly exposed do not foster the conditions required to form a protective patina. Key factors impacting patina formation are sheltering, bridge orientation, angle of exposure of bridge components, specific pollutants and debris (19). Inspections of UWS structures by other researchers have found that eastward exposures are the most aggressive due to their lower drying times. Southerly exposures were found to be the best for UWS and provided the greatest corrosion resistance.

Bridges/bridge elements are typically sheltered to some degree. The rust layers formed under those conditions are less compact with more non-adherent particles. In urban and rural environments sheltering does not have the same effect. Lower TOW typically lowers corrosion rates, but in heavily polluted and marine environments the absence of rain washing leads to an accumulation of pollution on surfaces and accelerates corrosion rate for longer exposures.

Bad structural details can lead to variability in UWS protective layer formation, including locations where deicing salts leak onto surfaces. The affected areas are usually localized. Stable patinas (e.g., 25-years old with 50 μm-thick goethite) are quickly destroyed by chloride contamination. Typically, the resulting patina thickens with the added presence of akaganéite. A damaged patina can recover over time, but it is a slow process and may take five years or longer.

Bridge designs can have a major impact on the performance of UWS bridges. Box girders trap condensation and should be avoided. Welded girder details such as re-entrant corners and horizontal stiffeners act as water traps and collect debris, thereby promoting corrosion. Joints and deck drainage systems need to be eliminated or limited. Bridge details should promote the removal of draining water from the bridge and prevent water collection on steel surfaces. Drain downspouts should extend below adjacent structural members (Figure 7). Crevices can be a significant problem with UWS. Those locations include faying surfaces at bolted splices under plates, bolt heads, nuts and washers. When the US 19 New River Gorge UWS arch bridge in West Virginia was cleaned in the mid-1990s, a large number of broken fasteners were replaced as part of the work.

With respect to aesthetics, weathering steels can present problems due to rust staining on the underlying concrete. Typically, this can be addressed with water runoff tabs on flanges, drip pans and concrete designs that eliminate or minimize the runoff and limit the consequences to the surface appearance. Painting structural concrete can also limit the staining.

For biennial inspections of UWS, it is recommended that inspectors examine the appearance of the patina/oxide film for color and texture (Figures 8, 9). Inspections should reveal when unfavorable environments exist that cause instability in the protective patinas and accelerated corrosion in the weathering steel. This can usually be determined by identifying visible scaling rust and heavy deposits of flaky rust on horizontal surfaces (Figures 10, 11). Other indications of potential problems include observations of coarse rust that readily flakes off in large particles compared to the fine particles that are scraped off of properly corroding weathering steel. Existing patinas should be wire brushed to see if a patina is adherent. Ultrasonic testing can be used for thickness inspection. Other physical assessments of the patina include looking for loose oxide debris, water streaks and pack rust in crevices (Figures 12, 13).

Maintenance is another factor in the performance of weathering steel. Older UWS bridges usually possess joints and possibly an excess number of deck drains. Both features can promote the leakage of rain/snow water onto the UWS, leading to corrosion. Joints must be kept watertight, or runoff should be carried off by troughs away from the UWS. Fascia girders on grade separation structures, which collect deicing salts and moisture kicked up by traffic, can also be problematic. Potential problems with unstable patinas need to be monitored or remedied by addressing drainage or protecting at-risk locations (e.g., beam ends under joints and splash zones) by zone painting (Figure 14).

Maintenance actions for UWS include:

- Blowdown of surface to remove debris
- Fixing leaky joints
- Washing steel
- Scraping off delaminating scaly rust
- Installing deflector plates and drip plates to divert water from the superstructure and abutments
- Cleaning drains and downspouts
- Caulking all crevices (op. cit. 8)

Steel bridges employ structural shapes with surfaces oriented in different directions. Typically, it is difficult to entirely prevent the creation of horizontal surfaces and possibly some water traps. Also, there will be varying exposures that facilitate wet-dry (bold exposure) conditions and periodic rain washing on the outer faces of fascia girders, which promote proper patina formation but are limited elsewhere under the bridge. This can be observed by studying various colors and textures of the patinas formed at other locations on an UWS bridge.

1.4 PAINTING AND OTHER CORROSION PROTECTION TREATMENTS FOR WEATHERING STEEL

A study performed by the American Iron and Steel Institute indicated that there was a first cost differential between new painted regular steel and UWS of 9.2 % in favor of UWS (20). The study indicated that uncoated weathering steel performed well on 63 candidate bridges in a variety of locations except in the Detroit area. Bridges designed and detailed in accordance with the FHWA Technical Advisory T5140.22 were predicted to perform well. Based upon the bridges inspected in this project (18-30 years old) the original selection of UWS was considered a cost-effective decision. At a minimum, it eliminated the need for an initial coating and in most cases at least one additional maintenance painting application. Most of those bridges should not require painting except under leaking deck joints. This results in low life-cycle costs. The Missouri DOT projected a life-cycle savings of 28-31% for UWS bridges compared to conventional painted structures.

For UWS in the fabrication shop, the NYSDOT specifies solvent cleaning to remove oil, grease and crayon markings followed by blast cleaning to SSPC SP 6 (Commercial Blast Cleaning). After blast cleaning, but prior to shipment from the shop, all exterior areas of the fascia steel are pressure washed with a stream of potable water to ensure uniform weathering (21). Other DOTs may specify steam cleaning in lieu of pressure washing. Blast cleaning to remove mill scale is recommended for UWS bridges as steel is anodic to mill scale and can pit in its presence when corroding (Figure 15).

Other DOT investigations revealed similar results, with signs of only localized problems (22). Those were generally attributed to: 1) water runoff from decks contaminated with deicing salts, 2) deck drain water blowing onto steel, 3) accumulation of debris on bottom flanges, and 4) bird nests. Chloride samples from patinas/rust had low chloride concentrations.

As previously noted, several of the first UWS bridges were subsequently painted when they were found to have progressive/unhindered corrosion. MDOT investigated the weathering steel corrosion problem and developed guidelines for painting problematic structures (23). Other DOTs encountering similar problems also painted UWS bridges that exhibited corrosion problems. The SSPC conducted research on painting weathering steel for the FHWA and several reports were subsequently prepared (24, 25). After the issuance of the FHWA T5140.22 guidelines, DOTs began to exercise more precautions about siting and designing weathering steel bridges. Subsequently, the number of corrosion problems with weathering steel decreased, and fewer UWS bridges were painted due to fewer corrosion issues. However, joints remained problematic and highway agencies began to paint beam ends. The T5140.22 recommendation was to paint beams/girders along their length to 1.5 times the girder depth. A KTC survey revealed differences in the extent of painting along the end of girders/beams. Some DOTs painted 2-3 feet from the beam ends and others painted them for 5, 10 and even 25 feet (Figures 16, 17).

The initial MDOT guidance recommended painting of UWS bridges exposed to significant amounts of salt from leakage on steel by the time they reached 15-20 years of age (op. cit. 3). Other MDOT research on maintenance painting of corroded weathering steel noted that sandblasting the steel was challenging due to numerous deep pits and fine pitting (op. cit. 22). Pits were difficult to completely clean of rust (Figure 18). MDOT identified several features of coatings/coating systems that are ideal for the maintenance painting of corroded UWS:

- Surface tolerance of large DFT variations due to painting on rough surfaces
- Insensitivity to rust and contaminants (e.g. chlorides) in pits that are difficult to remove
- Low vapor transmission rates to prevent osmotic blistering of the coating(s).

Subsequently, the MDOT recommended painting with epoxy zinc primers and mid-coats, as those could achieve the high builds necessary to cover irregular surfaces created by corroding weathering steel.

The SSPC preliminary report concluded that the major corrosion problems with UWS bridges included severe corrosion, scaling and pitting (op. cit. 24). Painting of uncontaminated weathering steel was not considered a problem. The major challenge is addressing chlorides that accumulate in pits. Blast cleaning was not found to be effective in removing those contaminants, and standard highway coatings including zinc-rich systems have not proven satisfactory. The report stated that MDOT found that joint leakage caused severe, although localized, corrosion. Salt spray had a less immediate effect as it covered nearly all of a structural member (e.g., girder) surface. However, the long-term impacts of salt spray can be as severe as leakage. That report stated that the rate of attack by crevice corrosion is greater than that on exposed UWS surfaces. It noted that pitting can impact the fatigue strength of UWS (addressed in current AASHTO design codes). Accumulation of debris and corrosion products creates an environment where UWS cannot dry out and prevents formation of a protective patina. The rust's capillary or wicking action draws salt solutions to many areas that would otherwise be unaffected. The report also noted that mill scale over steel results in more pitting than blast-cleaned steel.

The SSPC study included a four-year evaluation of painted weathering steel in three conditions: extensively pitted (chloride exposure), mildly corroded and non-pitted. It addressed the corrosion issue by creating a test matrix of UWSs subjected to differing environments, including severe industrial and marine exposures that charged the corroding surfaces with sulfur compounds and chlorides (op. cit. 25). Three methods of surface preparation were used: dry abrasive blasting, wet abrasive blasting and power-tool cleaning using rotary peening and non-woven abrasive discs. Chloride levels were measured to determine coatings' ability to tolerate different levels of chloride or other soluble salts on their surfaces, which ranged from 5 – 150 $\mu g/cm^2$. Test exposures included three bridges in Michigan, Pennsylvania and Louisiana and two fence locations — a moderate industrial environment and a severe marine environment. Coatings used included: an epoxy zinc system, a urethane zinc system, an epoxy mastic system, an ethyl silicate zinc system, a waterborne acrylic system and an oil alkyd system (control). Rusting and scribe undercutting were evaluated over a period of four years.

Based upon the findings of that test program, the SSPC report provided recommendations for painting over three field conditions: new non-corroded A-588 (low chloride), corroded (weathered) A588 (with low chloride exposure) and corroded A588 (with high chloride exposure). Bridge maintenance/painting recommendations were based upon bridge exposure conditions classified as severe or mild/moderate. The extent of painting was based upon specific bridge conditions:

<u>No Maintenance Option</u> (including deferred painting)

- Little or no deicing chemicals used in absence of a marine environment
- Non-leaking joints, an absence of joints and very light traffic
- Dry climates, rural areas, with no prolonged wet conditions
- Open structure with minimal angles, joints and faying surfaces (e.g., box girder) 20 ft. or more above the roadway

- Inspection reveals very little corrosion (intact mill scale) or very light small grained scale on top flange and other locations
- Long-term maintenance program includes future painting plans
- Ref. FHWA TA 5140.22

Paint Corroded Areas Only

- Evidence of severe localized corrosion, including heavy salt deposits
- Little salt spray exposure from below (e.g., grade separation) with light traffic — no trucks or non-highway (river) crossing
- Loose scale continues to develop in localized areas for 5 or more years, evidence of scale loss
- Configuration presents areas that tend to collect moisture and debris which are not readily cleaned by rain and are not readily accessible to drying conditions

Paint Entire Structure

- Corrosion and scale evident in many parts of structure (e.g., evidence of salt running along the entire bottom flange or salt spray from traffic on bottom of flange)
- Humid or salt-laden environment (e.g., near salt marshes, bays or coastal areas)
- Aesthetics important (e.g., desirable for the bridge to have a uniform appearance)
- Difficult to isolate corrosion-prone areas
- Corrosion rate data indicate that eventually the entire structure will require painting to perform safely for its entire design life

Preventive Maintenance (non-painting)

- Cleaning and providing adequate drainage for drains, scuppers and dams
    - This option is favored when such improvements can achieve major reductions in accumulations or distribution of moisture and chlorides into joints or along flanges.
- Surface chemical treatments (not currently in widespread use)
- Periodic washing with water.
- Some evidence exists this is effective in reducing the corrosion rate. Study indicates that low pressure water jetting cannot remove chlorides embedded in the steel. This approach would require frequent (annual?) washing with copious amounts of water. No economic studies have been performed to determine if this is cost effective.

Use of Protective Coatings on Corroded Areas Only

- Power tool cleaning to SP 11 leaves too many chlorides and corrosion products in pits, which is shown to reduce coating lifetimes. Dry or wet blasting provide equivalent coating performance. Wet blasting is slower than dry blasting. Blasting UWS takes 20-40 percent more time than regular steel. SSPC SP 10 surface preparation is recommended for blasting. Chloride levels of 50 μ/cm^2 or greater should be re-cleaned. 10-50 μ/cm^2 of chloride contamination is considered marginal. Because corroded UWS is rougher than normal steel, it requires a substantially higher volume of primer — 30-50 percent more. For a primer, a 3 mil minimum DFT is recommended.

- Coating Materials for Corroded UWS in Severe Environment
    - IOZ/Epoxy/Polyurethane
    - Organic Zinc/Epoxy/ Polyurethane
    - Thermally Sprayed Zinc/Epoxy
- Coating Materials for Corroded Zones in Mild/Moderate Environments
    - MCU Zinc/Epoxy/Polyurethane
    - Epoxy Mastic/Polyurethane

Full Repaint

- Surface preparation of corroded sections — abrasive blast (wet or dry)
    - For corroded UWS in severe environments. Previous systems noted above on corroded steel should be used with SSPC SP 10 surface preparation.
    - For non-corroded steel in severe environments. Previous systems for mild/moderate environments. For non-corroded UWS SSPC SP 11 power tool cleaning may be acceptable, but it is too slow. Can also use water jetting for surface preparation. Hand tool cleaning may be used for limited areas where there is no corrosion or dirt.
    - For corroded UWS in mild/moderate environment the chloride level must be below 50 μ/cm^2 using the first set of coatings systems listed above.
    - For non-corroded UWS a blast cleaned surface is recommended and all previous coatings may be used, including proven inhibitive oil alkyd. If using organic zinc/epoxy/polyurethane and the epoxy mastic polyurethane system, it may be possible to substitute a commercial blast SSPC SP 6 for the SSPC SP 10.
    - Primer thicknesses should be 3 mils above the peaks per SSPC-PA 2.

Other recommendations indicate that the root causes of corrosion should be eliminated rather than relying on maintenance painting to remedy a problem. Researchers found that UWS must have its patina removed before it is painted to achieve good performance when using barrier coating systems (26). The authors of that paper also stated that for corrosion-damaged UWS, repairs to corrosion-critical locations or locations significantly damaged by corrosion, paint systems were not generally suitable and effective for a sufficient period of time to be considered viable. They observed that painting corrosion-damaged UWS should only be done where further corrosion protection is not otherwise achievable.

In addition to thin film coatings, numerous protective treatments have been evaluated and proposed to protect the patinas on weathering steel, including phosphates and other inhibitive coatings (27, op. cit. 18). To date, these have not been widely used.

Albrecht (op. cit. 17**)** noted that the life-cycle costs of UWS and painted bridges were as follows:

- Lowest life-cycle cost is UWS where it performs acceptably
- Next lowest life-cycle cost is painted ASTM A572 (ASTM 709 grade 50)
- Next lowest life-cycle cost is remedially painted weathering steel (e.g. ASTM A588)
- Next lowest life-cycle cost is painted ASTM A36
- Highest life cycle cost is periodically hosed (annually) ASTM A588.

1.5 UNPAINTED AND PAINTED KYTC WEATHERING STEEL BRIDGES

The Kentucky Transportation Cabinet (KYTC) began using UWS in bridges in the 1970s. Most of those applications were relatively problem-free except for the KY 1893 bridge at Shawhan in Bourbon County. That bridge had leaking joints, which created significant corrosion problems at the beam-ends and bearings (Ref. Figures 2 and 3). The two largest UWS bridges KYTC were truss structures — the KY 81 Bridge over the Green River at Calhoun, built in 2001, and the KY 90 Bridge over Lake Cumberland near Somerset built in 2006 (Figures 19, 20). Both bridges prompted controversy due to their appearance, especially the significant amount of rust staining on the structural concrete and bridge decks. Due to the public reaction to those bridges, KYTC placed a general prohibition on the use of UWS on bridges in the public view. KTC researchers contacted KYTC districts to obtain a listing of other UWS bridges. About 15 bridges were identified as a result of that effort.

Some reports indicate that coatings on weathering steel perform better than on regular steels. Others note no difference in coating performance. A TXDOT maintenance painting project reported having more difficulty in blast cleaning UWS than conventional ASTM A36 steel.

Painted weathering steel (ASTM A588) was used on several large KYTC Ohio River bridges constructed since the 1970s. That steel was employed to provide a 50 ksi yield strength for design rather than to offer enhanced coating performance. While a conventional 50 ksi yield strength structural steel (ASTM A572) in thicknesses up to 2 inches was available for use on bridges in the early 2000s, KYTC officials decided to rely solely on weathering steels for bridges. Because of this policy, KYTC decided to apply coatings on these new bridges in locations that would be visible to the public. As a result, new steel bridges built in Kentucky from 2008 to the present were slated to use painted weathering steel. In some cases, KYTC has painted exterior portions of fascia girders on UWS bridges and left interior surfaces unpainted.

The future KYTC policy for addressing painted weathering steel bridges remains uncertain. Some KYTC officials have stated that once the existing coatings begin to deteriorate the affected bridges will not be repainted. Presumably, instead of maintenance painting, those bridges would be blast cleaned and used as UWS structures. In the absence of a firm KYTC maintenance policy addressing those bridges in the future, this research was conducted to provide potential guidelines to inform future maintenance actions on weathering steel bridges.

1.6 WORK PLAN

The study objectives approved by the KYTC Study Advisory Committee were:

1. Review the performance of uncoated and coated weathering structural steel and associated problems with corrosion on highway applications.
2. Determine guidelines for KYTC on usage of weathering steel on bridges in Kentucky. Those determinations would be based upon existing practice/guidance by other agencies, current performance of weathering steel and associated life-cycle costs.

To address those objectives, the study work plan included the following tasks:

Task 1. KTC was to conduct a literature survey on the use of weathering steel on bridges and associated corrosion problems including those related to the durability of painted weathering steel. KTC was to assess existing national guidance on the use of UWS and determine if DOT practices for deploying weathering steel conformed to existing guidelines or if they supplanted those with their own rules for deploying it. KTC was to survey selected SHAs concerning maintenance applications of coatings on UWS.

Task 2. Based upon the findings of Task 1, KTC was to prepare a series of laboratory accelerated weathering/corrosion and long-term field tests of painted weathering steel. Initial tests were to assess the performance of painted weathering steel with its equivalent grade of conventional painted steel. After that testing was completed, the weathered/corroded panels were to be abrasive blasted and re-tested to assess the ability of weathering steel to perform after maintenance painting (compared to conventional non-weathering steel).

Task 3. KTC was to summarize findings of Task 2 and determine painting practices on weathering steel bridges. The findings were also to be used to determine whether painted weathering steel performs better than conventional steel for new construction. KTC was also to determine if weathering steel can be successfully maintenance painted.

2. WORK ADDRESSING STUDY TASKS

In addition to the defined study tasks, KTC utilized findings from its field inspections on KYTC UWS bridges, which were performed from 2003 to 2016 under KYSPR Long-Term Monitoring studies. This allowed researchers to obtain good insights into the performance of those bridges as well as the maintenance performed on those bridges. That work identified where UWS had performed well and where remedial maintenance (including painting) or more focused inspections to assess patina formation might be required.

Of the 21 KYTC UWS bridges inspected, 6 had corrosion products indicative of progressive corrosion, at least locally, that warrant follow-up monitoring and possibly remedial work (e.g., spot painting). There were access issues on several bridges which prevented the KTC researchers from properly investigating the performance of the weathering steel in areas that were potentially problematic.

The UWS KY 1893 bridge at Shawhan was in poor condition at the bridge ends when initially inspected in 2003 (Figure 21). The bridge was built in 1977. The primary problem was leaking deck joints that deposited drainage from the deck onto the beam ends and bearings. The sheltered abutments suffered from poor air circulation; vegetation growing around them also impeded air flow under the bridge. As a consequence, the bearings, bearing plates, diaphragms and beam ends (especially at the lower flanges) possessed a heavy scaly rust build-up indicative of progressive (unhindered) corrosion. At least one diaphragm experienced nearly complete section loss due to corrosion (Reference Figure 2). A follow-up inspection in 2010 revealed that KYTC had rehabilitated the bridge by adding a latex overlay to the deck and replacing the failed joints/seals (Figure 22). In addition, the scaly rust at the bearings and bearing plates had been removed though those locations had not been zone painted (Figure 23). This bridge will be monitored in the future to assess if eliminating the leaking joints was sufficient to enable proper UWS performance.

Cut Back Road (CR 1169) over I-75 in Rockcastle County has a roadway clearance of 16.3 feet and is generally open, except for some vegetation build-up at the abutments. The bridge is a four girder jointless structure with no source of run-off impinging on the beams. The deck drain outlets were below the girders and were not an obvious source of problems either. However, inspections in 2015 and early 2016 revealed scaly rust on the lower flanges of the girders on both the top and bottom faces (Figures 24, 25). Several of those locations were at or near the abutments where the abundance of vegetation could potentially restrict air flow. However, scaly corrosion was evident on the top and bottom faces of lower flanges of the girders away from the abutments where the only likely source of moisture/chlorides would be aerosols kicked-up on the beams by traffic. The extent and pattern of scaly rust on the bottom faces of the girders seems to support that contention, as the extent of that corrosion is greater on the fascia girder facing traffic than on other girders further under the deck.

Inspections on the KY 81 Bridge have not revealed any problems to date. However, some coarse corrosion was evident on the undersides of diagonal members on the trusses of the KY 90 Bridge that may be problematic (Reference Figures 5, 6). These truss bridges are of concern as they contain fracture critical members. Recent work by others has indicated that the patinas on weathering steel may mask the presence of cracks during visual inspection (28).

Another UWS bridge not in accordance with T5140.22 is a small UWS beam bridge on KY 6 in Knox County that has low water clearance over a stream that is periodically overtopped by flash floods (Figure 26). Tide marks and debris deposits on lower flanges of beams confirm they are periodically overtopped by flash floods (Figure 27). Those locations and the presence of mill scale on the beams indicate that the bridge will probably experience progressive corrosion in the future. In 2014, KYTC rebuilt several other small bridges along KY 6 and elected to use duplex coatings (paint over galvanizing) to accommodate the low water clearances on those structures.

Several of KYTC's truss bridges were painted, including two small truss bridges on KY 3364 in Bourbon County (Figure 28) and KY 451 over North Fork of Kentucky River in Perry County (Figure 29). An earlier example of painted weathering steel are the tie-chords on the I-471 Dan Beard Bridge over the Ohio River at Newport (1974). The original paint on that bridge was overcoated in 2004. The coatings on all of those bridges are in good condition.

UWS bridges may not require painting if conditions are ideal, but they may require routine maintenance to preserve the patinas. Remedial maintenance (including painting) may be necessary where problems are detected. If KYTC is to use UWS on bridges, it must be cognizant of the issues that need to be addressed — starting with inspections. KYTC inspectors must be knowledgeable of properly performing weathering steel and be able to identify locations where the performance appears to be problematic. Signs of problems include variations in rust coloration, coarse surface rust, pitting and scaly rust. UWS bridges having those features should be flagged and questionable areas photographed. Follow-up action can be taken to monitor the corrosion and determine if remedial actions are necessary, including painting (spot, zone or full). Root causes of progressive/unhindered corrosion may be eliminated through proper maintenance. Removing vegetation at abutments can improve air flow at the beam ends and help prevent or minimize UWS corrosion problems (Figures 30, 31). Bridge designs incorporating UWS should not provide water traps (Figures 32, 33), and debris should be removed to help prevent long-term contact of moisture with weathering steel (Figures 34, 35).

The condition of UWS on bridges can vary over time. The patina evolves and may take up to 10 years to fully develop. It is fully functional (low corrosion rate) under a limited set of conditions that are changeable (e.g., growth of vegetation, leakage of joints, increased use of deicing salts, traffic pattern changes). The condition of the UWS patina needs to be monitored continuously and carefully over a structure's life. Generally, the changes will be slow to develop, but unfavorable ones cannot be ignored.

2.1 LABORATORY COATINGS TESTING

The study objectives addressed by the laboratory testing were intended to determine: 1) if weathering steel posed a problem at the time it underwent maintenance painting (compared to conventional bridge steel), and 2) if painted weathering steel should be considered for new construction.

Laboratory test specimens were obtained in conventional ASTM A36 steel and ASTM A606 (weathering steel provided in thicknesses less than 3/16"). Those steels were used to fit the test specimens in the laboratory test chambers. The alloy contents of the two steels are provided in Table 1. The alloy content of the ASTM A606 steel conformed to ASTM A588-10.

The laboratory testing used G85 — 11, “Standard Practice for Modified Salt Spray (Fog) Testing,” to evaluate the effect of the non-weathering and weathering steels. The steels were to be tested with coatings over blast-cleaned substrates (SSPC SP10/NACE No. Near White Blast Cleaning). Two substrate conditions were tested for each steel: 1) blast-cleaned new steel and 2) blast-cleaned corroded steel. To precondition (corrode) the steel panels, they were placed in a spray chamber and subjected to cyclic salt fog exposure for 2,000 hours (Figures 36-39) using a Timmons solution (0.05% NaCl + 0.35% NH_42SO_4). Prior to preconditioning, the mill scale on both the ASTM A36 and ASTM A606 panels was removed by grinding. To prevent accidental mixing of panels, one corner of each ASTM A606 panel was clipped.

Comparative testing of cyclic salt fog testing, per ASTM G85-11 using the Timmons solution and conventional salt fog testing per ASTM B117 using a 5% salt solution, indicated corrosion losses of a similar magnitude (by percent weight) and the decision was made to use the Timmons solution for tests because it more closely approximates an industrial environment. Three ASTM A36 panels exhibited an average weight loss of about 9.3% during the preconditioning process, compared to about 6.8% for three ASTM A606 panels. It was anticipated that the conditioning and follow-up accelerated corrosion testing by ASTM G85-11 replicated environments that would promote progressive corrosion of the weathering steel. The amount of corrosion weight loss of the ASTM A606 steel panels compared to that for the ASTM A36 steel indicated that the preconditioning corrosion process provided an atmospheric condition that was intermediate between atmospheric corrosion with bold exposure (normal weathering at about one half the corrosion rate of plain structural steels) and unhindered/progressive corrosion (extreme weight loss of the weathering steel equal to that of plain structural steels).

To evaluate the roughness of the corroded surfaces of the ASTM A36 and A606 steels produced by preconditioning, samples of each type were sectioned, polished and micro-photographed (Figures 40-42). The irregular corrosion surface profiles were evaluated by visually inspecting the high-magnification microphotographs and plotting the width of the peaks vs. the depths for both steels (Figures 43, 44). This work indicated that the corroded surface profiles of the ASTM A36 steel were deeper than those of the ASTM A606 steel.

Preconditioned steel panels were blast cleaned using a 40/50 steel grit mix to a SSPC SP10 near-white surface appearance. Some panels of both steel types were pressure washed at 4,500 psi using a 0^o spinner tip prior to blast cleaning. Two pieces of each type of steel panel type (washed and unwashed) were provided to a test laboratory for evaluation. They were cut up for surface chloride analyses, sectioning and microphotography, and SEM analyses. The chloride analyses were performed using SSPC Guide 15 (boiling water extraction per ASTM A512-04 Method A). The tests revealed no significant differences in chloride contamination between the two cleaning procedures. The blasted-only pieces averaged 26.6 $\mu g/cm^2$ of chloride contamination compared to an average of 23.5 $\mu g/cm^2$ for washed and blasted pieces (29).

Microphotographed sections of blasted profiles revealed that the steel surfaces contained pits from 2 to 5 mils in depth. Microphotographs of the sectioned steels revealed that deposits were trapped in pits in the surface profiles (Figures 45, 46). The surfaces were analyzed using energy-dispersive X-ray spectroscopy (EDS) in a scanning electron microscope (SEM) (Figures 47, 48). Small amounts of sulfur and chlorine were detected, corresponding to contamination from the Timmons solution used to promote corrosion during the preconditioning step. SEM examination revealed non-metallic deposits that were associated with the pits (Figures 49, 50). EDS analyses in the pits indicated high levels of chlorine and sulfur (Figures 51, 52). These high concentrations act as *hot spots* that promote localized high corrosion rates and coating failure sites.

Two types of coatings were used for the tests: 1) a barrier coating (enamel coating) and 2) a moisture-cure polyurethane zinc primer (termed an organic zinc coating). They were used as single-coat systems in an effort to promote coating failures and discern if steel type or initial conditions would impact coating performance. For the test program, panels of both steel types (ASTM A36 and ASTM A606) were tested. Both types of steels were tested in two initial conditions (new and preconditioned). Panels for each steel type and surface condition were tested with two surface preparation methods (blasted only and pressure washed and blasted).

Panels representing the types of steel, initial surface conditions and surface preparation methods were painted with full coats of both coating types. All coating applications were performed by spraying in the KTC spray booth using a controlled procedure to ensure consistent applications of the coatings. Five panels were painted for each steel, initial surface condition, surface preparation method and coating. Three of the fully painted panels received two four-inch scribes on the exposed surfaces to test for scribe undercutting. Representative full painted panels (un-scribed and scribed) of both steel types, initial conditions (new or preconditioned) and coatings are shown in Figures 53-65.

A second type of coatings test was conducted to compare the corrosion performance of the two steels in the coated and uncoated conditions. For this test, three panels of each type had half of their prepared surface masked and the other half blasted and painted along the 6-inch length of each panel. ASTM A36 steel was not tested in the new condition due to space limitations in the test chamber. The new ASTM A606 panels were completely blasted per SSPC SP 10. The unpainted portions of the panel faces were either the SP 10 for the new steel panels or rusted for the preconditioned ones. Representative half-painted panels of both steel types, initial conditions (new or preconditioned) and coatings are shown in Figures 66-75.

The coatings on the test panels were cured for 28 days at ambient conditions and then placed in the test chambers, per ASTM G85, and tested (corroded) for 5,000 hours. Every 1,000 hours the fully coated panels were removed and evaluated for rusting and scribe undercutting. Rusting evaluations were performed per ASTM D610-10, “Practice of Evaluating Degree of Rusting on Painted Surface.” A rust condition of 7 was considered panel failure, although all of the panels were tested for the full 5,000 hours. Scribe evaluations were performed in accordance with SSPC PA 15, “Method for Preparing

Steel Test Panels for Evaluation of Coating Performance," and scribe failure was taken as an undercutting width greater than 5 mm (0.197 in.). All panels were photographed every 1,000 hours throughout the test.

Table 2 summarizes testing results for the fully coated panels. All of the test panels with barrier coating (un-scribed and scribed) failed prior to the completion of the testing, typically within 1,000-2,000 hours of testing. All test panels with the organic zinc coating (un-scribed and scribed) passed the 5,000-hour test, although the coatings were severely chalked by the end of testing. Pictures of representative full-coated panels after testing are provided in Figures 76-86. Pictures of representative half-coated panels after testing are provided in Figures 87-96.

After the 5,000-hour exposures, the test faces of the half-coated panels were cleaned with a power wire brush to remove all of the surface corrosion product and adjacent paint (intact or failed). The panel thicknesses in the initially exposed surfaces as well as the ones, was measured in three locations and the results averaged. The back faces of all the panels were painted and did not experience any corrosion. The resulting measurements reflected any loss in panel thickness due to corrosion during the preconditioning process (where used). The difference between the thickness on the painted side and that on the unpainted side reflected the degree of corrosion protection a coating provides for various substrate conditions.

3. DISCUSSION AND CONCLUSIONS

Nationwide, DOTs predominately have a favorable opinion of UWS bridges (op. cit. 6). However, that reference includes KYTC and as noted in this report, there are some issues with KYTC UWS bridges that were only revealed by focused KTC inspections. Also, NYSDOT has experienced what appear to be significant corrosion problems on some of its bridges (op. cit. 7). That document noted that inspectors need to be aware of the UWS problems and that UWS bridges need to be maintained (including vegetation removal, painting at-risk areas and special high-pressure washing). UWS bridges should not be considered maintenance-free or painting-free for the life of a structure.

Weathering steel offers significant cost advantages over painted steel that warrant its consideration where it is viable. Kentucky has a relatively mild climate with sufficient wetting and drying cycles for locations with bold exposure, which should make many areas throughout the state good candidates for use of UWS. Generally, absent from the state are problematic macroclimates in which UWS performs poorly, such as industrial atmospheres and marine/coastal environments. However, there are microclimate issues that have been found to impact KYTC bridges on a localized level. In part, this is due to the fact that conditions for ideal patina formation are difficult to achieve uniformly across the various portions of a bridge. High humidity alone can promote progressive or unhindered corrosion. At least one KYTC bridge is suspected to suffer from this. Of the 21 bridges KTC researchers visited or inspected during the past three years, at least 6 have signs of progressive corrosion or poor patina formation. The most problematic of these are two UWS truss bridges (KY 81 and KY 90) due to the range of exposures, the potential for moisture and debris trapping and inspectability issues for fracture critical members on those bridges.

The past KYTC practice, similar to other DOTs, has been to disregard the FHWA T5140.22 guidelines and use UWS on an unrestricted basis. More recent KYTC steel bridges have incorporated ASTM A709 50W grade steel using paint. A new onramp being constructed on KY 4 over US 60 in Lexington uses UWS except for the outer faces of the fascia girders and within several feet of substructure elements, which are painted. It is uncertain whether the previous prohibition on completely unpainted weathering steel bridges will be maintained or lifted.

Laboratory tests performed as part of this study were intended to determine if weathering steel can be successfully painted after experiencing progressive corrosion. The selected coatings were expected to provide minimal corrosion protection. KTC researchers sought to determine whether there were differences in corrosion behavior between both new and corroded plain carbon and weathering steels with standard abrasive-blast surface preparation. Test results on full panels did not indicate significant differences between the performances of new or corroded steels for either conventional or weathering types (Table 2). That difference was expected to be caused by chloride contamination produced in the preconditioning (corroding) of the panels prior to blast cleaning. Laboratory evaluations indicated a reasonable level of chloride contamination and pitting/hot spots after abrasive blasting to a standard (SSPC SP 10) that is normally used for maintenance painting. Only a slight reduction (about 12 percent) in surface chloride contamination was measured between the blasted and washed-and-blasted surfaces. That did not result in enhanced performance of the test coatings for the preconditioned substrates (especially the barrier coating). Testing indicated that irrespective of the type of steel or initial surface condition (after abrasive blasting), choice of paint was the major factor. A question exists as to whether the KTC preconditioning actually replicated the amount of pitting that occurs on UWS bridges, as our results are at variance with some findings by others about pitting on UWS bridges previously noted in this report. Severe pitting would inhibit good surface preparation, result in higher chloride contamination under applied coatings and consequently result in reduced coating lives.

As expected, the organic zinc coating outperformed the barrier coating. For all steels/conditions it passed the corrosion testing for both the rusting and scribe undercutting criteria, while the barrier coating failed in just a few thousand cycles. On the fully coated panel tests using abrasive blasting, the barrier coating did not perform better on new steel compared to previously corroded steel for either the conventional or weathering grades. Perhaps a more protective barrier coating, such as an epoxy, would have provided a sharper contrast in performance between the various substrates, but the current testing indicates that substrate type/initial condition are less significant factors compared to coating type.

If applied in the field as part of a normal 3-coat paint system including intermediate and topcoats, the moisture-cure polyurethane zinc primer would have held up well and it is anticipated that type of paint system would provide 20-30 years of protection. The service performance of a 3-coat coating system on new steel would probably be superior to a maintenance coating due to better surface preparation, lack of salt contamination (e.g., hot spots) and possibly better coating application. For spot applications (painting beam ends under deck joints), a well-performing barrier coating, such as an epoxy, would probably be sufficient with a weathering topcoat such as an acrylic or polyurethane on the exterior surfaces exposed to direct sunlight. It is unlikely that KYTC will use weathering steel in the future on bridges with beam ends directly under joints. More KYTC bridge designs using UWS are either jointless or incorporate concrete diaphragms to shield the beam ends from direct contact with moisture. Where the latter detail is used, KYTC employs open joints with troughs to prevent moisture from impinging on the diaphragms. KTC inspections have shown that despite the use of jointless bridges, beams adjacent to abutments on deck girder bridges sometimes exhibit progressive corrosion, probably due to poor drying at those locations. Application of zone painting using a barrier coating at those locations would probably be sufficient to prevent further corrosion.

The half-painted test panels reveal several things (Table 3). First, the new weathering steel with the moisture-cure zinc coating had the greatest thickness in the painted area — no corrosion occurred there. The new weathering steel with the barrier coating had the second greatest thickness in the painted area. No conventional (ASTM A36) steel was tested in the new condition (without preconditioning). For all steels painted with the moisture-cure zinc coating, the differences in thicknesses between the painted and unpainted (exposed) steel was greater than for those steels with the barrier coatings. The conventional steel with the moisture-cure zinc coatings (blasted and blasted-and-washed) had larger thickness differences between the painted and unpainted portions due to the greater amount of corrosion occurring in the exposed conventional steel compared to exposed weathering steel.

During the power wire brushing of the panels, researchers discovered that there was intact organic zinc coating under the white (chalked) surface. While the chalked material was readily removed by the wire brushing, the underlying intact moisture-cure zinc was hard and difficult to remove. In general, the barrier coatings were completely failed after testing and some underlying corrosion had occurred where the barrier coatings had been placed.

KTC researchers have reached the following conclusions based on their literature reviews, field observations and laboratory testing:

1. UWS bridges constructed using current KYTC design practices may require some degree of follow-up painting after being placed into service. This may involve painting high stress areas (e.g., areas lacking good drying and bold exposure — at or adjacent to abutments).
2. It may take up to 10 years of service to assess the performance of patinas on UWS bridges. Biennial inspections should be suitable to assess their performance and provide the opportunity for any necessary maintenance. The biennial inspection should be focused on determining whether patinas are performing properly.
3. While UWS bridges may avoid one or more paint cycles, they are not maintenance-free and require attention, including clearing of brush adjacent to

abutments to promote air flow, debris removal from bridge steel and upkeep of joint seals.

4. The guidelines in FHWA T5140.22, if followed, would eliminate most, but not all of those problems. Low water clearances should be avoided as well as grade crossings less than 20 feet over a roadway.
5. The concept of building a UWS bridge and subsequently considering maintenance painting if the patina becomes unstable appears to be a practical option. Maintenance painting of problematic bridge locations will provide suitable performance, especially if abrasive blasting and multi-coat systems are used, including organic zinc-based primers.
6. UWS bridges can be investigated in more detail, including a focus on baseline steel section measurements and the investigation of patina corrosion products to identify bridges/locations where the weathering steel is not functioning properly.

KTC makes the following recommendations:

1. KYTC should develop a consistent policy on the use of painted and UWS bridges.
2. The use of UWS bridges should be restricted to deck girder types using jointless designs or the current KYTC detail that incorporates concrete diaphragms. KYTC should use the FHWA T5240.22 guidelines to determine where to use unpainted weathering steel. The use of UWS bridges with fracture-critical members is discouraged.
3. KYTC should investigate the performance of existing UWS bridges. As part of this work, the Cabinet should determine the most effective means of assessing patina performance. Baseline inspections should be performed on all KYTC UWS bridges to identify locations where patinas are not performing correctly. Based on these observations, recommendations could be advanced for remedial measures (including zone and total painting). Special emphasis should be placed on the two UWS truss bridges (KY 81 and KY 90).
4. Guidelines should be prepared for bridge inspectors so they may properly evaluate patinas. Additional guidance should be provided to KYTC maintenance personnel to properly maintain UWS bridges.

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6. TABLES

Table 1. Elemental Analysis of Steels Used in Accelerated Corrosion Tests

Element	ASTM A36 Mill Certification	ASTM A606 XRF Analysis
Carbon	0.18	Not Analyzed
Silicon	0.02	0.41
Manganese	0.42	0.93
Phosphorus	0.008	Not Analyzed
Sulfur	0.003	Not Analyzed
Chromium	0.03	0.66
Copper	0.09	0.43
Nickel	0.03	0.22
Iron	Not Analyzed	97.35

Table 2. Test Results for Full-Coated Test Panels (Un-Scribed and Scribed)			
Test Panel Steel and Condition	**Coating**	**Hours to Failure Un-Scribed**	**Hours to Failure Scribed**
ASTM A36 New Steel	Barrier	1 Panel 2,000 hours; 1 Panel 3,000 hours	All Panels 2,000 hours
ASTM A36 New Steel	Zinc	Both Passed 5,000 hours	All Passed 5,000 hours
ASTM A36 Preconditioned – Blast Only	Barrier	1 Panel 1,000 hours; 1 Panel 2,000 hours	All Panels 2,000 hours
ASTM A36 Preconditioned – Blast Only	Zinc	Both Passed 5,000 hours	All Passed 5,000 hours
ASTM A36 Preconditioned – Pressure Wash and Blast	Barrier	1 Panel 1,000 hours; 1 Panel 2,000 hours	All Panels 2,000 hours
ASTM A36 Preconditioned – Pressure Wash and Blast	Zinc	Both Passed 5,000 hours	All Passed 5,000 hours
ASTM A606 New Steel	Barrier	1 Panel 2,000 hours; 1 Panel 3,000 hours	1 Panel 1,000 hours; 2 Panels 2,000 hours
ASTM A606New Steel	Zinc	Both Passed 5,000 hours	All Passed 5,000 hours
ASTM A606 Preconditioned – Blast Only	Barrier	Both Panels 2,000 hours	All Panels 2,000 hours
ASTM A606 Preconditioned – Blast Only	Zinc	Both Passed 5,000 hours	All Passed 5,000 hours
ASTM A606 Preconditioned – Pressure Wash and Blast	Barrier	Both Panels 1,000 hours	All Panels 2,000 hours
ASTM A606 Preconditioned – Pressure Wash and Blast	Zinc	Both Passed 5,000 hours	All Passed 5,000 hours

Table 3. Thickness Measurements Test Results for Half-Coated Test Panels & Difference between Coated and Uncoated Areas in Inches				
Test Panel Steel and Condition	**Coating**	**Thickness of Coated Panel Area**	**Thickness of Uncoated Panel Area**	**Difference**
ASTM A36 Preconditioned – Blast Only	Barrier	0.174	0.176	-0.002
ASTM A36 Preconditioned – Blast Only	Zinc	0.184	0.174	0.010
ASTM A36 Preconditioned – Pressure Wash and Blast	Barrier	0.178	0.175	0.003
ASTM A36 Preconditioned – Pressure Wash and Blast	Zinc	0.184	0.167	0.017
ASTM A606 New Steel	Barrier	0.187	0.183	0.004
ASTM A606 New Steel	Zinc	0.193	0.185	0.008
ASTM A606 Preconditioned – Blast Only	Barrier	0.174	0.175	-0.001
ASTM A606 Preconditioned – Blast Only	Zinc	0.175	0.170	0.005
ASTM A606 Preconditioned – Pressure Wash and Blast	Barrier	0.177	0.176	0.001
ASTM A606 Preconditioned – Pressure Wash and Blast	Zinc	0.185	0.178	0.007

7. FIGURES


Figure 1. Deck Girder Bridge Showing Proper Appearance of UWS Patina

Figure 2. Severe Loss of Section on Web of Weathering Steel Diaphragm

Figure 3. Corroded UWS Bearing Under Leaking Joint

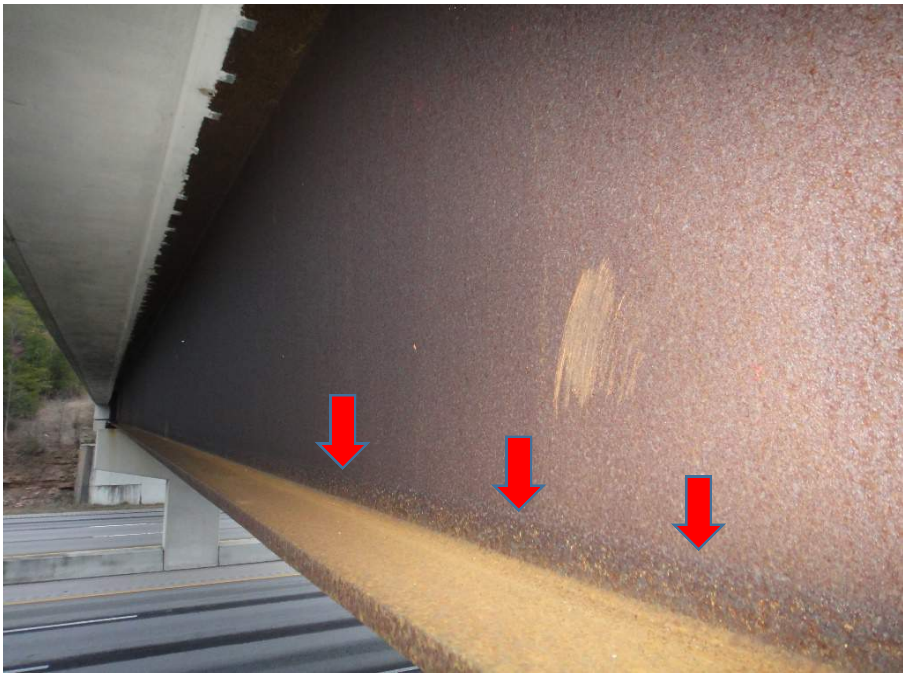


Figure 4. Fascia Beam of I-75 Overpass Bridge Showing Tight Rust in Middle of Web (Scrape Mark) and Scaly Corrosion and Rust Capillary Action on Lower Portion of Web (Arrows)

Figure 5. Underside of Truss Diagonal Showing Coarse Rust on KY 90 Bridge

Figure 6. Topside of Same Diagonal Opposite Location Shown in Figure 5

Figure 7. UWS Girder Bridge (Non-KYTC Bridge) Showing Effect of Inadequate Drain Pipe Clearance on Patina Formation

Figure 8. Lower Chord of UWS KY 90 Truss Bridge Showing Various Patina States

Figure 9. Coarse Patina on Lower Face of Lower Flange of I 75 Overpass Bridge

Figure 10. Scaly Rust from Unhindered Corrosion of Web of Beam KY 1893 Bridge

Figure 11. Unhindered Corrosion on Upper Face of UWS Girder on I 75 Overpass Bridge

Figure 12. Deposit of Corrosion Debris on Upper Face on Girder Lower Flange of UWS Beam

Figure. 13. Condensation Drip Marks on Web of KY 90 Approach Span

Figure 14. New York State DOT Maintenance Personnel Painting UWS under Deck Joint

Figure 15. Pitting on Lower Flange of UWS Steel Beam Caused by Presence of Mill Scale on KY 6 Bridge

Figure 16. Minnesota DOT UWS Girder Painted about Two Feet from End

Figure 17. Kansas DOT UWS Girder Painted About 25 Feet from Beam End

Figure 18. UWS Beam Showing Failed Coating at Beam End.
Note the Severe Pitting in Coating and on Adjacent UWS.

Figure 19. KY 81 UWS Truss over Green River at Calhoun, KY

Figure 20. KY 90 Bridge over Lake Cumberland near Somerset, KY

Figure 21. Corrosion under Deck Joint on KY 1893 Bridge at Shawhan, KY

Figure 22. KY 1893 Bridge Deck with New Overlay and Deck Seals

Figure 23. Rocker After Scaley Corrosion Product Removal on KY 1893 Bridge at Shawhan, KY

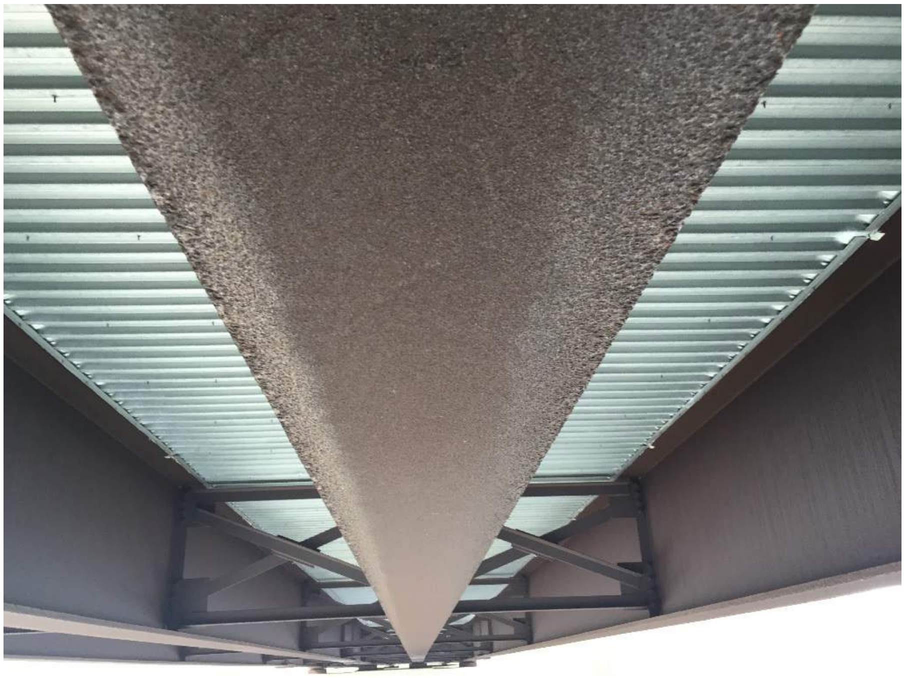


Figure 24. Scaley Corrosion on Bottom Face of Girder Flange of I-75 Overpass Bridge

Figure 25. Scaley Corrosion on Upper Flange of Lower Flange on I-75 Overpass Bridge

Figure 26. Low Water Clearance UWS Bridge on KY 6 in Knott County


Figure 27. Tide Marks on the Web and Debris Deposits on the Flange of a UWS Beam of the KY 6 Bridge Indicative of High Water (Overtopping)


Figure 28. Painted Truss Employing Weathering Steel KY 3364 Bridge in Bourbon County

Figure 29. Painted Truss Employing Weathering Steel – KY 451 over North Fork of Kentucky River

Figure 30. Vegetation Build-Up Around Abutments of KY 1893 Bridge

Figure 31. Vegetation Build-Up Around Abutments of I-75 Overpass Bridge

Figure 32. Water Ponding on Lower Chord of KY 81 Bridge

Figure 33. Water Ponding on the Lower Chord of the KY 90 Bridge

Figure 34. Lower Chord of the KY 81 Bridge Showing Build-up of Debris that Collects Moisture


Figure 35. Debris Collected on the Lower Chord of the KY 90 Bridge

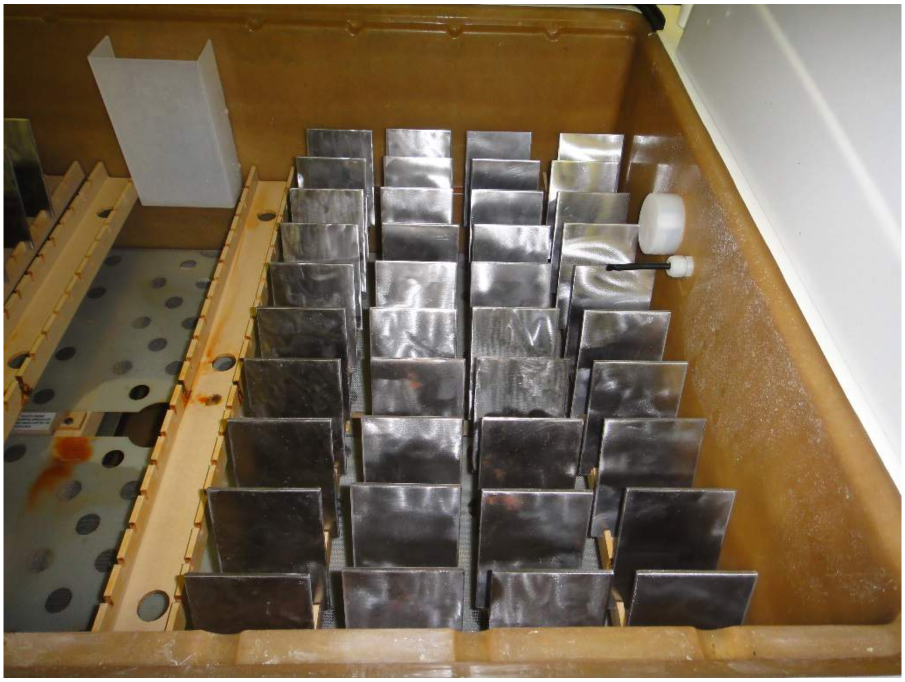


Figure 36. ASTM A 36 Steel Panels Prior to Preconditioning in an Accelerated Corrosion Test Chamber

Figure 37. ASTM A572 Steel Panels After Preconditioning in an Accelerated Corrosion Test Chamber

Figure 38. ASTM A 626 Steel Panels Prior to Preconditioning in an Accelerated Corrosion Test Chamber

Figure 39. ASTM A 606 Steel Panels After Preconditioning in an Accelerated Corrosion Test Chamber.

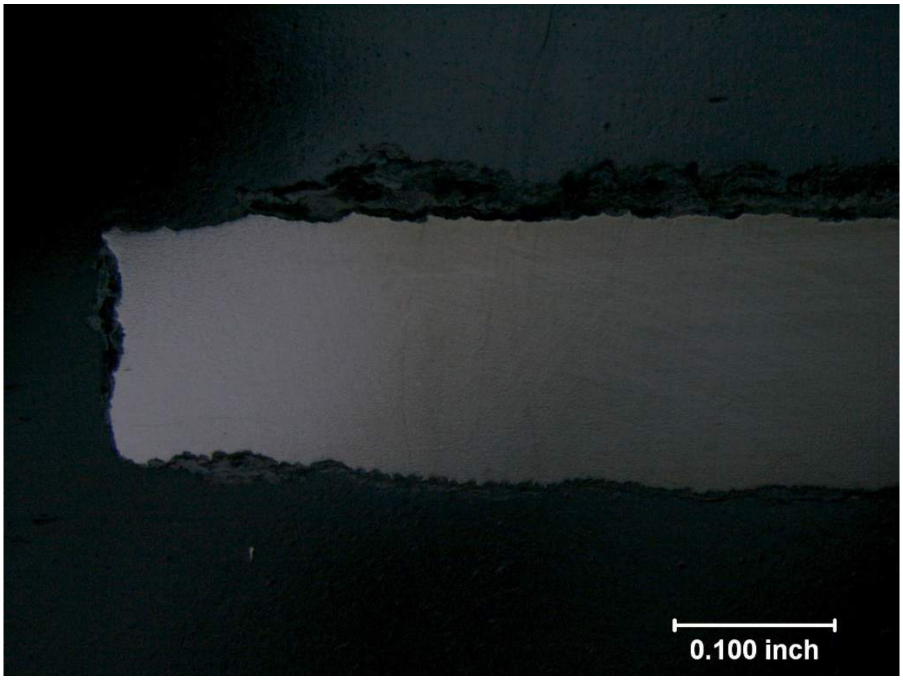


Figure 40. Section View of ASTM A36 Corroded Segment at Low Magnification

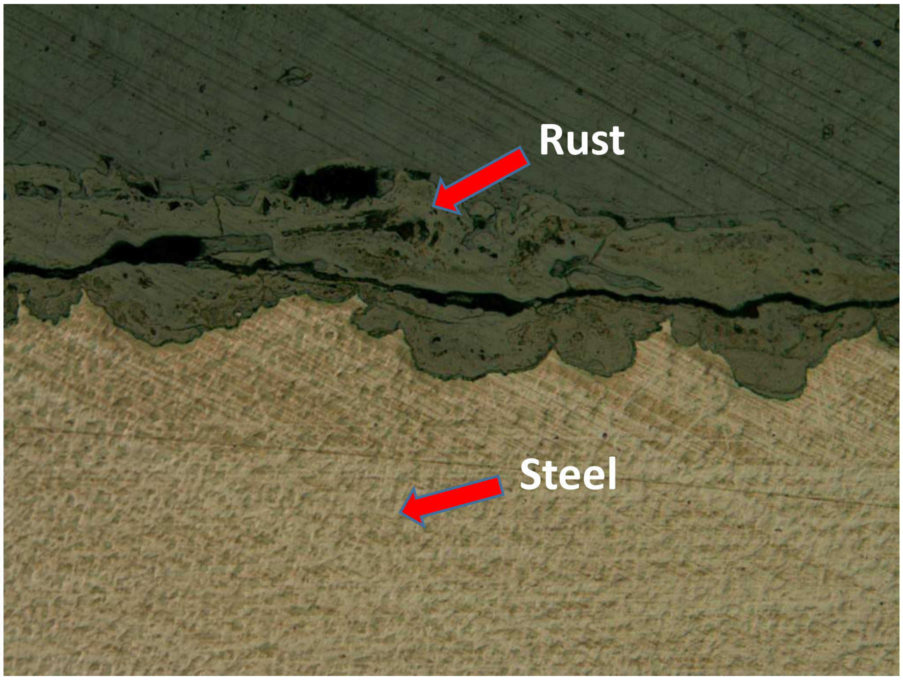


Figure 41. High Magnification Microphotograph of Corroded ASTM A36 Surface (Section View Not to Scale)

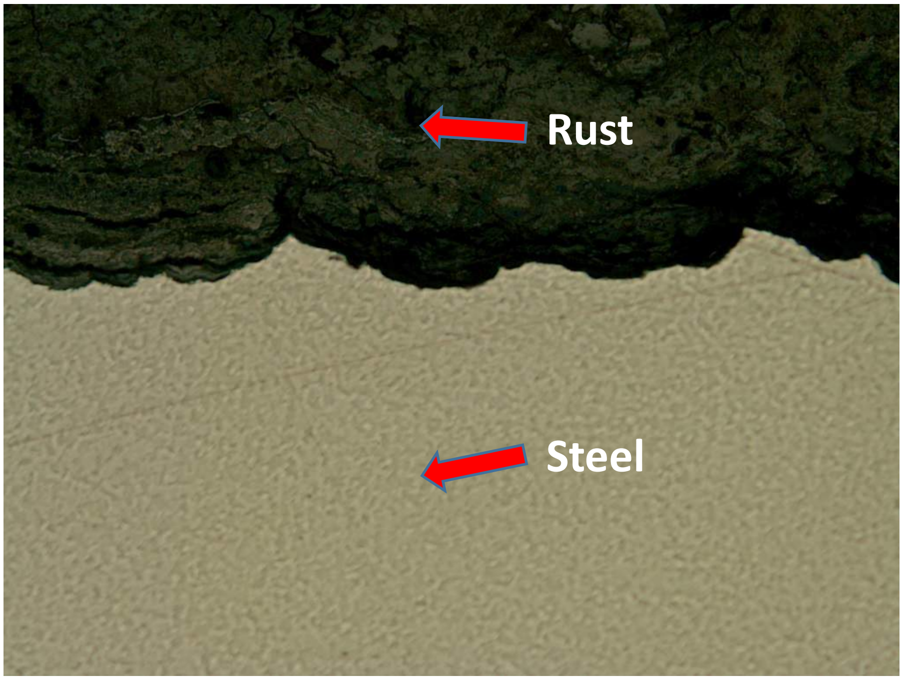


Figure 42. High Magnification Microphotograph of Corroded ASTM A606 Surface (Section View Not to Scale)

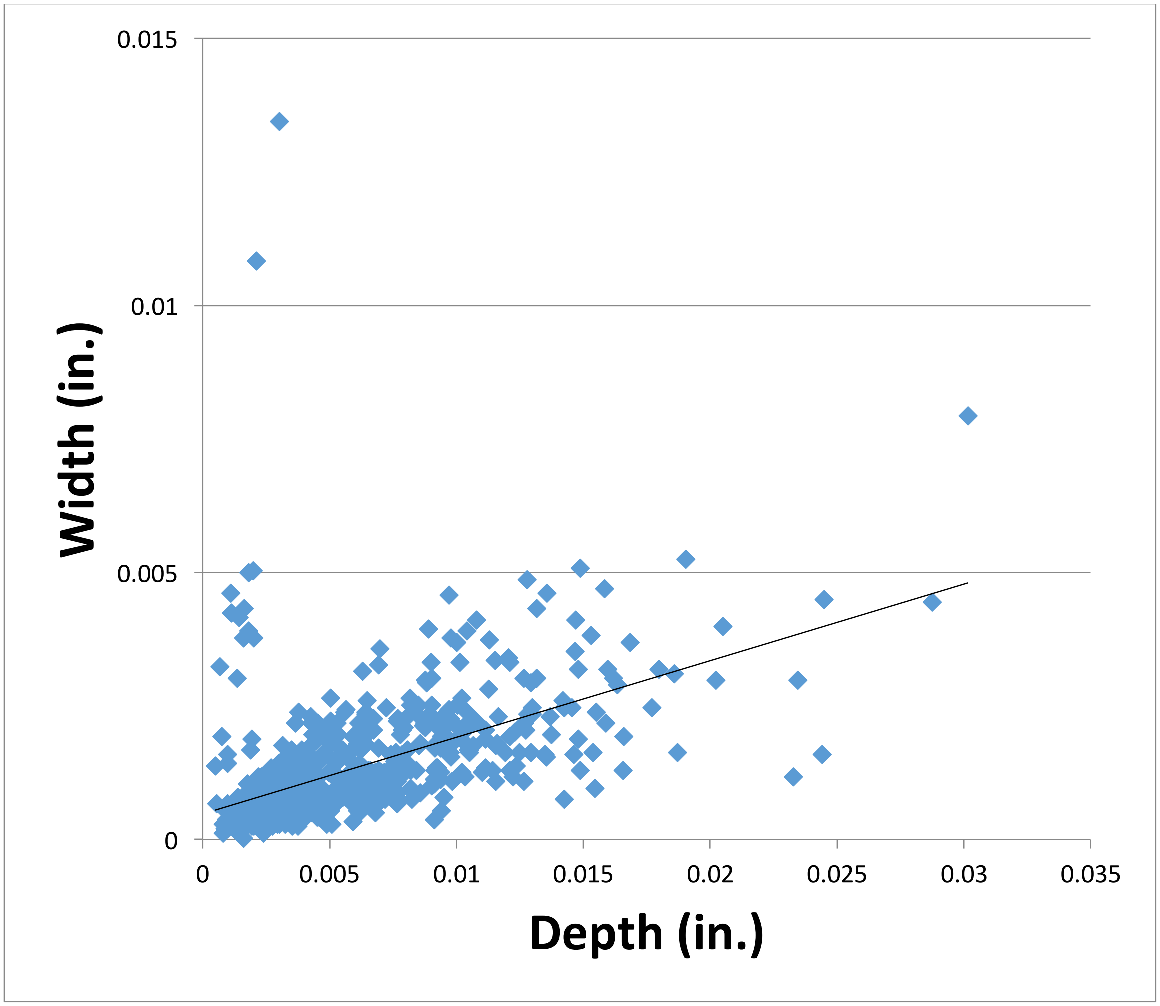


Figure 43. Surface Profile (Peak Width vs. Depth) for Section of Corroded ASTM A36 Steel

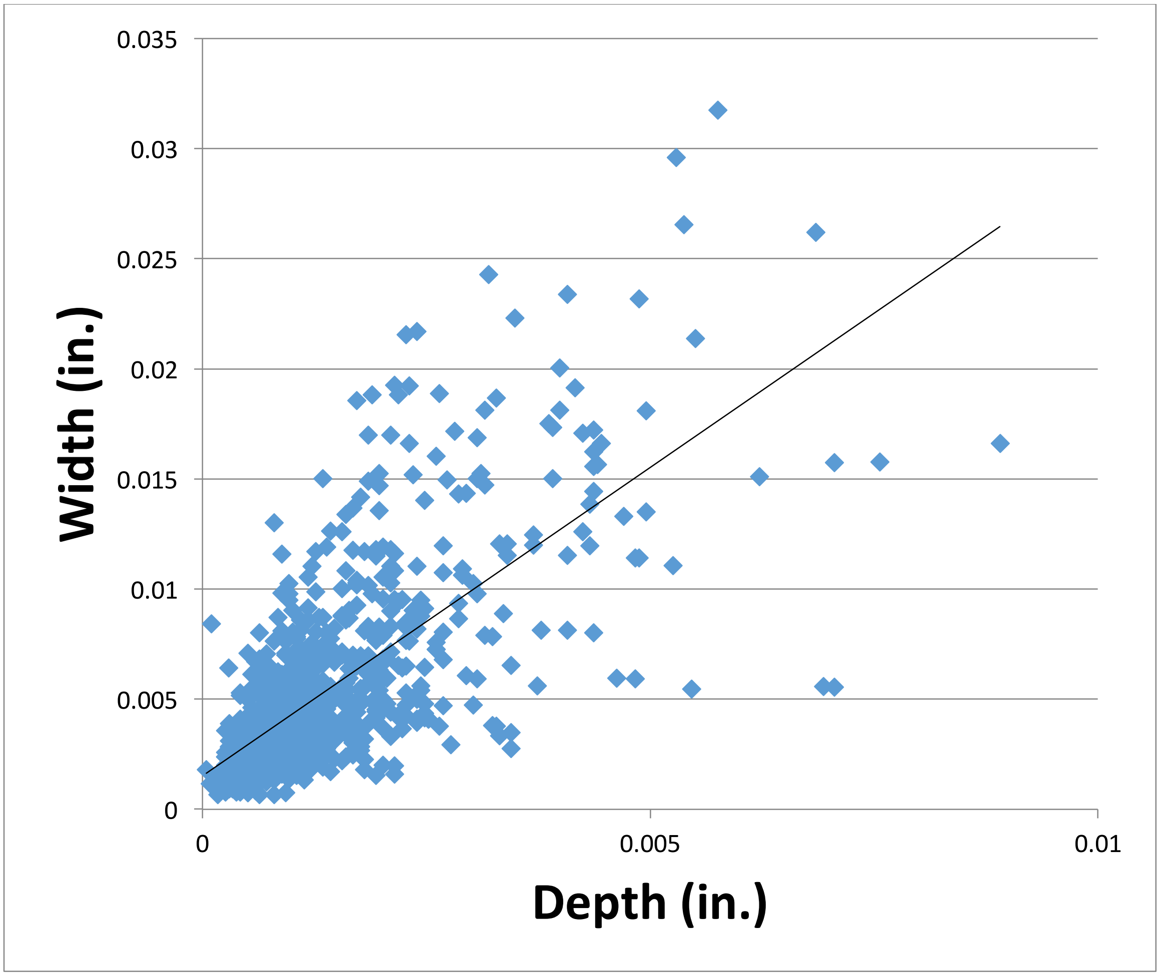


Figure 44. Surface Profile (Peak Width vs. Depth) for Section of Corroded ASTM A606 Steel

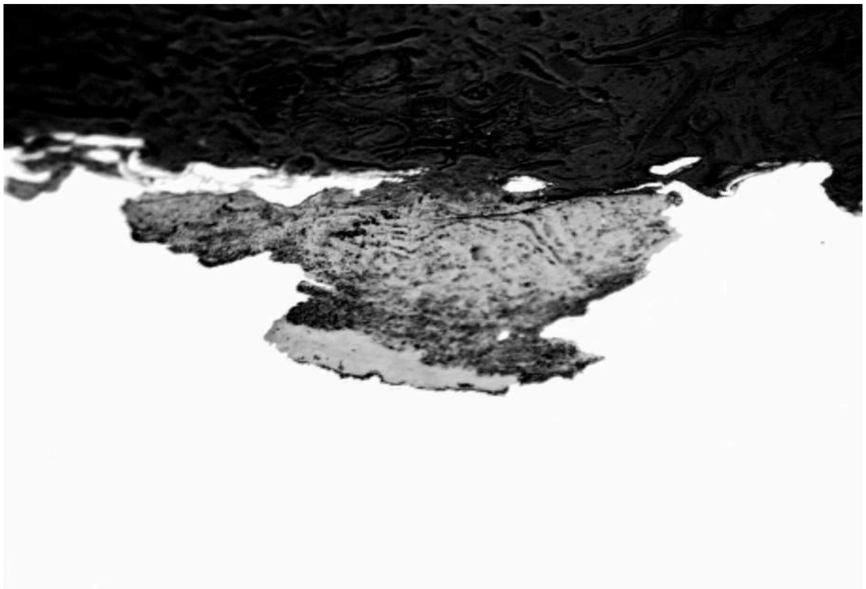


Figure 45. Microphotograph of Section of Blasted ASTM A36 Steel (Polished) Showing Deposit in Pit (Ref. 23)

Figure 46. Microphotograph of Section of Blasted ASTM A606 Steel (Polished) Showing Deposit in Pit (Ref. 23)

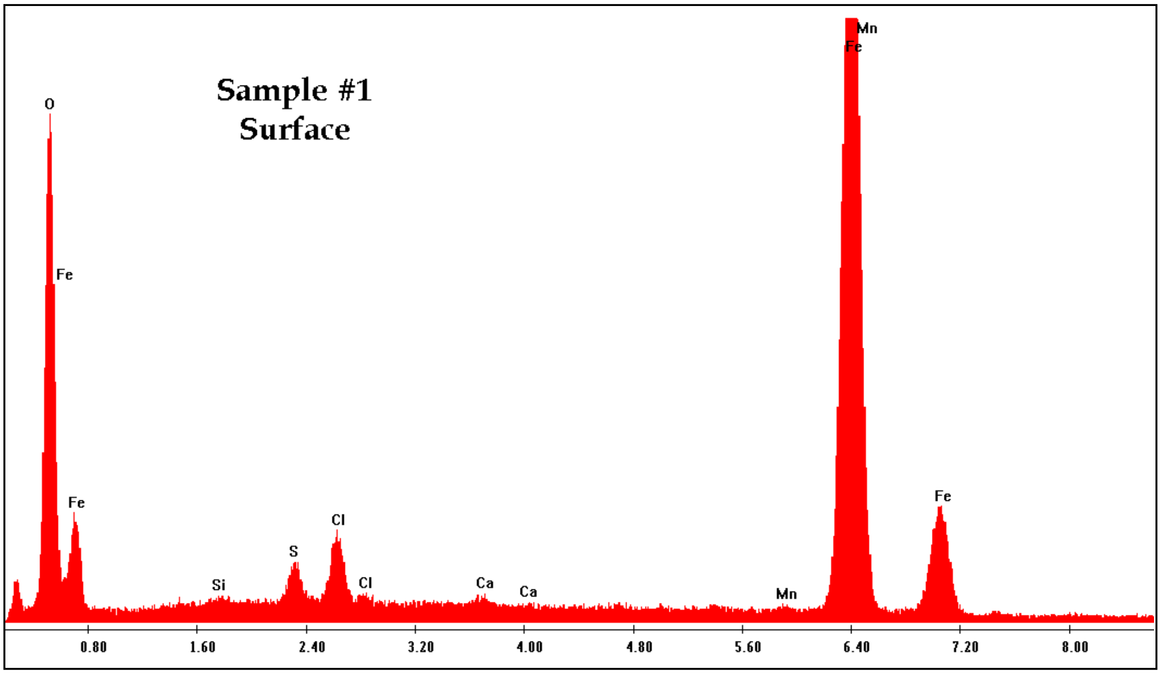


Figure 47. EDS Spectrum from Surface of ASTM A36 Steel Blasted Sample (Ref. 23)

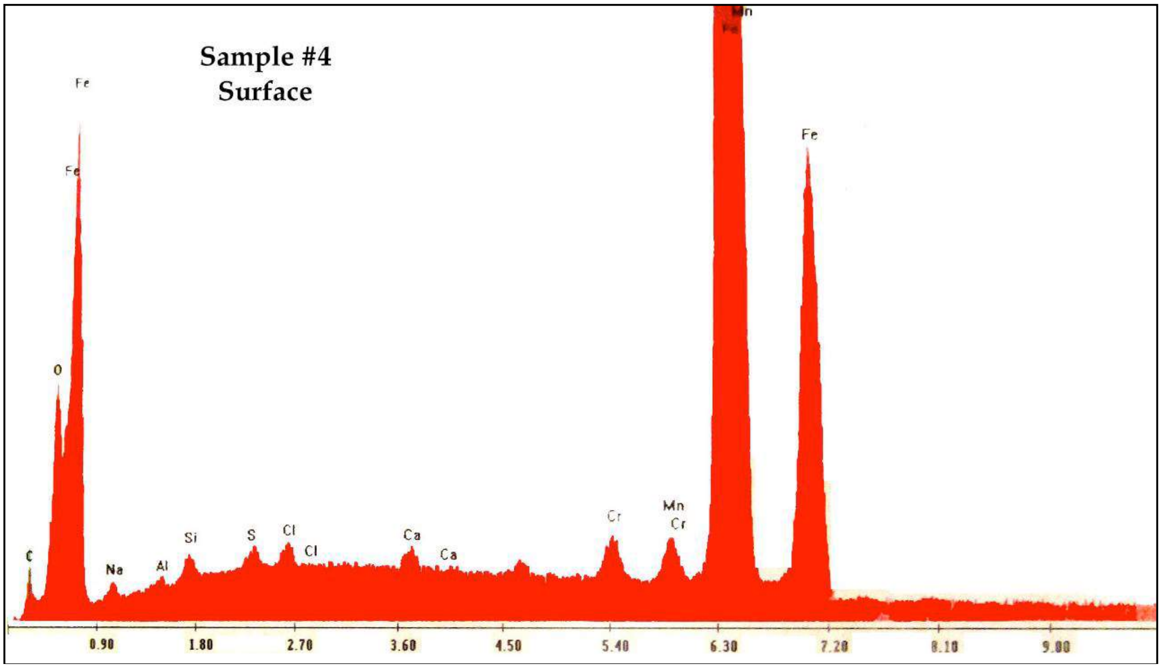


Figure 48. EDS Spectrum from Surface of ASTM A606 Steel Blasted Sample (Ref. 23)

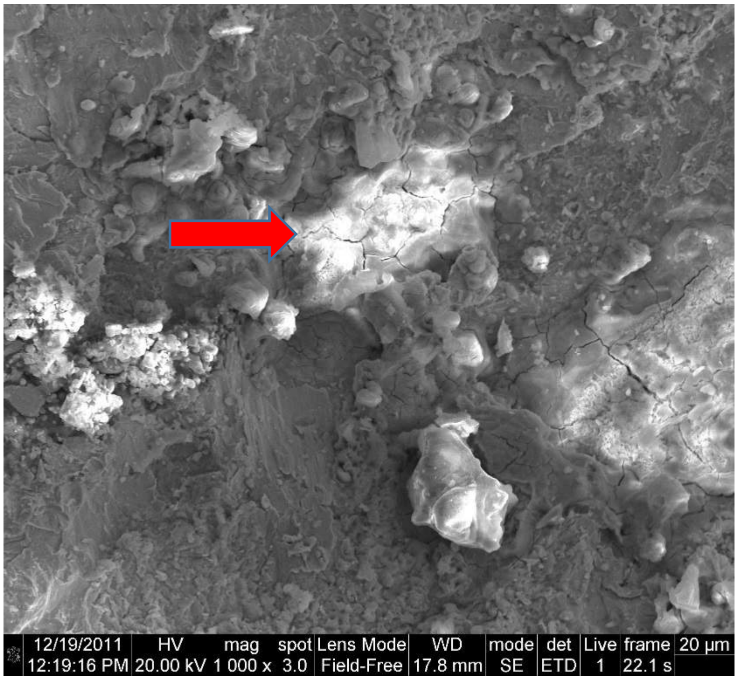


Figure 49. SEM of Chloride Inclusion “Hot Spot” (Arrow) in Blasted Surface of ASTM A36 Steel Specimen (Ref. 23)

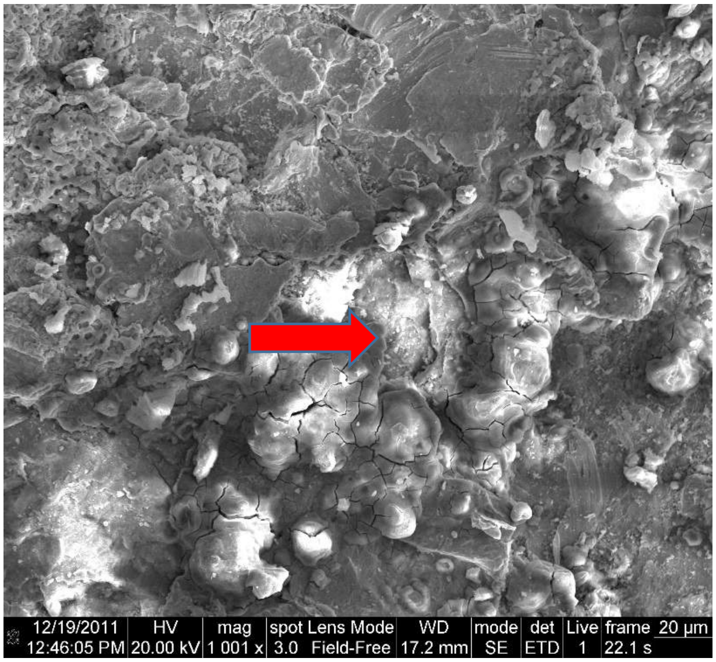


Figure 50. SEM of Chloride Inclusion *Hot Spot* (Arrow) in Blasted Surface of ASTM A606 Steel Specimen (Ref. 23)

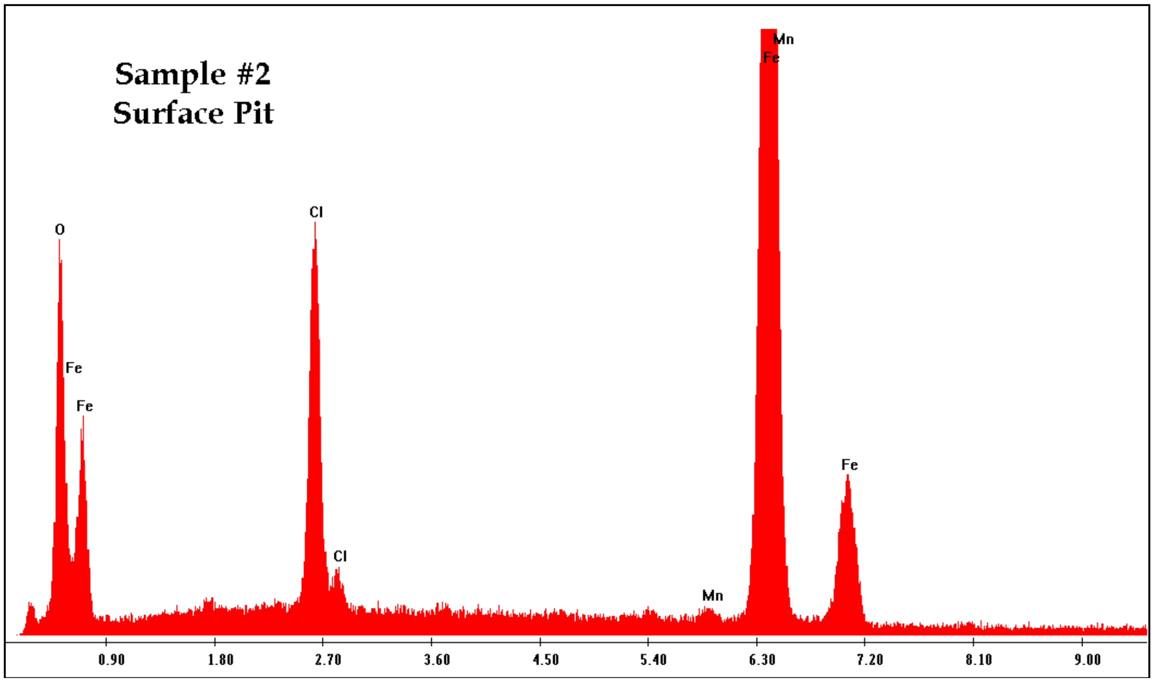


Figure 51. EDS Spectrum from Deposit in Pit of ASTM A36 Blast and Washed Sample (Ref. 23)

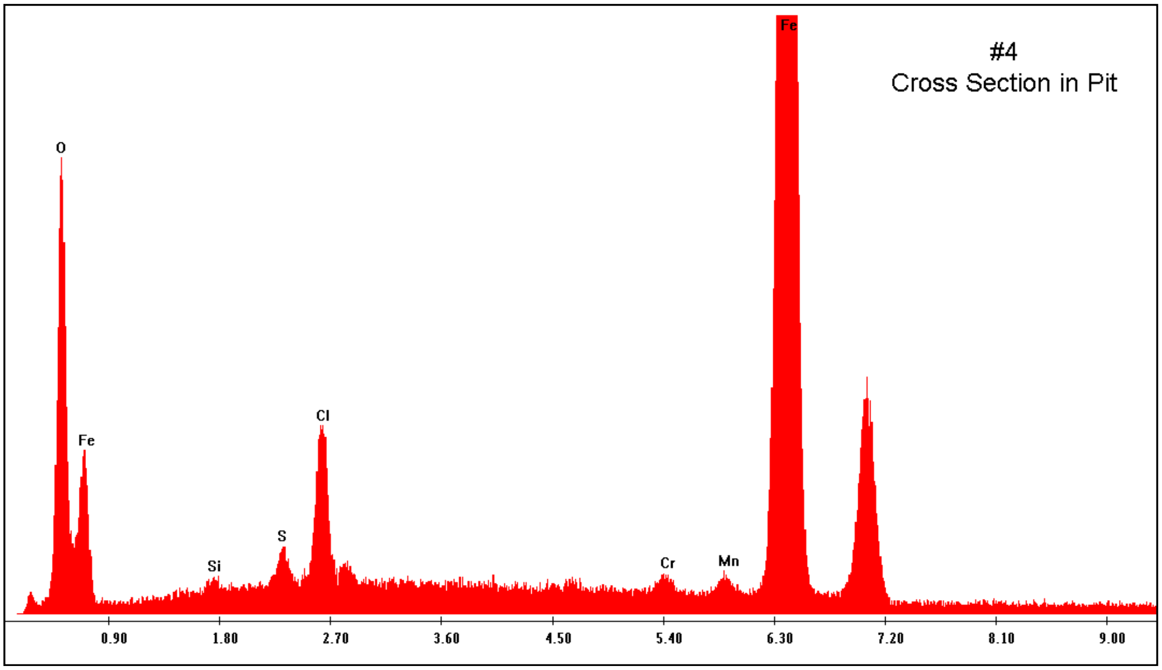
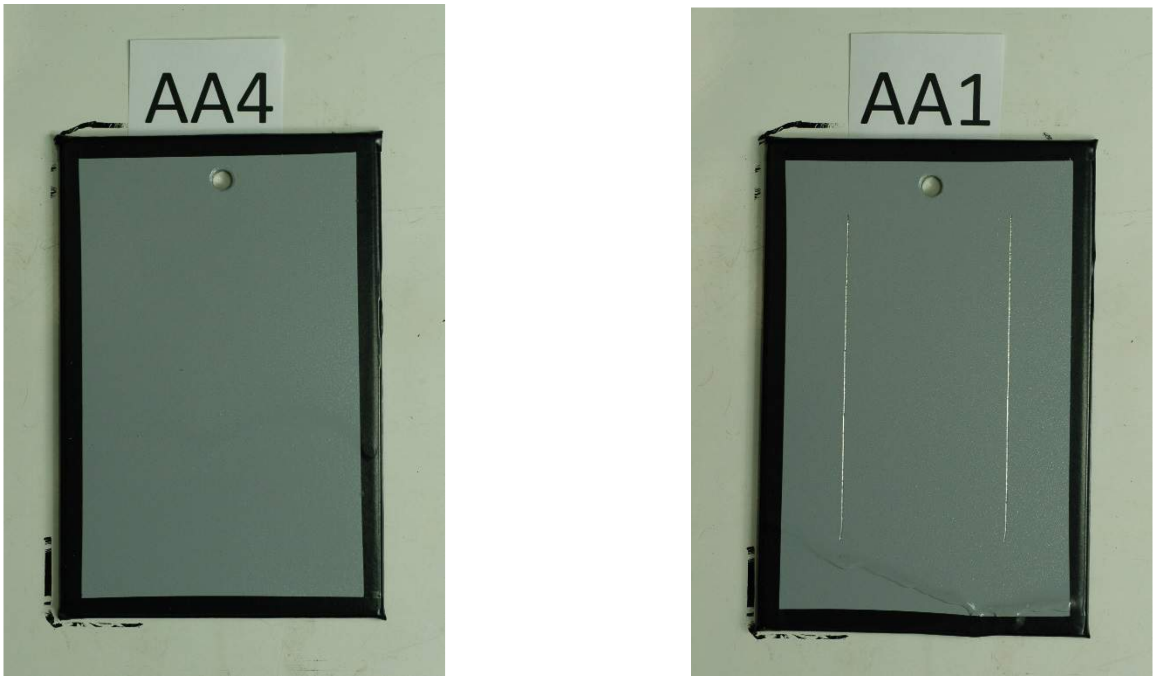


Figure 52. EDS Spectrum from Deposit in Pit of ASTM A606 Blasted Sample (Ref. 23)

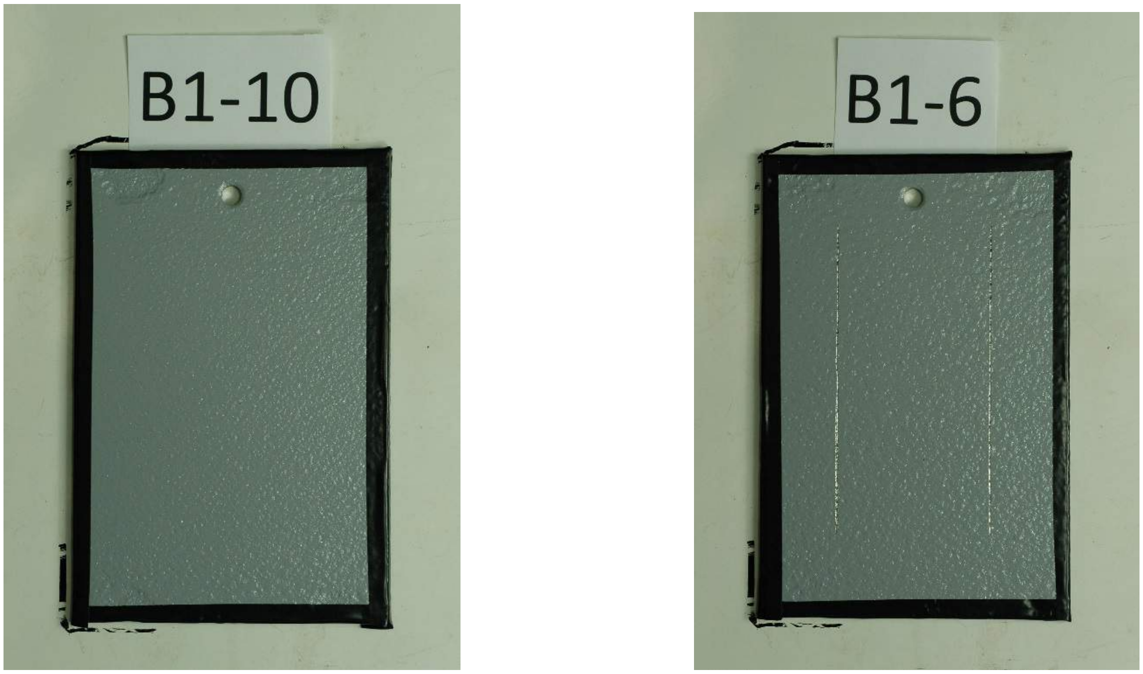


(a) (b)

Figure 53. New ASTM A36 Steel (Blasted) Panels Showing Barrier Coating in Un-Scribed (a) and Scribed (b) Condition.

(a) (b)

Figure 54. New ASTM A36 Steel (Blasted) Panels Showing Organic Zinc Coating in Un-Scribed (a) and Scribed (b) Condition

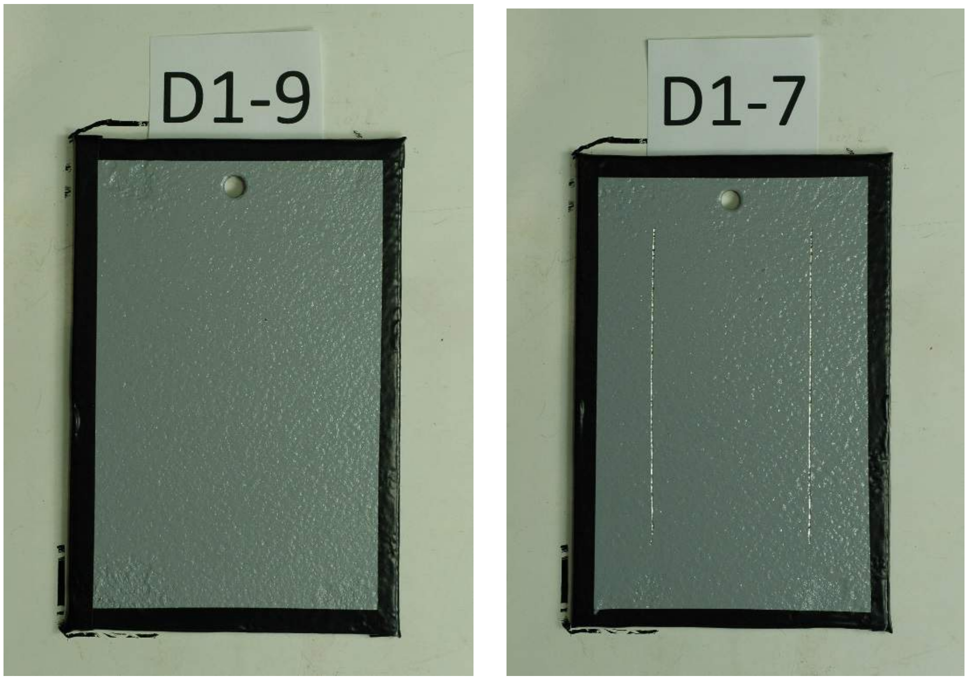


(a) (b)

Figure 55. Preconditioned ASTM A36 Steel (Blasted) Panels Showing Barrier Coating in Un-Scribed (a) and Scribed (b) Condition

(a) (b)

Figure 56. Preconditioned ASTM A36 Steel (Blasted) Showing Organic Zinc Coating in Un-Scribed (a) and Scribed (b) Condition

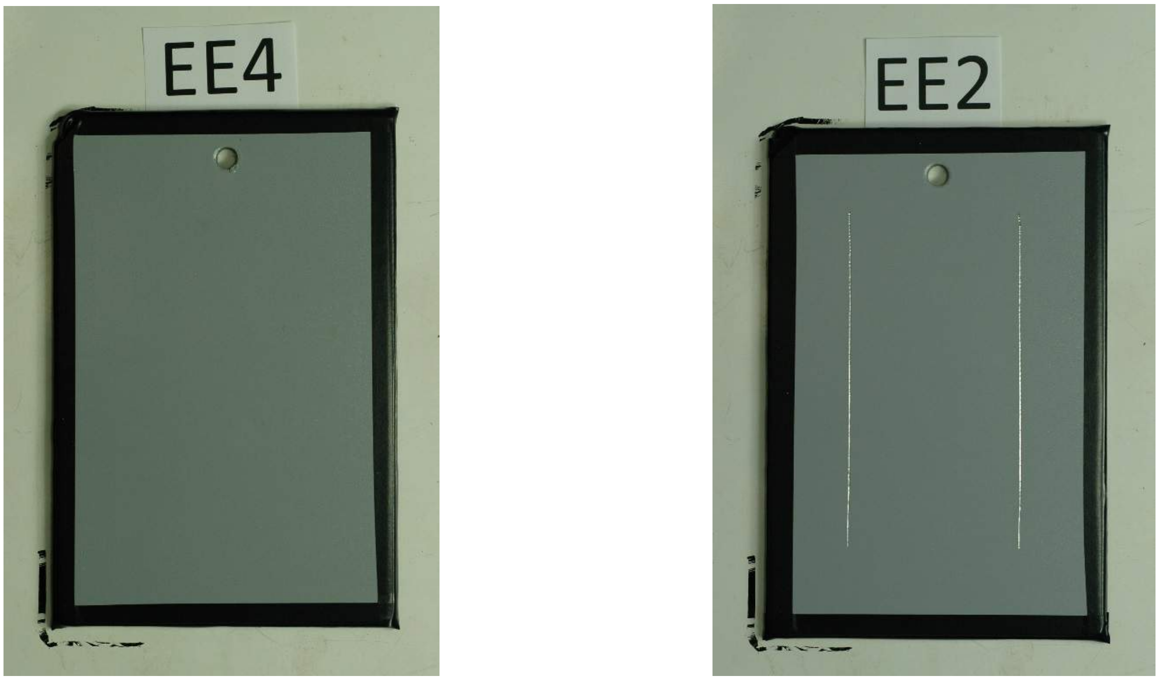


(a) (b)

Figure 57. Preconditioned ASTM A36 Steel (Blast and Pressure Washed) Showing Barrier Coating in Un-Scribed (a) and Scribed (b) Condition

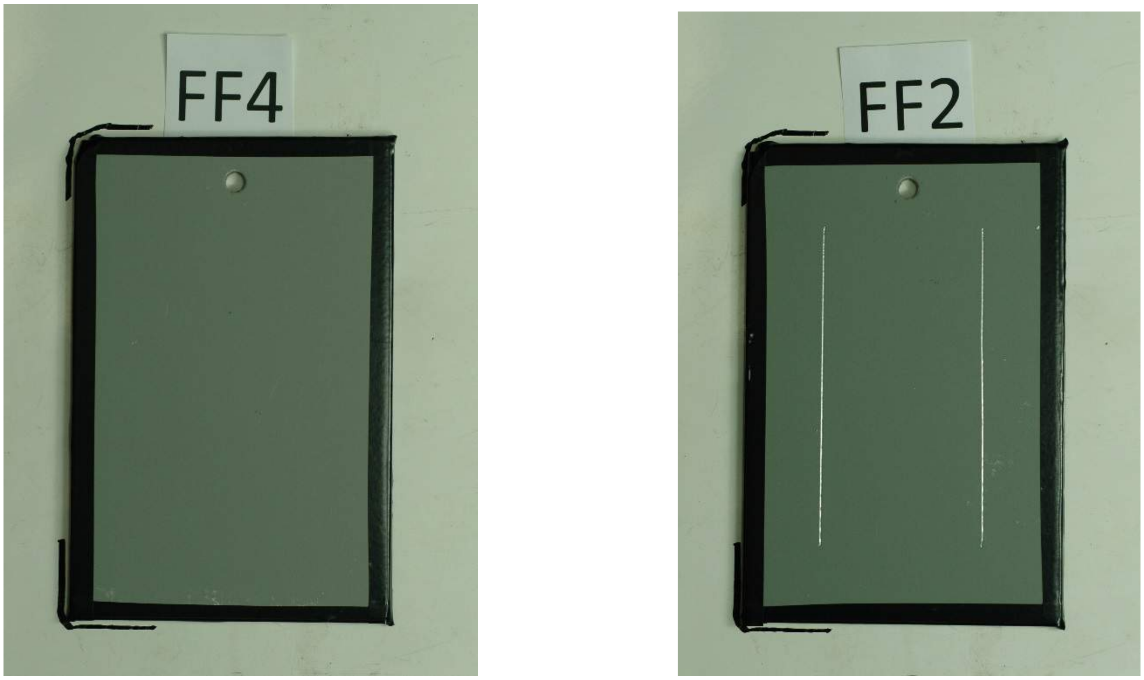
(a) (b)

Figure 58. Preconditioned ASTM A36 Steel (Blast and Pressure Washed) Showing Organic Zinc Coating in Un-Scribed (a) and Scribed (b) Condition



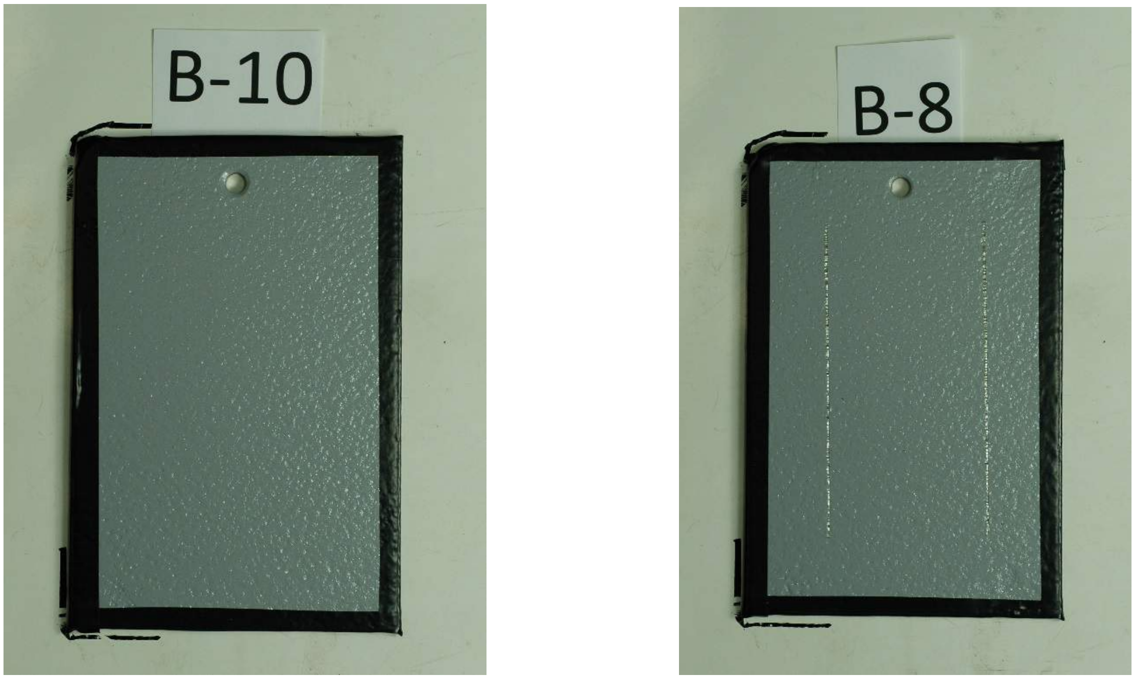
(a) (b)

Figure 59. New ASTM A606 Steel (Blasted) Panels Showing Barrier Coating in Un-Scribed (a) and Scribed (b) Condition



(a) (b)

Figure 60. New ASTM A606 Steel (Blasted) Panels Showing Organic Zinc Coating in Un-Scribed (a) and Scribed (b) Condition

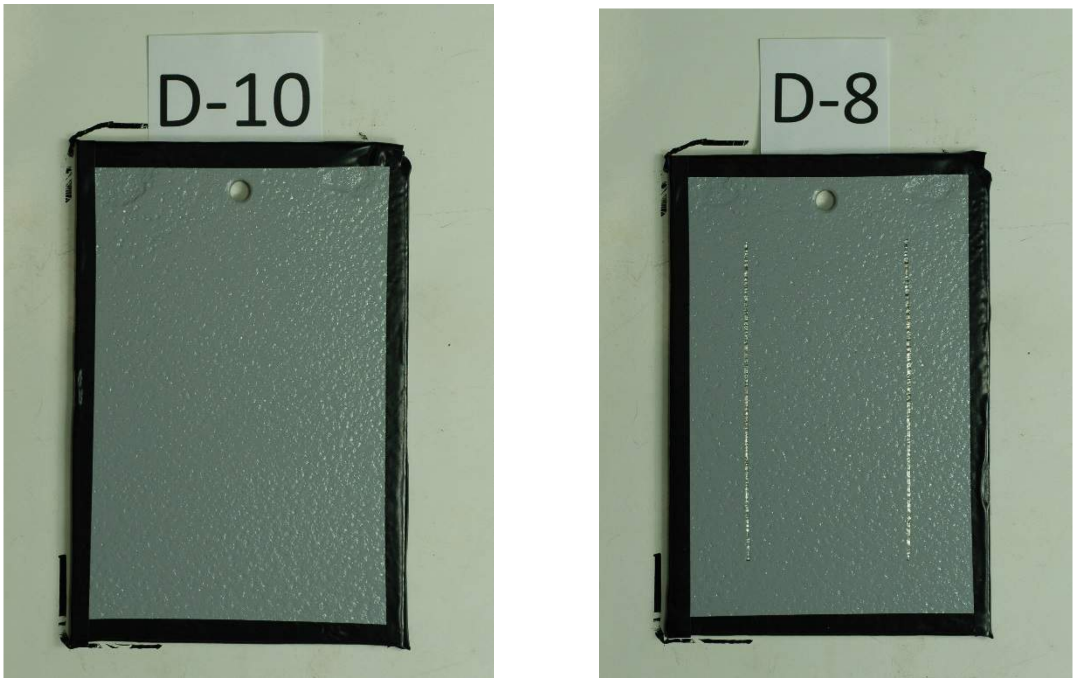


(a) (b)

Figure 62. Preconditioned ASTM A606 Steel (Blasted) Panels Showing Barrier Coating in Un-Scribed (a) and Scribed (b) Condition

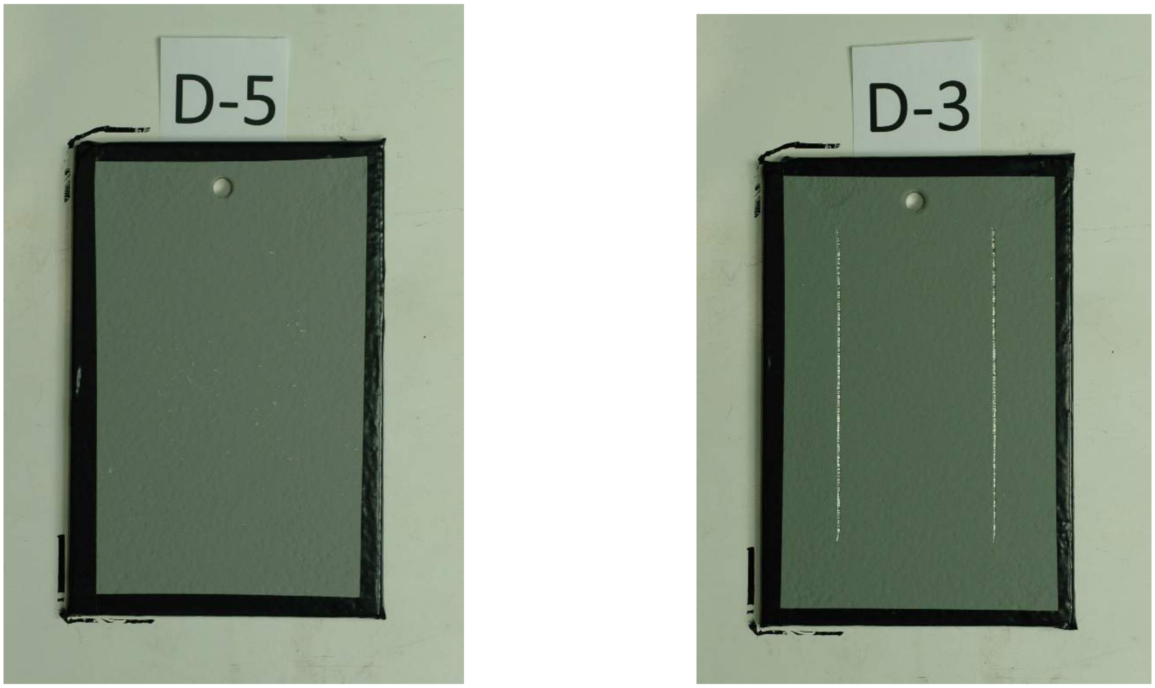
(a) (b)

Figure 63. Preconditioned ASTM A606 Steel (Blasted) Panels Showing Organic Zinc Coating in Un-Scribed (a) and Scribed (b) Condition



(a) (b)

Figure 64. Preconditioned ASTM A606 Steel (Blast and Pressure Washed) Panels Showing Barrier Coating in Un-Scribed (a) and Scribed (b) Condition



(a) (b)

Figure 65. Preconditioned ASTM A606 Steel (Blast and Pressure Washed) Panels Showing Barrier Coating in Un-Scribed (a) and Scribed (b) Condition

Figure 66. Half-Painted New ASTM A606 Steel (Blasted) Panel with Barrier Coating (Right Side of Panel)

Figure 67. Half-painted New ASTM A606 Steel (Blasted) Panel with Organic Zinc Coating (Left Side of Panel)

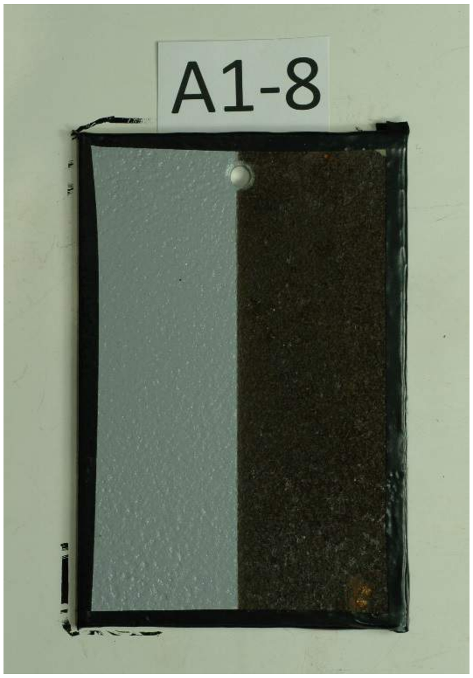


Figure 68. Half-Painted Preconditioned ASTM A36 Steel (Blasted) Panel with Barrier Coating (Left Side of Panel)

Figure 69. Half-Painted Preconditioned ASTM A36 Steel (Blasted) Panel with Organic Zinc Coating (Left Side of Panel)

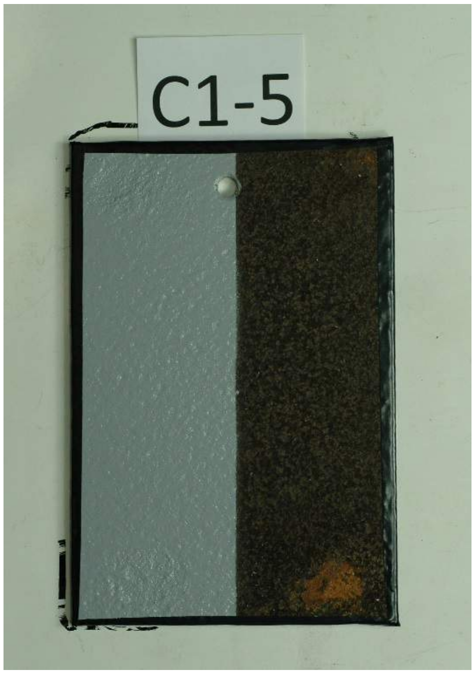


Figure 70. Half-Painted Preconditioned ASTM A36 Steel (Blast and Pressure Washed) Panel with Barrier Coating (Left Side of Panel)

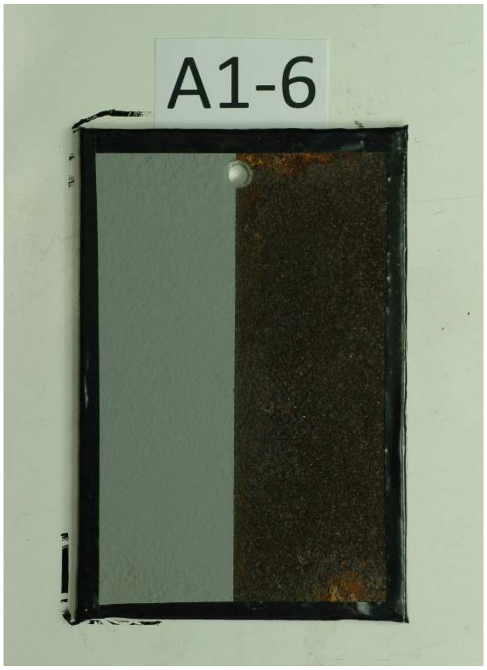


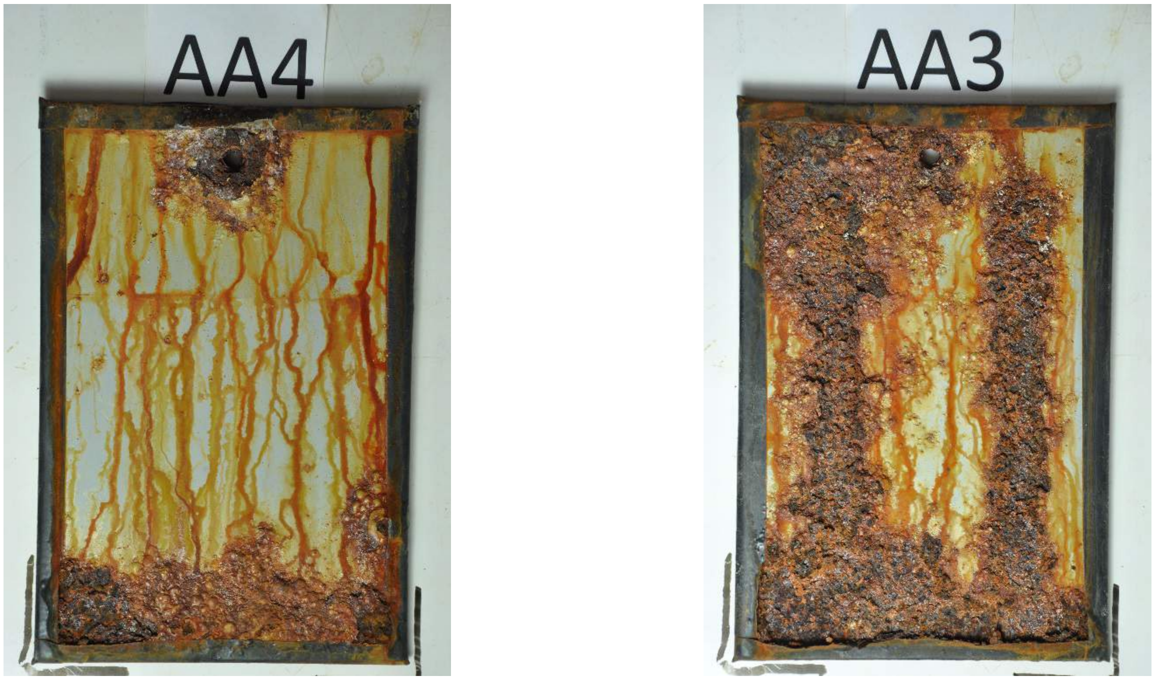
Figure 71. Half-Painted Preconditioned ASTM A36 Steel (Blast and Pressure Washed) Panel with Barrier Coating (Left Side of Panel)

Figure 72. Half-Painted Preconditioned ASTM A606 Steel (Blasted) Panel with Barrier Coating (Left Side of Panel)

Figure 73. Half-Painted Preconditioned ASTM A606 Steel (Blasted) Panel with Organic Zinc Coating (Left Side of Panel)

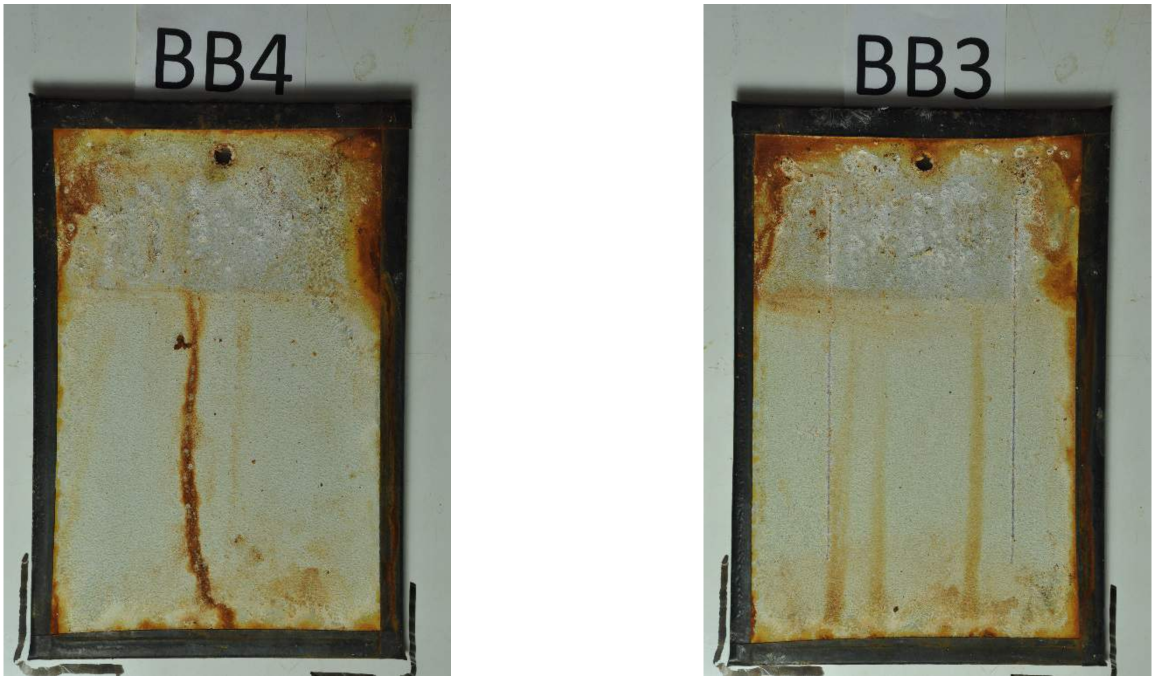
Figure 74. Half-Painted Preconditioned ASTM A606 Steel (Blast and Pressure Washed) Panel with Barrier Coating (Left Side of Panel)

Figure 75. Half-Painted Preconditioned ASTM A606 Steel (Blast and Pressure Washed) Panel with Organic Zinc Coating (Left Side of Panel)



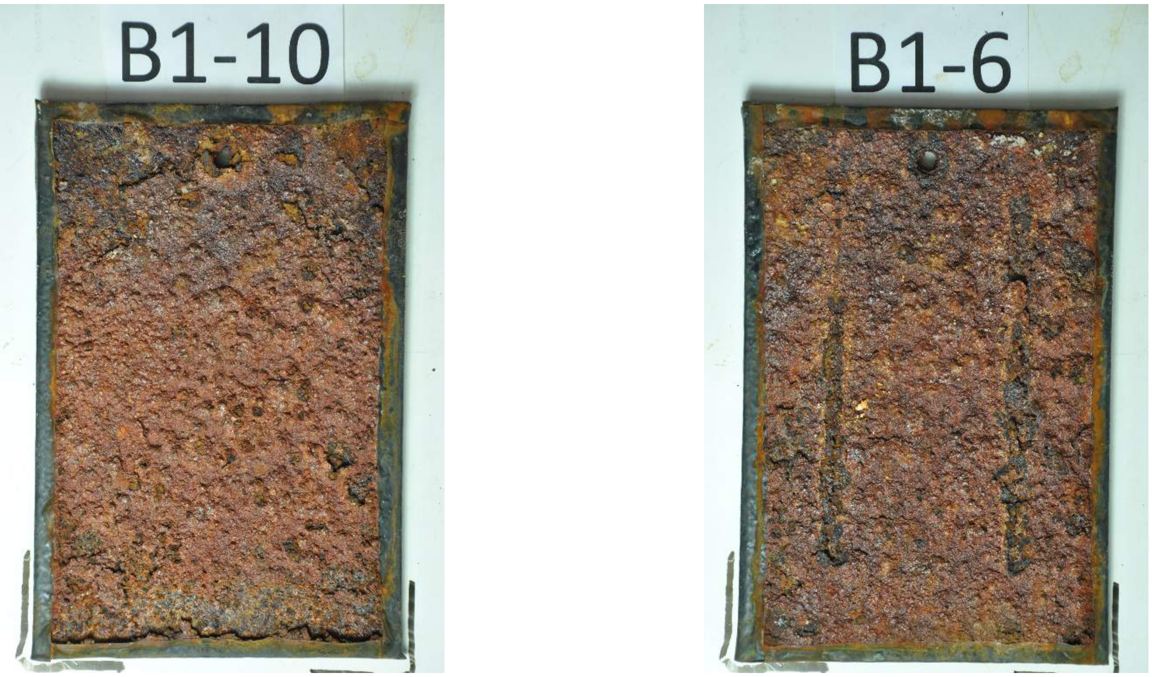
(a) (b)

Figure 76. New ASTM A36 Steel (Blasted) Panels Showing Barrier Coating in Un-Scribed (a) and Scribed (b) Conditions after 5,000 Hours of Testing



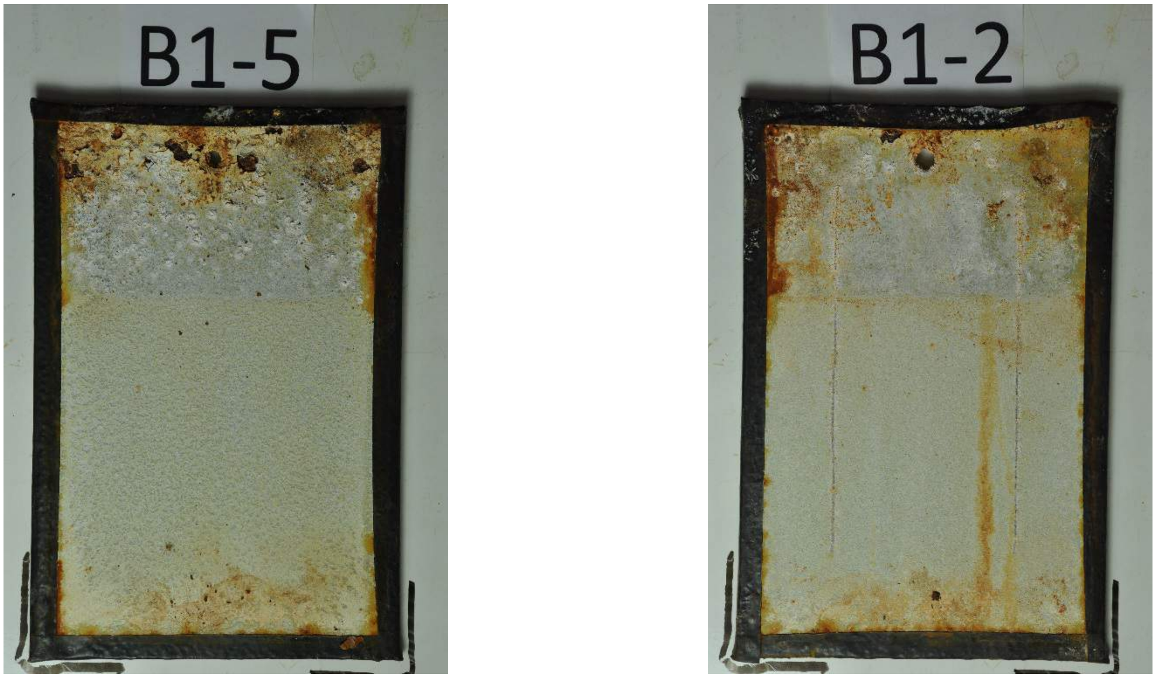
(a) (b)

Figure 77. New ASTM A36 Steel (Blasted) Panels Showing Organic Zinc Coating in Un-Scribed (a) and Scribed (b) Conditions after 5,000 Hours of Testing



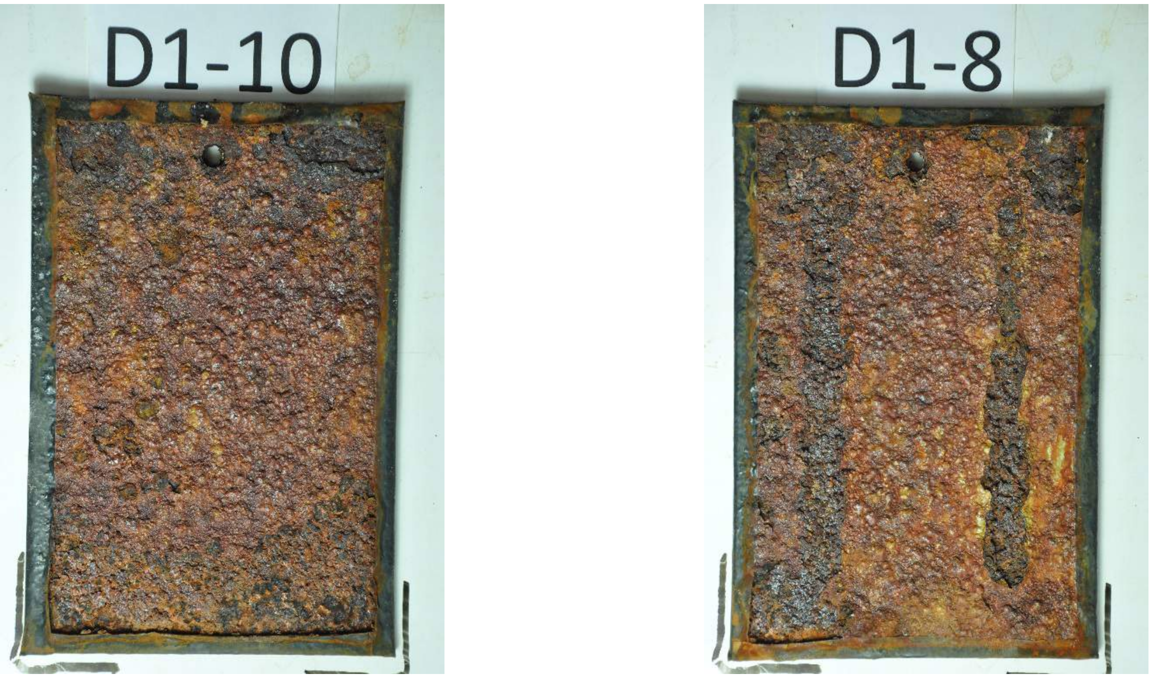
(a) (b)

Figure 78. Preconditioned ASTM A36 Steel (Blasted) Panels Showing Barrier Coating in Un-Scribed (a) and Scribed (b) Conditions after 5,000 Hours of Testing



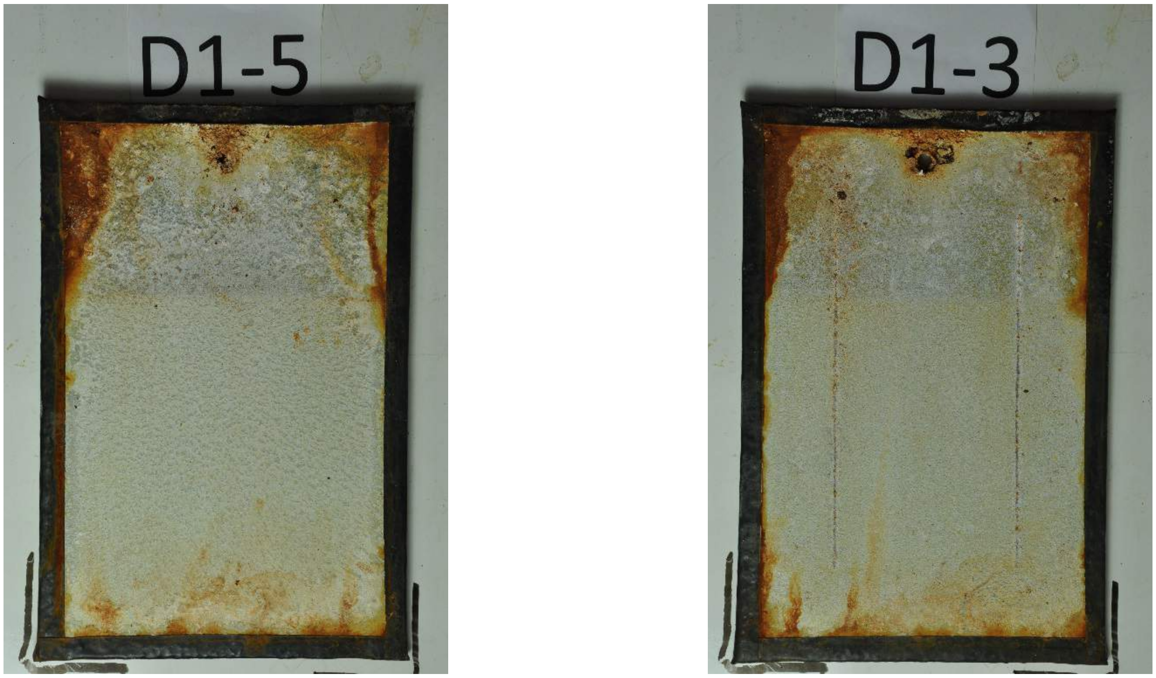
(a) (b)

Figure 79. Preconditioned ASTM A36 Steel (Blasted) Panels Showing Organic Zinc Coating in Un-Scribed (a) and Scribed (b) Conditions after 5,000 Hours of Testing



(a) (b)

Figure 80. Preconditioned ASTM A36 Steel (Blast and Pressure Washed) Panels Showing Barrier Coating in Un-Scribed (a) and Scribed (b) Conditions after 5,000 Hours of Testing.

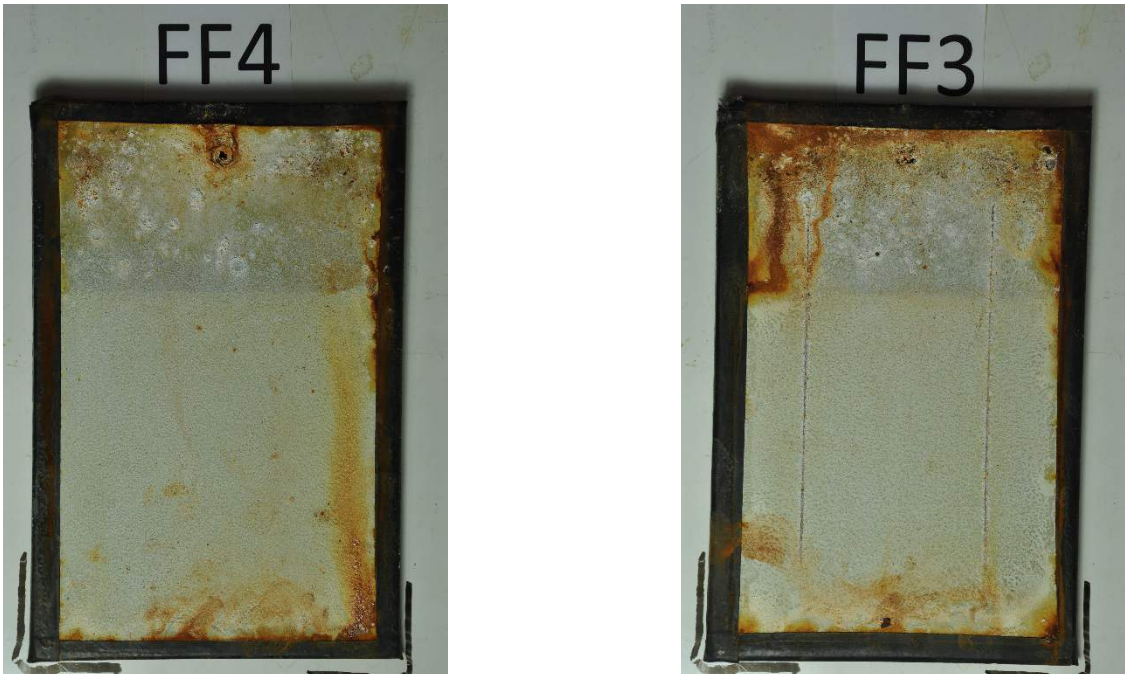


(a) (b)

Figure 81. Preconditioned ASTM A36 Steel (Blast and Pressure Washed) Panels Showing Organic Zinc Coating in Un-Scribed (a) and Scribed (b) Conditions after 5,000 Hours of Testing

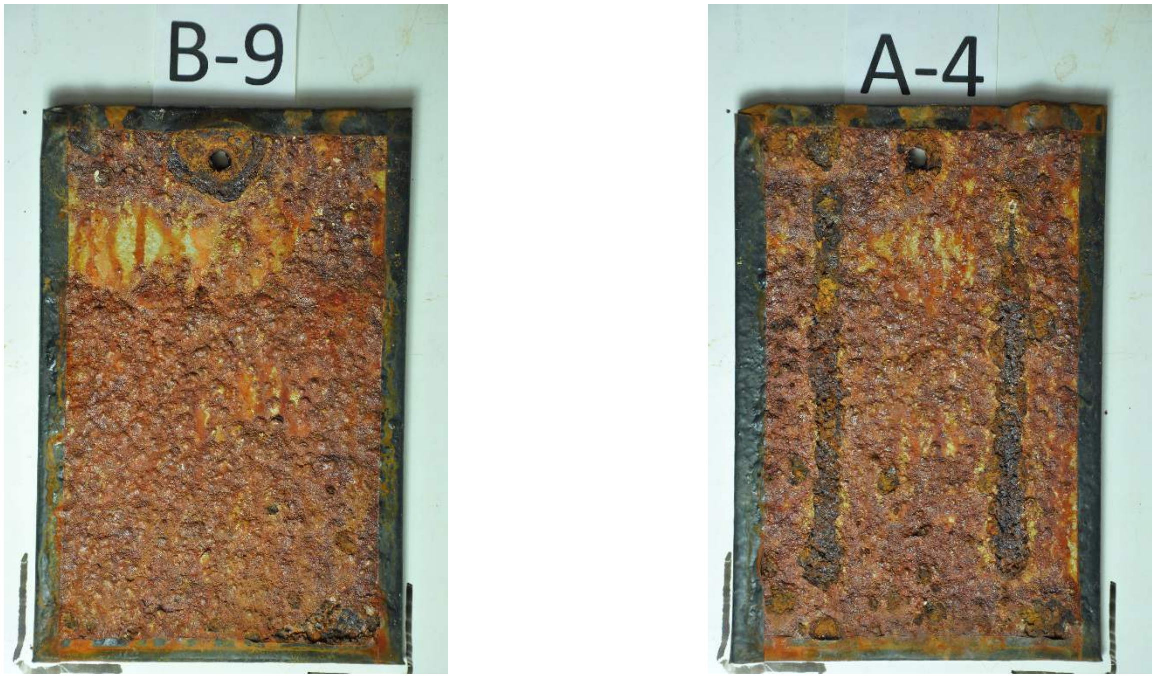
(a) (b)

Figure 82. New ASTM A606 Steel (Blasted) Panels Showing Barrier Coating in Un-Scribed (a) and Scribed (b) Conditions after 5,000 Hours of Testing



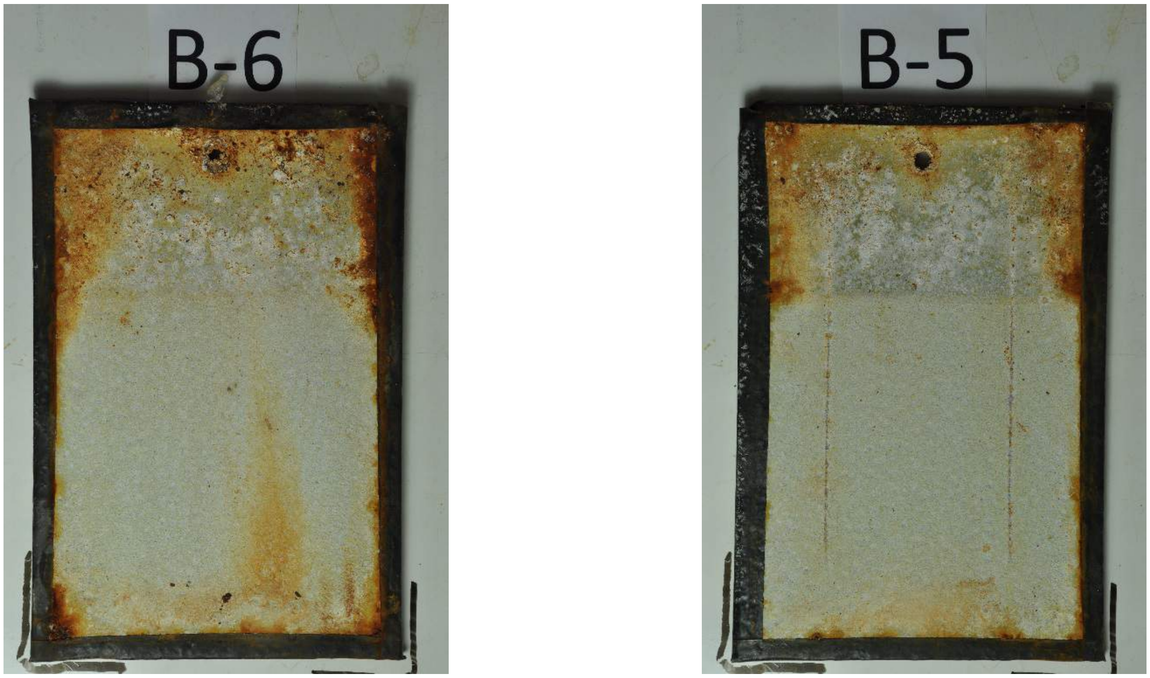
(a) (b)

Figure 83. New ASTM A606 Steel (Blasted) Panels Showing Organic Zinc Coating in Un-Scribed (a) and Scribed (b) Conditions after 5,000 Hours of Testing



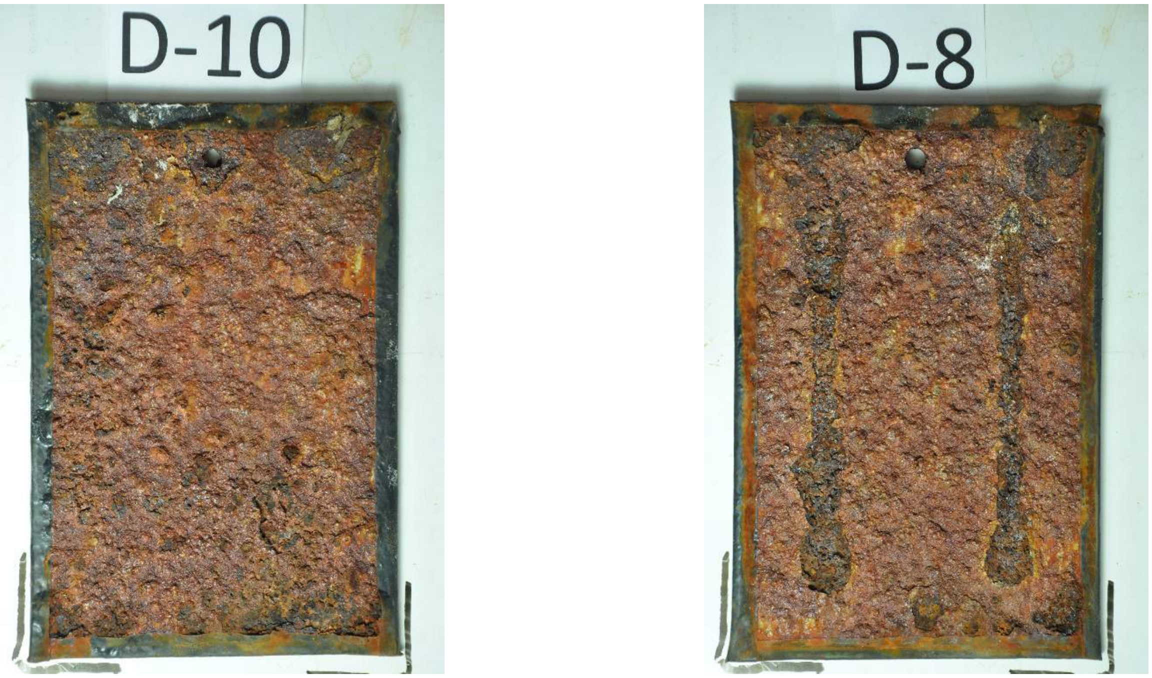
(a) (b)

Figure 84. Preconditioned ASTM A606 Steel (Blasted) Panels Showing Barrier Coating in Un-Scribed (a) and Scribed (b) Conditions after 5,000 Hours of Testing



(a) (b)

Figure 85. Preconditioned ASTM A606 Steel (Blasted) Panels Showing Organic Zinc Coating in Un-Scribed (a) and Scribed (b) Conditions after 5,000 Hours of Testing



(a) (b)

Figure 86. Preconditioned ASTM A606 Steel (Blast and Pressure Washed) Panels Showing Barrier Coating in Un-Scribed (a) and Scribed (b) Conditions after 5,000 Hours of Testing

Figure 87. Half-painted New ASTM A606 Steel (Blasted) Panel with Barrier Coating (Right Side of Panel) after 5,000 Hours of Testing

Figure 88. Half-Painted New ASTM A606 Steel (Blasted) Panel with Organic Zinc Coating (Left Side of Panel) after 5,000 Hours of Testing

Figure 89. Half-Painted Preconditioned ASTM A36 Steel (Blasted) Panel with Barrier Coating (Left Side of Panel) after 5,000 Hours of Testing

Figure 90. Half-Painted Preconditioned ASTM A36 Steel (Blasted) Panel with Organic Zinc Coating (Left Side of Panel) after 5,000 Hours of Testing

Figure 91. Half-Painted Preconditioned ASTM A36 Steel (Blast and Pressure Washed) Panel with Barrier Coating (Left Side of Panel) after 5,000 Hours of Testing.

Figure 92. Half-Painted Preconditioned ASTM A36 (Blast and Pressure Washed) Steel Panel with Organic Zinc Coating (Left Side of Panel) after 5,000 Hours of Testing

Figure 93. Half-Painted Preconditioned ASTM A606 Steel (Blasted) Panel with Barrier Coating (Left Side of Panel) after 5,000 Hours of Testing

Figure 94. Half-Painted Preconditioned ASTM A606 Steel (Blasted) Panel with Organic Zinc Coating (Left Side of Panel) after 5,000 Hours of Testing

Figure 95. Half-Painted Preconditioned ASTM A606 Steel (Blast and Pressure Washed) Panel with Barrier Coating (Left Side of Panel) after 5,000 Hours of Testing

Figure 96. Half-Painted Preconditioned ASTM A606 Steel (Blast and Pressure Washed) Panel with Organic Zinc Coating (Left Side of Panel) after 5,000 Hours of Testing.